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Natural resource management for poverty reduction and environmental sustainability in fragile rice-based systems

S.M. Haefele and A.M. Ismail, Editors

IRRI
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Contents

Preface

Rice is the major staple food in Asia, and about 95% of the world's rice is produced in the region. While much of the rice is produced in irrigated environments, the rice-based systems of the less favorable rainfed rice environments provide the livelihoods for 100 million farm families. Due to the low and unstable productivity levels in many of these rainfed areas, poverty is widespread. In addition, drastic weather events such as flooding or drought can have further destabilizing, long-term effects on poor communities. Thus, in a typical drought year, for example, food consumption is reduced, indebtedness is increased, assets are sold, and household members might migrate. Further on, the risk caused by such weather events reduces productivity, even in nonaffected years, because farmers avoid investing when they fear crop loss. Overcoming constraints and improving the productivity of the rainfed systems will make a substantial improvement to the livelihoods of many of the region's rural poor.

The two principal rainfed rice systems commonly distinguished are rainfed uplands and rainfed lowlands. Upland rice systems are grown on about 9 million ha in Asia, mostly on sloping land or on plateau uplands, and fields are not usually flooded. Upland rice commonly suffers from multiple constraints, including drought, high weed and disease pressure, and poor soils. Average yields are consequently only about 1 t ha^{-1}. Rainfed lowland rice in Asia covers about 46 million ha—i.e., almost 30% of the total rice area worldwide. Although this system includes favorable environments with conditions similar to irrigated systems, most areas face various biophysical constraints to rice production. The most important constraints include drought, flooding, salinity and other adverse soil conditions, pests and weeds, and average yields are about 2 t ha^{-1}.

Developing appropriate technologies for such disadvantaged areas and making options available to farmers are the main goals of the Consortium for Unfavorable Rice Environments (CURE). CURE is a regional platform led by national agricultural research and extension systems (NARES) comprising institutions from South and Southeast Asian countries together with the International Rice Research Institute (IRRI) as the coordinating hub. As a "network of national networks," CURE facilitates sharing of scientific knowledge, technology products, and information among the network members. Targeted technologies integrate improved germplasm with suitable crop and resource management options. The complexity and high variability of rainfed systems require flexible resource management options and related decision support tools to improve local decision making, according to the characteristics of the farm environments. Participatory approaches, incorporating contributions from farmers and extension staff, are a fundamental component of CURE's approach.

The main objectives of the CURE strategy are to reduce production risk, improve productivity, and increase crop diversity at the farm level. Given the importance of rice as a staple crop providing household food security, interventions that increase rice productivity can serve as a critical entry point in initiating and reinforcing agricultural growth and income generation. Technologies that reduce production risk caused by, for example, drought or flooding will favor input use and can have a major impact on system productivity. Improved rice technologies that reduce labor and land requirements for crops are needed to allow these resources to be released for other income-generating activities. And once rural households are able to grow enough food for their consumption, farmers will diversify their resources into other on-farm and nonfarm activities.

CURE members are working toward technologies, understanding, and knowledge that target the above objectives, and believe that sustainable productivity increases are realistic goals in most rainfed environments. Productivity increases in these agroecosystems will, in turn, have a substantial impact on poverty reduction in rural Asia. Increases in marginal productivity due to improved varieties and better resource management are often greater in low-potential than in high-potential systems. Accordingly, studies in India concluded that the marginal returns from government investments in technology and infrastructure are highest in unfavorable rainfed areas. Further, the vulnerability of people living in these regions has been amplified by the effects of the recent economic crisis, which, together with rising food prices and extreme weather events, have caused substantial increases in the incidence of poverty and even hunger.

This publication documents progress in the development of crop and natural resource management options within CURE over the past 5 yr. It brings together the studies presented at a workshop conducted in conjunction with the Fifth Annual Meeting of the Steering Committee of the CURE, 2006 Mar 6-7, at the BRAC Center in Dhaka. The papers are organized along the structure of CURE consisting of four working groups. The first two contributions provide an overview of current achievements and strategic approaches in the rainfed upland systems. This is followed by five papers focus on the drought-prone lowlands, which range in topics from principles of germplasm development for this environment to suitable management interventions such as direct seeding and fertilizer management to the analysis of diversification patterns in India. The subsequent three papers give an overview of ongoing work in submergence and flood-prone areas, where the introduction of submergence-tolerant germplasm could make an immense impact. The final section discusses the considerable progress possible in saline areas with a focus on coastal salinity, rice intensification, and diversified systems. It is hoped that these papers will contribute to the wider dissemination of knowledge and understanding of the improvements possible in these systems and of the scope to raise livelihoods of those that depend on these rice environments.

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Upland ecosystems

Food security, poverty, and environmental sustainability in the uplands: the strategic role of rice research

S. Pandey

The Green Revolution in irrigated areas of Asia led to a rapid growth in food productivity during the past four decades. The resulting increase in food production has been a major factor in reducing poverty and improving food security of the growing population. Many Asian countries are now self-sufficient or are close to being self-sufficient in food at the national level. While increases in production are still needed to meet the future demand of the growing Asian population, the prime justification for agricultural research is not just to 'increase the pile of food.' The major goal of agricultural research now is to encourage inclusive, equitable, and sustainable development through generation of technologies that help reduce poverty and protect the environment. This rationale is well-articulated in the report of the Task Force on Hunger (UN 2005) and is encapsulated in the millennium development goals (MDGs) of the United Nations.

It is argued in the report of the Task Force on Hunger that the MDG goal of halving the poverty by 2015 is unlikely to be achieved without targeted efforts to directly address the problems in hunger and poverty "hotspots." These are the areas where extreme hunger and poverty persist even though, at the national level, substantial growth in agricultural production has been achieved. In other words, these are the areas where the effects of growth in other parts of the country have not "trickled down." According to the Task Force on Hunger, "majority of hunger hotspots are located in rural areas with poor access to markets." In Asia alone, the Task Force has identified 76 such hotspots, accounting for more than 78 million malnourished children. These are typically mountainous upland areas or other locations that are remote and have poor marketing infrastructure. As a result, people in such areas are not able to participate in and benefit from the wider economic growth of the nation.

Much of the Asian uplands have the characteristics of these "hotspots." Rural people in these uplands suffer from severe poverty and food insecurity. For example, the incidence of poverty in the uplands is 52% in Lao PDR, 59% in Vietnam, 68% in Nepal, and 45% in northeastern India. These poverty rates are much higher than the corresponding national averages. In addition, poverty is much deeper in these locations (Minot et al 2003, Pandey et al 2006a). As an example, in remote regions of northern Vietnam, rice production is insufficient to meet consumption requirements of almost one-third of the households (Pandey et al 2006a), despite the fact that Vietnam is now a major rice-exporting country. A similar situation exists in the uplands of other countries such as Laos, Nepal, India, and Vietnam.

Many upland farmers belong to minority ethnic groups that are economically and socially marginalized. These upland communities are caught up in a doubly reinforcing vicious cycle (Fig. 1) that perpetuates poverty, food insecurity, and environmental degradation. The outer cycle is a familiar one that operates powerfully through the effect of rising population on environmental degradation as fragile marginal lands are more intensively cultivated. This leads to a further reduction in productivity and perpetuates the cycle. The second (inner cycle) operates through the lack of income-earning opportunities due

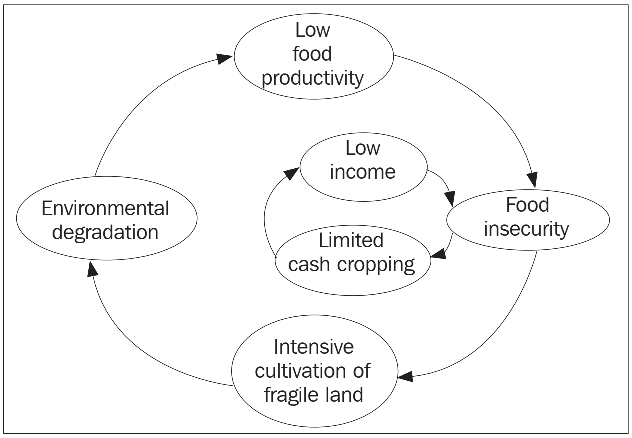

Fig. 1. Vicious cycle of low productivity, food insecurity, and environmental degradation.

to poor access to markets. Farmers use most of their land and labor resources to meet food needs by practicing subsistence agriculture. As a result, they have very few resources left to take advantage of whatever limited income-earning opportunities that may exist.

Mountainous uplands have important roles as these areas are rich in biodiversity—both in flora and fauna. These are also the catchments for many rivers that provide water for agricultural and other uses downstream. Forested areas are important sinks for carbon dioxide, which is a major greenhouse gas. However, some of these important ecological functions are likely to be adversely affected by agriculture. For example, the negative environmental effects of agriculture based on slash-and-burn practices in the forest margins are important concerns. Obviously, agricultural practices that have either benign or positive effects on the environment are needed for promoting sustainable growth.

There has been a sea-change in the attitude of national governments and international development communities regarding the need for a sustainable development of the uplands. The earlier policies were aimed mainly at extracting the natural resources from these upland areas that often presented political challenges to the national governments. Development of upland areas inhabited mainly by minority ethnic groups, who were mostly outside the mainstream of political process, was not the primary concern. However, the realization that an inequitable regional growth is unsustainable and that environmental protection of the uplands is important for the overall long-term growth of the country has led to a change in the policy of national governments towards uplands. There are increasing evidences that the marginal rate of return in agricultural research and investment may now be higher in unfavorable environments than in favorable irrigated environments (Fan et al 2000). In addition, the effect of agricultural research and investment in poverty reduction in these marginal areas has been found to be substantial (Fan et al 2003). Upland development agenda are now conspicuous in development strategies of various countries.

Uplands and upland rice: an overview

Upland agriculture is practiced in nonirrigated fields without impounded surface water. This widely occurs in mountainous areas but not exclusively so. Upland conditions may occur in lower elevations also. Similarly, upland areas do not have to be sloping, they can be flat also, as is the case of much of South Asian uplands. Upland rice is dryland rice grown in soils that do not hold rainwater for a considerable period of time. After the rains, water drains out of these fields fairly rapidly, so that crops grow in soils that are "aerobic" and in hydrological conditions similar to those for other upland crops such as wheat and maize.

Upland rice is grown in about 14 million ha worldwide. It accounts for about 11% of the world rice area and contributes to 4% of the total rice output. Of the 14 million ha of upland rice area, Asia accounts for two-thirds with Latin America and Africa having an equal proportion of the remainder (Fig. 2). Of the 9 million ha of upland rice area in Asia, South Asia accounts for about 60%, with the remainder being in Southeast Asia. As upland rice is mostly grown in rotation with other crops in Southeast Asia where shifting cultivation is practiced, the actual area under upland rice-based systems is much larger. Assuming a 3-yr rotation, the total area under upland rice-based systems in Asia is estimated to be about 15 million ha. About 50 million people are dependent on these systems for their livelihoods.

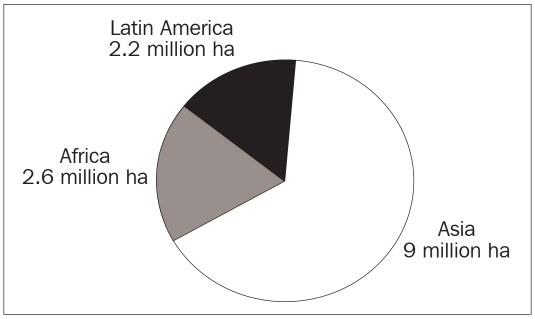

Fig. 2. Upland rice area, by region.

Upland rice systems are highly heterogeneous with the climate varying from humid to subhumid and the soils varying from fertile to highly infertile. Upland rice is also grown in flat to steeply sloping areas. Cultivation practice ranges from shifting to permanent cultivation. In Sri Lanka, Bangladesh, and India, most of the upland rice is grown under permanent cultivation systems. Shifting cultivation is more common in Laos, Vietnam, northeastern India, and Indonesia.

The growth rate in the yield of upland rice has been modest during the past 25 yr, indicating that the Green Revolution that led to a rapid growth in yield in irrigated areas has had almost no direct impact on rice productivity in the Asian uplands. Upland rice production practices have changed little, except in some pockets such as in southern Yunnan, with farmers mostly growing traditional varieties. The low observed yields, however, do not imply that high yields cannot be achieved when the crop is managed properly and some fertilizers are applied (George et al 2001).

The crops grown in the uplands vary considerably and upland rice farmers grow a range of crops such as maize, millet, yam, beans, and cassava. Upland rice is grown as a monocrop or as an intercrop. Despite this diversity, a general feature of the upland system is that it is inhabited by very poor farmers who grow food crops mainly for subsistence using very few inputs other than labor.

Rice is a crucial component of the diet of upland households. Yields are generally low, however, and at the aggregate level, the average yield of upland rice in Asia (1 t ha^{-1}) is much lower than that for irrigated (5 t ha^{-1}) and rainfed lowlands (2.3 t ha^{-1}).

Upland rice-based systems in transition

Historical evidence indicates that population density and market access are two important variables that determine the overall nature of agricultural production systems. A simplified typology of upland systems can be developed on the basis of these two major driving forces (Fig. 3). When population density is low and market access is limited, returns to labor are maximized by adopting an extensive land use strategy, such as shifting cultivation based on long fallow periods (mostly longer than 15 yr). The response to an increase in population in such situations will be a further expansion of shifting cultivation since the land is nonlimiting. However, when the land frontier is closed, further increases in population pressure provide incentives for intensified agricultural production. Farmers intensify land use by reducing the fallow period to 3-5 yr (Type 1). This type of production system accounts for about 14% of the Asian upland rice area and is mostly limited to the uplands of Laos, northeastern India, and Vietnam.

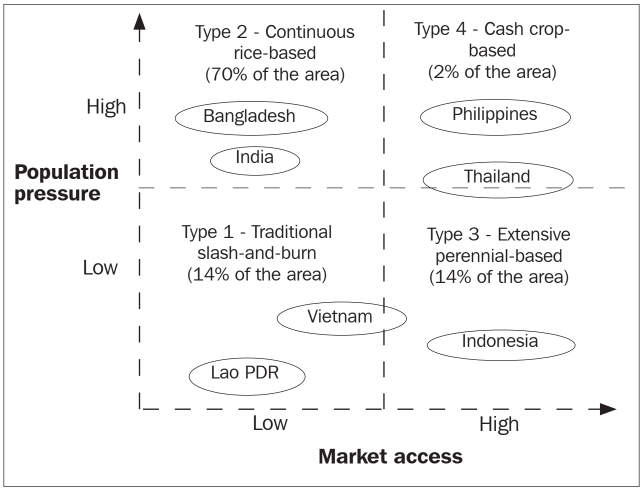

Fig. 3. Typology of uplands in Asia (adapted from Pandey 2000a).

Increasing population pressure when the land frontier is closed results in the intensification of land use by reducing the fallow period and ultimately a transition to a permanent system (Type 2) where rice is grown every year occurs. As market access is limited, farmers attempt to be self-sufficient by producing a range of agricultural outputs and the production system remains subsistence-oriented. Rice production becomes closely integrated with other crops and livestock in such systems. Upland production systems in densely populated areas of South Asia can be considered to belong to this category. This type of production system is currently the dominant one and occupies about 70% of the upland rice area in Asia.

With improvements in market access, upland farmers integrate various cash crops in their rice production systems. In areas with low population pressure, production systems tend to be somewhat extensive with perennials, such as oil palm and rubber, being important cash crops (Type 3). Upland rice is grown on separate fields or in the empty space in between the rows of young perennial crops. Upland rice production in Sumatra, Indonesia, provides a good example of this system. Where population density is higher and strong market demand from nearby urban centers exists, farmers tend to grow labor-intensive cash crops such as vegetables (Type 4). This type of upland rice system is mostly limited to the Philippines and northern Thailand and accounts for about 2% of the rice area. The upland rice systems of Yunnan where high-yielding rice is grown in intensive continuous cropping system that also includes various cash crops have Type 2 and Type 4 features.

As a result of transition to market-oriented systems, upland rice area has decreased in various countries during the past couple of decades. A major shift out of upland rice has occurred in the Philippines and Thailand, with the area of upland rice in these countries now being very small. On the other hand, upland rice area in India and Indonesia has remained fairly stable. In the case of Laos and Vietnam, there has been some decline due to the government policy of discouraging the production of upland rice.

Why do farmers grow upland rice?

Despite its low yield and high labor intensity, farmers continue to grow upland rice, which highlights the role of upland rice in farmers' livelihood systems. There are at least six reasons why farmers grow upland rice (Pandey 2000b).

Resource base

Upland fields represent the major land endowments of upland farmers. For example, in northern Vietnam, uplands account for as much as 83% of the farm and contribute to more than half of the household rice supply (Pandey et al 2006a). Rice production in the uplands is a part of the farmers' livelihood systems, especially for those who have very limited access to irrigated land.

It has been observed that, in Laos, even those farmers who have sufficiently large irrigated fields tend to grow some upland rice (Souvanthong 1995). There may be several reasons for this. An important factor is the spread of labor use. Upland rice is normally established and harvested earlier than lowland rice, and hence, by growing both upland and lowland rice, farmers are able to spread labor use over a longer span and avoid labor bottlenecks.

"Hungry months"

In most parts of South and Southeast Asia, upland rice is normally harvested about a month earlier than lowland rice. Typically, upland rice is harvested in September while the harvest of main-season lowland rice starts in October/November. Even though the output of upland rice may be small, it serves the important role of supplying the family food needs during these "hungry months" of September/October when the previous year's food stock has been exhausted and the lowland crop of the current year is yet to be harvested. *Upland rice plays an important role in bridging the gap in food supply during these critical months. This "time value" of upland rice has not been adequately recognized in research and policy circles where importance is often judged in terms of quantitative indicators such as area or production.*

This "bridging" role of upland rice is clearly illustrated by the consumption data from Batangas, Philippines, where upland rice is grown along with cash crops such as coconut and

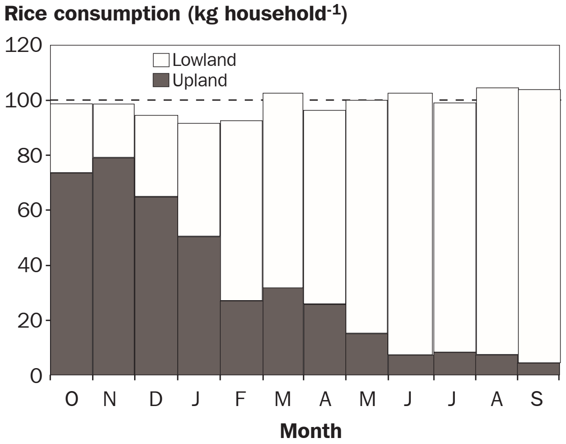

Fig. 4. Time pattern of consumption of upland and lowland rice in Batangas, Philippines (Pandey 2000b)

sugarcane (Fig. 4). Upland rice is the main food during October/November. After lowland rice is harvested in November, its share in the total rice consumed increases as it becomes the dominant source. A similar pattern of consumption is observed in eastern India, Nepal, and Vietnam.

Low opportunity cost of labor and land

In upland areas with low access to markets, the opportunity cost of family labor tends to be low due to limited gainful employment opportunities (farm or nonfarm). Similarly, the opportunity cost of land tends to be low as it is used mostly for subsistence production. Under such conditions, it makes economic sense to use family labor and land to produce upland rice for subsistence rather than to purchase rice in the market. In addition, a market-based strategy for meeting the food needs is not viable as farmers do not have adequate purchasing power due to lack of income. The importance of upland rice may change with increases in the opportunity costs of land and labor as market linkages develop. However, as mentioned in the previous section, upland rice area in Asia has remained more or less stable over the past several decades, except in the Philippines and Thailand.

Price risk

Reliance on market-based strategy for meeting food needs can expose farmers to unacceptable levels of risk if the price of cash crops is volatile. *The avoidance of this price risk is one of the major reasons for subsistence production of food grains.* In addition, food markets in developing countries tend to be thin and isolated due to high transport cost and low agricultural productivity. Production of upland rice in a large proportion of farm in remote locations is a strategy to protect against this price risk (Fafchamps 1992).

Preference of ethnic minorities

Production of upland rice is a way of life for many ethnic minority groups who inhabit the mountainous areas. Even in highly commercialized production systems, ethnic minority groups continue growing upland rice. However, this motivation probably accounts for a very small proportion of upland rice area.

Quality and suitability to alternative use

Traditional varieties of upland rice are believed to be of higher quality than lowland rice in many cultures. Even those farmers who have adequate quantity of lowland rice still produce some upland rice for its quality. For commercial farmers, this also could give some price premium in the market, even though yields are lower. In addition, upland rice is believed to be more suitable for certain uses such as for festivals and for making special products like rice cakes, beaten rice, and rice wines.

Rice research: a critical entry point for poverty reduction in the uplands

Rice is an important staple of upland inhabitants. More than 40 million people depend directly on growing rice for their food needs in the marginal agricultural uplands of South and Southeast Asia. Lack of income and high transportation cost associated with making purchases from outside make subsistence-oriented production of rice an economically rational strategy for upland farmers. As poor farmers typically equate food security with rice self-sufficiency, they tend to devote their land and labor to rice production until household rice needs are met, leaving few or no resources for generating cash incomes. Therefore, helping farmers produce rice more efficiently is a key entry point for developing an improved livelihood system based on a firm foundation of food security. Improvements in land and labor productivity are thus needed to convert the double vicious cycle mentioned earlier to a self-reinforcing double virtuous cycle (Fig. 5). Higher rice productivity will help release resources (both land and labor) needed to facilitate the process of income generation, which is an important exit pathway from poverty. Increased productivity will also reduce the pressure to expand cultivation to fragile marginal areas, thus generating environmental benefits.

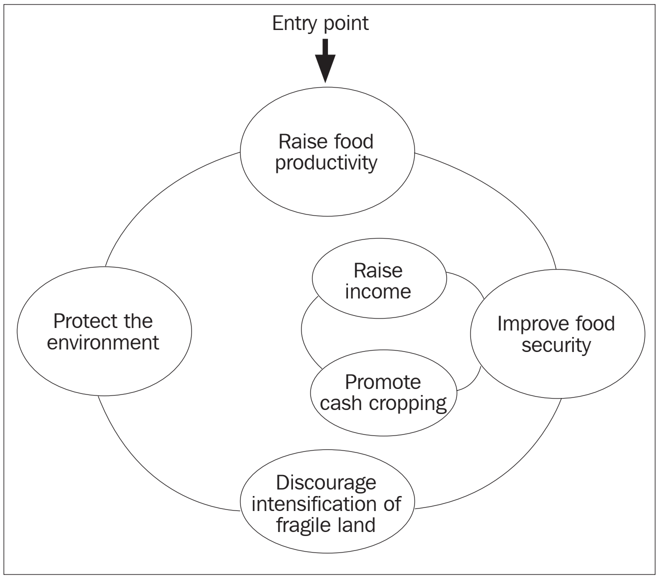

Fig. 5. Rice research as an entry point in the process of converting the vicious cycle into a virtuous cycle.

This role of rice research is exemplified by the recent patterns of development in the uplands of Yunnan (Pandey et al 2004a). The production system there changed over time from a shifting cultivation-based subsistence system to a commercially oriented, predominantly fixed cultivation system within a span of about 10 yr. Farmers now grow food and cash crops mainly in permanent fields. Productivity of the staple crop rice (and especially of upland rice) has increased over time as farmers have adopted more intensive methods of rice production. Further, some of the steeply sloping land previously under the upland rice-fallow rotation is now being "returned" to forest.

The main strategy used by the government of Yunnan for dealing with food insecurity and environmental degradation associated with extensive land use system based on shifting cultivation was to intensify the use of a limited area of land for agricultural production. This was supported through various policy initiatives such as granting long-term tenure security to farmers, subsidies for the construction of terraces, input subsidies, and promotion of new high-yielding upland rice varieties.

The improvement in the productivity of upland rice as a result of these changes also encouraged cash cropping by relaxing the food insecurity constraint at the household level. With their food requirement being increasingly met from their own production, farmers looked for opportunities to generate cash incomes by producing various crops for the market. This strategy also gave environmental dividends as some of the land that was previously used for agricultural production could be retired for forest plantation. Improved food productivity helped to take some of the marginal land out of production.

Paradigm shifts in approach to upland research

Although IRRI started research on upland rice in a programmatic fashion at the start of the 1990s, the earlier work focused much on component technologies. Emphasis was on evaluating suitable japonica germplasm and characterizing and understanding plant responses to various biotic and abiotic stresses. This work is summarized well in Piggin et al (1998). Although important in generating scientific understanding, this past work did not always lead to the development of specific technologies ready for dissemination to farmers. Concerns were expressed that the impact of upland research has not been discernible. A clear vision on the role of upland rice and a strategy for generating impact were not adequately articulated.

Over the past several years, IRRI has gone through a considerable rethinking of its role and strategy for upland development. This has resulted in the following major paradigm shifts in our approach to upland research.

1. *Recognition that increasing rice productivity is a critical entry point in the uplands.* The role of improvements in rice productivity in the uplands in initiating a broader process of income growth to achieve poverty reduction was not adequately recognized in IRRI's earlier work. IRRI has now clearly articulated that an improvement in rice productivity is a critical entry point in addressing the problems of food insecurity, poverty, and environmental degradation (Fig. 5). Increases in rice productivity in the uplands are now seen as an essential part of the process of income growth and diversification. Improved productivity can relax the food insecurity constraint and release valuable farm resources such as land and labor that are needed for engaging in other activities for income generation. Household food security and income growth are thus seen not as competing but as complementary and mutually reinforcing goals. This change in approach puts IRRI's work on the uplands very much in line within the broader context of the MDGs and with the recommendations of the Task Force on Hunger.

2. *Emphasis on conservation of resources through intensification of favorable pockets within the upland domain.* Earlier work on the uplands emphasized the need to develop technologies that promote in-situ conservation of rice field resources such as nutrients and moisture, even at the cost of some yield sacrifices. Such systems with low productivity require an expansion of area for increasing production.

The experience of the Green Revolution has clearly highlighted the limitation of such strategies focused narrowly on in-situ conservation. It is clear that the rapid increase in yield in the intensive rice bowls of Asia in the wake of the Green Revolution generated tremendous environmental benefits by avoiding the need to expand the rice area into fragile ecosystems. Had rice yield remained at its pre-Green Revolution level of 1.9 t ha^{-1}, current production would have required more than double the current area. Such expansion of rice area would have most certainly incurred high environmental costs. The experience of the Green Revolution thus demonstrated clearly that intensification in favorable areas is the best strategy to achieve wider scale conservation of natural resources. It goes without saying that technological and other opportunities for preventing environmental damage within the intensive areas also need to be fully utilized. The same argument applies to upland systems where intensification of favorable pockets can generate environmental benefits.

The validity of this position is also supported by the recent developments in the uplands of Yunnan as discussed earlier. Intensification of upland rice areas in the lower slopes and terraces in southern Yunnan facilitated the conversion of steeper slopes where upland rice used to be grown into forested areas (Pandey et al 2004a).

3. *Emphasis on landscape management rather than on rice field management*. The major focus of much of the earlier work reported in Piggin et al (1998) was at the field scale. Although useful for understanding the field-level processes, such an approach fails to capture the various resource flows and interactions at the landscape level that determine the options available. Soils, water, and nutrients flow down the slope through natural processes and the pattern of flow is altered by various "filters" or landscape features, which may be natural or man-made. By altering these resource flows, the pattern of land use in the upper part of the landscape determines the options available in the lower part. Given this, land use and resource conservation strategies for the uplands are better designed at the landscape level rather than at the field level.

In the context of rice production, the two major components of the landscape are sloping uplands and flatter fields that naturally occur in lower slopes and valley bottoms within the mountainous terrain. Flatter fields also include terraces that are constructed in sloping areas. These terraces and flatter fields (or upland paddies) where rice can be grown under the more productive and stable wetland culture provide an important opportunity for intensification. Irrigated rice technologies, with some adaptation, are suitable to these upland paddies. Hence, improving the productivity of these upland paddies can be an important strategy for reducing the intensification pressure for rice production in the fragile sloping uplands (Pandey and Minh 1998, Pandey et al 2004b).

As opposed to the traditional focus on upland rice only, IRRI has now developed a two-pronged strategy aimed at improving the overall landscape management while providing household food security. This consists of efforts to improve the productivity of rice in both upland paddies and in sloping uplands. Households with limited access to upland paddies are dependent on sloping uplands to meet their food needs.

While continuing to address the problems of these households through technology improvements targeted to sloping uplands, IRRI has now embarked on the task of improving the productivity of upland paddies to achieve a wider impact at the landscape level. *This paradigm shift is also highlighted by IRRI's current focus on "rice in uplands" rather than on "upland rice" per se.*

Technological opportunities

The paradigm shifts discussed above have led to considerable refocusing of IRRI's work in the uplands during the past 4-5 yr. Using the scientific advances made earlier and as a result of new approaches, several upland technologies with high potential impact are now ready or are in the pipeline. These include high-yielding aerobic rice varieties and cropping systems technologies to improve and stabilize the upland systems. Details of these technological opportunities are provided in Pandey et al. (2006b).

Concluding remarks

Addressing the problems of hunger, ill health, and environmental degradation in regions of extensive poverty is now firmly placed on the agenda of international development agencies and national governments. Much of the Asian uplands is characterized by high incidence of poverty, poor physical access to markets, ill-functioning marketing institutions, and subsistence-oriented agriculture with low productivity. Many of the poor belong to minority ethnic groups who are economically and socially marginalized, and they are truly the poorest of the poor. They tend to devote their limited resources of land and labor to meet their food needs, leaving few or no resources for income generation. Rising population pressure and the consequent intensification of marginal areas for food production have contributed to environmental degradation and a further reduction in agricultural productivity. Upland areas are caught up in a vicious circle that perpetuates poverty, food insecurity, and environmental degradation. Uplands perform important local, regional, and global environmental functions such as biodiversity conservation, water catchment protection, and greenhouse gas absorption. Development strategies must therefore seek to achieve a sustainable reduction in poverty and food insecurity while protecting the environmental functions of uplands.

Given the importance of rice as a staple crop, interventions that increase rice productivity can serve as a critical entry point in initiating and reinforcing the process of agricultural growth and income generation in the uplands. Improved technologies for rice-based systems will promote income-generating activities by freeing household resources that are currently tied up in meeting food needs. Achievement of household food security and income growth can thus be seen as complementary and mutually reinforcing goals. Increases in productivity will also help protect the fragile upland environment by reducing pressure to intensify food production in steeply sloping fields and forest margins. In this way, improved productivity of upland rice-based systems can contribute substantially to achieving the MDGs. Technological opportunities now clearly exist for making an impact on poverty and hunger reduction in these upland areas through increased productivity of rice-based systems.

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Rice disease management in the uplands of Indonesia and the Philippines

C.M. Vera Cruz, N.P. Castilla, Suwarno, Santoso, E. Hondrade, R.F. Hondrade, T. Paris, and F.A. Elazegui

Rice diseases are major constraints in the uplands. Strategies to address these constraints include rice and crop diversification and seed health management. In Lampung Province, Indonesia, the use of rice cultivar mixture as an approach to reduce neck blast and improve yield was studied from 2002 to 2006. Interplanting rows of susceptible and resistant varieties can more effectively reduce neck blast on susceptible varieties if the level of resistance of the components and the proportion of the resistant variety was increased. Row interplanting improved the yield of the more susceptible component in cropping years 2003-04 to 2005-06 and maintained resistance to both leaf and neck blast and the yield of the resistant component. However, our challenge is to retain high productivity while maintaining the diversity of rice and crop genotypes grown in single fields. In Arakan Valley, Philippines, farmers intercrop rice with different crop species to increase the resilience of the system and increase food production. Within a 3-yr period, the upland rice area increased tenfold and the number of farmers adopting mixed cropping increased. In areas of Arakan where farmers grow rubber as a cash crop, diversification schemes for legume-rice cropping systems are also being evaluated to increase their income. Farmers in Arakan and Lampung were trained on integrated seed health management to improve seed quality and crop productivity. A community seed bank in Arakan was established in cooperation with local government units.

Keywords: rice blast, disease management, genetic diversification, rice cultivar mixture, crop mixture, seed health management, community seed bank

The key biotic constraints identified in upland areas are weeds, diseases, insects, and nematodes. This paper deals with strategies for disease management in the uplands of Indonesia and the Philippines, with emphasis on disease (blast) endemic at the study sites. Management strategies evaluated under these environments include the use of rice genetic diversification in blast-endemic areas, crop mixture, and seed health management.

Indonesia's upland rice area occupies about 1 million ha, representing less than 10% of the total rice area (Syaukat and Pandey 2005), whereas data from the mid-1990s (http://www.irri.org/science/cnyinfo/philippines.asp) show that the Philippine upland area is about 4%. Average yield in Indonesia is only about 2.58 t ha^{-1} in 2004 (Suwarno, pers. commun.), although varieties with higher yield potential have become increasingly available. Despite its low contribution to total rice production in Indonesia, upland rice remains important because it serves as a source of food and livelihood of farmers, much like in the uplands of Arakan, Mindanao, in the Philippines, where average upland rice production ranged from 0.8 to 2.0 t ha^{-1} in 1994–2005 (Hondrade, pers. commun.). Because of various biophysical constraints (Suwarno et al 2001, Soenarjo et al 2001, Dierolf and Yost 2001), most farmers in the uplands of Indonesia only produce rice for household consumption and sell only when they have a surplus.

One of the constraints in the uplands of Indonesia is blast, a fungal disease caused by *Magnaporthe oryzae* (Suwarno et al 2001). Longer periods of leaf wetness and water stress, and nutrient uptake imbalance in these areas favor blast epidemics (Kingsolver et al 1984, Webster and Gunnell 1992, Thurston 1998), making the disease more destructive here than in irrigated areas. Along with the growing trend toward cultivation of nitrogen-responsive, improved varieties is the farmers' tendency to apply more nitrogen, which creates an environment more conducive to blast. Most of the released varieties appear to have major or single genes that are easily overcome by the pathogen population. Developing durably resistant varieties is one of the primary objectives of upland rice breeding programs, but resistant varieties become susceptible after only two to three successive cultivations (Soenarjo et al 2001). The breakdown of resistance has generally been attributed to the fast development of new races of the pathogen that are virulent to released varieties and to the diversity of pathogen populations (Kiyosawa 1982, Correa-Victoria and Zeigler 1993). Complementary strategies to breeding programs are therefore needed to reduce blast and extend the durability of resistance genes used in the breeding program (Leung et al 2003). One such strategy is the cultivation of different varieties in the same field, as already practiced by upland farmers in Indonesia, mainly to ensure the desired grain quality and yield stability. Before the use of cultivar mixtures for blast management can be recommended to farmers, its efficiency in reducing blast and increasing yield and its suitability to cropping practices should be evaluated. Results of related studies conducted in other locations cannot be extrapolated to the uplands of Indonesia because of differences in the resistance and agronomic traits of cultivated varieties, population structure of the pathogen, environmental conditions, and cropping practices.

Potential of rice genetic diversification in blast management

Several experiments have demonstrated the potential of managing blast by diversifying or mixing varieties or lines with different resistance genes under both irrigated and upland rice conditions. Previous studies indicate that growing several varieties or multilines with different levels of resistance can effectively reduce blast (Chin and Husin 1982; Bonman et al 1986; Koizumi 1994, 2001). Leaf blast severity on mixtures of susceptible varieties and resistant varieties or lines decreased with a reduction in the proportion of susceptible varieties (Shindo and Horino 1989, Koizumi 1994). Large-scale farmer-participatory field experiments in China have demonstrated that blast can be managed using cultivar mixtures in large rice production systems. The experiments showed that interplanting one row of a susceptible variety with every four or six rows of a resistant hybrid indica rice reduced neck blast and increased the yield of the susceptible variety while maintaining the yield level of the resistant variety (Zhu et al 2000).

The efficacy of cultivar mixtures in reducing blast can be attributed to the fact that the strategy creates the necessary conditions that maximize control by cultivar mixtures (Mundt 1994). Cultivar mixtures have been demonstrated to reduce wind-dispersed foliar diseases, such as rust and powdery mildew. Just like blast, the hosts of all these diseases are cereals (wheat, barley, and oat). The pathogens are aerially dispersed and interact with the host following the gene-for-gene model and produce several infection cycles in a growing season. Reduction of these diseases in mixtures of plants or varieties under a polycyclic situation has been attributed to several underlying mechanisms that may work simultaneously. The most commonly reported mechanisms are 1) the dilution effect (assumed to be the most important effect)—the inoculum is reduced due to the presence of resistant plants, which limits pathogen reproduction; 2) barrier or spatial effect—the distance between susceptible plants and resistant plants is increased, thereby minimizing the deposition of inoculum on susceptible plants (Burdon and Chilvers 1976, Trenbath 1977); and 3) induced resistance—the diverse pathogen populations allow nonvirulent races on a component to induce resistance against normally virulent races (Chin and Wolfe 1984, Chin et al 1984, Lannou et al 1995, Calonnec et al 1996).

Field experiments on effects of rice genetic diversification on blast intensity and yield

Three experiments were conducted in naturally infected farmers' fields in an upland area in Lampung Province, Indonesia. The project site is located in Rama Murti III, a rice-growing village of Seputih Raman, one of the municipalities in Central Lampung District. The average farm size is 0.65 ha and rice is grown yearly from November to March. Farmers in this village have been growing both traditional and improved varieties. During a focus group interview conducted in 2003, farmers stated that blast is the most important pest, especially when improved varieties are grown. Nevertheless, farmers prefer to grow more improved varieties than traditional varieties to increase yield. The overall objectives of the field experiments were to determine whether mixtures of varieties cultivated by farmers can reduce neck blast and improve yield and to analyze the population structure of the pathogen in pure and mixed stands.

Cropping year (CY) 2002−03. An exploratory experiment was conducted in CY 2002−03 to determine whether mixing traditional and susceptible varieties, as done in China, can be used to manage blast. In Indonesia, traditional varieties are generally more resistant to blast and have more stable yield probably due to the presence of several resistance genes and high genetic diversity within varieties (Suwarno et al 2001). Despite some undesirable traits such as low yield potential, long duration, and tall stature, traditional varieties have good eating quality and stable yield. Planting of traditional varieties with modern varieties would also allow in situ conservation of traditional varieties that face the risk of extinction with the increasing adoption of improved varieties and modern cropping practices. However, the interplanting system adopted by farmers in China does not have practical relevance to their Indonesian counterparts. Growing one row of susceptible variety has reduced blast in China, but, in Indonesia, the shorter, susceptible variety will be easily outcompeted if only one row is interplanted with the tall traditional variety.

The experiment involved interplanting of three to six rows of Cirata with one to six rows of Sirendah. Cirata is a short (98 m) improved variety that is highly susceptible to blast, whereas Sirendah is a tall (153 m) traditional variety that is moderately resistant to leaf blast and highly resistant to neck blast. Leaf blast incidence was assessed at around 60 d after sowing as the percentage of leaves with leaf blast lesions in a hill; neck blast incidence was evaluated at harvest as the percentage of panicles with neck blast lesions in a hill. Grain yield hill^{-1} in all experiments was measured from a 5-m^2 area in each plot and adjusted to a moisture content of 0.14 g H_2O g^{-1} fresh weight. Grain yield hill^{-1} reflects the overall effects of blast, competition, and other agronomic factors on the ability of a variety in mixed and pure stands to produce grains.

Results showed that row interplanting of Cirata and Sirendah at the proportion tested cannot effectively reduce both leaf blast severity (Fig. 1a) and neck blast incidence (Fig. 1b). The absence of significant effects of cultivar mixtures in this experiment may be due to the possibility that, when more than one row of Cirata is planted, one to six rows of Sirendah cannot effectively prevent the spread of spores from one hill of Cirata to another. This allowed a substantial exchange and production of inoculum. Because of its tall stature, Sirendah may have also affected wind movement and trapped the spores within the adjacent hills of Cirata.

CY 2003−04 and 2004−05. Two trials of another experiment were conducted in farmers' fields in CY 2003−04 and 2004−05 to determine the effect of level of resistance in susceptible components on blast incidence and grain yield. The susceptible components were Cirata and Way Rarem, a moderately

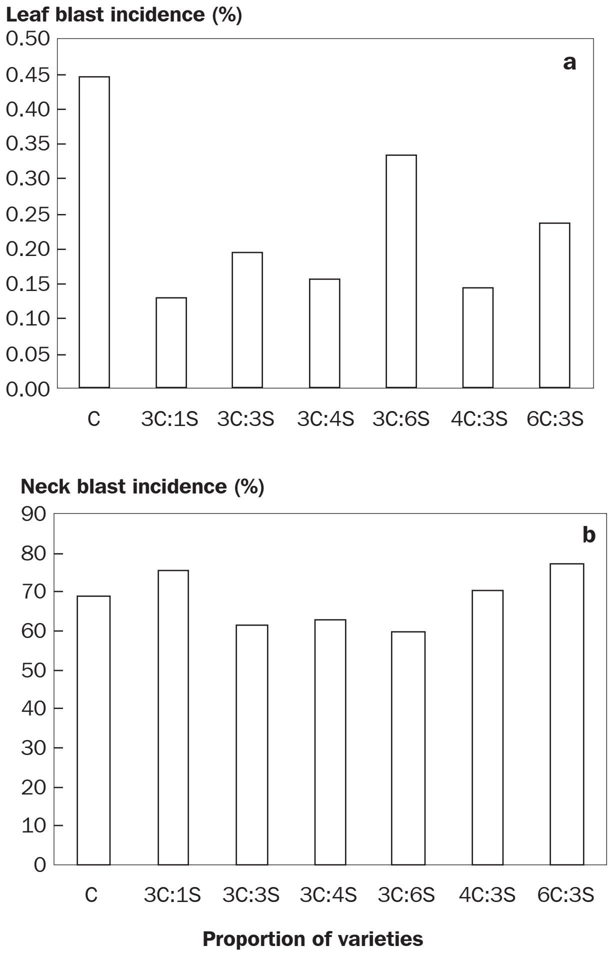

Fig. 1. Leaf blast severity (a) and neck blast incidence (b) on Cirata and Way Rarem in pure and mixed stands in CY 2002–03.

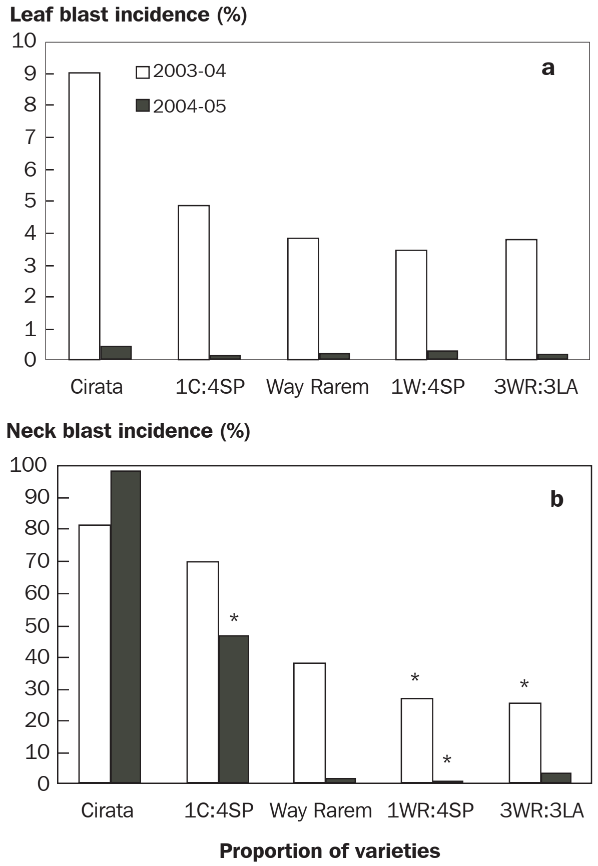

Fig. 2. Leaf blast (a) and neck blast incidence (b) on Cirata and Way Rarem in pure and mixed stands in CY 2003–04 and 2004–05. *= significantly different from pure stand of corresponding variety.

susceptible variety. Since no popular improved and traditional varieties are completely resistant to blast in Lampung Province, the susceptible components were interplanted with moderately resistant varieties such as Situ patenggang and Lampung Arak, which are respectively improved and traditional varieties. Thus, the treatments were composed of 3 two-component mixed stands: a) one row of Cirata: four rows of Situ patenggang (SP), b) one row of Way Rarem (WR): four rows of SP, c) three rows of WR: three rows of Lampung Arak, and d) pure stands of the components. Only one row of Cirata was interplanted with Situ patenggang because the previous experiment showed that neck blast on Cirata is not reduced when more than one row was interplanted with a resistant variety. Another mixed stand had one row of Way Rarem to determine whether interplanting more than one row of a moderately susceptible variety can also reduce blast; three rows of Way Rarem were interplanted with a moderately resistant traditional variety in another mixed stand. The experiment was laid out using a randomized complete block design with four replications. Each plot measured 5.2 m × 5.5 m and had a 5-m distance from each other. Limboto, a variety that is moderately resistant to leaf blast and neck blast, was planted between plots to minimize interplot interference.

Leaf blast on Cirata and Way Rarem did not significantly differ between pure and mixed stands in both CY (Fig. 2a). When interplanted with Situ patenggang, neck blast on Cirata was on average reduced by 14% in CY 2003–04 and by 52% in CY 2004–05, but differences were significant only in CY 2004–05 (*P*=0.024) (Fig. 2b). In CY 2003–04, neck blast on Way Rarem was reduced by 29% when interplanted with Situ patenggang (*P*=0.022) and by 34% when interplanted with Lampung Arak (*P*=0.024). In CY 2004–05, interplanting Way Rarem with Situ patenggang reduced neck blast by 77% (*P*=0.036), but interplanting it with Lampung Arak had no effect on the amount of the disease. Neck blast incidence on Way Rarem was markedly lower in the second than in the first trial, whereas that on Cirata did not significantly change across trials, indicating a possible shift in the structure of the pathogen population on Way Rarem but not on Cirata. The reduction in neck blast incidence on Way Rarem in mixed stands did not result in significant yield increases in both trials. In CY 2004–05, neck blast incidence on Way Rarem was even too low to cause any significant yield reduction in both pure and mixed stands. On the other hand, neck blast incidence on Cirata was significantly correlated with yield (r=-0.611, P<0.012, n=16). Thus, a reduction in neck blast incidence on this variety has been translated into yield improvement as shown by the higher grain yield in mixed stands (P=0.045 in CY 2003–04 and P=0.080 in CY 2004–05) than in pure stands. When interplanted with Sirendah, the relative grain yield (determined by dividing the grain yield of mixed stand by that of pure stand) of Cirata was higher than that of Way Rarem in both seasons (2.1 vs 1.2 in CY 2003–04; 2.1 vs 1.2 in CY 2004–05).

CY 2005–06. Since the result of the field experiment in CY 2004–05 showed that interplanting more than one row of Way Rarem with a resistant variety can significantly reduce neck blast, another experiment was established to compare the effect of interplanting more than one row of Cirata and Way Rarem with a resistant traditional variety. The experiment was established in a split-plot design with variety (Cirata or Way Rarem) as main plot and number of interplanted rows (two, four, or six) of either variety with one row of Sirendah as subplot. Sirendah was selected because the results of the participatory varietal selection (PVS) trials in CY 2004–05, which involved farmers from several villages, showed that it was one of the most preferred varieties. Plot size was 6 m × 8.5 m, and distance between plots was 6 m. As in previous experiments, Limboto was planted between plots to minimize interplot interference.

Leaf blast incidence was significantly higher on Cirata than on Way Rarem (P=0.004) but did not differ between pure and mixed stands (Fig. 3a). Neck blast incidence was also higher on Cirata than on Way Rarem, but the effect of planting ratio varied according to variety (Fig. 3b). Interplanting Cirata with Sirendah did not reduce neck blast on Cirata, whereas interplanting two rows of Way Rarem to every row of Sirendah reduced neck blast incidence on Way Rarem by 81% (P=0.004). When evaluated as a group, mixed stands of Way Rarem had lower neck blast incidence than the pure stands (P=0.013). Neck blast incidence on Way Rarem decreased substantially as its proportion in mixed stands decreased (r=0.995, P=0.0005, Fig. 4). Mixing Cirata with Sirendah had no effect on the absolute value of grain yield (Table 1). However, the relative yield of Cirata was higher in mixed stands with four to six rows than in those with only two rows, which may be due to the combined adverse effects of Sirendah (which is taller in stature) and high neck blast incidence. The yield of Way Rarem did not significantly differ between pure and mixed stands despite the reduction in neck blast incidence. Since the experiments were not designed to analyze the interaction between components in mixed stands, it cannot be confirmed whether yield variation in mixed stands is affected by competition between components. A second trial of this experiment is in progress in CY 2006–07 to confirm the results.

In all trials, the incidence of leaf and neck blast and yield of the more resistant component did not significantly differ between pure and mixed stands.

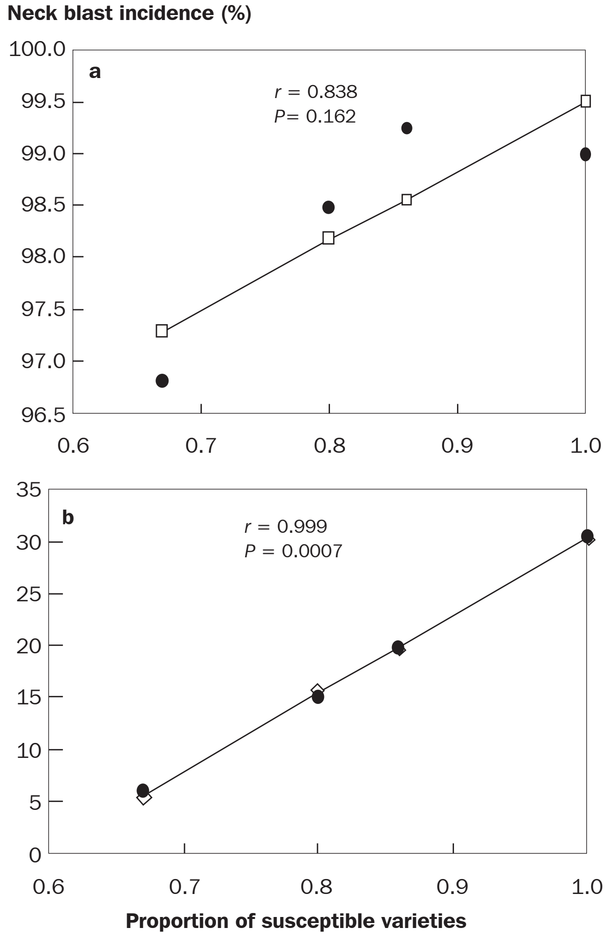

Fig. 3. Relationship between neck blast incidence and proportion of Cirata (a) and Way Rarem (b) to Sirendah.

Virulence analyses of blast pathogen isolates collected from experimental plots. Isolates of the blast pathogen were collected from infected leaves and panicles during the conduct of the field experiments and maintained at the Indonesian Institute for Rice Research. Phenotypic virulence analyses were made on the population of isolates collected from Cirata and Way Rarem in mixed and pure stands in all CY to determine the composition and virulence of races based on reaction type on seven standard Indonesian differentials. In CY 2002–03, eight races on Cirata were identified, the predominant ones being race 133 (50.52%), race 173 (16.49%), and race 33 (14.43%). In CY 2003–04, seven races each were collected from Cirata and Way Rarem (Fig. 4a), whereas in 2004–05, 13 and 9 races were identified from Cirata and Way Rarem, respectively (Fig. 4b). Race 33, which is virulent to four differentials, was predominant on Cirata in both CY (39% in 2003–04 and 48% in 2004–05). In contrast, the dominant race found on Way Rarem changed from one CY to another—race 33 was predominant in CY 2003–04 (59%) but was replaced by races 1 and 3 in CY 2004–05 (41% and 21%, respectively). Races 1 and 2 were virulent to only one and two differentials, respectively. The predominance of these avirulent races on Way Rarem in CY 2004–05 may account for the reduction in neck blast incidence. The virulence of isolates collected from Cirata significantly differed between pure and mixed stands (Table 1). Mixed stands were significantly associated with highly virulent isolates (χ^2=17.37, P<0.0002). On the other hand, the isolates collected from Way Rarem were less virulent than those from Cirata and there was no significant difference in the virulence of isolates collected from pure and mixed stands. Differences in virulence pattern were observed

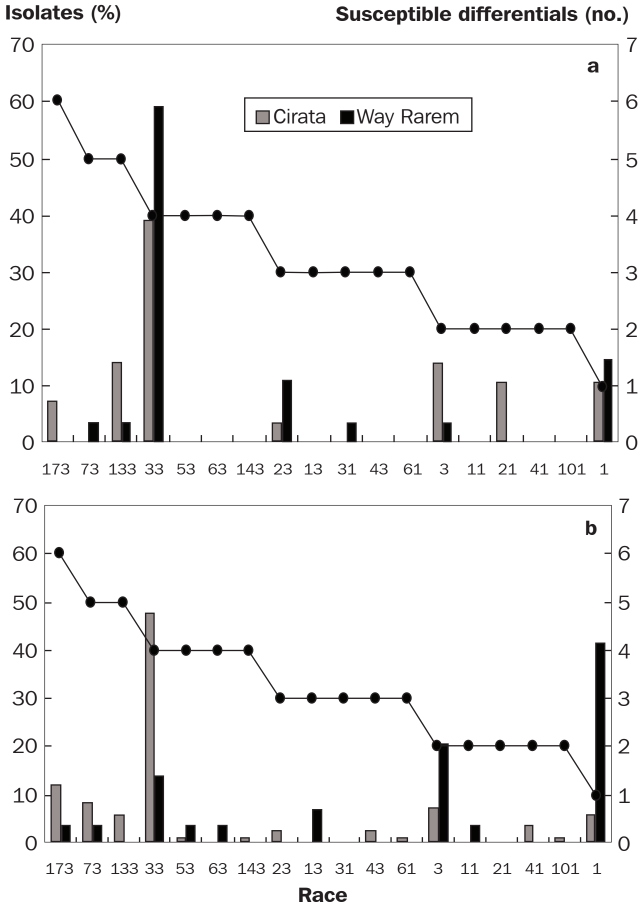

Fig. 4. Frequency of races collected from Cirata and Way Rarem in CY 2003–04 (a) and 2004–05 (b). The second y axis shows the number of differentials that are susceptible to each race.

Table 1. Blast incidence on and grain yield of Cirata and Way Rarem in pure and mixed stands.

Proportion (no. of rows)[a]	Leaf blast incidence (%)	Neck blast incidence (%)[b]	Grain yield	
			Absolute	Relative[c]
2C : 1S	16.72	96.81	5.44	0.799 b
4C : 1S	9.55	98.47	8.04	1.491 a
6C : 1S	12.52	99.24	5.90	1.148 ab
Pure stand C	15.38	98.98	6.27	
Mean[d]	13.54 a	98.38 a	6.41 b	1.146 a
2WR : 1S	0.38	5.91 b	15.55	0.960 a
4WR : 1S	0.95	14.96 ab	15.17	0.996 a
6WR : 1S	1.68	19.69 ab	14.91	0.960 a
Pure stand WR	1.72	30.49 a	16.36	
Mean	1.18 b	17.76 b	15.50 a	0.972 b

[a]C = Cirata, S = Sirendah, WR = Way Rarem. [b]*, ns = significantly different and not significantly different, respectively, at $P<0.05$ using LSD from the pure stand of the corresponding variety. [c]Calculated as grain yield in mixed stand divided by grain yield in pure stand. [d]Mean values of varieties followed by different letters are significantly different at $P<0.05$ using LSD.

across CY (Table 2). The virulence of the isolates collected from Cirata was higher in the first CY than in succeeding years (nonzero correlation = 32.13, $P<0.0001$). In CY2002–03, the predominant races 133 and 173 on Cirata were virulent to five and six differentials, respectively, whereas race 33, which was predominant in the succeeding CY, was virulent to fewer differentials (Table 3). It is apparent that the number of virulent races decreased across cropping seasons, in comparison with the avirulent races based on the susceptible differentials. The number of avirulent races also increased on the third year of the trial, especially on Way Rarem. This may be due to the increase in the proportion of resistant components in the mixed stands.

Table 2. Frequency of races collected from Cirata and Way Rarem in pure and mixed stands categorized according to the number of susceptible differentials.

Susceptible differentials (no.)	Cirata[a]		Way Rarem[b]	
	Pure	Mixed	Pure	Mixed
1 to 3	29	2	17	13
4	34	19	17	5
5 to 6	9	19	3	1

[a]$\chi^2 = 24.16$, $P = 0.001$, df = 2. [b]$\chi^2 = 2.56$, $P = 0.27$, df = 2.

Table 3. Frequency of races collected from Cirata at different cropping years categorized according to the number of susceptible differentials.[a]

Susceptible differentials (no.)	CY 2002–03	CY 2003–04	CY 2004–05
1 to 3	6	11	20
4	17	11	42
5	49	4	12
6 to 7	25	2	10

[a]Nonzero correlation = 32.13 , $P<0.0001$, df =1.

Further phenotypic and genetic analyses of blast isolates will be conducted to better understand the population dynamics of the blast pathogen. The isolates will be further characterized using near-isogenic lines carrying different blast resistance genes as differentials to accurately assess the pathotype and determine the combination of resistance genes that will be effective in the project site. Molecular analysis of the isolates will also be done using avirulence gene probes or polymerase chain reaction-based markers to characterize the genotype of the pathogen population. More trials may be necessary to determine whether the shift in race structure of the isolates can be associated with the resistance and proportion of varieties in pure and mixed stands and to confirm whether cultivar mixtures can enhance the durability of resistance genes.

One issue regarding the use of cultivar mixture is that it may lead to the occurrence of complex races—those that can infect two or more components of a mixture (DiLeone and Mundt 1994). Complex races can overcome resistance genes and reduce the efficacy of the mixtures (Mundt and Browning 1985). To address this issue, adaptation of isolates collected from

CY 2005–06 and 2006–07 to components in mixed stands will be determined by inoculating collected isolates on Cirata, Way Rarem, and Sirendah and by quantifying leaf blast and neck blast incidence on inoculated plants.

Phenotypic and genetic diversity of upland rice varieties

The phenotypic and genotypic variations of upland varieties in Lampung Province are being evaluated at IRRI to increase the ability to precisely select genetically diverse components in cultivar mixtures. Genetic relatedness among varieties is being determined using randomly distributed molecular markers across the rice genome and selected defense gene markers that are associated with blast resistance. The results of these analyses will be used as basis in identifying a set of varieties that can be used in cultivar mixtures. Varieties that are distantly related and that differ in resistance to blast will be combined and their overall performance in the field analyzed to validate the relationship between genetic diversity and field performance. Such field trials will also help identify agronomic traits that are suitable for cultivar mixtures. Furthermore, several plants of a variety will be sampled to confirm whether the durability of blast resistance of traditional varieties is due to genetic variation within a single plant.

Selection and deployment of diverse breeding lines with blast resistance

Broad-spectrum blast resistance is important to withstand the variable pathogen population and to alleviate the need to change rice varieties frequently. Breeding lines with resistance to blast have been evaluated by farmers through PVS since CY 2003–04. The institutionalization of PVS in Lampung will substantially increase cultivar diversification in the area, aside from improving the varietal evaluation system and providing farmers with a choice of varieties with desirable traits. Replicated yield trials of promising breeding lines in the Tamanbogo Research Station in Lampung Province served as the mother trial; these were managed by the research staff of the Indonesian Institute for Rice Research. At around the hard dough to ripening stages, 30–50 farmers were invited and each was asked to evaluate all the lines and identify three most preferred lines and one least preferred line. Farmer-managed baby trials of selected lines were done in different villages of central Lampung District (Table 4). The selected breeding lines were grown under irrigated conditions to produce at least 100 kg of seeds in the dry season at the Tamanbogo Experiment Station and packages of 5–10 kg seeds of promising lines were distributed to selected farmers. To further enhance on-farm varietal diversity, farmers were allowed to share or sell the seeds produced to other farmers. The diffusion of seeds of the selected breeding lines in the area was monitored to determine the degree of acceptance of each variety. Breeding lines selected from the national breeding program based on agronomic traits will be evaluated for blast resistance by artificial inoculation with all blast races and resistant lines will be selected.

Table 4. Cultivated areas, number of farmers, and amount of seeds distributed in different villages of Lampung Province, Indonesia, during the baby trials in CY 2005–06.

Village	Cultivated area (ha)	Farmers (no.)	Distributed seeds (kg)
Tamanbogo	2.61	10	101
Sukadana Ilir	10.25	11	370
Rukti Basuki	2.25	8	85
Rama Nirwana	13.25	14	510
Rama Murti	8.0	21	320
Kali Bening	15.0	42	450
Kali Pasir	6.0	-	204
Gedung Dalam	5.0	-	160
Bangun Rejo II	10.0	-	300
Reju Binangun	4.0	-	120

Mixed cropping system in the uplands of Arakan, Philippines

The upland rice area in Arakan reached almost 2,800 ha, the highest in the early 1990s. However, drought occurred in 1999 and reduced that arable area to only 950 ha. In 2002, only about 377 ha of land was planted to upland rice for several reasons: 1) decreasing fertility of the soil due to soil erosion, 2) perennial weed problem, 3) high cost of seeds, and 4) unavailability of credible seed sources. Surprisingly, in 2003, the cultivated area increased to 2,958 ha due to an upland rice production enhancement project that involved local government units, the University of Southern Mindanao, and the Consortium for Unfavorable Rice Environment (CURE).

In addition, mixed cropping of nonrice crops grown in a rice-based system allowed farmers to intensify production for food security and income enhancement. For example, a farmer-cooperator in Arakan chose to plant either mungbean, peanut, or maize in tandem with rice. Farmers were shown and taught how agronomically compatible crops can be intercropped and were encouraged to adopt a system that suits their preferences and the climatic and soil conditions in the area. Farmers considered ease of planting and harvesting as criteria for adopting an intercropping system. This participatory approach enabled farmers to adopt their preferred system. In this farming community in Arakan, one can see the transformation of the landscape from a monoculture to a diversified array of rice and nonrice fields. Data showed that upland rice area expanded tenfold to 3,000 ha within a 3-yr period and that mixed cropping has been adopted by more farmers in several municipalities in the Arakan Valley Complex, the “upland rice belt” of Cotabato Province in Mindanao Island.

In partnership with several universities (Clemson University, Kansas State University, Oregon State University, University of Southern Mindanao) and the Philippine Rice Research Institute under a USAID IPM-CRSP project, we are evaluating current and improved diversification schemes for integrated pest management (IPM) in legume-rice cropping systems in the Arakan Valley Complex. Initially, we have evaluated a crop diversification scheme that includes planting rice and vegetables intercropped with young rubber trees. The objectives included determining the performance of rice and mungbean as a function of rubber tree age, both in monoculture bands and in mixed bands of rice varieties and rice-mungbean intercrops. We are assessing the IPM needs for these systems and developing strategies to meet these needs. Farmers' fields from three municipalities in the Arakan Valley Complex were used in the experiment. In each municipality, there was a pair of rubber plantings, one field with 1-yr-old rubber trees and the other field with 3-yr-old trees. The pairs were selected in such a way that the only difference between the two plantings in a pair was the age of the rubber trees. Hence, there was one field (~one farmer cooperator) in each of the three municipalities and in each of the 1- and 3-yr-old rubber plantings. Initially, surveys were made to assess the injuries caused by major insect pests, diseases, and weeds in each rubber production system. We are currently evaluating the importance of the observed pest problems and the effects of the different cropping systems on both pest problems and productivity. In the preliminary analysis, weeds are indicated as a particularly important problem. We are carrying out this study over a 3–4-yr period.

Operationally, the diversification of germplasm or crop genotypes should serve as the basis for providing functional groups of different organisms, herbivores, predators, pathogens, microbial antagonists, and weeds a way to interact with one another, such that an increase or decrease in the population of one organism is subject to the check and balance imposed by the populations of the other organisms. Therefore, potentially damaging species usually never become abundant enough to constitute a big threat in stable agricultural systems. In such a system, rice varieties preferred by farmers, which may not be resistant to diseases, may be deployed longer. Because of the diverse genotypes and phenotypes grown in mixture in the same fields, it has been hypothesized that traditional agricultural systems are more "durable" to insect pests, diseases, and other stresses (Wolfe 1985). However, although this may be so, traditional agriculture would never have provided the quantity of food needed to fulfill the need of the growing human population in the past decades. Our challenge is to retain the high productivity of modern upland varieties and to maintain the diversity of the genotypes grown in single fields.

Seed health for rice crop and pest management

A seed health approach has been recommended as the most appropriate strategy to manage seedborne pathogens for disease control (Mew et al 2004). In addition to seedborne pathogens (including incidence and number of all potential pathogens associated with seeds), this approach also considers physical characteristics (deformed seed, partially filled seed, and discolored seed and impurities as vital to the success of seed health management to ensure good crop management (Fig. 5a). Thus, in assessing the importance of seedborne pathogens in crop management, it is necessary to consider them as an integral component of seed health. It is in this context that the concept of seed health is practiced for rice crop and pest (insect, weed, and disease) management (Mew et al 2004). Based on studies of Mew and coworkers (Diaz et al 1998), the use of the total seed health approach to relate seedborne pathogens to crop production and disease management has produced dramatic results by increasing yield 5–20% through the use of high-quality seeds for planting.

Based on a participatory rural appraisal conducted in 2003 in the uplands of Arakan and Lampung, the farmers' own-saved seeds from the previous rice harvest served as rice seed stocks for planting. Using own-saved seeds directly as seed stocks, farmers were not able to clean and sort seeds prior to sowing due to labor shortage, causing deterioration of seed quality with continuous use over many cropping seasons. Thus, by removing poor seeds such as discolored seeds caused by pathogen infection or seed lots with seed contaminants (pathogen sclerotia, weed seeds, etc.) (Fig. 5a), the potential seedborne inocula as well as the number of pathogens carried by seeds are minimized. Thus, the risk of introducing seedborne pathogens in rice production areas is also reduced. This idea is based on the observation of Mew and coworkers (Mew et al 2004) that "good crop management can be achieved by using good quality instead of poor quality seeds for planting." Simple methods of cleaning seeds include winnowing, wind blowing, manual seed sorting and flotation in water (Fig. 5b). Seed health as a concept is easily understood by farmers, extension specialists, and policymakers.

Training farmers on seed health management

Under the activities of the Consortium for Unfavorable Rice Environment (CURE), we used a farmer participatory approach to assess their perceptions of seed health management and to demonstrate the effect of improved seed quality on pest pressure and rice yield. The use of clean seeds for planting is one way of managing pests and crop production simultaneously. Inasmuch as the use of poor-quality seeds is a constraint that is

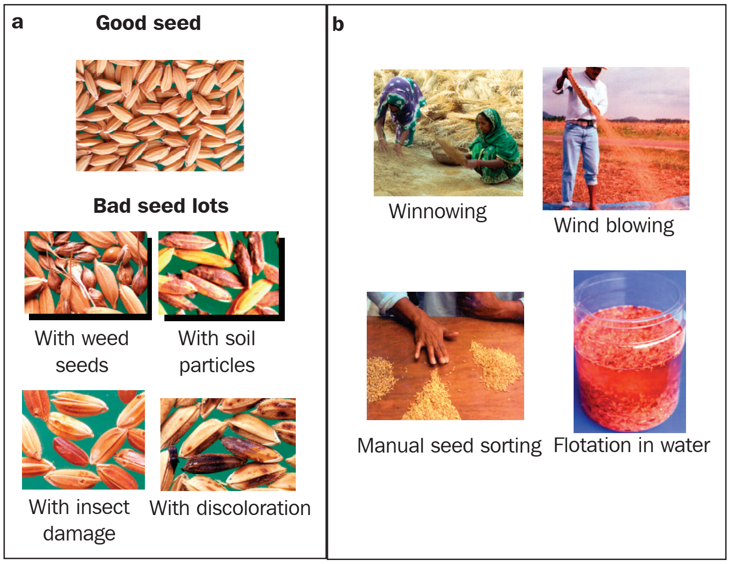

Fig. 5. (a) Examples of clean/good seeds vs. bad seeds and (b) different methods of cleaning seeds.

not easily recognized by farmers, creating and enhancing awareness of farmers on the importance of clean seeds was done by conducting training-workshops and regular visits to enforce the technology and assess their fields. It was emphasized that rice seed health management involves (1) proper seed cleaning by winnowing and/or flotation, (2) using good/clean seed for planting, (3) roguing variety mixtures and tall weeds at least three times throughout crop growth (to begin before flowering stage or during panicle harvesting), and 4) proper storage of clean and well-dried seed. At the end of the growing season, many participating farmers immediately applied what they learned. The use of high quality seed in Arakan enabled them to produce good seeds for planting and increased their grain yield. The clean seed technology was adopted; it has now become an integral part of their pest and crop management approach. Duplicating the Philippine experience, the clean seed technology is being promoted among farmers in the uplands of Indonesia through training. Interestingly, the farmers who were trained by the seed health technologist became farmer-trainers themselves in the village.

Seed health management through the community seed bank

Using the concept of seed health management to ensure an adequate supply of premium-quality seeds, the establishment of a community seed bank (CSB) has resulted in improved seed quality for farmers participating in CURE. The CSB is a network of farmers who have been trained in seed health management to produce quality seed for rural households. In focus group discussions, farmers have identified poor seed quality as a constraint to improved productivity. An outcome of participatory methodologies, the process of establishing a CSB involved seed health training following the training-workshop on managing seed health. Through this activity, NARES teams in the Philippines and Indonesia promoted *in situ* conservation by actively using farmers' preferred traditional and modern varieties and devising effective seed storage, multiplication, and distribution systems in cooperation with local government units (LGUs). The NARES team partnered with LGUs to give a formal structure for promoting seed health practices over a wider area. The LGU agricultural service unit acted as a 'bank' or safekeeper of seeds produced by the participating upland rice farmers. Members withdraw the seeds at the start of the cropping season with no interest or other charges imposed. In Indonesia, CSB farmer-cooperators have also trained other farmers in their communities to disseminate seed health practices over a wide area and to sustain quality seed production. Consequently, the CSB contributed to household food security among resource-poor farmers who have no access to certified seeds from either public or private seed producers.

Summary and future research activities

The field experiments on rice genetic diversification show that row interplanting with a resistant variety can more effectively reduce neck blast on a moderately susceptible than on a highly susceptible variety. In contrast to results of previous studies, neck blast was more effectively controlled than leaf blast in the second and third experiments. In field experiments in upland areas in the Philippines, which had a lower neck blast pressure than our project site, Bonman et al (1986) observed that leaf blast was more effectively reduced than neck blast using three-component mixed stands, which are generally regarded as more effective than two-component mixed stands. Our results suggest that cultivar mixtures, even those with only two components, can effectively control neck blast if components have adequate levels of resistance.

The field experiments show the potential of using cultivar mixture for blast management in the uplands of Indonesia and serve as a basis for developing strategies that would increase the efficacy of cultivar mixtures in reducing blast and improving yield. Among the options that may be evaluated in future experiments is the use of components with higher levels of resistance to reduce blast, increasing the number of components, decreasing the proportion of susceptible varieties, and testing a combination of these approaches. The use of cultivar mixture must be integrated with other blast management options to reduce neck blast sufficiently enough to get the desired yield.

The practical value of cultivar mixture depends on its suitability to farmer preferences. An approach to determine options for mixing cultivars that would suit the needs of farmers is to conduct focus group interviews to obtain detailed information and tailor on-farm evaluations of the most promising options to their preferences. At crop maturity, farmer field days can be conducted to increase awareness, get their feedback, and allow them to identify their most preferred approach.

The check and balance imposed by populations of different organisms interacting with one another operates in the presence of diversified rice germplasm or crop genotypes. Therefore, potentially damaging species usually do not become abundant enough to threaten a stable agricultural system. In such a system, rice varieties preferred by farmers, which may not be resistant to diseases, may be deployed longer. Our challenge is to retain the high productivity of modern upland varieties and to maintain the diversity of rice and crop genotypes grown in single fields. We aim for an integrated gene management approach for better disease control and more effective use of crop genetic resources.

Seed health management is a vital component of crop production and pest management. To minimize potential damage caused by seedborne pathogens, seed health practices should be integrated into farmers' crop management systems. Thus, to control diseases associated with seedborne pathogens, it is advisable to take a total seed health approach, instead of focusing on individual seedborne pathogens, unless its effect has been proven as the cause of damage to the crop. Quality seed for planting is essential for effective pest management and sustainable crop production.

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Lowland ecosystems

Germplasm development for drought-prone environments: progress and implications for crop and natural resource management

A. Kumar and G.N. Atlin

Drought is the most severe constraint to rainfed rice production. Drought effects are most severe in unbunded upland fields and upper-toposequence bunded fields that do not accumulate standing water. Drought reduces productivity, both through direct effects on biomass production and grain set and through disruption of crop management operations, including transplanting, fertilizer application, and weed management. The most important of these crop management disruptions, induced by water shortage at critical times, is delayed transplanting. Drought risk is a major cause of low input use by farmers, constraining productivity, even in favorable years. There is great genetic variation in tolerance for drought stress, direct seeding in dry soil, and delayed transplanting. In areas where transplanting is likely to remain the major establishment system, varieties with tolerance for both drought and delayed transplanting are needed to reduce risk and to increase productivity. In light-textured soils, direct seeding of drought-tolerant varieties in dry soil in unpuddled fields has the potential to eliminate the risk of transplanting failure and to advance maturity sufficiently to permit the production of a post-rice crop. However, varieties for use in this establishment system must be highly weed-competitive and have a high degree of tolerance for drought at the reproductive stage. The IRRI breeding program now routinely screens lines targeted at dry direct seeding systems for rapid early biomass accumulation, a trait that has been shown to be closely associated with weed competitiveness. Lines targeted for transplanted systems are screened for yield under transplanting as 60-d-old seedlings. For both systems, advanced breeding lines are screened both for yield potential and for yield under continuous recurring stress after maximum tillering. This research has shown that yield under drought stress has a moderate positive correlation with yield potential, permitting the development of varieties with high yield potential combined with stress tolerance. It has also been shown that hybrids are higher yielding than purelines, on average, under both moderate lowland stress and delayed transplanting. Lines and hybrids combining high yield potential with yields of more than 2 t ha^{-1} under severe lowland stress and more than 1.5 t ha^{-1} under severe upland stress have been identified. Such varieties have the potential to reduce risk and increase overall productivity in drought-prone environments.

Keywords: breeding, direct seeding, drought, hybrids, rainfed rice

Drought occurs frequently in the upland and lowland rainfed rice ecosystems of South and Southeast Asia, causing severe yield loss. Worldwide, approximately 20–25 million ha of rainfed rice are frequently affected by water stress. Eastern India, with more than 12 million ha of rainfed rice area, is the worst affected (Huke and Huke 1997). In this region, drought losses are most severe in the rice bowl states of Chhattisgarh, Madhya Pradesh, Bihar, Jharkhand, Orissa, and Uttar Pradesh. Northeastern Thailand and Laos, with more than 5 million ha of drought-prone rainfed rice area, are the other severely drought-affected areas in Asia. Drought risk also reduces productivity, even in favorable years, because farmers avoid investing in inputs when they fear crop loss (Pandey et al 2005). In addition to rainfed areas, drought also affects production on millions of hectares of dry irrigated areas that depend on surface irrigation; in drought years, river flows and water impounded in ponds, tanks, and reservoirs may be insufficient to irrigate this crop (Maclean et al 2002).

There is substantial genetic variability in the rice germplasm that can be used to develop more productive varieties for water-short environments. The objectives of this paper are to identify breeding objectives for particular drought-prone target environments, assess progress in the development of more drought-tolerant cultivars for these environments, and highlight their potential contribution to productivity enhancement and risk reduction when combined with appropriate crop management systems.

Target environments for drought germplasm improvement

A local watershed in which rainfed rice is grown can often be characterized as a *toposequence*, a series of terraced fields that drain into each other. Within distances of several hundred meters, the toposequence may include unbunded uplands and bunded but drought-prone upper fields that do not retain standing water, well-drained mid-toposequence fields, and poorly drained lower fields in which water accumulates to depths of 1 m or more during the rainy season. Water-related stresses are variable across years in drought-prone upper fields because of variability in the amount and distribution of rainfall, but they occur with reasonably predictable frequency in a given field based on toposequence position and soil texture. Yield variability due to water availability can be great even within single fields due to soil texture variability and uneven soil level. This micro-scale variability results in very large estimates of genotype × location × year interaction and residual errors in the analysis of rainfed rice trials, complicating selection (Cooper et al 1999).

Farmers are experts at categorizing fields according to toposequence-driven differences in hydrology, targeting varieties with appropriate duration and plant type to specific environments. On 4–5 million ha in the eastern Indian plateau, in unbunded fields at the top of the toposequence, farmers grow extremely short-duration, drought-tolerant upland rice varieties. In upper bunded fields, farmers tend to grow short-duration, photoperiod-insensitive varieties that flower before the withdrawal of the monsoon, escaping late-season drought stress. In these fields, farmers establish rice crops either by transplanting or direct seeding, but transplanting has become widespread since the adoption of high-yielding semidwarf varieties in the 1970s. In well-drained mid-toposequence fields, farmers grow the same high-yield-potential varieties grown by farmers with irrigation and usually establish their crops via transplanting. In the lower flood-prone fields, farmers usually direct-sow photoperiod-sensitive varieties that flower as the rains cease and stagnant water levels begin to decrease (Mackill et al 1996). Individual farmers often have fields at several toposequence levels and thus often grow several varieties, each adapted to a particular hydrological environment.

The principal target environments requiring germplasm with improved drought tolerance are unbunded uplands and bunded upper fields at the top of the toposequence; drought occasionally occurs in the lower fields but is relatively rare because these fields benefit from runoff and seepage from the upper fields and usually remain saturated long after the upper fields are dry. Bunded upper fields are the largest and most important target environment for drought tolerance breeding, both because of their extent and because of their potential for improved productivity. Rainfed rice breeding programs need to develop varieties with the duration, plant type, and stress tolerance required for this environment, which recurs across millions of hectares in most rice-growing areas. But farmers rarely adopt varieties that are poor in cooking or eating quality, even if stress tolerance were improved. Rainfed farmers are also interested in varieties that combine a degree of stress tolerance with the ability to produce high yields in favorable years or in parts of the field (i.e., the lowest corner of a drought-prone field) that are more productive. Thus, quality and yield potential are also key breeding targets for drought-prone environenments. Unwillingness to compromise on quality and yield potential, particularly on bunded lands, has meant that adoption of new varieties has been infrequent in rainfed systems. A relatively few improved varieties, including Swarna, Sambha Mahsuri, IR36, IR64, BR11, and MTU 1010 (sometimes referred to as "megavarieties"), together now account for much of South Asian rainfed rice production. Most of these varieties are valued for their quality, marketability, and yield potential under favorable conditions and have proven very difficult to replace. However, they were selected under favorable irrigated conditions and are not tolerant of the major abiotic stresses of rainfed environments, including drought. They are suitable mainly for favorable, mid-toposequence fields, but their high yield potential and desirable grain quality push farmers to adopt them in fields above their optimum level of adaptation. Farmers with drought-prone fields are thus in urgent need of options, but adoption of varieties with improved stress tolerance is only likely if they retain the quality and agronomic features of current megavarieties. The key task for rice breeding programs focusing on improvement of abiotic stress tolerance is therefore the development of varieties that combine improved stress tolerance with preferred quality and high yield potential under favorable conditions.

Physiological and agronomic effects of drought and implications for germplasm improvement

Direct effects of water shortage on growth and yield

The direct effects of water shortage on growth and yield can be acute, at critical crop stages, or they may be growth-limiting effects of continually recurring nonsaturated conditions. Much more attention has been paid to the former than to the latter, but it is likely that growth reduction due to intermittent soil drying throughout the season in upper fields causes greater overall losses. Rice yield is linearly related to the number of days in the growing season in which soil is saturated (Boling et al 2004, Haefele et al, this vol). The ability to maintain biomass accumulation in relatively dry soils is therefore a key feature required in drought-tolerant varieties. Intermittent soil drying substantially reduces biomass production and, therefore, total yield potential. IRRI research has shown substantial genetic variation in the ability of upland or lowland rice cultivars to maintain biomass accumulation in dry soils. For example, in a set of lowland cultivars evaluated at IRRI under intermittently drained conditions in the wet season of 2005, yields averaged 1.6 t ha^{-1}, a reduction of more than 50% relative to the fully irrigated control. In this trial, there was a range in total biomass production among cultivars of 4.1 to 7.4 t ha^{-1}. Variation in total biomass production was more closely related to final grain yield than was harvest index (HI) in this trial (Table 1).

Table 1. Cultivar differences in yield, harvest index, and biomass production in an intermittently dried lowland field, IRRI, 2005 wet season.

Designation	Harvest index	Grain yield (t ha^{-1})	Biomass (t ha^{-1})
IR70213-10-CPA 4-2-2-2	0.28	2.1	7.6
IR79670-125-1-1-3	0.26	1.9	7.3
PSBRc 80	0.30	1.6	5.2
PSBRc 14	0.34	1.7	4.9
IR36	0.31	1.3	4.2
PSBRc 82	0.40	1.6	4.1
Mean	0.32	1.6	5.5

However, drought is especially damaging immediately before and during flowering (Atlin et al 2006, Ekanayake et al 1990, Garrity and O'Toole 1994), so tolerance at this stage is particularly critical. This is especially true in upland rice, where brief periods of drought around flowering can result in near-complete spikelet sterility. For this reason, much research on drought tolerance has focused on tolerance for stress at flowering stage. Genetic variation exists within *Oryza sativa* for the trait (Atlin et al 2006). Some varieties have a high degree of tolerance for short periods of stress around flowering, whereas others experience markedly reduced seed set and harvest index. A set of varieties was evaluated at IRRI under rainfed upland conditions in the wet seasons of 2004 and 2005. In both seasons, drought at flowering resulted in severe stress between panicle initiation and anthesis. For a subset of lines with similar days to flowering under nonstress conditions, mean yield and harvest index are presented in Table 2. In this set, yields ranged from 0.7 to 2.3 t ha^{-1}. Nearly all of the variation in yield was explained by the variation in harvest index; lines that are high-yielding under stress, such as IR71525-19-1-1 and CT6510-24-1-2, were able to maintain a high level of seed set under stress at flowering. The physiological basis for this differential tolerance is unknown.

Table 2. Mean yield and harvest index of rice cultivars exposed to severe reproductive-stage stress under upland conditions at IRRI, 2004 wet season.

Designation	Days to flowering	Yield (t ha^{-1})	Harvest index
	Non-stress	Stress	
IR71525-19-1-1	86	2.3	0.22
PSBRc 82	87	0.7	0.11
IR71700-247-1-1-2	88	1.1	0.16
IR77298-12-7	89	1.2	0.17
IR77298-14-1-2	89	0.9	0.12
PR26406-4-B-B-2	89	0.8	0.09
CT6510-24-1-2	90	2.0	0.19
IR72875-94-3-3-2	90	0.7	0.11
UPL RI 7	90	1.9	0.16
APO	91	1.7	0.18
LSD$_{0.05}$		0.7	0.06

Because crop phenological stages differ in their sensitivity to drought, researchers have devoted considerable effort to the development of screening techniques that permit genotypes of different growth durations to be evaluated in common experiments at equivalent levels of stress at key stages such as flowering. These include techniques such as line-source irrigation (Lanceras et al 2004), which subjects cultivars to a constant stress gradient throughout the season, or field designs that permit each genotype to be irrigated independently (Lafitte and Courtois 2002), allowing stress to be imposed or removed at the same stage of development for each cultivar in the trial. However, these methods are not practical in a breeding program that must screen hundreds of lines. The IRRI breeding program screens for drought tolerance using protocols (described below) where stress is repeatedly imposed on a large nursery or trial on a uniform date, starting before the first genotypes in the trial flower, with cycles of stress and re-irrigation repeated until harvest. Variety means in screens of this type are highly correlated with means from trials in which stress is precisely applied at the sensitive flowering stage (IRRI, unpubl. data).

Effects of drought on crop management and agronomic practices

Transplanting delay. To a rice farmer, the word "drought" means not only physical water shortage that affects plant growth and development but also a lack of sufficient water to support land preparation, transplanting, fertilizer application, and weed control operations. All of these operations are dependent on the presence of a standing water layer in the paddy. If they are delayed or omitted, large yield losses often ensue, even though plants have not suffered physiological water stress. Losses from these management disruptions may be as great as those from direct drought damage. Cultivars differ in their sensitivity to these management disruptions and these differences can be exploited in the development of more resilient varieties for drought-prone environments.

Transplanting is the management step that is most vulnerable to water shortage. The optimum age of seedlings at transplanting is 2–4 wk old, but rainfed farmers must often plant seedlings that are much older due to water shortage. Farmers cannot transplant until sufficient water accumulates in fields to permit puddling (usually 400–500 mm of rainfall); often, this may not occur until seedlings are 60–80 d old. Such delays result in large yield losses because of reductions in both panicle number and weight. In experiments conducted at IRRI in 2005, transplanting 65-d-old as opposed to 22-d-old seedlings resulted in a yield reduction of more than 50%, averaged across 125 cultivars. Yield reductions due to delayed transplanting were experienced on this scale in large areas of eastern India in 2004, and in the Nepali *terai* and adjoining regions of Uttar Pradesh in 2006. Even high-rainfall regions that are not considered drought-prone, such as southern Cambodia, may experience severe losses due to delayed transplanting resulting from an early-season pause in the monsoon.

Weed management. Water shortage also affects weed management. Standing water in lowland fields after sowing or transplanting suppresses the germination of weed seedlings. Under the nonflooded, aerobic conditions characteristic of upland or drought-affected lowland fields, weed seedlings germinate freely. Most upland weed species grow more quickly than rice in nonsaturated soils, resulting in greater competition from weeds under drought conditions. The widespread indigenous eastern Indian rainfed lowland establishment and weed-management practice of *beushening* (also known as *beusani* or *biasi*, among other variants), which consists of dry direct sowing, followed by uprooting the standing crop about 1 mo after broadcast seeding by plowing, followed by planking and replanting of uprooted seedlings (Singh et al 1994), is also highly sensitive to water shortage; the uprooting and replanting process is dependent on the presence of standing water in the field and cannot be conducted when early drought occurs, resulting in a failure of weed control. Extensive genetic variation among rice cultivars with respect to weed competitiveness has been documented both for upland (Zhao et al 2006a) and lowland (Haefele et al 2004) systems, but little effort has been made to exploit this variation in the development of cultivars for water-short environments. Recently, however, Zhao et al (2006b) showed that weed-suppressive ability and weed competitiveness under upland conditions are strongly associated with rapid seedling growth in the first 4 wk after sowing, a trait for which substantial variability exists within and among the major rice germplasm groups (Zhao et al 2006c).

Germplasm development for drought-prone environments

The development of cultivars adapted to drought-prone environments or to production systems that need less water requires that both high yield potential and a suite of adaptations to environment-specific types of water shortage be "packaged" in a single cultivar. Breeding methods used and progress achieved in the development of drought-tolerant, water-efficient cultivars will be considered for two specific production environments: drought-prone unbunded uplands and bunded upper terraces. These are distinctly different target environments, requiring different traits to optimize cultivar performance. As noted above, these traits include not only improved drought tolerance *per se* at the vegetative and reproductive stages but improved weed competitiveness and, in the case of transplanted crops, tolerance for delayed transplanting.

It should be noted that farmers do not usually want cultivars that are drought-tolerant but low in yield potential in favorable years. They want cultivars that not only respond to favorable conditions but that also "protect" an economically useful yield under drought conditions. Therefore, breeding lines should be screened under both stress and nonstress conditions. Most studies in which large populations of unselected lines have been screened under stress and nonstress conditions show that there is a low but positive correlation between yield under stress and yield potential (Atlin et al 2004). It is therefore possible to identify varieties with both high yield potential and relatively high yield under stress.

Developing cultivars with improved drought tolerance for bunded upper terraces

The most drought-affected lowland fields are upper-toposequence bunded fields that are established by transplanting or traditional broadcasting methods. Critical traits for these fields include the ability to maintain biomass accumulation in intermittently dry fields, tolerance for severe stress at flowering, tolerance for delayed transplanting, and responsiveness to favorable conditions when they occur.

Screening for drought tolerance. Bunded (lowland) fields regularly affected by drought are usually upper-toposequence fields with light to medium soil texture. These fields are without standing water for much of the growing season and may dry out repeatedly. Screening of cultivars targeted at this environment should mimic these intermittently dry conditions. Effective screening for lowland drought tolerance can be done even in the wet season in trials situated in upper, light-textured fields that can be easily drained. Care should be taken to ensure that the field used is at the top of the toposequence, and that there is no higher field from which water will flow into the drought screening site. Because the objective of screening is to identify cultivars with improved yield under stress, screening is conducted in replicated trials consisting of two-row plots to achieve adequate precision. Seedlings are transplanted into puddled soil in such fields, and then the trial is drained 7 d after transplanting. The field should be allowed to dry until the soil cracks and/or the surface is completely dry. The field should not be irrigated again until the local check variety is wilting, and the water table is at least 1 m below the surface. If tensiometers are installed, the field should be irrigated when soil water tension equals –40 kPa at a depth of 20 cm. When these conditions are achieved (the time needed for this to occur will vary with soil texture and rainfall), the field is then re-irrigated. One day after re-irrigation, the field is drained again. The cycle of stress followed by re-irrigation and drainage is repeated until the field is finally drained for harvest. Drought tolerance is expressed simply as the yield produced by a cultivar under stress.

Screening under this type of managed stress has identified large differences among lowland breeding lines and mega-varieties in yield under stress at IRRI (Table 3). Several lines (e.g., the pureline IR77298-14-1-2 and the hybrid IR80228H) have been identified that are comparable in yield potential to current elite irrigated varieties under nonstress conditions but that outyield them substantially under stress. Screening for grain yield under drought stress has now been incorporated as a routine cultivar evaluation step by IRRI and by several Indian breeding programs in collaboration with the IRRI-India Drought Breeding Network, a collaborative network serving drought-prone rainfed environments. This network tested a number of breeding lines developed at IRRI as well as at different national research institutes in India for their performance under drought. These lines were screened in alpha lattice design with three replications under fully irrigated conditions and two levels of stress. In one stress level, fields were drained out just after transplanting, water from rains was never allowed to stand, and the trial was never irrigated. These experiments generally had experienced more severe stress, resulting in at least 70% reduction in mean yield as compared with control mean yield. In the second stress level, fields were drained out after 35–40 d of sowing with the aim of screening the lines for reproductive stress.

The mean yield reduction in these experiments ranged between 30 and 60% and these experiments were classified as "moderate stress." Screening under severe drought, moderate drought, and irrigated control at Raipur identified breeding lines of 100–120 d duration that had yield potential between 4.0 and 5.2 t ha^{-1} and that produced a grain yield of 1.7–2.1 t ha^{-1} under severe drought stress (Table 4). These lines exhibited a combination of the drought tolerance of donors and the yield potential of high-yielding, drought-susceptible cultivars. Among the 120–140-d duration group, breeding lines with yield potential of 6.3 t ha^{-1} and yield of up 1.9 t ha^{-1} under severe drought stress (Table 5) were identified. The screening also showed that the widely grown rainfed variety Swarna is mildly tolerant, whereas the related variety Sambha Mahsuri was shown to be extremely susceptible to drought stress.

Screening for tolerance for delayed transplanting. Delayed transplanting is probably the main cause of yield loss due to drought in rainfed lowand systems, but tolerance has rarely been systematically evaluated or incorporated as a rice breeding objective. Variability in tolerance for delayed transplanting appears to be large, even in photoperiod-insensitive germplasm. In the 2005 wet-season evaluation of 125 medium-duration, photoperiod-insensitive varieties transplanted as 65-d-old seedlings, cultivar mean yields ranged from 0.3 to 3.3 t ha^{-1}. Some elite breeding lines and cultivars produced high yields when transplanted as 25-d-old seedlings but performed very poorly under delayed transplanting. A notable example is the tungro-resistant IR64 derivative IR77298-14-1-2, which yielded 4.0 t ha^{-1} under normal management, but only 1.8 t ha^{-1} under delayed transplanting. Other entries produced relatively high yields under both conditions; for example, the hybrid IR80642H yielded 4.4 t ha^{-1} when transplanted as 25-d-old seedlings, with a reduction to only 3.3 t ha^{-1} as 65-d-old seedlings. In general, hybrids were more tolerant than purelines (Table 6).

Developing cultivars with improved drought tolerance for unbunded uplands

Upland rice is grown as a subsistence crop in unbunded upper fields by some of the poorest farmers in Asia. Upland rice growers use few improved varieties and, because of risk of crop loss due to drought or weed pressure, apply only small amounts of fertilizer to their fields. Recently, studies in traditional upland

Table 3. Yield, days to flowering, and harvest index of medium-duration varieties and breeding lines under severe intermittent lowland drought stress and full irrigation, IRRI, 2006 dry season.

Line	Days to flowering		Harvest index		Yield (kg ha^{-1})	
	Stress	Non-stress	Stress	Non-stress	Stress	Non-stress
IR77298-14-1-2	94	85	0.21	0.40	1241	3278
IR80461-B-7-1	95	84	0.22	0.37	1076	3675
IR80228 H	101	85	0.27	0.46	920	5782
PSBRc 82	104	91	0.10	0.36	256	2647
Trial mean	100	88	0.10	0.34	447	2233
$LSD_{.05}$	8	2	0.10	0.16	355	944

Table 4. Yield, days to flowering, and harvest index of medium-duration varieties and breeding lines under three levels of water stress, IRRI-India Drought Breeding Network, 2005 wet season.

Line	Grain yield (kg ha^{-1})			Days to flowering			Harvest index		
	Stress level			Stress level			Stress level		
	None[a]	Moderate	Severe	None	Moderate	Severe	None	Moderate	Severe
				Tolerant lines and cultivars					
Baranideep	5523	3926	1415	82	87	87	0.42	0.40	0.38
CB00-15-24	4972	3106	1383	81	83	82	0.40	0.40	0.36
IR74371-3-1-1	4971	3872	1229	83	83	88	0.41	0.42	0.34
				Widely grown varieties					
MTU1010	2915	1922	635	86	92	91	0.28	0.21	0.13
IR64	5231	2905	516	87	90	90	0.41	0.35	0.17
IR36	4192	1993	116	85	97	94	0.41	0.27	0.04
Trial mean	4589	2763	767	84	89	91	0.38	0.32	0.22
$LSD_{.05}$	781	934	358	4	5	3	0.05	0.08	0.11

[a] Mean of 7, 3, and 1 trial for non-stressed, moderately stressed, and severely stressed trials, respectively, in southern and eastern India.

Table 5. Yield, harvest index, and days to flowering of 120–140-d duration entries from the IRRI-India Drought Breeding Network at Raipur, 2005 wet season.

Designation	Grain yield (t ha^{-1})			Harvest index			Days to flowering		
	Control	Moderate stress	Severe stress	Control	Moderate stress	Severe stress	Control	Moderate stress	Severe stress
ARB6	6.7	4.3	1.9	0.37	0.43	0.40	79	78	81
IRMBP-2	6.1	3.2	1.3	0.38	0.32	0.35	82	84	85
Mahamaya	6.5	1.9	0.6	0.34	0.19	0.14	92	93	96
PSBRc 9	5.8	4.3	1.6	0.42	0.42	0.37	90	89	91
Sambha Mahsuri	6.7	0.8	0.0	0.41	0.09	0.0	103	111	[a]
Swarna	6.0	2.1	1.3	0.38	0.25	0.34	103	110	126
(Swarna/ IR42253)-54	6.4	2.8	1.7	0.42	0.33	0.38	83	85	80
$LSD_{0.05}$	0.7	0.6	0.4	0.04	0.06	0.07	1	1	5

[a]Failed, did not flower.

Table 6. Agronomic performance of 10 hybrids versus 115 inbred purelines when transplanted at 22 or 65 d after sowing, IRRI, 2005 wet season.

Cultivar type	Days to flowering		Height (cm)		Harvest index		Yield (kg ha^{-1})	
	Seedling age at transplanting							
	22	65	22	65	22	65	22	65
Hybrid	85.0	113.5	114.7	89.8	0.41	0.38	4976	2674
Inbred	81.5	112.9	118.9	91.6	0.37	0.28	3377	1484
Pr > F	ns	ns	ns	ns	0.0012	<0.0001	<0.0001	<0.0001

rice-growing areas of Yunnan (Atlin et al 2006) and Laos (Saito et al 2006) have demonstrated that improved upland rice varieties have at least 50% higher yield potential than traditional cultivars and can serve as the basis for more productive and sustainable upland rice-based cropping systems. However, since upland systems are almost exclusively rainfed, adoption of such systems will depend on the development of varieties that combine high yield potential with high levels of drought tolerance and weed competitiveness.

Screening for tolerance for upland stress. Strategies for drought-tolerance screening under upland conditions are similar to those described above for lowland management. Most upland varieties are photoperiod-insensitive, so if temperatures permit, dry-season screening is the preferred option for reliably imposing stress. Many upland varieties have a moderate degree of vegetative drought tolerance but are often highly susceptible to stress around flowering. For this reason, screening protocols should emphasize tolerance for stress at flowering. At IRRI, drought screening is conducted in replicated yield trials of fixed lines that have been previously selected for yield potential and disease resistance. Screening trials are conducted in an unbunded, well-drained field at the top of the toposequence. There should be no irrigated or flooded trial planted above the drought screening site. Lines should be screened in trials with at least two replicates. Plots should be at least two rows. Trials are direct-sown into dry soil. The field should be irrigated to maintain soil water potential near field capacity until canopy closure, or for about 30 d after sowing, at which time the frequency of irrigation is reduced. Irrigation is withheld until the soil surface is completely dry, susceptible check varieties are severely wilted, and the water table is at least 1 m below the surface. If tensiometers are installed, the field should be irrigated when soil water tension reaches –50 kPa at a depth of 30 cm. When the target levels of soil dryness and plant stress are reached, the field should be liberally irrigated. Enough water should be applied to saturate the root zone. This is likely to require 60–80 mm of water. The stress cycle is then repeated until harvest. Yield and harvest index should be determined.

There is evidence that differences in drought tolerance measured in this screen are predictive of differences observed under natural stress in the target population of environments. For example, at IRRI, 30 varieties were screened under severe upland stress artificially imposed in the 2005 dry season. The same varieties were screened under rainfed upland conditions at IRRI in the 2004 wet season and 2005 wet season. In both of these years, severe drought stress occurred at flowering. The correlation between variety means for grain yield in the dry-season stress screen and under natural stress in the wet season was 0.87, indicating that the ability of the artificial drought screen to predict performance under natural stress was high (IRRI, unpubl. data).

Selection of random breeding lines under artificial stress has been shown to result in gains under natural stress in the wet season. Venuprasad et al (2007) screened several hundred lines from the crosses Apo/IR64 and Vandana/IR64 in the dry season of 2003. The lines were evaluated for grain yield under both severe upland stress and irrigated control conditions. Selected lines from both the stress and the irrigated control screens were then evaluated under natural stress at IRRI in the wet seasons of 2004 and 2005. Yield gains under natural stress were greater in the subset of lines selected under artificial stress than under fully irrigated conditions. Selection under stress gave no gains under nonstress conditions.

Screening for weed competitiveness. Upland rice cultivars that compete well against weeds are often thought to be tall, rapid in early growth, and have droopy leaves and high specific leaf area. These traits have been linked to low yield potential in some studies (Jennings and Aquino 1968, Kawano et al 1974) but not in others (Garrity et al 1992, Ni et al 2000, Fischer et al 2001). More recently, Zhao et al (2006b) have shown that differences in cultivar weed competitiveness in direct-sown rice are largely determined by differences in the rate of seedling biomass accumulation in the first 4 wk after sowing. They observed that, averaged over 3 yr, there was a twofold difference between the most and least competitive cultivars in weed biomass at 9 wk in plots that were hand-weeded once 3 wk after sowing, and that there was no tradeoff between yield potential and weed competitiveness. Improved weed competitiveness can be selected for in replicated trials by visually rating advanced breeding lines for total biomass 4 wk after sowing (Zhao et al 2006b). Screening for seedling biomass accumulation has been incorporated as a routine screening step in the IRRI rainfed and aerobic rice breeding programs. Cultivars with high seedling biomass accumulation tend to be erect, moderately drought-tolerant, and derived from the *indica* and *aus* germplasm groups.

Direct seeding to reduce drought risk in drought-prone upper fields

As noted above, rice establishment either by transplanting or through the traditional beushening/biasi practice in bunded upper fields frequently leads to heavy crop yield loss because of delayed transplanting, exposure of the transplanted seedlings to early drought, or failure of weed control. In crops where establishment has been delayed due to lack of standing water in fields, the risk of drought occurring during the reproductive stage or grain filling is also increased. Direct seeding in dry soil, with herbicide-based weed control, may be a useful alternative to transplanting or beushening in areas where early-season drought is frequent. Direct seeding can be undertaken in dry or moist soil starting with the earliest rains, and it therefore allows establishment to take place 4–6 wk earlier than is possible in puddled, transplanted systems. Early establishment reduces drought risk during flowering and grain filling associated with early withdrawal of the monsoon and, because direct-sown crops mature approximately 10–14 d earlier than transplanted crops seeded on the same date, increases the probability of successfully establishing a post-rice rainfed crop. Direct-seeded establishment also eliminates the risk associated with delayed transplanting, which occurs when rainfall is insufficient for main-field puddling by the time seedlings are ready to be removed from the nursery bed; planting over-aged seedlings due to early-season drought is a major cause of yield reduction in light soils and upper rainfed terraces.

Cultivars differ substantially in their adaptation to dry direct-seeded establishment. Component traits include weed competitiveness, seedling vigor, ability to maintain biomass development in intermittently dry fields, and tolerance for late-season drought. The development of adapted cultivars with these traits is therefore an important element in the design of successful direct-seeding establishment systems in rainfed upland and shallow lowland systems. Drought-tolerant upland varieties for direct seeding with a yield potential of 4-5 t ha^{-1} that produce yields of more than 1 t ha^{-1} under severe drought stress have been identified. The yield potential of these materials is not greater than that of current elite aerobic adapted varieties Apo and PSBRc 80, but yields under moderate drought stress are three- to fourfold higher (Table 7).

Hybrid rice: a technology for water-stressed environments

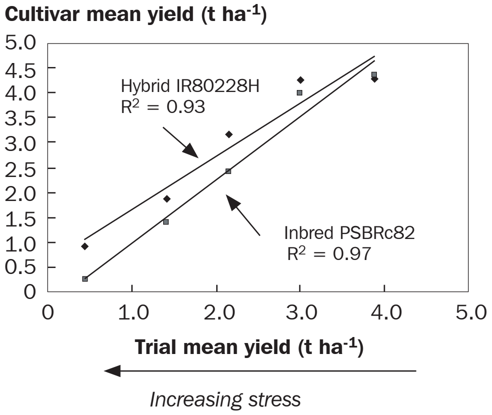
Hybrid varieties appear to offer a route to combining improved tolerance for drought stress with high yield potential, particularly in drought-prone lowland fields. In field experiments conducted at IRRI during the dry seasons of 2004 through 2006, hybrids previously not selected for drought tolerance have been compared with elite purelines from the IRRI irrigated and rainfed lowland breeding programs under the moderate intermittent drought stress protocol described above, which reduces trial mean yield from approximately 4–5 to 1.5–2.0 t ha^{-1}. Hybrids have consistently outyielded purelines under this level of stress by an average of about 1 t ha^{-1}, about 60% (IRRI, unpubl. data).

Table 7. Yield of drought-tolerant upland breeding lines under nonstress and severe intermittent upland drought stress applied following maximum tillering, IRRI, 2005 dry season.

Line	Nonstress yield (t ha^{-1})	Stress yield (t ha^{-1})	Days to flowering (nonstress)
IR78875-190-B-1-3	4.6	0.8	81
IR71525-19-1-1	4.2	1.4	85
IR78875-131-B-1-3	4.1	1.0	85
IR78875-131-B-1-2	4.0	1.0	79
IR74371-54-1-1	4.0	1.1	75
Apo	3.4	0.2	80
LSD $_{0.05}$	1.1	0.3	

The advantage of hybrids is both proportionately and absolutely greater under moderate stress than under fully irrigated conditions. This is illustrated by the comparison of yields of the elite pureline variety PSBRc 82 and the hybrid IR80228H, evaluated in five trials at IRRI under a range of hydrological conditions (see figure). The two varieties did not differ in yield under nonstress conditions, but in trials with a mean yield level of 2 t ha^{-1} or less as a result of water stress, the hybrid had a significant advantage.

The tolerance of hybrids for moderate water stress and, as noted earlier, for delayed planting, combined with their high yield potential in favorable environments, has led to their rapid adoption in eastern India, where they have been introduced by the commercial seed sector over the last 5 yr. Particularly in the drought-prone shallow lowland areas of the poorest states in the region, including Jharkhand, Bihar, Uttar Pradesh, and Chhattisgarh, smallholders have been eager to replace short-duration but drought-susceptible varieties such as IR64 and IR36 with hybrids.



Yield of an elite inbred and a hybrid compared under a range of water stress levels in five trials conducted at IRRI in the wet and dry seasons of 2005 and 2006.

Generating impact: participatory varietal selection in the target environment

To increase the probability of uptake of improved varieties, it is important to determine that their performance is maintained under the variable conditions faced by farmers, which may not be predicted by on-station performance (Atlin et al 2001), and that they have end-use and quality characteristics preferred by farmers. Experience has shown that cooking quality and performance under farmer management are the primary drivers of the adoption and spread of rainfed rice varieties (Mackill et al 1996). Low-cost and effective participatory varietal selection methods have been adapted for determining farmer preferences and assessing the performance of rainfed rice varieties under farmer management (Atlin et al 2002).

Most rainfed rice varieties with high impact in South Asia have been disseminated primarily via farmer-to-farmer spread. Measures can be taken to increase the rate of adoption of promising released varieties. Links among breeding programs, seed production programs, and agricultural development and extension organizations operating at the community level can be developed to target varieties where they are needed and to identify key farmers who will be instrumental in disseminating varieties within the community, once they are convinced of their value (Subedi et al 2001). One example of such an approach is a project to disseminate varieties with improved tolerance for submergence in low-lying areas of West Bengal (S.K. Mallik, pers. commun.). In this program, breeders collaborate with extension workers to identify communities frequently experiencing severe crop loss because of flooding and where farmers are strongly interested in obtaining tolerant varieties. Meetings are organized in the targeted communities to identify farmers with a strong interest in evaluating new varieties. These farmers serve as the conduit for improved germplasm into the community, ensuring that it is evaluated on appropriate land types. Such targeted approaches can reduce the need for expensive, large-scale seed production programs, make use of existing social arrangements for the dissemination of new varieties, and have the potential to foster the rapid spread of truly superior varieties.

Conclusions

Drought is a severe and an ongoing risk for rice producers who farm upper terraces with light soils, under both upland and lowland management. Several adaptations are required to increase productivity and reduce risk of crop loss due to drought on these lands, including increased ability to maintain vegetative biomass growth in intermittently dry soils, increase weed competitiveness, and increase tolerance in delayed transplanting and tolerance for severe drought stress at flowering. There is substantial genetic variation in all these traits. High-yielding cultivars tolerant of lowland drought stress and delayed transplanting have been developed. Hybrid varieties are particularly promising for drought-prone lowland fields due to their tolerance for moderate drying during vegetative growth and for delayed transplanting.

Direct-seeded systems offer considerable promise for drought-prone lowland fields, allowing farmers to establish their crops earlier, reducing the risk of drought during the critical flowering and grain-filling periods. Direct seeding also eliminates the risk of yield loss due to transplanting delay. Cultivars with improved yield under stress and improved adaptation to direct-seeded establishment in nonsaturated soils are best developed through direct selection for rapid early growth in dry soils, and for yield under stress imposed repeatedly after maximum tillering. This type of screening can be conducted in the dry season, or in upper, light-textured fields that can be easily drained in the wet season. This has been adopted as the principal screening method for drought tolerance by the IRRI rainfed and aerobic rice breeding programs. Drought-tolerant cultivars adapted to direct seeding, otherwise known as aerobic rice cultivars, which combine yield potential of more than 5.0 t ha^{-1}, yields of at least 1.5 t ha^{-1} under severe stress levels that reduce yield to zero in most improved lowland rice varieties, and a high level of weed competitiveness, have been developed by IRRI and collaborators. These cultivars are ready for evaluation as the basis for intensified management systems for drought-prone rainfed lowland rice environments.

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Notes

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Challenges and opportunities of direct seeding in rice-based rainfed lowlands of Asia

A.L. Rathore, A.M. Mazid, H. Pane, P. Romyen, S.M. Haefele, and D.E. Johnson

The method of crop establishment practiced by rice farmers is a key variable that determines subsequent crop management and opportunities to improve productivity. Transplanting is widely practiced where farmers have adequate supply of labor and good control over water on their fields, while direct seeding is preferred in traditional rainfed systems, as an alternative to transplanting in areas where farmers are seeking to save labor costs, and in drought-prone rainfed systems. This paper discusses some general issues related to the rice establishment method in the lowlands, indicating opportunities to improve productivity in traditional or well-established direct-seeded systems and in systems where direct seeding is an alternative to transplanting. While direct seeding offers advantages, good management with a focus on weeds is critical for successful crop establishment. Flexible crop establishment and management systems will be essential to enable farmers to adjust their practice to local conditions and their environment. This can only be achieved with substantial effort and partnership between the official, commercial, and informal sectors operating in the rural areas.

Keywords: direct seeding, diversification, population shift, post-rice crop, weeds, rice

Rainfed lowland rice is widely grown on fields that are level to gently sloping, bunded to retain water, and are flooded for at least part of the growing season. Depending on climate, soil characteristics, and topography, the plant-available water resources vary substantially in space and time. At the field level, the position within the toposequence can have a major effect on available water resources and the exposure of the rice crop to drought stress (Wade et al 1999, Fukai et al 2000). Rainfed lowlands may be classified as favorable or unfavorable, depending on rainfall, moisture availability, and susceptibility to flooding. The favorable rainfed area accounts for about 20% of the total rainfed lowland (Mackill et al 1996). The remaining 80% is less favorable and rice in this area suffers from varying degrees of drought, submergence, and both drought and submergence.

While rice production has been transformed over much of Asia in recent decades, with rice yields rising by 2.4% per annum from 1968 to 1999 (IRRI 2004), the greatest yield improvements occurred in irrigated areas where yield has risen in the last three decades to 5.8 t ha^{-1}, compared with 2.1 t ha^{-1} in the rainfed areas. Increases have been achieved with the introduction of improved germplasm, higher nutrient inputs, better crop and pest management, and, in many cases, mechanization. With the expected shortage of irrigation water in South and Southeast Asia (Bouman and Tuong 2003), it is likely that the rainfed lowlands will have an increasingly important role in meeting the demand for rice in the face of increasing population (Zeigler and Puckridge 1995). Further, as rainfed lowlands have a high incidence of poverty, increasing productivity in this ecosystem will help ensure food security.

The particular method of crop establishment determines, more than do other factors, the subsequent management options and crop performance in a particular biophysical and socioeconomic environment. In lowland ecosystems, three principal methods of rice establishment are used: dry direct seeding (DDS), wet direct seeding (WDS), and transplanting. Dry direct seeding consists of sowing dry seeds on dry or moist soils, whereas in WDS, pregerminated seeds are sown on water-saturated soils. Transplanting involves replanting of rice seedlings grown in nurseries to puddled and saturated soils. The preferred establishment method largely reflects the degree of water control a farmer has, the labor he has available, the accessibility of chemical weed control methods, and the need and opportunities to intensify and/or diversify the production system. Any change in any of these factors can convince a farmer to change his preferred establishment method. Such changes occur today in many rainfed systems as well as in intensive, irrigated systems. This paper discusses some general issues related to the rice establishment method in the lowlands, pointing to opportunities to improve productivity in traditional or well-established direct-seeded systems and systems where direct seeding is an alternative to transplanting. Changes in the weed flora caused by the shift to direct seeding and related issues are treated in the third part of this document. Lastly, we look at the possibilities and options of more flexible crop establishment and management systems.

General crop establishment issues

Dry direct seeding is probably the oldest rice establishment method (Pandey and Velasco 2002), but this has long ago given way to transplanting and more intensive cropping, especially in the favorable lowlands. By the 1950s, transplanting had become the dominant crop establishment system in most Asian countries as it has the major advantage of higher and more stable yield. Transplanting gives the farmer a substantial advantage in terms of controlling weeds as rice seedlings have a considerable size advantage over the germinating weeds and fields can be immediately flooded, thereby suppressing the majority of weed species. Another advantage is the higher indigenous N supply in permanently flooded fields because of the comparatively high biological N_2 fixation under such conditions. Transplanting also improves the chances of good crop establishment (i.e., less seed per area is needed), providing sufficient water resources for land preparation.

Dry direct seeding of rice has remained the preferred establishment practice in areas where labor is in short supply, the human population density is low, and/or hydrological constraints prevent land intensification. Increasing labor cost was one major reason for the shift from transplanting to direct seeding in several Asian countries (Pandey and Velasco 2002). Apart from lower labor requirements, limited and unstable water supply is an important factor that favors the use of direct-seeded systems. Dry direct seeding allows earlier establishment as compared with transplanting, thus reducing deep percolation and evaporation losses from early-season rains. The roots of direct-seeded rice tend to be deeper, finer, and more extensive; as a result, these crops consistently perform better under drought conditions (Ingram et al 1994, Singh et al 1995, Castillo et al 1998, Fukai et al 1998). In addition, direct-seeded rice matures earlier than transplanted rice; using modern, photoperiod-insensitive varieties reduces total crop water consumption and the risk of late-season drought (Cabangon et al 2002, Rathore and Sahu 2002, Sharma et al 2005). Earlier establishment and shorter crop duration may open opportunities for system intensification through a post-rice crop (Pandey and Velasco 2002). In the absence of soil puddling, however, deep percolation rates during the season can be higher. Thus, reduced water losses at the beginning of the season may be associated with higher water losses later in the season, depending on soil characteristics, topographic position, and duration of flooding. In drought-prone environments, also frequently characterized by limited nutrient availability, weed competition for water and nutrients may contribute greatly to crop losses. Under early-season drought spells, the competitive advantage of weeds rather than actual drought damage often results in crop abandonment. Thus, although direct seeding offers substantial advantages and opportunities, direct-seeded systems tend to be not as robust as transplanted systems and their management tends to be more critical for successful crop establishment, effective weed control, and high and stable yields.

Improving productivity in existing direct-seeded systems

In the rainfed lowland rice areas of eastern India (about 12.8 million ha) that are subject to shallow and intermediate flooding depth, biasi, beushening or beusani is a traditional rice establishment method, popular among farmers in 50–80% of the area (Koshta et al 1991, Nayak and Lenka 1988, Tomar 2002). In the biasi system, with the first rains, dry rice seed is broadcast on fields; followed at 20–35 d after emergence and when there is 5–10 cm of water on the fields by wet plowing to control weeds (Fujisaka et al 1993). Unlike many weeds, rice is able to recover after biasi, provided there is sufficient water in the fields. Farmers may also do some supplementary hand weeding to control subsequent weed growth.

Studies in the 1990s have shown that different dry seeding practices for could improve crop growth and increase the chances of growing a second crop. In eastern India, sowing dry seed in dry soil could be done before the rains start, while sowing dry seeds in moist soil, as practiced with the biasi system, requires 112 mm on average (Table 1). In comparison, crop establishment by transplanting (including the necessary soil puddling) and wet plowing in the biasi system require approximately 500 mm of rainfall.

Rice established by dry direct seeding (DDS) on dry soil suffers less from water deficit, resulting in better rainfall use efficiency. It gave the best yields across the 5 years of study (Table 2). Further, rice established by DDS in dry soil could be established, on average, 15 d earlier than DDS rice sown in moist soil and 60 d ahead of transplanted rice (Table 1). This headstart considerably reduced the effect of drought on rice in the moderate and severe drought years (1999 and 2000) and improved the performance of a post-rice crop. From 1995 to 1998, chickpea after DDS rice in dry soil gave the best yield; in the moderate-drought year, 1999, only DDS in dry soil permitted a second crop (Table 2). Independent of establishment method, no second crop could be established in the severe drought year 2000.

A similar amount of cumulative rainfall is required for biasi as for transplanting (Table 1), indicating a major constraint of the biasi system. Poor rainfall after crop establishment delays wet plowing and often causes high crop losses due to weed competition. Improved weed management options based on row seeding, interrow cultivation, and herbicide use may eliminate the need for biasi at the early tillering stage and provide a pathway to improving crop productivity. Line sowing rather than broadcasting permits interrow cultivation and easier hand weeding, and the application of either preemergence (pendimethalin) or postemergence herbicide (fenoxaprop + chlorimuron ethyl + metsulfuron) provides further options (farmers generally prefer postemergence herbicide because of visible effects and availability of water in the field at the time of application). The effect of establishment and weed management options on weed pressure was investigated in on-farm experiments in the region in 2005 (Table 3). Significant differences in weed density and biomass between establishment and weed management methods were observed, but they were generally small and all treatments achieved similar levels of weed control. However, the labor necessary for a similar level of weed control was much lower in cases where DDS was combined with the use of herbicides (Table 4). Therefore, herbicide use may become an important component of weed management options in direct-seeded systems, especially in regions where labor availability is a limiting factor and/or in years with early-season drought when biasi operation would be much delayed.

A different management system with seasonally changing establishment methods is practiced in the rainfed lowlands of central Java. There, two rice crops and often a vegetable crop are harvested from fields in one year in areas with a total rainfall of about 1,500 mm (Pane et al 2005). In this system, dry direct-seeded rice *gogorancah* is grown at the beginning of the rainy season, followed by a transplanted rice crop *walikjerami.* Both rice crops may be subject to flooding at varying periods,

Table 1. Average time of establishment and corresponding cumulative rainfall in five seasons (1995 to 2000), depending on rice establishment method, in an on-station experiment at Raipur, Chhattisgarh, India (Rathore and Sahu 2002). For all establishment methods, rice was grown under rainfed conditions without irrigation.

Establishment method[a]	Event[c]	Day of year	Cumulative rainfall (mm)
DDS dry	Sowing	159	0
	Establishment[b]	177	131 ± 51
DDS moist	Sowing	180	134 ± 55
	Establishment[b]	195	261 ± 61
DDS biasi[b]	Sowing	174	113 ± 52
	Establishment[b]	193	255 ± 60
	Biasi operation	219	532 ± 106
T	Transplanting	219	496 ± 112

[a] Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), dry direct seeding broadcast in moist soil and biasi operation (DDS biasi), and transplanting (T). [b] 1998-2000 only. [c] Establishment refers here to a plant size comparable with seedling size at transplanting.

Table 2. Effects of rice establishment method on rice and chickpea grain yield in five seasons with varying rainfall in an on-station experiment at Raipur, Chhattisgarh, India (Rathore and Sahu 2002). Rice and the post-rice crop were grown under rainfed conditions without irrigation.

Crop	Establishment method[a]	Grain yield (t ha^{-1})				
		1995-96[b]	1996-97[b]	1998-99[b]	1999-00[c]	2000-01[d]
Rice	DDS dry	6.76	5.71	4.61	4.22	3.12
	DDS moist	5.57	3.99	4.21	3.61	0.82
	DDS biasi	-	-	3.55	2.72	0.68
	T	4.54	3.69	3.25	1.69	0.39
Chickpea	DDS dry	0.82	0.92	1.10	0.62	NE
	DDS moist	0.78	0.81	0.96	NE[e]	NE
	DDS biasi	-	-	0.88	NE	NE
	T	0.64	0.68	0.69	NE	NE

[a] Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), dry direct seeding broadcast in moist soil and biasi operation (DDS biasi), and transplanting (T). [b] Good to normal year. [c] Moderate drought year. [d] Severe drought year. [e] NE: no establishment of a post-rice crop because of drought.

Table 3. Weed density and biomass as influenced by method of establishment and weed and fertilizer management in on-farm trials (2005) at Kotanpali, Chhattisgarh, India.

Treatment	Weed density[b] (plants m^{-2})		Weed biomass (g m^{-2})	
	20 DAE	35 DAE	20 DAE	35 DAE
Establishment method[a]				
DDS dry	8.1	3.5	18.6	10.1
DDS moist	8.2	3.5	13.3	10.2
DDS biasi	8.2	3.8	13.9	12.3
LSD (5%)		0.2	3.0	1.4
Weed management				
Preemergence herbicide[c]	7.0	3.6	13.3	11.6
Postemergence herbicide[c]	8.8	3.3	16.6	9.8
Biasi system	8.7	3.9	15.8	11.2
LSD (5%)	0.2	0.2	2.2	1.3

[a] Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), and dry direct seeding broadcast in moist soil and biasi operation (DDS biasi). [b] log transformed. [c] See text for details.

Table 4. Average labor requirements (man-days ha^{-1}) by establishment method, in on-farm trials (2005) at Kotanpali, Chhattisgarh, India.

Establishment method[a]	Land preparation, establishment	Weed control	Others	Total
DDS dry[ab]	25	26	60	111
DDS moist[ab]	20	24	63	106
DDS biasi[a]	20	88	63	170

[a] Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), and dry direct seeding broadcast in moist soil and biasi operation (DDS biasi). [b] for DDS dry or moist, average values for the use of pre- and postemergence herbicides are shown; no herbicide was used in the DDS biasi; all establishment methods included one hand weeding.

duration, and depth, depending on seasonal climate and toposequence. In this labor-intensive system, dry seeding of rice helps farmers make maximum use of the potential growing season. Studies on yield constraints on farmers' fields examined yield losses to weeds to find ways to increase productivity. Over 2 yr of additional weeding and fertilizer led to higher yields across the toposequence (Fig. 1). Yield gains by farmer's weeding practice were least on the lower portion of the toposequence and, on average, in excess of 1 t ha^{-1} elsewhere (Table 5). The yield gains with additional weeding were relatively minor compared with those of farmer's weeding practice, indicating that farmers achieve effective weed control. While weed species were similar across the catena, weed densities were least at the lower positions as compared with the higher positions (38, 78, and 91 plants m^2, respectively). Sixty-seven weed species were recorded in the direct-seeded crops of which approximately half also occurred in the transplanted crops. The yield gains using farmer's fertilizer practice were broadly similar to those using farmer's weeding practice, and there was opportunity for yield gains with additional fertilizer applications, particularly on fields in upper positions. These results highlight basic processes in the toposequence and their effect on rainfed lowland rice. Water accumulates in the lower part of the landscape, minimizing water stress and facilitating weed control there (but submergence may become a problem). Limited water availability in upper positions causes higher weed competition and lower attainable yields. Soil fertility often decreases toward the upper positions and limited water availability might further decrease nutrient availability to the crop.

Dry direct seeding is also widespread in the rainfed lowlands of northeast Thailand. Pandey et al (2002) indicated that farmer's choice of crop establishment method depends on various factors such as weed incidence, rainfall pattern, topographic position, field hydrology, labor availability, and tractor availability. Also, farmers may shift to transplanting, depending on seasonal abundance and timing of the rains. Competition from weeds in direct-seeded rice causes serious yield losses, and it was shown that, with farmers' practices, 24% of yields were being lost to weed competition (clean weeded vs farmer's weeding practice: 2.67 v 2.04 t ha^{-1}, SE = 0.11). In this study, farmers applied postemergence herbicides at 70 DAS, long past the interval when effective control could be expected. The effects of weeds were compounded by other factors—farmers reported greater losses in drier years and, further, with greater levels of weed infestation, farmers applied less fertilizer. The degree of losses may be affected by their position in the toposequence and weed density and weed biomass were greatest in the upper positions on the slope (Nantasomsaran and Moody 1995). Further, weed biomass in direct-seeded rice was more than three times that in transplanted areas. Farmers use less labor for hand weeding in northeast Thailand than in central Java and many farmers seek alternative employment in urban areas during the cropping season. Thus, Pandey et al (2002) concluded that farmers accept a lower yielding but labor-saving technology (i.e., DDS with imperfect weed control), especially in areas or fields where environmental conditions are less favorable for high yields (drought-prone regions and/or upper fields). This allows them to maintain some income or food from rice cultivation and pursue more remunerative off-farm activities.

Direct seeding as an alternative to transplanting

The decreased availability of labor and the increasing labor cost in many areas of Asia have led farmers to adopt direct seeding in place of transplanting (Pandey and Velasco 2002). Malaysia was one of the first countries in Asia where this transition occurred. The green revolution started to have an impact in Malaysia in the 1960s. In the 1970s, rice production in irrigated schemes was changing to double cropping, and in the 1980s, there was a shift from transplanting to direct seeding (Ho 1998). As farmers elsewhere face increasing labor costs and greater need for improvement in labor productivity, the transition to direct seeding continues.

Rainfed rice is grown in more than 1.0 million ha of the High Barind Tract, Bangladesh, and about 80% of this land lies fallow in the post-rice season (Mazid et al 2002). Farmers traditionally transplant the crop, but DDS is also feasible, permitting subsequent cash crop such as chickpea (Mazid et al 2003). A challenge, however, in the rainfed rice systems is to improve reliability while at the same time improving overall system productivity. To achieve this, in the Barind of Bangladesh, direct seeding was proposed as an alternative to transplanting to enable an earlier harvest and to allow a rabi crop (e.g., chickpea or mustard) to be grown on the residual moisture (Mazid et al 2002). Direct seeding allows earlier establishment as the land can be prepared after only about 150 mm of rain has fallen, compared with 400 mm needed for transplanting (Saleh et al 2000). Further delay of transplanting, by up to a month, is caused by insufficient early-season rains in one year out of two. Delayed transplanting reduces crop performance because of the use of old seedlings and the higher risk of exposure to drought at the reproductive crop stage.

In the High Barind Tract of Bangladesh, the productivity of two rice cultivars when direct seeded or transplanted was evaluated in a trial conducted in 2001-04 (Mazid et al 2006). Modern cultivar BR39 (crop duration of 120–125 d) was compared with the widely used variety Swarna (150–155 d duration). Establishment treatments were (1) *transplanted rice* (TPR)—soil puddled prior to transplanting and plots hand-weeded twice at 30 and 45 d after transplanting (DAT); and (2) *dry direct-seeded rice* (DSR)—sown into moist soil with a preemergence herbicide application (oxadiazon), followed by one hand weeding. Rainfall in May and early June was sufficient in 2001 and 2004 for sowing dry-seeded rice into moist soil in June (Fig. 2). In 2002 and 2003, an abrupt onset of the monsoon resulted in flooded fields; pregerminated seed was thus sown on saturated soil in DSR plots as flooding receded. Inadequate rainfall in 2003 resulted in transplanting being delayed until late September. Yield of DSR generally exceeded that of TPR, and the extremely low yield of transplanted rice in 2003 resulted from very late transplanting. Over 4 yr, the mean yield of direct-seeded BR39 was 2.6 t ha^{-1} (SED = 0.13) compared with 1.8 t ha^{-1} for the TPR treatment.

Table 5. Yield gains (kg ha^{-1}, means over sites), by management treatment and toposequence position (adapted from Pane et al 2005).

Year and season	Toposequence position[a]	Gain by farmer's weeding	Gain by additional weeding	Gain by farmer's fertilizer	Gain by additional fertilizer	Gain by additional fertilizer and weeding
2000 Gogorancah						
	1	1653	80	778	782	278
	2	1059	–	1345	980	154
	3	1147	188	630	460	192
	4	712	294	1001	112	416
Overall SE 522						
2001 Gogorancah						
	1	1368	2	962	540	431
	2	819	220	845	410	413
	3	1529	130	1006	132	–
	4	772	266	779	487	268
Overall SE 354						

[a] Toposequence position: 1 = high, 2 = upper mid, 3 = lower mid, 4 = low.

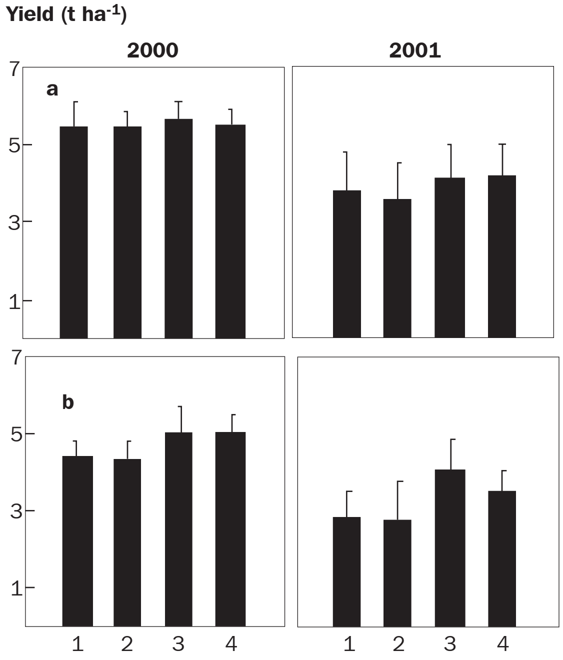
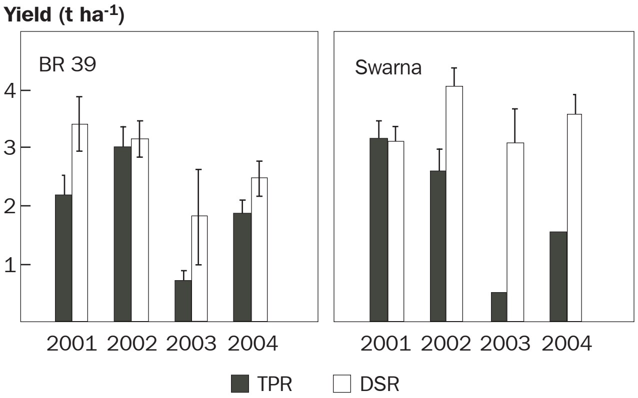


Fig. 1. Rice grain yield (mean ± standard error bars) in relation to toposequence position and cropping season; a) yield with intensive weeding and fertilizer; b) yield under conventional farmer practices. Toposequence position: 1 = high, 2 = upper mid, 3 = lower mid, 4 = low (adapted from Pane et al 2005).



	2001	2002	2003	2004
DSR Planting date	26/6 dry seed	3/7 wet seed	20/6 wet seed	14/6 dry seed
TPR Planting date	27/7	2/8	27/9	16/7
Rainfall (mm)				
May	235	95	73	100
June	367	312	248	454
July	268	228	97	176

Fig. 2. Effect of crop establishment and weed control method on grain yields (t ha^{-1}) of two rice cultivars BR39 and Swarna in the rainfed lowlands of the High Barind Tract (adapted from Mazid et al 2006).

The average yield difference between the two establishment methods was even larger for Swarna, yielding 3.4 and 1.9 t ha^{-1} for the DSR and TPR treatment, respectively. Direct-seeded rice was usually established 1 mo earlier (3 mo earlier in 2003) and DSR rice crops matured faster (data not shown). The different establishment methods for rice however resulted in a shift in weed composition, with densities of the perennial and annual grasses, *Cynodon dactylon* and *Echinochloa crus-galli* and that of annual sedge *Fimbristylis miliacea* increasing under DSR.

Direct seeding as an alternative to transplanting and as an approach to reduce costs and improve flexibility has also been demonstrated in the rice-wheat system of the Indo-Gangetic Plains (Singh et al 2005). A significant portion of the rice-wheat areas are irrigated, but many of the constraints, particularly with regard to weed management, are common in the rainfed areas. In the rice-wheat systems, the attainable yields of direct-seeded and transplanted rice crops are similar, but the potential losses to weeds and the need for effective weed management are much greater in direct-seeded systems (Singh et al, this vol). In the Indo-Gangetic Plains, rice can be direct-seeded either with pregerminated seed sown on puddled soil or dry sown, either after conventional dry tillage or with zero tillage, using the tractor-mounted seed drills used for the wheat crop. The application of pendimethalin, a preemergence herbicide, followed by one hand weeding, has been shown to be effective, controlling the majority of weeds in the studies over five seasons (Singh et al 2005).

Relation between establishment method and weed species

Changes in weed populations, resulting from the shift from transplanting to direct seeding, were recorded in Malaysia, one of the first areas in Southeast Asia to revert to direct seeding (Fig. 3). Broadleaved weeds, including *Sagittaria* and *Monochoria* species, dominated weeds in transplanted ricefields in the late 1980s. But with a change to direct seeding, grass weeds achieved greater importance. *Echinochloa* spp., previously relatively minor weeds in transplanted rice, became the dominant weeds in direct-seeded rice. The annual grass *Ischaemum rugosum* and perennial grasses *Leersia hexandra* and *Panicum repens*, not previously recorded, also presented new threats. Substantial changes in the composition of weed flora with the change to direct seeding have also been recorded in the irrigated systems of India (Singh et al, this vol) and in the rainfed systems in Bangladesh. This information form a substantial knowledge base that can be used for weed management in some of the most important rice production areas in Asia. Many of the weed species present are common to these systems and the transition from transplanting to direct seeding is reflected in changes in the composition of weed populations. These shifts tend to be toward competitive grasses, including *Echinochloa* species, *Leptochloa chinensis*, and *I. rugosum* in irrigated wet-seeded rice and the perennial sedge *Cyperus rotundus* in dry-seeded rice. In the rainfed systems, *C. dactylon*, *F. miliacea* and *E. crus-galli* all increased under dry-direct seeded rice compared with transplanted rice. The management of such

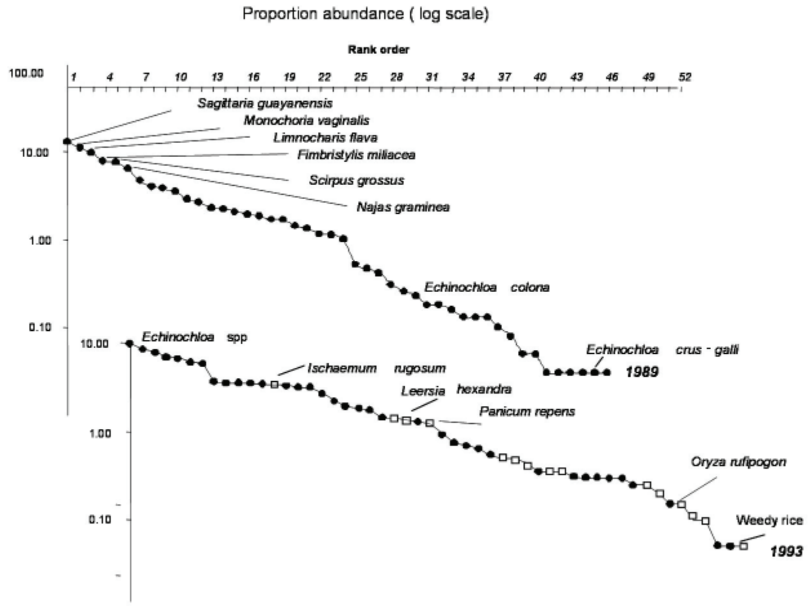


Fig. 3. Changes in weed species composition on farmers' fields in Kemuba, Malaysia, resulting from the change from transplanting (1989) to direct seeding (1993) of rice. Species are ranked in terms of their proportional abundance based on area coverage. Species not present in 1989 are indicated by hollow squares in the 1993 abundance curve (modified after Mortimer and Hill 1999).

weeds is challenging and requires farmers to anticipate changes in weed populations and exploit integrated strategies comprising tillage, water, and crop management to complement herbicide application. In Malaysia, by 1993, *O. rufipogon* (a wild rice) and "weedy" rice (*Oryza sativa*) were widespread in the weed flora, having not been recorded in 1989 (Fig. 3). Weedy rice (*O. sativa*), characterized by high grain shattering, has become a serious problem in Malaysia and Vietnam and has subsequently been reported elsewhere in Asia (Tensaout et al, this vol; Azmi et al 2005). The vigorous growth of this weed results in serious yield losses, and its rapid spread threatens the sustainability of direct-seeded rice production. Control of weedy rice is particularly difficult because of its close relation to the crop, though strategies combining preventive and cultural measures have been shown to be partially effective. A further outcome of the shift to direct seeding and the concomitant increased reliance on herbicides has been that certain weed species, including *Sphenoclea zeylanica* and *F. miliacea*, have developed resistance to herbicide 2,4-D (Watanabe et al 1997). More recently, possible ALS (acetolactate-synthase) inhibitor-resistant biotypes of *Bacopa rotundifolia* and *Limnophila erecta* have been reported (Azmi and Baki 2003). This is likely to be an increasing concern as the intensity of herbicide use increases.

Fewer studies have been conducted on the effects of changes in traditional direct-seeded systems on weed species composition. It is likely, however that similar problems, with an increase in pernicious grass weeds in particular, will emerge, as in the cases described above. Indications of this trend were apparent in the first year of experiments in Raipur, eastern India, where line seeding of rice was compared with the traditional biasi and where the principal weeds occurring were *Echinochloa colona*, *Eclipta prostrata*, and *I. rugosum.* These species also occurred in both direct-seeded and transplanted systems in Java and Thailand, along with the troublesome perennial weeds *C. rotundus* and *C. dactylon* (Pane et al 2005, Moody 1989).

Need for flexible and integrated establishment options in rainfed lowlands

Rainfed lowlands are highly variable in terms of soil and hydrological conditions, and this variability is often related to the undulating topography. Considerable temporal variability within the season and between years is added by variations in seasonal rainfall patterns, seasonal rainfall quantity, and interseasonal drought spells. These factors, together with farmers' available resources, varietal preferences, and cropping practices, will greatly affect the feasibility of options for direct seeding. Further, due to variable rainfall patterns, a feasible option in one year may not be possible in the subsequent year. In some regions, farmers react to these conditions with great flexibility. In eastern India, for example, farmers that usually do DDS may transplant if monsoon rains come early (Fujisaka et al 1993); in northeast Thailand, farmers may shift between transplanting and direct seeding, depending on monsoon rainfall and topography. However, research approaches and current recommendations often neglect the potential of a range of crop management options, which could help farmers achieve more flexibility, while at the same time cater to local variability. An example of this approach is given in Figure 4: a decision tree that gives the options and some issues that farmers may encounter with respect to crop establishment and weed management in the rainfed system. Such information, in turn, have to be integrated with their own field

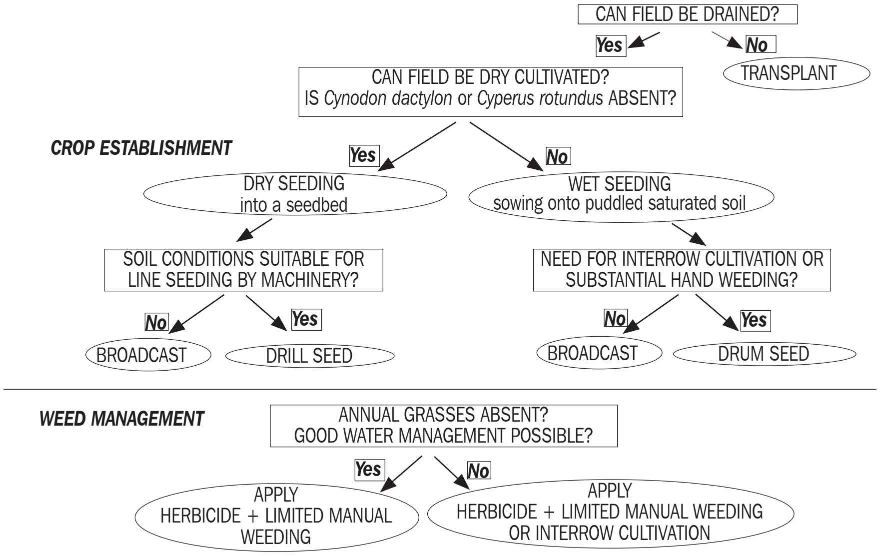


Fig. 4. Illustrative decision tree for adoption of direct seeding with respect to favorable rainfed lowland rice (modified after Johnson and Mortimer 2005).

experience, resources, and observations. Given the conditions in many rainfed environments, such flexible solutions should be better suited to help farmers respond to the highly variable environment and to secure their livelihoods. However, the practicability and the final design of such decision tools need to be adjusted locally, based on results of participatory evaluation and adaptation.

While such options may increase the productivity of rice-based systems, changes in crop establishment need to be reflected in changes of weed management. Farmers' practices, which provide reasonable weed control in transplanted systems or the traditional biasi system is unlikely to be adequate in dry direct-seeded rice. Introduction of direct-seeded systems without adjusted weed management can lead to high crop losses, rapid buildup of weed populations, and failure or non-acceptance of the technology. The introduction of weed management interventions, involving, for example, interrow cultivation and herbicides, was shown to enable sufficient weed control. As farmers move from transplanting or biasi system to (other) direct-seeded systems, however, they will need more information on the management of weeds and how they may limit undesirable shifts in weed populations (Johnson and Mortimer 2005). The commonality in weed populations in direct-seeded rice, across a range of environments, offers scope to develop means of assisting farmers in their decision making. The studies in India on direct seeding have shown that *E. colona*, *C. rotundus*, and *Commelina diffusa* are discouraged by wet seeding, while it has the opposite effect on *I. rugosum*, *L. chinensis*, and *F. miliacea* (Singh et al 2005). Further gains in the development of such knowledge, which predict undesirable shifts in weed population, will help develop and refine the ways to help farmers prevent these from occurring. In addition, it could also be used to manage existing weed populations in specific locations by choosing the adequate (i.e., weed flora-suppressing) establishment method. Schemes of alternating establishment methods could become part of integrated weed management strategies. Varietal development offers further opportunities. It has been repeatedly shown, for example, that cultivars with high seedling vigor and fast early growth reduce weed competition and yield losses due to weeds (Zhao et al 2006). Increased drought tolerance would also contribute to narrow the competitive advantage of weeds, especially in water-limited lowland environments. Establishment of rice breeding programs specifically targeting varieties for direct-seeded lowland systems could therefore contribute considerably to the performance, acceptability, and sustainability of these systems.

As production systems evolve, farmers will need considerable support to enable them to exploit the potential of many of the various options. This is particularly true of herbicides, where farmers may have little experience, and poor access to information. Farmers will need substantial information and continuing guidance to enable them to use products safely and effectively. In many locations, this is only likely to be achieved with substantial effort and partnership between the official, commercial, and informal sectors in the rural areas. Concerted efforts are therefore required not only to identify effective options but also to enable farmers to adapt these in appropriate ways according to prevailing circumstances. This presents further challenges in terms of the provision of adequate information to rural communities.

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Notes

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Molecular analysis of weedy rice in northwest Bangladesh

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Surveys of incidence and phenotypic variation of weedy rice in transplanted rice were conducted in northwest Bangladesh. Weedy rices varied in a range of traits, including plant height, grain size, pericarp color, shattering, and presence of awns. In 2005, the frequency of the traits early maturity and free shattering varied in the range of 6–12% of hills. Genotyping of individual plants (microsatellite markers at 19 loci) indicated that weedy rice plants were more polymorphic than cultivars plant. Allele sharing was present between crop and weedy rices, both within and between sampled locations. Phylogenetic analysis suggested that weedy rice may have arisen through in situ natural hybridization among rice cultivars, coupled with the process of de-domestication through genome instability.

Keywords: direct seeding, microsatellite, rice, weedy rice

The term 'weedy rice' refers to populations of *Oryza* species (usually *O. sativa*) that possess varying combinations of undesirable agronomic traits, including poor grain quality (grain size and colored pericarps) and early grain shattering (Mortimer et al 2000). Poor grain quality lowers commodity value, whereas early shattering reduces harvestable yield. Inter- and intrapopulation variation is also noticeable in characters such as plant height, tiller number and development, heading and shattering time, seed dormancy, awn length, hull color, and caryopsis pigmentation (dark red through red/pink to white). These traits may confer competitiveness against the crop; for example, as a consequence of vigorous tillering, leading cultivar yield may be reduced. Weedy rice (or 'red' rice) is present in rice agriculture in more than 50 countries across Africa, Asia, Latin America, and the USA, but it has more recently (Post 1985) emerged as a threat to rice production in Southeast Asia (Baki et al 2000). The relatively rapid emergence of weedy rice in Southeast Asia has been associated with the adoption of direct (predominantly wet) seeding of rice in irrigated rice systems that have switched from transplanting. Yield losses due to weedy rice infestations are reported to vary considerably (cultivar yield losses from weedy rice infestation densities of 10 plants/m^2 range from 35 to 74% and, at high infestation, lodging of weedy rice results in total yield loss). An additional constraint is related to the direct and opportunity costs of their management and control. The cryptic nature of both weedy rice in grain samples and in the vegetative state in the crop respectively prohibits effective control by seed cleaning of farm-saved seed and by hand weeding in the early life of the crop. While protecting yield in the current season, manual weeding is likely to be palliative in the long term, since seed contamination may be inherent in farm-saved seed and weedy rices may persist in soil seed banks.

The origins of 'weedy rice' remain unclear. Farmers often refer to 'off-types' in a developing transplanted rice crop to describe individual plants that are morphologically distinct from the majority of the crop. Typically, these are more advanced phenologically or bear noticeably distinct morphological traits from the bulk of the crop. A common presumption is that these plants result from inadvertent cultivar mixing in seed preparation or is caused by field variability. Off-types may, however, also constitute weedy rice ecotypes of *O. sativa,* having arisen by agroecological selection. There are three sources of genetic variation on which such selection may act. The first is heterozygosity resident within existing cultivar lines. The second is variation arising through gene introgression with feral rices, giving rise to hybrid populations. Variable mutation frequency among cultivars is the third source of genetic diversity. None are mutually exclusive and selection for weediness by any mechanism may potentially occur; segregation and recombination lead to heterozygosity and diversity of genotypes and ecotypes.

Clearly, the most difficult weedy rices to manage are those that resemble the cultivar morphologically and in terms of life history, and recruitment may occur in both transplanted and direct-seeded crops. Where seed stocks for transplant nurseries contain weedy ecotypes, the probability that they will be transplanted as seedlings, together with the cultivar, will depend both on the intensity of selection for uniformity by the farmer and the vegetative similarity of the phenotypes. Recruitment into direct-seeded crops may arise from sown seed and by volunteer seeding from the seed bank. Both wet and dry seeding as a crop establishment practice alters selection processes in that it removes the suppressive influence of standing water in transplanted rice on the germination and recruitment of weeds from seed, including volunteer rice. Where transplanting into saturated soil occurs in the absence of standing water, recruitment of weedy rice from seed into the crop may occur, but individuals are at a competitive disadvantage with the crop because of size differences. Clearly, selection for grain shattering prior to crop harvest and seed dormancy are key fitness traits that will ensure the persistence of weedy rice in the soil seed banks of direct-seeded rice agroecosystems.

In Bangladesh, dry broadcasting of seed is used to establish both deepwater rice (Morton and Rema 1987) and early kharif aus rice (World Bank 1995) and seed quality remains a matter of concern (Danielsen et al 2005). Farm-saved seed is reported to become contaminated with off-types over successive seasons. The use of direct seeding in rainfed rice in Bangladesh and its recent further promotion by the use of drum seeding technology (Mazid et al 2005) to save labor raise the question of sustainability of the technology, given the potential threat that arises from the ingress of weedy rice into rice production systems. In this paper, we report survey analyses of the presence of weedy rices and initial results from a molecular analysis of the genetic structure of transplanted rice populations in Bangladesh.

Material and methods

Field surveys

Two surveys to assess the occurrence of weedy rice phenotypes were conducted in the Rajshahi District in the Barind region of northwest Bangladesh. The first was conducted in 1999/2000 in the winter (boro) and the following monsoon (aman) season in transplanted rice. Farmers were requested to identify 'weedy' rices or 'off-types'(all phenotypic combinations) in the field at early/mid-maturity and fields were then sampled using a random-walk sampling procedure. A minimum of 50 fields were sampled for 10 plants in each season in each year. Plant height relative to the crop was recorded in the field. Grains were sampled from individual plants and visually characterized for color in the field. The existence of awns was noted. Shattering was judged by a simple manual pressing test and grain size assessed by measurement of 1,000 grain weight.

The second survey in the 2005 aman season focused on farms from three villages (Shaympur, Changmari, and Chandonpat) in the region of Rangpur in the Barind. These were chosen because field inspection indicated an increased intensity of weedy rices over previous seasons. One hundred and fifty rice hills (three randomly placed quadrats of 10 × 15 hills, per field) were randomly chosen in each of the 10 fields and the frequency of 'weedy' rices assessed. This survey focused on weedy rices, which were identified by early maturity. The cultivar was predominantly BR11, with traditional varieties Volter and BR28 occurring at two sampling locations. Crops were transplanted in all (but one) location. Single panicles from individual plants of weedy and cultivars from individual fields were collected and individually bagged. Individual plants were at least 1 m apart.

Plant material and genomic DNA extraction

Genomic DNA from cultivated (C) and weedy (W) rice was extracted from young leaf tissue of single plants using the DNEasy plant mini kit (QIAGEN) following manufacturer's instructions. DNA was individually extracted from 9 and 15 plants raised from individual seeds of C and W collections, respectively, from each of four field locations (1, 3, 6, and 8, Table 1). The crude nucleic acid precipitates were suspended in 150 µl of elution buffer and quantified by electrophoresis in agarose gels (1%) and kept at -20 °C. A total of 96 rice genomic DNA samples, comprising 36 C plants and 60 W plants, were genotyped at 19 microsatellite loci.

Table 1. Sampling locations, crop cultivar and frequency (± standard error of the mean, SEM) of weedy rices in 2005. At each location, three randomly located quadrats containing 50 hills were scored for the presence of weedy rices (defined as free-shattering, early-maturing plants). All fields had been transplanted, except field 1, which was direct-seeded.

Field number and village name	Cultivar	Frequency (%, mean ± SEM) of weedy rices
1 Shaympur	BR11	6.4 ± 0.59
2 Shaympur	BR28	12.2 ± 1.82
3 Shaympur	BR11	10.9 ± 0.59
4 Shaympur	BR11	11.3 ± 1.15
5 Changmari	BR11	5.8 ± 0.80
6 Changmari	BR11	6.7 ± 0.77
7 Changmari	BR11	6.9 ± 0.44
8 Chandonpat	Volter	5.6 ± 0.59
9 Chandonpat	BR11	6.9 ± 0.59
10 Chandonpat	BR11	6.2 ± 0.59

Genotyping

The microsatellite loci used were described by Panaud et al (1996) and Chen et al (1997). Ten of these markers (RM009, RM010, RM011, RM018, RM080, RM210, RM212, RM231, RM232, and RM255) were chosen, having been previously associated with weedy traits (Brès-Patry et al 2001) and the other 9 (RM001, RM003, RM019, RM038, RM148, RM205, RM216, RM261, and RM263) were taken randomly from the remaining rice genome. The original sources and motifs for these markers can be found in Temnykh et al (2000). Charrel (2002) has previously shown that these markers are not co-inherited.

PCR reactions involved 20 ng of template DNA, 5 µl of 2× Reddy^{TM} PCR master mix (ABGene) containing 1.5 mM of $MgCl_2$, 1 µM of forward labelled primer (fluorescent forward primer labelled with either cyanine 5 (blue) or cyanine 5.5 (green) dyes was incorporated into PCR products to enable detection of the DNA fragment), and 1 µM reverse primer. Reactions were thermocycled as follows: 3 min at 95 ºC, 30 cycles of 94 ºC for 30 s, annealing temperature (Panaud et al 1996, Chen et al 1997) for 30 s and 72 ºC for 30 s, and a final extension at 72 ºC for 10 min. PCR reactions were conducted with a robocycler gradient temperature cycler (Hybaid thermal cycler). PCR products were first visualized on 1.5% agarose gels stained with ethidium bromide. Fragment analyses were conducted with an automatic genetic DNA sequencer CEQ 2000 (Beckman Coulter) with standard loading and electrophoresis conditions. Fragment lengths were estimated with the help of WellRED fluorescent dye labelled DNA fragment size standards (dye in red) and analyzed with Genescan computer software (Beckman Coulter).

Statistical analysis

The distribution of alleles over loci, the number of unique alleles, and the observed heterozygosity were calculated using Genetix 4.1 (Belkier et al 2000). Cluster analysis of individual genotypes based on the proportion of shared alleles (Chakraborty and Jin 1993) between cultivated and weedy rice was performed using the unweighted pair-group method arithmetic average. At the population level, genetic distances (Nei 1972) between populations were calculated using Population 1.2.28 software (Langella 2002), with bootstrapping (100 replicates). The phylogenetic tree was visualized with Treeview (Page 1996).

Results

Surveys

In the 1999/2000 survey, 'weedy rices' identified by farmers to be present in modern variety crops (BRRI and IR) were predominantly taller than the crop, had white pericarps, and did not shatter easily; the proportion with respect to red pericarps, ranged from 12 to 18% (Table 2). The frequency of awned seeds was slightly higher than that of unawned seeds, but the difference was not statistically significant. Plants bearing freely shattering panicles were found at low frequency (~ 5%) and only in crops of traditional varieties. In the 2005 survey, all plants identified as weedy were free shattering and early maturing, and occurred with a frequency in the range of 6–12%. Visually, they appeared evenly dispersed within the fields sampled (data not shown).

Table 2. Summary of weedy rice traits from populations occurring in transplanted rice fields in 1999/2000. Data are the percentage of plants that fall into each category by trait. BRRI = Bangladesh Rice Research Institute-released cultivars, IR = IRRI cultivars, Traditional = unimproved varieties. Log likelihood values statistically assess similarity of frequency of individual trait categories, by cultivar group.

Crop cultivar group	Grain size (relative to crop cv)			Pericarp color			Awns		Height at maturity (relative to crop cv)			Shattering (%)
	Similar	Larger	Smaller	White	Red	Pink	Present	Absent	Taller	Same	Shorter	
Bangladesh (boro season, 1999)												
BRRI	82.2	7.5	10.3	74.3	13.1	12.6	49.5	50.5	55.0	30.8	14.2	0.0
IR	76.0	9.3	14.6	80.0	12.0	8.0	44.0	56.0	57.3	25.3	17.3	0.0
Traditional	81.1	8.5	10.3	79.2	17.0	3.8	49.1	50.9	71.7	25.5	2.8	5.2
Log-likelihood (P Ho)	5.65 (0.46)			8.26 (0.08)			0.71 (0.701)		17.4 (0.002)			
Bangladesh (T-aman season, 2000)												
BRRI	81.2	9.1	9.7	82.9	12.8	4.3	42.2	57.8	80.2	13.2	6.6	0.0
IR	71.6	14.2	14.2	77.6	17.9	4.5	41.0	59.0	78.8	15.2	6.1	0.0
Traditional	86.1	5.2	8.8	81.4	16.5	2.1	45.4	54.6	91.1	4.7	4.2	4.1
Log-likelihood (P Ho)	17.01 (0.01)			4.67 (0.32)			0.743 (0.69)		15.41 (0.004)			-

Genetic relationships

Pooled across all 19 loci in the 94 plants analyzed, 75 different alleles were detected. These varied in size, typically from 100 to 200 base pairs (bp). Figure 1a illustrates the pattern of distribution of allele sizes for a representative locus (RM009). In this instance, larger alleles were relatively rare, small bp differences in size being evident between the majority of W and C samples, which were not consistent with respect to location sampled. Figures 1b – d illustrate that, for all but two loci, there were more alleles per locus in W samples than in the cultivar, allele sharing between W and C samples occurred at every locus, and unique alleles were much more abundant in W samples, with only three being unique to C samples. In three of the locations sampled (1, 3, and 6), the most frequent allele in both C and W plants was identical for the majority of the loci, in contrast to location 8 where approximately half of the loci showed a different allelic frequency between C and W samples (Fig 1e).

In summary, W samples showed a higher level of polymorphism with a greater number of alleles (from 27 to 47) than C samples (20 to 21) and a greater number of unique alleles: 7 to 27 unique alleles for W and 1 to 2 unique alleles for cultivated rice (Table 3). The level of heterozygosity was slightly higher in W samples (2, 8, and 4%) than in samples of C plants (0, 1, and 0%) in all locations, except in location 1, where cultivated and weedy rice had the same percentage of heterozygotes (2%). The difference in repeats between cultivated and weedy alleles varied from 1 (RM001) to 35 repeats (RM009) and the most frequent difference in repeats was with 1, 2, and 8 repeats (data not shown).

Figure 2 a illustrates the genotypic relationships among individuals. Clustering did not simply dichotomously distinguish C and W plants entirely at the highest level, although W plants from locations 6 and 8 (Group I) grouped away from other accessions. All cultivar plants from the same location grouped together but crop plants from location 6 grouped with weedy plants from location 3 (Group II). Overall, three different groups were evident: Group I, composed of weedy rice from Changmari and Chandonpat; group II composed of cultivated plants from Changmari and Chandonpat together with weedy plants from

Table 3. Genetic diversity in rice in four fields in Rangpur District, northwest Bangladesh. The number of alleles, percent heterozygosity, and number of unique alleles per sampled population of crop (C) and weedy (W) rices are given. Locations are indicated in Table 1.

Location	Cultivar	Crop establishment	Phenotype	Sample size	Alleles present (no.)	Heterozygosity (%)	Unique alleles (no.)
F1	BR11	DSR	C	9	20	2	1
			W	15	35	2	17
F3	BR11	TPR	C	9	21	0	1
			W	15	27	2	7
F6	BR11	TPR	C	9	20	1	0
			W	15	47	8	27
F8	Volter	TPR	C	9	21	0	2
			W	15	36	4	16

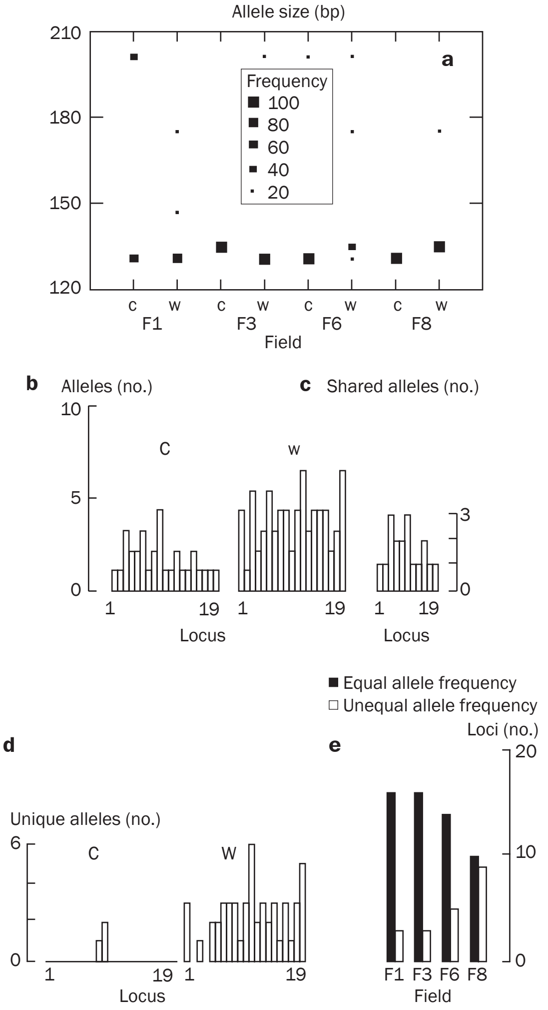

Fig. 1. Genotypic analysis of cultivated (C) and weedy (W) rice in northwest Bangladesh, using 19 microsatellite markers. a) Allele distribution at a representative locus (RM009) in C and W plants from three locations (Table 1). b) The total number of alleles per locus. Loci are ordered 1–19 as described in the text. c) The number of shared alleles. d) The number of unique alleles. e) Similarity in allele frequency across loci, by comparing the most frequent allele at each locus in C and W rice. Equal allele frequency indicates the number of loci where the most frequent allele is common to both C and W samples at those loci.

Shaympur; and group III composed of cultivated and weedy rices from Shaympur.

Figure 2b summarizes the genetic relationships at the population level. The traditional cultivar (Volter, location 8) and associated W plants are at opposite ends of the tree to BR11 cultivars and weedy samples, with the exception of weedy accessions from location 6. Weedy rice samples from the other two locations (1 and 3) were intermediate and closer to the cultivar from location 6.

Discussion

The 1999/2000 field surveys indicated phenotypic variation within rice crops, which farmers associated with off-types or weedy rices. At least 50% of these plants in the boro season and more than 75% in the *aman* season were taller than the crop and most had grains similar to the cultivar and white pericarp, with an equal likelihood of seeds being awned. A much smaller frequency of plants exhibited seed with colored pericarps and plants with freely shattering panicles were only associated with traditional cultivars. Such phenotypic variation within a rice crop may be interpreted as resulting from varietal mixtures being sown in addition to small-scale heterogeneity under field-growing conditions. The second survey sampled plants that exhibited early maturity and seed shattering. While a twofold elevation in mean frequency was present in three of the field locations over the nine others, the variation among individual quadrats per location was noticeably consistent, suggesting an even distribution of weedy rices in the field. This in turn suggests that, across locations, transplanting was occurring from nurseries using mixed seed stocks and that no selective removal of off-types occurred at planting.

This study confirms previous reports (Panaud et al 1995, Wu and Tanksley 1993) that single sequence repeats (microsatellites) can detect a high level of polymorphism among rice populations and that loci may exhibit multiple alleles. Genotypic analysis indicated that weedy rices were genetically distinct from crop cultivars, containing a significantly greater number of unique alleles than the companion crop plants, the number varying among sample locations. This result is sample

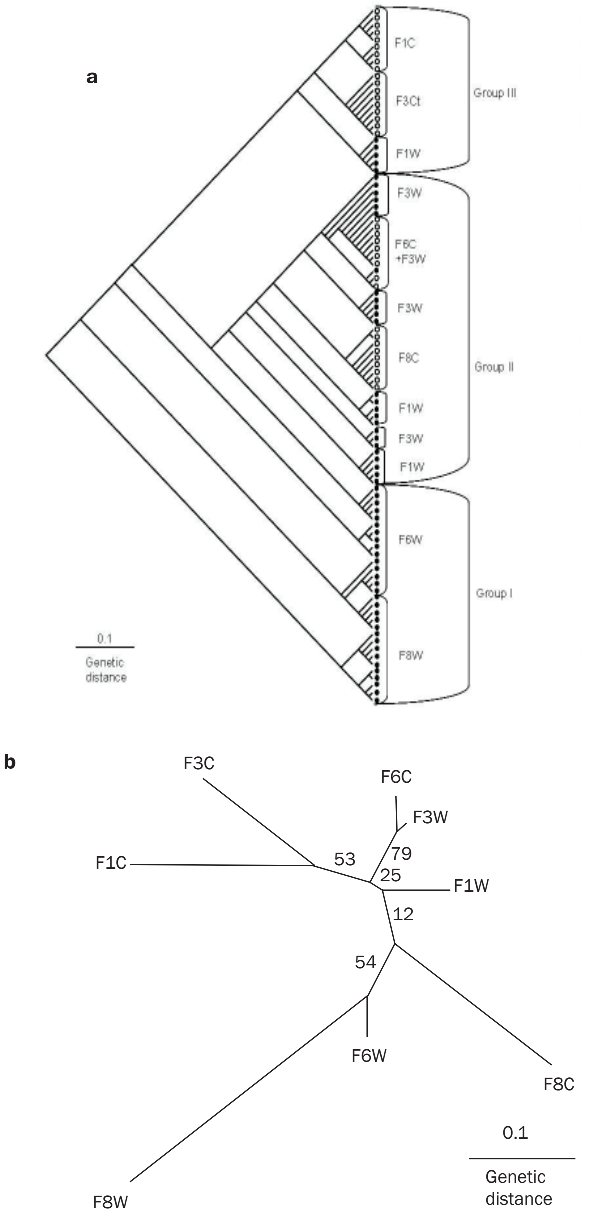

Fig. 2. a) UPGMA cluster analysis based on the proportion of shared alleles among C (open circles) and W (closed circles) individuals from four locations (F1, F3, F6, and F8, see Table 1). Each branch indicates one individual. b) Unrooted neighbor phylogram representing the phylogenetic relationships among populations based on Nei's (1972) genetic distance (D_m). Each branch represents a population, numbers are % bootstraps.

size-dependent and further analysis increasing the number of cultivar plants may alter this conclusion, although Charrel (2002) reported similar findings in an analysis of weedy rice from Malaysia.

Microsatellite marker distribution also indicated allele sharing between crop and weedy rices both within and between sampled locations. Figure 2a illustrates individuals clustering within their sample groups, with the noticeable exception of W individuals from location 3, which segregated with C plants from location 6. Genotypic assignment analysis (IMMANC, Rannala and Mountain 1997) indicated that these W genotypes were not statistically different from the group identified as C plants in location 6. Phenotypic misclassification in the field or sample contamination are possible causes of this joint segregation. Figure 2b clearly distinguished BR11 cultivars (locations 1, 3, and 6 from the traditional cultivar Volter (location 8). Similarity between C populations is to be expected since they are of the same cultivar parentage. At the population level, W plants from location 6 were more closely clustered with the cultivar and weedy rices from location 8 as were W plants from location 1 to the Volter cultivar. This raises the hypothesis that gene flow may have occurred between BR11 and Volter, giving rise to the weedy rices sampled at location 6.

The evolution of weedy rices through gene flow and hybridization among modern cultivars, traditional varieties, and possibly wild rices (*O. rufipogon*, *O. nivara*) occurring in the landscape has been proposed by a number of authors (e.g., Oka and Chang 1961, Chen et al 2004). In northwest Bangladesh, while farmers predominantly use modern rice cultivars, traditional varieties and landraces may constitute a gene pool of weedy traits particularly, if not highly inbred. However, the outcrossing rate in *O. sativa* is commonly reported to be low and rarely higher than 5% (Oka 1988, Chen et al 2004). Moreover, a very low number of heterozygotes were recorded in this study (Table 3). This argues against the hypothesis of in situ natural hybridization. Similar conclusions were drawn by Charrel (2002).

Brès-Patry (2000) observed that crosses between distantly related *Oryza* species and in particular between indica and japonica varieties may produce descendants with a cultivar phenotype but with genome instability. Moreover, restricted recombination of independent genes becomes apparent after only seven generations in hybrids involving indica and japonica rice (as reviewed in Abdullah et al 1996). Instability of the cultivar genome or 'de-domestication' may therefore be involved in the evolution of weedy rice. Such a hypothesis receives some support from field observations on phenotypic changes observed by farmers. Moody (1994) noted that farmers do not use their own seeds more than three times because they observed variation in plant sizes ("high-low" or "up-down" appearance), a deviation of the cultivars from their original appearance ("run-away") and lower yield (up to 10%) in the third crop. These changes in the crops occur faster with modern cultivars than with traditional varieties. Such observations would suggest evolution of cultivars and therefore the possible appearance of weedy traits.

The diversity of genetic mechanisms underlying weedy rice evolution (and their relative importance) remains unknown, particularly the strength and predominant direction of geneflow between feral and cultivated rices (Suh et al 1997). 'De-domestication' of cultivated rice due to genome instability represents an alternative but not exclusive mechanism and may have contributed to the relative rapidity in emergence of weedy genotypes elsewhere in Asia (Baki et al 2000), where feral rices are rare. Furthermore, Xiong et al (1999) and Brès-Patry et al (2001) reported a significant correlation between morphology and weedy traits that corresponds to a tight colocalization of most of the QTLs on a limited number of chromosomal regions. Once present, weedy rice ecotypes may provide a source of genetic variation that could hybridize with cultivars (measurement of the hybridization rate between cultivars and weedy rice was shown to range from 1 to 52% (Langevin et al 1990)) and can then serve as a reservoir, leading to further genetic variation.

Similar microsatellite studies to that reported here on weedy rice populations from other regions in Asia (Tensaout et al, unpubl.) indicate that, in sympatric populations, weedy rice plants differ from cultivar plants by a higher number of SNP alleles (bigger or intermediate size) and also by the presence of unique alleles that are shared between weedy rices from different fields. These differences in allele size could be used to develop molecular markers to detect weedy rice genotypes in grain where morphological traits were lacking, particularly if they were associated with unique sequences for which primers could be designed.

While this study is limited in scope, it raises important issues for the intensification of direct seeding in Bangladesh, in the light of the experience from elsewhere in South and Southeast Asia. If weedy rices are preexisting in farm-saved seed stocks used for transplanted rice crops, it is to be expected that they will occur in direct-seeded crops, as noted in Table 2 (location 1). If those ecotypes evolve a combination of seed dormancy and early shattering traits, the sustainability of direct-seeded rice may well be threatened, with severe implications for rice cropping.

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Notes

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Water by nutrient interactions in rainfed lowland rice: mechanisms and implications for improved nutrient management

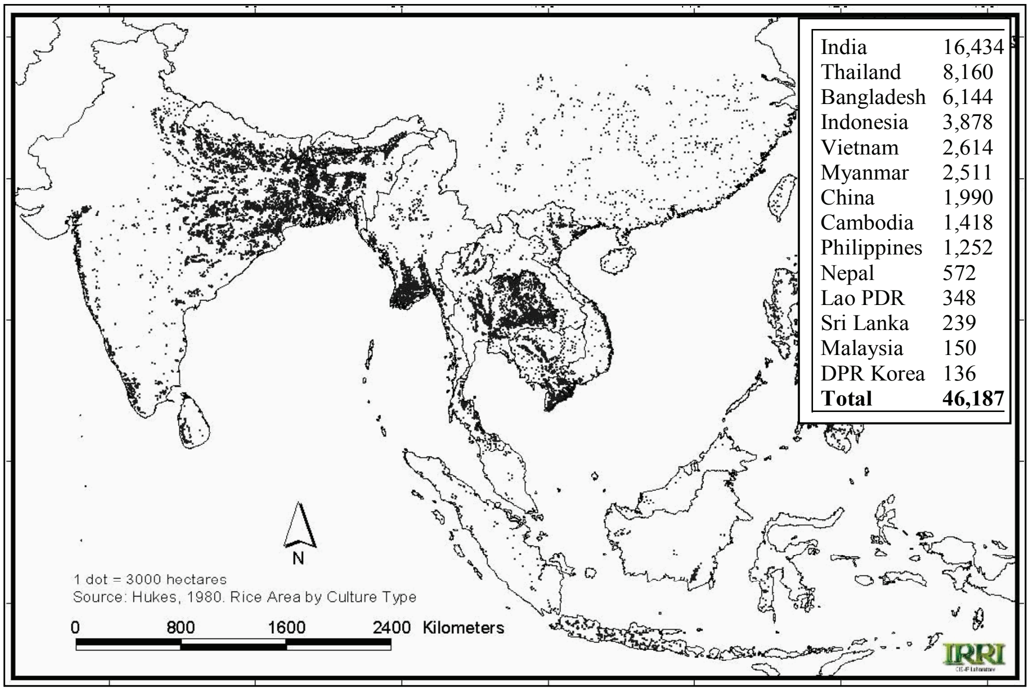
S.M. Haefele, Y. Konboon, S. Patil, V.N. Mishra, M.A. Mazid, and T.P. Tuong

Rainfed lowland rice in Asia covers about 46 million ha—almost 30% of the total rice area worldwide. Although this system includes favorable environments with conditions similar to irrigated systems, most of the areas in this ecosystem face various biophysical constraints, drought stress being the most important limitation to production. To evaluate the possible effects of water stress on nutrient availability and management in rice, the following analysis reviews the processes involved in nutrient by water interactions, reports some results on water by nutrient interactions observed in field experiments, and distills the most important consequences for fertilizer use in drought-prone environments.

Keywords: drought, nutrient management, rainfed lowlands, rice

The rainfed lowland system in Asia covers about 46 million ha—almost 30% of the total rice area worldwide (Maclean et al 2002; Fig. 1). Rainfed lowland rice (*Oryza sativa* L.) grows in bunded fields that are flooded for at least part of the season. Apart from the bunds, there is no water control, and drought as well as submergence can limit crop growth within one season and in the same field. In addition, small to medium height differences in the landscape result in considerable short-range variability in water availability and several important soil characteristics (e.g., soil texture, soil fertility, toxicity occurrences) in most rainfed lowlands (Mazid et al 1998, Oberthuer and Kam 2000). Although this system includes favorable environments with conditions similar to irrigated systems, most of the areas in this ecosystem face various biophysical constraints. Overall, drought stress is the most important limitation to production in the rainfed lowlands and is estimated to affect frequently about 19-23 million ha (Garrity et al 1986). Severe and regular droughts affect mainly the rainfed lowlands in eastern India, northeast Thailand, and parts of Myanmar, Cambodia, and Laos (Fig. 1), but regional weather patterns, topography, and soil characteristics cause considerable drought-risk variations within and beyond these countries. Given the far-reaching consequences of this regular and widespread constraint to the livelihood of more than 200 million of the world's poorest people, considerable research efforts have been undertaken to develop technologies mitigating the effect of drought and increasing productivity in rainfed lowland rice. The key elements needed to achieve these goals are improved germplasm, better use of available water resources, and improved plant nutrition. Superior germplasm can reduce drought risk by shortening crop duration, increasing drought tolerance, having a higher yield potential, and improving tolerance for other abiotic and biotic stresses (Jearakongman et al 1995, Mackill 1986). Increased water use efficiency can be achieved by direct seeding (Ingram et al 1994, Singh et al 1995, Castillo et al 1998, Cabangon et al 2002, Rathore and Sahu 2002, Sharma et al 2005), subsoil compaction (Ghildyal 1978, Wickham and Singh 1978, Trébuil et al 1998, Harnpichitvitaya et al 2000), land leveling (Lantican et al 1999), and rainwater harvesting (Bhuiyan 1994).

Nutrient management is rarely seen as an option to mitigate drought stress, although it may alleviate the effects of drought in some circumstances (Biswas et al 1982, Tanguilig and De Datta 1988, Otoo et al 1989, Zaman et al 1990). However, nutrients are recognized as the second most limiting factor in many rainfed lowlands and the limited use of fertilizers does contribute considerably to the low productivity of rainfed rice-based systems (Wade et al 1999, Pandey 1998). The limited and unreliable water supply is often referred to as one of the main reasons for the limited fertilizer use in rainfed lowland rice. Certainly, high production risk partly explains farmers' reluctance to invest in inputs such as fertilizer. But in addition, several other hypotheses are often used to explain the farmers' low nutrient application rates in an environment frequently characterized by low natural soil fertility. Traditional-type varieties are often described as not responding well to inorganic fertilizer (Mackill et al 1996). For modern-type varieties, increased yields from fertilizer application, even under water-limited conditions, are well documented. However, a general assumption is that the return to applied fertilizer decreases with increasing drought stress. Also, it is commonly believed that a better crop (i.e., more biomass) due to fertilizer application will consume more water. Increased crop water consumption in an environment where available water resources are limited might then contribute to an even higher drought risk. Variable soil aeration due to flooded and nonflooded conditions is assumed to greatly affect nutrient availability and to enhance nutrient losses. However, many of the processes related to water by nutrient interactions in rainfed rice-based systems and their consequences for system



India	16,434
Thailand	8,160
Bangladesh	6,144
Indonesia	3,878
Vietnam	2,614
Myanmar	2,511
China	1,990
Cambodia	1,418
Philippines	1,252
Nepal	572
Lao PDR	348
Sri Lanka	239
Malaysia	150
DPR Korea	136
Total	**46,187**

Source: Hukes, 1980. Rice Area by Culture Type

Fig. 1. Distribution and area (in million ha) of rice-based rainfed lowlands in Asia. Produced by the GIS Unit at IRRI based on Huke (1982) and Huke and Huke (1997).

productivity are not well understood. Therefore, the objectives of the following analysis were to review the processes involved in nutrient by water interactions, to report water by nutrient interactions observed in field experiments, and to distill the most important consequences for fertilizer use in drought-prone environments.

Principles and processes of nutrient by water interactions in rainfed rice

Transpiration and biomass production

It is generally agreed that the cumulative transpiration of a crop from establishment to harvest is linearly related to total dry-matter production at a given site and season (de Wit 1958, Tanner and Sinclair 1983). Across sites and assuming that no other major biotic or abiotic stress occurs, the slope of this relation (i.e., transpiration efficiency, TE) is mostly dependent on crop species (Briggs and Shantz 1913, de Wit 1958) and mean seasonal daytime saturation vapor pressure of the air (Bierhuizen and Slatyer 1965, Tanner and Sinclair 1983, Ehlers and Goss 2003). Given that the seasonal saturation deficit of the air is determined by the site-specific climate and that crop characteristics determining TE are mostly related to the carboxylation pathway (C_3 versus C_4 plants) and the energy requirements to produce different biomass compositions (Tanner and Sinclair 1983), the scope to improve the TE of a given crop seems to be very limited. So, because rice biomass production is only driven by total transpiration and the saturation deficit of the air, the only way to improve crop production is to increase transpiration. But how can better nutrient supply, crop establishment, or any other management intervention contribute to higher transpiration in an environment where total water resources are limited by seasonal rainfall?

Water balance elements in rainfed lowland systems

A general answer to this question is that the total amount of water available for transpiration by the crop is not directly related to the total amount of seasonal rainfall but is strongly affected by various other site and crop characteristics. Transpiration is only one component of the total seasonal water balance; the other components are evaporation, deep percolation (including lateral subsurface water flow or seepage), surface-runoff, and changes in soil water storage. The importance of most water balance elements varies from site to site and changes within the season, but transpiration, evaporation, and deep percolation are typically the largest elements. Average evapotranspiration rates of rice fields in the wet season are 4–5 mm d^{-1}. However, maximum values in subtropical regions before the onset of the monsoon, during drought periods, or after the rainy season can be as high as 10–11 mm d^{-1} (Tabbal et al 2002, Kung 1971). Rates for deep percolation range from 1–5 mm d^{-1} in heavy clay soils to 25–30 mm d^{-1} in sandy and sandy loam soils (Bouman and Tuong 2001, Suzuki et al 2003, Tsubo et al 2005). But even in sandy soils, maximum deep percolation rates occur mainly on upper landscape positions. In lower positions, the (purged) groundwater level is often close to the soil surface, and seepage losses are partly replaced by lateral inflow from higher fields. Heavy rainfalls leading to surface runoff or bund overflow do occur regularly, but related water losses are less important in most lowlands because bunded fields have a considerable storage capacity and losses at field level are often partly compensated for by gains from higher fields. Increasing water resources available for transpiration, and hence higher biomass formation, without any change in the total seasonal water resources can therefore be achieved by decreasing water losses to any of the other water balance components. However, note that reduced water losses at the field level may result in reduced water availability further downstream (Tuong et al 2005).

The effect of nutrients on available water resources

According to many studies, TE is not seriously affected by plant nutrition, except perhaps in the case of very severe deficiencies (de Wit 1958, Yoshida and Coronel 1976, Fischer and Turner 1978, Tanner and Sinclair 1983, Ehlers and Goss 2003). Nevertheless, fertilizer application consistently increases biomass production even under water-limited production conditions without significant increases of total water consumption by the crop (Viets 1962, 1967; Power 1983; Ehlers and Goss 2003). As indicated above, evaporation is an important water loss mechanism but changes considerably during the growing period. Assuming ample water supply, evaporation is high at the beginning of the season when the crop cover is sparse and becomes small when the ground is well shaded by the canopy. Inversely, transpiration is low at the beginning of the season and approaches maximum values (about 90% of the potential evapotranspiration) at a leaf area index (LAI) of about 3 to 4 (Tanner and Sinclair 1983, Ehlers and Goss 2003). Bouman et al (2005) estimated for irrigated rice that about 30% of the seasonal evapotranspiration is evaporation and 70% is transpiration. However, small changes of that distribution may greatly affect yield. Tuong (1999) gave an example in which the fertilizer-induced decrease of evaporation from 41 to 29% of total evapotranspiration (without any change in total ET) increased rice yield from 2.1 to 4.8 t ha^{-1}. In this case, the high evaporation in the unfertilized treatment was solely caused by a slow and incomplete closure of the crop canopy. Both conditions are encountered frequently in rice-based rainfed lowlands where indigenous soil fertility is often limited (Garrity et al 1986, Akbar et al 1986, Van Bremen and Pons 1978).

Water losses through surface runoff will not be affected significantly by the crop. They occur mainly during heavy tropical rains when water is overflowing the bunds. This is a fast process and water uptake of the crop during that time will be small compared with the runoff. In contrast, water percolation out of the rooting horizon (deep percolation) is a much slower process, depending mostly on soil characteristics. As indicated earlier, percolation rates are of a similar order of magnitude as the potential transpiration rates of a closed canopy. Therefore, total biomass above and below the ground can have a significant effect on deep percolation losses and simultaneously increase crop transpiration. Further on, root biomass is closely related to aboveground biomass, and total root length increases linearly until about panicle initiation, remaining relatively stable thereafter (Pradeep et al 1994, Ingram et al 1994). Hence, fast crop development, closure of crop canopy, and the coupled root development could reduce deep percolation losses and increase the relative share of water used for transpiration.

Compared with most other rainfed crops, lowland rice is characterized by shallow roots because of their limited transport capacities for oxygen during anaerobic (flooded) phases. Although modified by rice cultivar, type of establishment, and soil characteristics, about 90% of the total root system is usually restricted to the upper 0.2 m in rainfed rice (Pradeep et al 1994, Pantuwan et al 1995). Soil water storage of plant-available water (field capacity to permanent wilting point) in the rhizosphere is therefore small, ranging between 20 and 60 mm of water. Nevertheless, management factors and varieties do affect root development and thereby modify the ability of the crop to use water stored in the soil (Sharma et al 1987, Mambani et al 1990, Ingram et al 1994, Castillo et al 1998).

Because increased transpiration is almost completely achieved by reducing unproductive water losses, fertilizer use will in general not increase the risk of crop failure due to drought. A slightly higher risk might occur in longer dry spells if the limited soil water reserves in the rhizosphere are the only available water source for the crop. In that situation, evaporation and percolation approach zero and higher crop transpiration will cause a faster decline of soil water reserves. Improved nutrition might also result in lower drought risk at the end of the season if maturity delays caused by nutrient deficiencies (e.g., P deficiency) are avoided.

The effect of water resources on nutrient availability

The particular challenge in understanding processes related to nutrient dynamics and availability in rainfed rice is the variability of the water regime and its effects on soil chemistry. Changes of the soil redox potential affect the soil reaction (pH value) and the stability and/or solubility of minerals and ions. It also determines the activity of different groups of soil microorganisms and the nutrient transformations catalyzed by them. All of these processes change the availability of nutrients to the crop and possible nutrient losses. Seng et al (1999) showed that loss of soil water saturation on acid, sandy soils may depress rice growth by inducing increased acidity, Al toxicity, and/or P deficiency. Results from Bacon et al (1986) suggest that repeated wetting and drying cycles and related nitrification/denitrification cycles may cause high N losses and low mineral N availability at later growth stages. In addition, plant uptake of nutrients is at least partially dependent on the cumulative water uptake with the transpiration stream (mass flow) (O'Toole and Baldia 1982). Reduced water availability and the related reduced transpiration, therefore, will affect nutrient uptake, even if nutrient concentrations in the soil solution remain the same. But how these processes interact and affect indigenous nutrient supplies or fertilizer uptake/losses at the field level in rice-based rainfed lowlands as compared with irrigated rice or upland crops was rarely investigated.

Field observations of nutrient by water interactions in rainfed rice

Results from two on-station and on-farm experiments

Numerous experiments investigating the effect of either water or nutrient management in rainfed and irrigated systems have been reported but much fewer studies have been conducted on the interactive effects of water and nutrient availability in rice. Below, we describe results from two experiments in which both factors were varied.

The first experiment was conducted in farmers' fields from March to June 1994 in Tarlac, Philippines (15^{o} 62′ N, 120^{o} 73′ E) on a silty clay loam (Typic Tropaquept), described in detail by Castillo et al (2006). The experiment had four replicates in a split-plot design with four different water treatments as main-plot factor and four different N-management treatments as sub-plot factor. The water stress treatments were WW (well-watered throughout the growing season), WS$_{MT}$ (stress at maximum tillering stage), WS$_{FL}$ (stress at flowering), and WS$_{GF}$ (stress at grain filling). Nitrogen treatments used were designated N$_0$, N$_{60}$, N$_{120}$, and N$_{180}$, and differed in the N rate applied (0, 60, 120, and 180 kg N ha^{-1}, respectively). In the drought treatments, water was drained at the start of each stress period and irrigation was withheld until leaf-rolling score reached 5 (O'Toole et al 1979). When rainfall during the stress period prevented the attainment of the desired stress level, the stress was terminated before the crop reached the subsequent phenological phase. The rice (variety IR72) was direct-seeded, and identical and sufficient rates of P and K were used in all treatments.

The second experiment was conducted during the 2004 dry season at the experimental farm of IRRI, Los Baños, Philippines (14^{o} 30′ N, 121^{o} 15′ E). The experiment had four replications in a split-plot design with three different water regimes as main-plot factor and five different N-management treatments as sub-plot factor. The water regimes applied were CF (continuous flooding), AWD20, and AWD80 (alternate wetting and drying, irrigated when soil water potential at 0.15 m depth reached either -20 kPa or -80 kPa; continuously flooded 14 d after heading). The nitrogen treatments used were N0 (no N applied), N180 (180 kg N ha^{-1} applied in for splits of 45 kg each [basal, mid-tillering, panicle initiation, and flowering]), NSPAD35, NSPAD38, and NSPAD41 (45 kg N ha^{-1} basal plus + topdressed application of 45 kg N [during tillering] or 25 kg N [after maximum tillering] whenever the SPAD reading dropped below 35, 38, or 41, respectively). The rice variety was direct-seeded, and identical and sufficient rates of P and K were used in all treatments.

The agronomic efficiency of N (AEN) was calculated based on the yield increase due to N application divided by the N rate (kg yield increase per kg N applied) and internal efficiency of N was estimated by dividing total grain yield by total aboveground N uptake (kg grain per kg N uptake) according to Cassman et al (1998) and Witt et al (1999).

Experiment 1 concentrated on the effect of drought stress during particular crop growth phases. However, periodic rainfalls during stress phases WS$_{FL}$ and WS$_{GF}$ caused limited stress levels in these later growth stages. Neither drought stress in the early (WS$_{MT}$) nor that in the late growth stage (WS$_{GF}$) caused yield losses, but severe yield losses due to stress at flowering were observed (Table 1). Only the WS$_{TL}$ treatment prolonged crop duration and the crop under this treatment was harvested 10 d after the other water treatments. Water stress, N rate, and their interaction had a significant effect on grain yield and total N uptake, but AEN was only significantly affected by water stress (data not shown). The high drought sensitivity of rice at the time around flowering, a significant but much smaller effect of drought at panicle initiation, and the possible compensation of drought damage during the vegetative growth stage by a longer crop duration were repeatedly reported in the literature (IRRI 1980, Yambao and Ingram 1988, Castillo et al 1992, Wopereis et al 1996). As in the case of yield, only water stress at flowering caused a reduced N uptake, although the reduction in N uptake was less dramatic as compared with yield losses (Table 1). Drought stress at flowering caused spikelet sterility, thereby damaging the sink for N and assimilates, and N taken up remained in the straw. The data in Table 1 also showed that, with increasing yield level and N rate, the internal efficiency of N (IEN) (kg grain per kg N uptake) and the AEN (kg yield increase per kg N applied) dropped quickly. However, the water

Table 1. Selected results from Experiment 1, conducted at Tarlac, Philippines, during the 1994 dry season (adjusted from Castillo et al 2006[a]).

Nitrogen treatment	Parameter	Unit	WW	WS$_{TL}$	WS$_{FL}$	WS$_{GF}$
N0	GY	t ha^{-1}	2.8 b	3.9 b	1.1 a	3.4 bc
N60	GY	t ha^{-1}	4.4 a	5.2 a	1 a	3.5 b
N120	GY	t ha^{-1}	4.9 a	4.9 ab	1 a	5.1 a
N180	GY	t ha^{-1}	4.6 a	4.5 ab	0.3 a	5.3 a
N0	Nup	kg ha^{-1}	53 c	77 b	45 c	60 c
N60	Nup	kg ha^{-1}	88 b	110 a	65 b	80 b
N120	Nup	kg ha^{-1}	123 a	109 a	83 ab	120 a
N180	Nup	kg ha^{-1}	129 a	102 a	88 a	136 a
N0	IEN	kg kg^{-1}	53	51	24	57
N60	IEN	kg kg^{-1}	50	47	15	44
N120	IEN	kg kg^{-1}	40	45	12	43
N180	IEN	kg kg^{-1}	36	44	3	39
N0	AEN	kg kg^{-1}	-	-	-	-
N60	AEN	kg kg^{-1}	22 a	10 a	0 ns	4 ns
N120	AEN	kg kg^{-1}	15 ab	7 b	0 ns	12 ns
N180	AEN	kg kg^{-1}	8 b	3 b	0 ns	10 ns

[a] For each parameter and in each column, means followed by the same letter (a,b,c) are not significantly different at the 5% level by DMRT. Water treatments included a fully irrigated control (WW) and treatments were drought stress applied at maximum tillering (WS$_{TL}$), flowering (WS$_{FL}$), or grain filling (WS$_{GF}$). Parameters shown are grain yield (GY), total aboveground N uptake (Nup), internal efficiency of N (IEN), and agronomic efficiency of N (AEN).

treatments did not cause significant differences in N uptake and AEN across N treatments, except when drought stress occurred at flowering.

Experiment 2 focused on the effect of different levels of intermittent drought stress throughout the season, except around flowering. Maintaining different levels of leaf greenness (i.e., different SPAD values) allowed maintaining specific levels of N limitation or saturation dependent on water availability. The rates applied showed that less N was necessary to maintain a specific leaf N status with increasing water stress (Table 2). Grain yields across all fertilizer treatments decreased with increasing water stress but the sole reasons for this effect were the decreasing control yields (i.e, a lower indigenous nutrient supply) and lower average N rates per water treatment (the average N rate of the four N treatments, excluding the control, were 173, 158, and 148 kg N ha^{-1} for the water treatments CF, AWD20, and AWD80, respectively). Consequently, the average agronomic efficiency of N across the four fertilizer treatments even increased with decreasing water availability (average AEN of 10.0, 10.5, and 11.5 kg yield increase per kg N applied for the water treatments CF, AWD20, and AWD80, respectively). Although higher N rates did increase N uptake in most cases, highest yields could be achieved with lower N rates when less water was available. And the highest AEN was even recorded for the lowest N rate and N uptake at the highest drought stress level. However, it must be noted that N rates were only applied when the field water situation was favorable, either around establishment when the field was saturated/flooded or before/shortly after irrigation.

Table 2. Selected results from Experiment 2, conducted at IRRI, Philippines, during the 2004 dry season.

N treatment	Parameter[b]	Unit	WW[a]	AWD20	AWD80
Control	Nappl	kg ha^{-1}	0	0	0
N180	Nappl	kg ha^{-1}	180	180	180
SPAD35	Nappl	kg ha^{-1}	110	110	90
SPAD38	Nappl	kg ha^{-1}	150	150	130
SPAD41	Nappl	kg ha^{-1}	250	190	170
Control	GY	t ha^{-1}	3.5	2.9	2.3
N180	GY	t ha^{-1}	5.4	4.8	3.9
SPAD35	GY	t ha^{-1}	5.3	4.4	4.0
SPAD38	GY	t ha^{-1}	5.0	5.1	3.8
SPAD41	GY	t ha^{-1}	5.7	4.9	4.2
Control	Nup	kg ha^{-1}	59	53	45
N180	Nup	kg ha^{-1}	119	117	111
SPAD35	Nup	kg ha^{-1}	103	97	92
SPAD38	Nup	kg ha^{-1}	122	129	98
SPAD41	Nup	kg ha^{-1}	153	146	130
Control	AEN	kg kg^{-1}	-	-	-
N180	AEN	kg kg^{-1}	9.4	9.1	7.7
SPAD35	AEN	kg kg^{-1}	13.0	11.5	16.4
SPAD38	AEN	kg kg^{-1}	10.0	12.4	11.9
SPAD41	AEN	kg kg^{-1}	7.6	8.9	9.8

[a] Water treatments included a fully irrigated control (WW) and treatments were irrigation applied only when soil water tension dropped below -20 kPa (AWD20) or -80 kPa (AWD80). [b] Parameters shown are N rate applied (Nappl), grain yield (GY), total aboveground N uptake (Nup), and agronomic efficiency of N (AEN).

Characteristics of nutrient uptake in rainfed lowland systems

To improve our understanding of indigenous soil fertility, nutrient uptake from applied fertilizers, and internal nutrient use efficiency in rainfed systems, we reanalyzed selected data from a previously analyzed and described database on fertilizer trials conducted between 1995 and 1997 (Wade et al 1999). Selected data covered 37 different trial sites and three consecutive seasons at most sites— i.e., nine sites in northeast Thailand, eight sites in the Philippines, eight sites in Indonesia, four sites in Bangladesh, five sites in India, and three sites in Laos. The term “site” as used here does not necessarily describe far-apart locations but includes close-by sites with clearly different water regimes, including five fully irrigated sites. About half of the sites were located on-station, whereas the others were situated in farmers’ fields. At each site, a set of fertilizer treatments was established in a randomized complete block design with three replications. Only results from two treatments were used in this analysis, the PK treatment (inorganic P and K fertilizer only) and the NPK treatment (inorganic N, P, and K fertilizer applied). Fertilizer rates and application procedures were adjusted to regional recommendations but were identical within each location (for details, see Wade et al 1999). The data were grouped into two sets: one set for all data from northeast Thailand where only traditional-type varieties were used, and a second set for all other sites where modern type varieties were grown (i.e., the few sites where traditional-type varieties were grown outside of Thailand were not included in the analysis).

Average field water status for each experiment was rated visually once a week (1: ponded water; 2: wet soil surface; 3: dry soil surface). Dominant field water status levels for the crop development stages pre-flowering, flowering (± 1 wk around flowering), and post-flowering were reported by Wade et al (1999) but, for the purpose of this study, we calculated an average numerical value of the field water status for the whole cropping season (referred to as “field water stress” in the text below), ranging between minimum water stress (= 1) and maximum water stress (= 3).

The AEN and IEN were calculated as described above. Indigenous N supply (INS) was estimated based on total aboveground N uptake in the PK treatment, and recovery efficiency of applied N (REN) was calculated as total aboveground N uptake in the NPK treatment minus N uptake of the PK treatment divided by the N rate applied. The results from this database were then compared with those of a large study in irrigated systems described by Dobermann et al (2003) and Witt (2003). Note that all observations from the studies in irrigated systems were measured in farmers' fields, whereas a considerable number of sites in the rainfed lowland systems (all trial sites in northeast Thailand and about one-third of the other sites) were on-station trials.

Descriptive statistics of the indigenous N supply and grain yield in the PK treatment for northeast Thailand, all other rainfed lowland sites, and the respective observations from irrigated systems are shown in Table 3. The data indicate increasing indigenous N supplies in the order: northeast Thailand < all other rainfed lowland sites < irrigated systems. But although soils in northeast Thailand were clearly the least fertile, their INS is within the lower range of low-fertility soils in irrigated systems. Differences in INS between irrigated systems and all lowland sites, excluding northeast Thailand, were small and the INS covered a very similar range in both systems. In this context, it must be noted that most lowland sites experienced some water stress during the season (details below). This affected N uptake from indigenous sources and the actual INS observed in rainfed conditions underestimated the potential INS much more than in irrigated systems where the actual INS was close to the potential INS (Janssen et al 1992).

Table 3. Descriptive statistics of the indigenous N supply (INS) and grain yield (GY) in the PK treatment for northeast Thailand, all other rainfed lowland sites, and the respective data from irrigated systems.

Item	Unit	Rainfed lowland		Irrigated[a]
		Northeast Thailand	All other sites	
		n = 26	n = 87	n = 155
INS 25%	(kg ha^{-1})	35	36	41
INS mean	(kg ha^{-1})	38	48	54
INS 75%	(kg ha^{-1})	41	63	65
Mean GY in PK treatment	(t ha^{-1})	1.7	2.7	3.9

[a] Data from Dobermann et al (2003); each observation represents the average value from four successive crops.

Table 4. Mean values for applied N rate, grain yield (GY), agronomic efficiency of N (AEN), recovery efficiency of applied N (REN), internal efficiency of N (IEN), and harvest index (HI) in the NPK treatment for northeast Thailand, all other rainfed lowland sites, and the respective data from irrigated systems.

Item	Unit	Rainfed lowland		Irrigated[a]
		Northeast Thailand	All other sites	
		n = 26	n = 87	n = 173
N rate	(kg ha^{-1})	50	102	110
Grain yield	(t ha^{-1})	2.4	4.1	5.6
AEN	(kg grain kg^{-1} Napl)	15.4	14.0	16.3
REN	(kg kg^{-1})	0.33	0.28	0.42
IEN	(kg grain kg^{-1} Nupt)	43	55	57
HI		0.28	0.43	0.48

[a] Data from Witt (2003); each observation represents the average value from six successive crops. Shown are results for treatment with optimized, site-specific nutrient management.

To compare the average performance of the fully fertilized NPK treatment between sites and systems, several N use efficiency indicators were calculated (Table 4). At all sites in northeast Thailand, the applied N rate was homogeneous and low, according to the regional recommendation (50 kg N ha^{-1}). In contrast, the N rate applied at the other rainfed lowland sites did vary considerably (from 60 to 140 kg N ha^{-1}) and appeared to be excessively high in the Philippines (140 kg N ha^{-1}). Exclusive use of traditional varieties in northeast Thailand explained the low harvest index, IEN, and grain yield, and the high N rate in the Philippines contributed to the low average AEN and REN for rainfed lowland sites outside of northeast Thailand. Nevertheless, the average AEN in the rainfed systems was only slightly below the average AEN for optimal site-specific nutrient management in irrigated systems and did not indicate a substantially lower yield response in rainfed systems. Assuming similar input and output prices, this would also suggest comparable economic returns to N fertilizer use.

However, these average values gave no indication if the yield response to fertilizer use declined with increasing water stress. Water stress in rainfed environments is unpredictable and can occur almost every season. Assuming a negative relation between yield response and water stress (i.e., decreasing returns to fertilizer use with increasing water stress), the incentive to use fertilizer would be limited due to the risk involved. To approach this question, grain yields of both treatments (NPK and PK treatment) and for both groups of lowland sites were plotted against the average seasonal field water stress monitored at each site (Fig. 2). The smaller data set from northeast Thailand covered a large range of average field stress levels (Fig. 2a). The exclusive use of traditional-type varieties caused low yield levels and yield increases were small because of the low N rate applied (50 kg N ha^{-1}). All observations at the lowest water stress level (irrigated conditions) were from one site (Ubon) with very low indigenous soil fertility, explaining the low yield level there. Grain yield differences between the NPK and PK treatments did seem to decrease with increasing water stress, but the yield gains due to N application were fairly stable between water stress levels 1.7 to 2.3. At the highest water stress level (2.7), hardly any yield difference between both treatments was observed and the extremely low harvest index values (data not shown) indicated that drought stress at flowering caused substantial spikelet sterility. The larger data set covered only rainfed lowland sites outside of northeast Thailand where modern-type varieties were used (Fig. 2b). It showed generally higher yields, and yield gains resulting from N application were larger (average N rate of 102 kg N ha^{-1}). The yield response to N application did not seem to decrease substantially with increasing water stress but the maximum water stress occurring was lower than in northeast Thailand.

Although caution is necessary when comparing our relatively small data set with the large data base described by Dobermann et al (2003) and Witt (2003) due to different experimental setups, several clear differences, similarities, and trends emerged from the analysis. One major reason contributing to the low productivity in rainfed systems is the still widespread

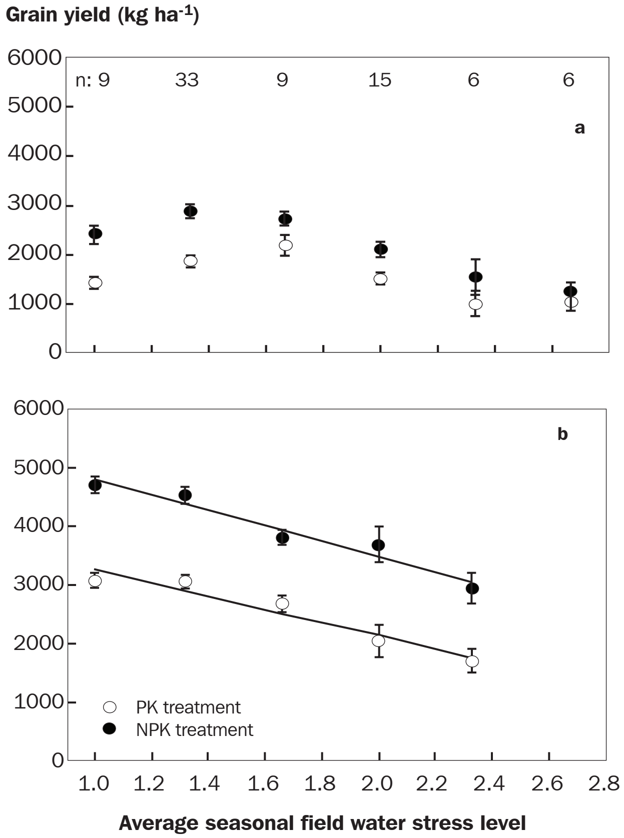


Fig. 2. Rice grain yields for the NPK and the PK treatments, depending on average field water stress observed during the season in northeast Thailand (a) and all other rainfed lowland sites (b) including sites in India, Philippines, Laos, Bangladesh, and Indonesia). The number of observations included in each data point is given in the upper part of each graph and is identical for NPK and PK treatments. Error bars indicate the standard error. Yield values for each treatment followed by the same letter are not significantly different at P ≤ 0.05, according to Tukey's Studentized Range Test. Field water stress levels were scored according to 1 = flooded, 2 = wet soil surface, and 3 = dry soil surface.

use of traditional-type varieties with low yield potential and low harvest index (Naklang et al 2006). Average INS in rainfed lowlands might be lower than in irrigated systems, but even the very low INS in northeast Thailand was within the range of INS observed in irrigated systems. It is also important to note that the actual INS determined by plant uptake in rainfed systems—i.e., under water-limited conditions— underestimates potential INS by a much larger fraction than usual under irrigated conditions. Accordingly, the yield development of the PK treatment in Figure 2 strongly suggests that the measured actual indigenous N supply decreased with increasing water stress, which was also observed in Experiment 2 described earlier (Table 2). Therefore, increasing water stress reduces the availability of indigenous nutrients to plants and enhances prevailing nutrient deficiencies. The generally positive relation between water and nutrient availability was also concluded by Viets (1967).

Surprisingly, the yield response to applied N (AEN) under rainfed conditions was only slightly below the values observed in irrigated systems, although average REN and IEN were lower than those in irrigated systems (Table 4). This was even true for the sites in northeast Thailand where only traditional-type varieties were used and confirmed by the results from experiment 2 (Table 2). Therefore, neither traditional-type varieties nor limited water resources necessarily cause low N response, with the exception of drought occurrence around flowering as previously discussed. However, traditional varieties and/or limited water resources contribute to lower attainable yields. This causes lower total nutrient requirements to reach the attainable yield and, as a consequence of faster decreasing returns to applied nutrients at lower attainable yields, considerably lower optimal and efficient N rates. Nevertheless, the returns to applied nutrients can be similar for a traditional variety or a water-limited crop as compared with an irrigated modern variety if low rates are used under rainfed and high rates are used under irrigated conditions. The other surprising result was that the return to applied N remained almost constant across a considerable range of average water stresses, whereas the same stress caused a decreasing indigenous N supply. Again, this was confirmed by the results of experiment 2 (Table 2). In the on-farm as well as on-station experiments, fertilizers were mostly applied when the field water situation was favorable and good uptake by the crop could be expected. Such conditions did occur and prevail for a few days at most sites and it is well documented that increased nutrient concentrations in the rhizosphere from N fertilizer applications last a few days only (Cassman et al 1993). In contrast, nutrient supply and uptake from indigenous sources is much more evenly spread throughout the season and is therefore more dependent on the average seasonal water availability. Accordingly, the study by O'Toole and Baldia (1979) suggests that N, P, and K uptake was linearly related to cumulative transpiration with and without water limitations. A lower supply from indigenous N, P, and K sources with increasing water stress was also suggested by Naklang et al (2006). Therefore, normal transpiration around the time of inorganic fertilizer application and reduced average seasonal transpiration could explain the different behavior of indigenous and applied nutrients in relation to drought. An increased relative contribution from chemical fertilizer to plant P nutrition with decreasing water availability was also described in a review by Viets (1967). The author hypothesized that the decreasing availability of indigenous P in drier soils caused the plants to extract more P from the more highly soluble fertilizer P.

Consequences for nutrient management in rainfed lowland environments

Based on the results summarized and described above, the following conclusions can be drawn:

- Reduced crop growth during vegetative growth resulting from water stress can be compensated for by a longer crop duration. Water stress around flowering causes the most severe yield losses in rice; the second most sensitive crop growth phase is panicle initiation, but related yield losses are much smaller. Germplasm improvement is possibly the only option to reduce related crop damage.

- Apart from these specific effects of water stress in particular growth stages, a general effect of limited water resources is to lower attainable yields by reducing cumulative transpiration and, thereby, gas exchange. Because of lower attainable yields and diminishing yield increments, fertilizer application rates in water-limited conditions must be lower to achieve an efficiency similar to that in irrigated systems. The lower yield potential of traditional-type varieties makes the same adjustment necessary.
- If N use is adjusted to the attainable yield determined by water availability and/or variety type, yield increases and the related economic rates of return to fertilizer use (AEN) in rainfed environments can be the same as those in irrigated systems.
- In the studies described above, drought stress did reduce the actual indigenous N supply. There are indications that other indigenous nutrients are affected in the same way as shown here for N. But the conclusion that applied inorganic N is not (or less) affected by limited water supplies might not fully apply to nutrients with slower uptake mechanisms and single applications (e.g., P fertilizer). However, N is the most limiting nutrient in most rainfed lowland systems and any measure improving N nutrition will contribute to increased production.
- In all studies described above, N was only applied at favorable conditions for crop growth and limited N losses. As a consequence of the mechanisms outlined above, this application strategy is obligatory to achieve good returns to N fertilizer.

But what do these conclusions imply for fertilizer management in rice-based rainfed lowlands? Current fertilizer recommendations for rice in rainfed environments are adjusted to regional conditions, but they are, in most cases, uniform within these regions. Given the high variability of germplasm, water availability, soils, and their modification by topography, such uniform recommendations seem of limited value to guide nutrient management at the field or farm level. The principal mechanisms outlined above could serve to substantially improve current nutrient management recommendations. They are also flexible enough to allow adjustment to a wide range of environments and to the system elements most important for rice cropping—i.e., landscape, rainfall, soil characteristics, and rice variety. In addition, farmers need information about optimal application strategies in water-limited environments. The flexibility is limited in the case of P and early application is necessary, either incorporated into the soil at establishment or topdressed within 20 d after establishment. However, N is usually applied in two to three splits, which can be adjusted to the variable field water situation. Linquist and Sengxua (2003) defined "windows of opportunity" for N applications and proposed an early application (0–30 d after transplanting) and a late application (14 d before to 7 d after panicle initiation). A further option could be to target a third application at about flowering, when the likelihood of drought in this critical growth phase could be easily evaluated in the field. It was shown that crop N uptake at that time can be high, but it is less clear if the additional N uptake in a relatively low-yielding environment could be translated into significant yield gains (Cassman et al 1997, Peng et al 1998).

For upscaling, two principally different approaches seem possible. If the region is very heterogeneous, the best choice could be to use farmers' local knowledge and to supply them with adequate decision support tools to enable the selection of adjusted resource-use options for individual fields (see, for example, Lampayan et al 1994). Obviously, farmers are making such decisions already (Wijnhoud et al 2003), but researchers should contribute their knowledge to improve farmers' existing site-specific resource management. The other option could address regions with limited variability within the region. In this case, researchers could estimate average attainable yields, depending on the variety type used, average water availability/limitation for the most prevailing toposequence categories, and frequency of complete crop loss due to extreme drought events. Then, uniform fertilizer options for the most common field situations could be developed, using the framework outlined above.

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Agricultural diversification in rainfed regions of India: policy and research implications

S. Pal

Traditional farming systems in rainfed areas have always been diversified. Farmers have traditionally grown various food and nonfood crops and raised livestock mainly to meet domestic needs. In some regions, these traditional, subsistence-oriented systems are now changing rapidly to market-oriented systems for income generation, and the objective of this study was an initial assessment if such developments are also ongoing in the drought-prone rainfed lowlands of eastern India. Across India, agriculture and allied sectors have shown a considerable change in the composition of its value. The value share of forest products especially decreased and increases occurred in the value share of livestock commodities. The value share of crops decreased slightly in the most recent data, and the same was observed for the share of cereals within the crop sector. However, regional trends show that the eastern regions, where most rainfed rice is grown, continued to be dominated by rice-based production systems, and that the rice area even increased in eastern India. Diversification did occur in some states in eastern India but is overall limited until today mainly because of unfavorable agroclimatic conditions. To promote diversification better, there is a need to accelerate public investment in agriculture, improve the efficiency of public delivery systems, and strengthen research efforts. Research should focus on location-specific technologies and management practices to address the high diversity of rainfed systems in the region.

Keywords: diversification, India, rainfed rice

Agricultural diversification has traditionally been a strategy to reduce risk and optimize use of farm resources. Indian farmers followed this strategy not only by growing diverse crops having different input requirements, maturity period, and ability to withstand adverse weather conditions but by engaging in other farm enterprises such as raising livestocks. However, with the spread of irrigation and high-yielding varieties (HYVs) and the dissemination of improved crop management practices, crop yields grew rapidly and became more stable, especially in irrigated regions. Of late, yields also improved in rainfed regions, particularly in high-rainfall regions because of the spread of modern varieties, adoption of better moisture management practices, and exploitation of available limited irrigation potential (Pandey and Pal 2000). As a result, diversification for risk reduction remained a practice in dryland agriculture with low and unstable crop yields and farm income.

During the last decade or so, there has been tremendous pressure on product prices and farm income. This is because of falling international prices of agricultural commodities due to the increase in crop productivity in Asian countries. This is forcing the government and crop growers to search for income-augmenting options. At the same time, intensification of agriculture has put tremendous pressure on natural resources, threatening the sustainability of production systems. Therefore, agricultural diversification is also seen as a strategy to promote sustainable use of natural resources. This option has gained considerable attention in the context of depleting irrigation water, particularly groundwater, in the northwest plains of India. It is advocated that diversification of the rice-wheat system in this region toward less-water-demanding field and horticultural crops will increase farm income and conserve groundwater as well.

The rainfed regions of India are also witnessing some changes in their agricultural systems. There were limited intensification opportunities for agriculture in dryland areas, and therefore, farmers opted for diversification toward horticultural crops to manage risk and enhance their income. However, the high-rainfall regions of eastern India have some favorable areas. These regions are using different strategies to intensify and diversify agriculture. These strategies have their own limitations and implications for agriculture growth, food security, and management of natural resources and risks. This paper analyzes these issues. The paper first presents the broad patterns of intensification and diversification of agriculture in India. This is followed by a discussion on the major drivers of diversification. Finally, the paper analyzes the policy and research implications of agricultural diversification and intensification in the high-rainfall regions of eastern India.

Diversification of agriculture

Agriculture and allied sectors in India have shown a considerable change in its value composition. With the focus on forest conservation, there has been a sharp reduction in its percentage share in the total value of agricultural and allied output—the contribution was reduced to less than half during the last three decades. Field and horticultural crops continued to be the dominant contributor of agriculture output but its share decreased over time. Its share was 70% or more during 1972-92 (triennium average), but it dropped to 66.5% during 2001-03, largely owing to a slowdown in the growth of crop yield. Livestock continued to be a high-growth sector and its share rose persistently from 15% in the early 1970s to 25% in the early 2000s. During the 1990s, fisheries has also shown considerable growth and its share rose to 4.5% during 2001-03 (Table 1).

Within the crop sector also, some changes have been made over time. As shown in Table 1, pulse crops were the losers with the inception of the green revolution, and the trend continued even in the 1990s. After the early 1990s, cereals also registered a decline in their contribution to agricultural income, reducing their share to 36% during 2001-03. Oilseeds, sugarcane, and fibers showed some fluctuations in their share, mainly originating from price-induced volatility in area and production. This was more so in the case of oilseeds showing a rise in their share from 9.4% in 1980-82 to 12.3% in 1990-92 because of better price incentives. This, however, dropped to 10.5% in 2001-03. Lately, sugarcane has also shown a decline in its share.

Table 1. Changes in value share (%) of agricultural commodities in India.

	1970-72	1980-82	1990-92	2001-03
Agriculture				
Crops	72.2	72.2	70.1	66.5
Livestock	14.7	17.8	21.4	24.6
Fisheries	2.6	2.6	3.4	4.5
Forestry	10.5	7.4	5.1	4.4
Crops				
Cereals	38.4	39.2	39.5	35.8
Pulses	9.5	8.0	6.7	5.3
Oilseeds	10.3	9.4	12.3	10.5
Sugarcane	8.0	8.8	8.5	7.7
Fibers, spices, etc.	15.0	14.2	13.2	14.0
Fruits and vegetables	18.8	20.5	19.7	26.7

Source: Centre for Indian Economy database.

Fruits and vegetables have shown a consistent increase in their contribution to agricultural income. Their share increased from 19% in 1970-72 to 21% in the 1980s and 1990s, which further rose to 27% in 2001-03. Some analysts believe that part of this significant growth could be attributed to the data and accounting procedure of the government. Fruits and vegetables were given less attention in their coverage during the green revolution period. Because of the recent focus on agriculture diversification, these crops are being adequately captured in official statistics. Even if we consider this factor to discount the contribution of fruits and vegetables, their share has shown an appreciable increase over time. This trend is obviously for income considerations.

Regional patterns of diversification

The patterns of agricultural diversification are not uniform across the different regions of the country. The only common trend of diversification in all the regions is the increase in the share of the livestock sector in the total value of agricultural output. The crop sector has, however, shown distinct regional patterns of diversification (Joshi et al 2004). The share of nonfood crops increased in all regions, except for the northern region, and the increase was conspicuously high in the southern and western regions, raising their share to 72 and 64% respectively. Both regions mostly practiced dryland agriculture until recently, when private investments were made in groundwater irrigation development and public funds were used to promote a watershed development program. The northern region continued to practice the rice-wheat system because of stable yields under irrigated conditions. Both crops also received price assurance under the minimum support price scheme of the government. This turned out to be a disincentive to farmers to diversify toward high-value nonfoodgrain crops. The eastern regions also, as seen subsequently, continued to be dominated by rice-based production systems primarily because of agroclimatic conditions.

Aside from the major regional trends in agricultural diversification, there were some changes in cropping sequences that were masked in aggregate statistics. The most important among these involved boro rice in eastern India, winter maize in Bihar, kharif maize in southern India, and vegetables in the northern hills and eastern India. These changes in cropping systems marked the beginning of the intensification of these otherwise low-productivity regions. Crop yields and farm income also registered a significant growth. In fact, the recent increase in the production of these crops is attributed to these changes in cropping sequences. These broad patterns thus show that Indian agriculture is moving toward diversification wherever technological, infrastructure support, and price incentives are available.

Diversification in Eastern India

There is no visible trend of diversification at the regional level in eastern India (Table 2). In fact, in the process of intensification, the area under rice and wheat has increased over time, the losers being coarse cereals and pulses. Now, both rice and wheat account for 81% of the gross cropped area; rice alone occupies 72% of the area. Rice area increased significantly due to cultivation of boro rice on fallow lands under irrigated conditions, and this trend may continue with the expansion of groundwater irrigation.

These broad regional trends mask the changes in cropping pattern at the state level. These changes are shown in Table 3. In Bihar and eastern Uttar Pradesh, the rice-wheat system is expanding, but wherever there are opportunities, high-income-generating crops such as sugarcane come up. In Madhya Pradesh, oilseeds, mainly soybean, has spread widely and the area under foodgrains has been reduced from 81% in 1973-75 to

Table 2. Diversification of cropping patterns in eastern India.

Crop	Crop area share (%)			
	1973-75	1983-85	1993-95	2001-03
Rice	67	64	69	72
Wheat	6	8	8	9
Coarse cereals	7	6	4	4
Pulses	8	8	5	3
Oilseeds	5	6	6	5
Fibers and sugarcane	4	4	3	4
Others	3	4	5	3

Source: IRRI database.

63% in 2001-03. In West Bengal also, area under foodgrains has decreased by 9% during the same period, while it has expanded under oilseeds and vegetables. The states of Assam, Jharkhand, Chhattisgarh, and Orissa continued to be largely rice-based, with the crop occupying 82% or more of the gross cropped area. These are the states having low and unstable rice productivity because of adverse agroclimatic conditions. Intensification of these rice-growing areas is extremely challenging but highly rewarding as most of the poor people are directly dependent on rice-based production systems. These states, however, grow vegetables in winter on favorable land having irrigation facilities. Since vegetables are grown as cash crops, providing income within a short period, farmers adopt modern varieties and apply high doses of farm inputs. However, the proportion of such lands is very small.

Drivers of diversification

A number of studies have analyzed the drivers of diversification in Indian agriculture. These are changing demand and consumer preferences, institutional and technical support, and government policies (Joshi et al 2004, Vyas 1996). We review here the main results of these studies.

The food consumption basket is changing rapidly. Consumers now prefer more high-value quality products such as fruits, vegetables, and livestock products and less of cereals. Not only is per capita consumption of coarse cereals on a decline, rice and wheat are also showing a decrease in consumption. This is because of the increase in income level and rapid urbanization (Paroda and Kumar 2000). It is very likely that this trend will accelerate in the future and, therefore, these demand-side forces would significantly increase the incentive for diversification toward high-value products.

On the supply side also, there were significant developments. There has been emphasis on irrigation development and management of water and soil moisture through public and private investments. The scheme to promote drip and sprinkler irrigation has given tremendous boost to horticultural crops. Concurrently, there was emphasis on strengthening technological support and developing rural infrastructure, which motivated the private sector to engage in the delivery of farm inputs and supply management, thereby encouraging farmers to shift to high-value crops. These measures were very effective in diversifying the production systems, especially in the central and western regions. The eastern region suffered because of inadequate development on these fronts, as well as the unfavorable agroclimatic conditions. Some of the lands in the high-rainfall areas were mainly suitable for rice cultivation, and there were limited diversification possibilities.

There have been some important institutional developments in Indian agriculture, which have also encouraged diversification (Pal et al 2003). The National Horticultural Board was established following the pattern of other commercial commodities such as tea, coffee, and dairy to promote horticultural production in the country. The Agricultural and Processed Food Products Export and Development Agency (APEDA) was established to promote the processing of agro-products and improve the access of Indian farmers and processors to global markets. Both these institutions have made important contributions in terms of increasing the production of horticultural and other high-value products. Concurrently, reforms were initiated in the domestic market to attract the private sector. Agro-processing firms were permitted to buy produce directly from farmers. This also led to the development of some sort of contractual arrangement between agro-industry and farmers. Under this arrangement, farmers and industry agreed to buy produce of certain quality on predetermined or market-linked prices. Both parties have incentives (to farmers, a better price and to industry, assured supply of quality raw material) to honor the contract. High-value crops, mainly horticultural crops and dairy, were the major beneficiary of this contractual arrangement. This, therefore, encouraged the diversification of production systems.

Finally, government policies and price incentives have also contributed to diversification toward high-value crops. Because of lower prices of cereals, particularly coarse cereals, farmers shifted to high-value crops wherever opportunities existed. This, coupled with favorable government policies, such as tax incentives to attract private investment, including foreign

Table 3. Diversification of cropping systems in the eastern states of India.

	Foodgrain area (%)		Change in area share	
	1973-75	2001-03	Increase	Decrease
Uttar Pradesh	87	84	Wheat, rice, and sugarcane	Coarse cereals and pulses
Bihar	91	92	Wheat	Coarse cereals and pulses
Assam	79	82	Rice	Pulses and others
Jharkhand	96	98	Rice	Coarse cereals
Chhattisgarh	89	94	Rice	Oilseeds
Orissa	89	89	Rice	Pulses
Madhya Pradesh	81	63	Oilseeds	Coarse cereals and pulses
West Bengal	89	80	Oilseeds, jute, and vegetables	Pulses

Source: IRRI database.

direct investment in agro-processing and other related activities, gave adequate incentives for agricultural diversification. On the input side, policies allowing the importation of foreign seed and planting material of fruit and vegetable crops helped improve their productivity and generated greater farm income.

Diversification and small farms

Household food security considerations largely determine the cropping pattern on small farms. Therefore, food crops are likely to dominate the cropping pattern. At the same time, small farms have rather surplus labor, allowing them to look for income-augmenting opportunities. It is found that labor-intensive activities, like horticultural crops and livestock, are also preferred by small farms. The Simpson index of diversification was found to be 18-21 on small and marginal farmers as against 8-12 of medium and large farmers (Singh et al 2002). Small farmers have better control on the use of farm inputs and crop management and they therefore have better responses to income-augmenting opportunities. Also, diversification toward high-value activities provides high, quick, and regular returns and is therefore preferred by small farmers. Thus, small farmers are better placed in terms of diversification of cropping systems, provided they have access to credit facilities to invest in modern inputs and technologies.

Emerging issues

Policy issues

Notwithstanding the benefits of agricultural diversification, concerns of national food security are still relevant today. This implies that the country should be able to produce enough foodgrains to meet the demand, while promoting diversification in some areas. This means that there should be adequate incentives for farmers to produce foodgrains, which can be maintained by extending technological and price support for these crops. On the other hand, there should be encouragement for diversification of the cropping system towards nonfoodgrain crops. Therefore, policymakers have to strike a balance between food security and diversification objectives.

To promote diversification, infrastructure and delivery of support services should be good. But there is evidence that public investment in agriculture is either stagnant or declining in real terms (Roy and Pal 2003). Also, there are rigidities and inefficiencies in irrigation, credit, and extension systems, which may pose binding constraints to the diversification process. It is unlikely that private investment will compensate for public investment primarily because of limited access of farmers to institutional credit. Therefore, there is a need to accelerate public investment in agriculture and improve the efficiency of public delivery systems.

Although diversification of agriculture and rural livelihood opportunities are critical to employment generation and poverty alleviation in the rainfed areas, these pose some challenges. We have seen that resource-use inefficiencies, degradation and depletion of natural resources and the associated environmental externalities, and loss of biodiversity are common elements in the intensification and diversification of favorable areas. The first major challenge is how to avoid these adverse consequences in the process of intensification and diversification of rainfed areas with low and unstable yields (Hazell 1995). Second, public investment in rainfed areas of eastern India is rather low and public systems like market, public extension, and credit are highly inefficient. This must be corrected in order to promote diversification in this region. Third, there is considerable variation in land quality in the rainfed regions and, often, fertile lowlands are owned by large farmers. Therefore, intensification in these lands will accentuate the income disparity in the rural areas. Fourth, in some areas where shifting cultivation is practiced, the issue of property rights needs to be addressed. Finally, high-value commodities have a high price risk, which should be managed through an appropriate insurance program.

Research issues

The rainfed regions practice mixed farming systems and therefore a uniform approach similar to that followed in the irrigated regions may not be useful. Location-specific technology and management practices may be desirable for the intensification and diversification of these regions. It is possible that, in favorable lowlands, some of the varieties and management practices of the irrigated region could be adopted. But, in most uplands and deepwater lowlands, a location-specific development strategy should be followed. In terms of specific interventions, since soil moisture and pest infestations are the binding constraints in rainfed regions, technological options to address these problems would go a long way in improving crop productivity. The intensification process will put more pressure on soil fertility and therefore efforts will be needed to restore and maintain soil fertility by adopting appropriate practices for soil nutrient management and control of soil erosion by water runoff. The enormity of the task requires a strengthening of research capacity and targeting of research efforts in the region. Further work is in progress to address this important question in the context of the Indian agricultural research system.

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Submergence- and flood-prone areas

Biophysical constraints in flood-prone ecosystems: impacts and prospects for enhancing and sustaining productivity

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Rice is often the only crop that can be grown in flood-prone ecosystems during the monsoon season, but its productivity is greatly affected by floods based on the intensity and duration of rainfall, quality, depth and duration of standing water, and time and frequency of flooding. Although India has the largest area under rainfed lowlands and flood-prone ecosystems in Southeast Asia, other countries such as Thailand, Bangladesh, Indonesia, Vietnam, and Myanmar are also seriously affected. The average productivity in these areas varies between 0.5 and 0.75 t ha^{-1}. The quality of floodwater (pH, gas diffusion, turbidity) and light intensity determine the extent of plant survival and productivity, and this makes extrapolation of research findings from one place to another ineffective because of variation in these factors as well as in soil and other climatic factors. Submergence enhances ethylene accumulation in the internodes, which promotes stem elongation, exhaustion of carbohydrate reserves, chlorophyll degradation, and weakening of the antioxidant defense esystem. Use of photoperiod-sensitive cultivars helps reduce losses in grain yield because of the flexibility in using relatively older seedlings for transplanting with minimum yield losses. Rice varieties with higher submergence tolerance are desired in flood-prone ecosystems, particularly when they combine tolerance for other major abiotic stresses prevailing in these ecosystems, which will then help increase and stabilize productivity. Greater dependence on dry-season farming could contribute to food security in these fragile areas if proper water management and harvesting as well as suitable rice and nonrice crops and varieties are made available.

Keywords: floodwater characteristics, rice, turbidity, stagnant flooding, submergence

In most Asian countries, food security is dependent on availability of sufficient rice as the principal staple. Moreover, about 2.5 billion people worldwide, of which 95% live in Asia are dependent on rice, with East and South Asia, accounting for 42 and 35% of worldwide rice consumers, respectively (Rothschild 1998). IRRI (1993) categorized rice land ecosystems into four types: irrigated, rainfed lowland, upland, and flood-prone. The area under the rainfed lowland ecosystem is about 25% of the total cultivated rice area, with the largest area being in the irrigated ecosystem (54%) and the smaller areas concentrated in upland and flood-prone ecosystems (13 and 9%, respectively). In the irrigated ecosystem, rice fields have assured water supply for one or more crops a year. The upland rice ecosystem varies from low-lying valleys to undulating and steep sloping lands with high runoff and lateral water movements. The flood-prone rice ecosystem is subjected to uncontrolled flooding, for as long as 5 mo at a time with water depth varying from less than 0.5 m to more than 4.0 m. Intermittent flooding with brackish water caused by tidal fluctuations is also experienced in coastal areas. Besides floods, rice in these areas could also suffer from intermittent drought and soil problems such as acid sulfate and excess salinity and alkalinity.

The rainfed lowlands of South and Southeast Asia are mostly in the warm subhumid and humid tropics (Wade et al 1999). Throughout the rainfed rice ecosystems, the amount and seasonal distribution of water supply are considered the most important determinants of productivity (Zeigler and Puckridge 1995, Wade et al 1999). Water supply varies greatly within the rainfed lowland ecosystem; it ranges from shortage to excess and water stress can occur during different stages of crop development. Predominant dryland conditions are usually associated with upland rice while prolonged deepwater conditions (>50 cm water depths) are associated with deepwater and floating rice areas (De Datta et al 1981).

Areas and duration of water stagnation

Rainfed lowland rice areas encompass a great diversity of growing conditions based on hydrology, which vary according to the amount and duration of rainfall, depth and extent of standing water, flooding frequency, time of flooding within the growing season, soil type, and topography. Based on hydrology, rainfed lowlands are broadly classified into five categories (Khush 1984, Singh and Singh 2000):

- Shallow and favorable rainfed lowlands: rainfall and water control are more or less adequate. Short periods of drought stress or mild submergence may occur but these are not a serious constraint. Supplementary irrigation may be available.
- Shallow and drought-prone rainfed lowlands: growing conditions range from upland with no standing water

to lowland with water bonding in the field for at least sometime during the season; the rainy period is about 90–110 d and water deficit may occur at any growth stage. Crops generally are not subjected to submergence.

- Shallow, drought- and submergence-prone rainfed lowlands: complete submergence usually takes place due to heavy rains and overflow from adjacent rivers and streams. Extended periods of no rain are also expected, causing water deficit during the growing season. Soils generally have light texture and low fertility.
- Shallow, submergence-prone rainfed lowlands: depth of floodwater is usually shallow but complete submergence for up to 10 d or more may occur during periods of heavy rainfall.
- Medium deep, waterlogged rainfed lowlands: water accumulates and stagnates for 1–4 mo because of impeded drainage. Water depth may vary from 25 to 50 cm.

An analysis of drought and flood patterns in the shallow rainfed lowland subecosystem reveals that about 6.4% (6.1 million ha), 11.8% (11.3 million ha), 6.3% (6.0 million ha), and 5.4% (5.2 million ha) are favorable, drought-prone, drought- and submergence-prone, and submergence-prone, respectively (Table 1). The area under the medium-deep ecosystem is about 6.3% (6.1 million ha), and that under deep and very deep water ecosystems is about 14.6% (14.0 million ha). Due to this heterogeneity in flood-prone areas, different types of traditional rice cultivars are being grown by farmers. These cultivars are low-yielding but possess one or more of the adaptive traits required for the particular area and flooding pattern. Broadly, three major rice categories are found: deepwater rice, which can survive water depths of 50–100 cm; floating rice, which can survive in water depths of up to 300 cm; and tidal wetland rice, which can survive submergence, sometimes with salty water, for short periods. Deepwater and floating rices escape complete submergence by growing fast through internode expansion and by leaf elongation to keep pace with the rising floodwater, and are commonly harvested after the water recedes. The flooding pattern in this ecosystem also varies with respect to time of inundation during the season; rate of water rise; maximum water depth; and duration, time, and rate of water recession. A drastic change in any one of these variables can sometimes result in crop failure. Rice is often the only crop that can be grown in the flood-prone areas but the extreme uncertainty of the hydrologic patterns often discourage farmers from using modern varieties or farm inputs.

India, by far, has the largest area under rainfed lowland and flood-prone ecosystems in South and Southeast Asia. In addition, large areas also exist in Thailand, Bangladesh, Indonesia, Vietnam, and Myanmar. The total area has not changed much over the last two decades, but there have been some changes within countries. For example, large increases were observed in Thailand, Cambodia, Indonesia, and Laos, while the area decreased in Myanmar and the Philippines (Haefele et al 2004). The area under favorable rainfed lowlands is greater in Myanmar, whereas drought-prone areas are the largest in India. In Thailand, an appreciable area is classified as drought-prone, while large areas in Bangladesh, India, and Indonesia fall in the submergence-prone, medium deep, and deepwater categories (Table 1).

Table 1. Estimated rice area ('000 ha) in rainfed lowland and flood-prone/deepwater ecosystems.

Country	Shallow (0–25 cm)				Medium-deep (25–50 cm)	Deepwater (>50 cm)	Total rainfed lowland + deepwater	Total area
	Favorable	Drought-prone	Drought- and submergence-prone	Submergence-prone				
India[a]	1,100	5,800	2,600	1,100	3,000	4,000	17,600	43,500
Bangladesh	847	837	1,001	1,608	747	3,066	8,106	12,306
Thailand	513	3,166	1,437	723	200	500	6,539	8,677
Myanmar	1,224	283	0	784	699	557	3,547	6,488
Vietnam	663	332	0	554	195	870	2,614	5,573
Cambodia	72	275	762	0	623	85	1,817	2,104
Laos	116	116	116	0	0	0	348	695
Indonesia	811	231	0	261	320	4,916	6,539	12,391
Philippines	765	241	60	141	303	45	1,555	3,515
Total (South and Southeast Asia)	6,111	11,281	5,976	5,171	6,087	14,039	48,665	95,249
Percentage[b]	6.4	11.8	6.3	5.4	6.4	14.7	51.0	100

[a] Based on Singh (2002), Singh and Singh (2000), and Anonymous (2005) for India; data of other countries are from Mackill et al (1996), Myaint (2004), Sarom (2004), Alihamsjah (2004), Wade et al (1999), Bell and Seng (2004), and Haefele et al (2004). [b] Percentage of land compared with total land.

Rice productivity in rainfed lowlands

The average productivity of rice in rainfed lowlands is much lower than in irrigated systems and it also varies greatly. Rice yield is relatively higher (2.0 t ha^{-1}) in the favorable rainfed subecosystem, followed by drought-prone (1.5 t ha^{-1}) and medium-deep waterlogged (0.8 t ha^{-1}) ecosystems. In drought- and submergence-prone as well as in the submergence-prone subecosystems, average yield is low, a mere 0.5 t ha^{-1} (Singh 2002). In Myanmar, average yield in flood-prone areas is 0.8 t ha^{-1}, which is lower than that under favorable conditions where it averages about 3.4 t ha^{-1} (Myaint 2004). In almost all countries in South and Southeast Asia, the productivity of rainfed lowlands in general is much lower than that under favorable conditions (Sarom 2004). The choices of cultivars based on land topography and hydrology also vary considerably. High- yielding semidwarf cultivars are rarely grown in this subecosystem. In favorable, drought- and submergence-prone, and some submergence-prone subecosystems (medium type) where water scarcity is comparatively less severe, farmers generally prefer high-yielding semidwarf rice cultivars. For example, during a recent survey in eastern India, we observed that Swarna is the leading variety in farmers' fields in Orissa, West Bengal, and Bihar. This is because in normal years (about two out of three), farmers can guarantee reasonable yield using this modern dwarf variety, not like their local landraces. However, in years where drought or submergence occurs, yields are mostly very low or the entire crop may be lost, even if they use the traditional, more adapted varieties. In medium-deep and deepwater subecosystems, farmers predominantly use the local tall and photoperiod-sensitive landraces that can tolerate stagnant flooding because suitable modern varieties are not available.

Production constraints in flood-prone areas

Biological constraints

Insect pests are the major biotic constraints to rice production in the rainfed environment. The characteristic high humidity and temperature during the monsoon season facilitate the buildup of pest populations. The yellow stem borer (*Scirpophaga incertulas*) is the most damaging insect in all deepwater and submergence-prone areas in South and Southeast Asian countries. Damage due to rats, snails, and crabs is common in all rainfed lowland and deepwater ecosystems. Other insects such as green leafhoppers (*Nephotettix* sp.), leaffolders (*Cnaphalocrosis medinalis*), brown planthoppers (*Nilaparvata lugens*), and caseworms (*Nymphula depunctalis*) are serious problems in shallow and medium-deep rainfed lowlands. Green leafhoppers are the vectors of tungro virus and are potentially damaging enough to cause huge yield losses. Hispa (*Diclodispa armigera*) and nematodes are important pests in lowland and deepwater rice environments of Assam, Orissa, and West Bengal. In Goalpara and Nowgong districts of Assam, a considerable area suffers from ufra, which is caused by the parasitic plant nematode *Ditylenchus angustus*. In Myanmar, ufra is the most serious problem in flood-prone areas.

Diseases are the next important biotic constraints that limit rice production under all ecosystems in Asia. Bacterial leaf blight (*Xanthomonas campestris* sp. *oryzae*) is the most damaging rice disease in the entire rainfed lowland ecosystem. Besides leaf blight, sheath rot (*Sarocladium oryzae*) and sheath blight (*Rhizoctonia solani*) are known to cause appreciable yield losses in some pockets of rainfed lowland environments. False smut (*Ustilaginoidea virens*) is also fast emerging in recent years as a major rice disease, especially in rainfed lowland and deepwater areas in India and Bangladesh.

Rice is affected by weed infestation in all ecosystems; however, this is less of a problem under flooded conditions. Wild rice is a menace, especially in the rainfed lowland and deepwater ecosystems. Farmers are able to identify wild rice in their fields only at the flowering stage, resulting in immense losses in yield and expenses for its eradication. High-yielding cultivars with a visual marker such as a purple base or a purple leaf sheath can be useful in distinguishing weedy rice and eradicating it at an early stage.

Physical constraints

The uncertainty of occurrence, duration, and amount of rainfall substantially affects the productivity of rainfed lowland and flood-prone rice ecosystems. Inadequate rain at the onset of the rainy season in May and June delays seedbed establishment, leads to poor land preparation, favors the buildup of pest pressure, and results in less vigorous seedlings. Inadequate rain in July and August delays transplanting and leads to poor recovery from transplanting shock and to poor vegetative growth. The dry soils also encourage weed growth and prevent proper land preparation for transplanting.

In Bangladesh, India, and Myanmar, flooding occurs during the wet season between June and November. Crucial to survival and yield of the rice crop are the age of the plants at the start of inundation, the rate of water rise, and the duration of the floods. Many parts of the tidal, deepwater, and rainfed lowland rice areas are subject to abrupt increases in water level (commonly referred to as flash floods) that completely inundate the crop. These floods occur after local or remote heavy rains and may result in complete submergence for several days with the consequent delay in development and a reduced stand.

Bangladesh has three predominant rice-growing seasons that are commonly affected by floods. The traditional wet-season (monsoon) crop called transplanted aman (*T. aman)* is grown from mid-June through November/December. The dry season or *boro* is grown from November/December to March/April and the third or early-monsoon crop is *aus*, grown from March through July using short-maturing, photoperiod-insensitive varieties. Flash floods in the northwestern region of Bangladesh commonly occur at three different periods: early flood from May to June, monsoon flood from mid-July to August, and late flood due to excess rain any time after August. Early floods can damage boro rice at later stages or aus and T. aman at the seedling stage. Flooding from July to August delays the harvesting of transplanted aus (T. aus) and transplanting of T. aman. This type of flood constitutes a major risk for T. aman, the major rice crop in most rainfed areas of Bangladesh. Late floods, on the other hand, can damage the T. aman rice.

In eastern India, submergence has been identified as the third most important constraint to rice production (Hossain and Laborte 1996, Khush and Sarkarung 1998). In another study across different agroclimatic zones of India, flooding, poor drainage, and waterlogging are identified as the key constraints to agricultural production in the humid and subhumid plains of the Gangetic Delta, while drought, problem soils, and soil erosion are the key constraints in the eastern subhumid plateau of Chhattisgarh and Chhotonagpur.

Eastern India represents almost all flood-prone subecosystems of rice, ranging from flash floods to semideep and deepwater, where submergence occurs during early or late vegetative stages for about 1–2 wk (in flash floods) and 3–6 wk in semi-deep conditions. Stagnant flooding also occurs in several parts of Bihar, Orissa, West Bengal, and Assam, inundating the fields to different depths and durations and adversely affecting rice growth and yield. In flash-flood areas, the water is invariably laden with silt, which is deposited on leaf surfaces, causing mechanical damage and hindering underwater photosynthesis of submerged rice plants (Setter et al 1997, Ram et al 1999). In deepwater areas where dry direct seeding is practiced during the months of May and June, the crop usually suffers from drought if rain is delayed after the initial showers, while submergence occurs at the early growth stages due to heavy rains in July. In flash-flood areas too, submergence and/or drought could occur either alone or in succession, depending on the timing and intensity of rains, causing severe yield losses. Under extreme conditions, complete crop failure has been observed, as seen in the 2006 wet season where severe drought devastated rice in eastern India and farmers harvested their crops prematurely for use as fodder for animals.

In Thailand, deepwater rice is sown in April–May, about 2–4 mo before the floods. However, rice may encounter extreme drought stress during this period, particularly if early showers result in premonsoon germination and establishment (De Datta and Malabuyoc, 1988). Similar conditions are also commonly experienced in Cambodia where drought could occur early in the season. The loss of yield is further aggravated by heavy damage by thrips, brown planthoppers, and grasshoppers. These problems, coupled with excessive rain at later stages, reduce productivity and increase the incidence of fungal diseases in the grain, leading to poor grain quality and reduced grain-filling (Sarom, 2004). The common trend in flood-prone areas is that inundation begins sometime in June–August and reaches a peak in October or November. The water then recedes in December and early January (Catling 1992). Excessive rain from September to October, coupled with high floods in the Tonle Bassac and Mekong rivers, cause flooding in downstream lowlands, particularly in low-lying fields. The strong current of flash floods laden with silt can damage leaves, even if submergence is only for a few days. Reduced rain in October and early cessation of rain in November can adversely affect rice yield because of the crop's high sensitivity during the reproductive phase. Most vulnerable are late-duration varieties, followed by medium- to short-maturing varieties in the deltas of Tonle Bassac and Mekong rivers (Nesbit 1997). In Indonesia, rice is sown at the beginning of the rainy season (around October) and the crop is harvested in February or March. For dry-season planting, the local rice types adapted to swampy areas are known to be tolerant of submergence or flooding at early stages for up to 1 wk. They mature within 105-130 d without lodging and are tolerant of drought at the later stages.

Further constraints to rice production in flood-prone areas arise from the widespread incidence of problem soils. Common soil constraints include salinity/alkalinity, Fe toxicity (~7 million ha), and acid sulfate soils (~2 million ha; Haefele et al 2004). Iron toxicity, zinc deficiency, salinity, and sodicity are some of the major problems in India. Soil salinity is recognized as a major problem, particularly in coastal areas of Myanmar, Thailand, Vietnam, and Bangladesh. Acid sulfate soils are common in Thailand, Vietnam, Bangladesh, and the south coastal regions in India; it is a major constraint in Indonesia. Mineral toxicity can occur in saline, sodic, acid sulfate, peat and dry land soils. Some of the most common minerals causing toxicity are iron, manganese, aluminum, boron, and hydrogen sulfide. In Cambodia, Laos, and northeast Thailand, nitrogen and phosphorus deficiencies and iron toxicity are common, and some soils are deficient in potassium and micronutrients (Haefele et al 2004).

Yield losses caused by various biophysical constraints in flood-prone areas

Annual rice yield losses caused by various biophysical constraints were estimated in different eastern Indian states (Siddiq 1998). Adverse climate and water stress together account for 25% of the losses, while insect pests account for about 20%; diseases; 15%, adverse soils, 14%; and weeds, lodging, rodents, low irradiance, etc., together, for about 26% of all losses. The total annual yield loss in rice attributed to these constraints is about 14 million t, of which 4.6 million t are lost in rainfed lowlands. In Cherapunji, India, rainfall is highest in the world, exceeding 5,000 mm yr^{-1}. On average, 300,000 ha of rice crop is lost each year because of flash floods (Das et al 1994). In our survey of the northern districts of West Bengal, and Kishangaunj and Araria districts of Bihar (December 2005), we observed that farmers in deepwater/flood-prone ecosystems kept their land fallow because of severe water stagnation. The productivity of such areas is also very low because of excess water inundation and flooding. Overall, the estimated annual yield losses in deepwater ecosystem alone amount to 1 million t. If these losses are partially recovered, the average productivity in rainfed lowlands and flood-prone areas can be easily raised to 2.0 t ha^{-1}.

In Thailand, the yield constraints mentioned by farmers were weeds (90% farmers); drought (55%); rats (54%); insects 25% (brown planthoppers, stem borers, green leafhoppers, and thrips); crabs 22%; birds 11%; diseases 10% (blast and ragged stunt virus); and flooding 22% (Puckridge et al 2001). In Bangladesh, about 22% of the country is flooded every year and 50% of water development expenditures are spent on flood control and drainage.

Floodwater characterization

Field surveys

Rice in general is tolerant of anaerobic soil conditions; however, excessive flooding may result in various environmental stresses that are associated with partial or complete submergence. The variations in floodwater characteristics across locations induce different responses in various cultivars and hence, the conclusions drawn about flooding tolerance from information gathered at one site may not be extrapolated to others (Ram et al 1999, 2002). Studies on survival percentage of the same set of cultivars in different locations in Bangladesh, Thailand, and Indonesia also support this contention (Setter et al 1982, Ito et al 1999). Flooding from clear water generally causes less damage than silted or turbid water associated with overflows of rivers or from heavy rains in catchment areas. The extent of damage from flooding is greatly affected by the climate and conditions of the floodwater such as temperature, water turbidity, turbulence, depth, and light penetration, among others (Das et al 2009).

Light intensity

Light penetration through floodwater affects plant growth and survival to a great extent. When floodwater is turbid, only meager amount of solar radiation reaches the canopy and thus limits the plant capacity for photosynthesis (Ram et al 2002). In the brightest profile (bright sunlight and clear water), photosynthesis was sustained at 50% of the maximum rate at 0.75 m water depth, while the dimmest profile decreased photosynthesis to the compensation point at 0.25 m water depth (Setter et al 1987a). Whitton et al (1988) observed that low light intensity in floodwater in Bangladesh was due to the presence of algal colonies on the surface of the water. The underwater light intensity is a major controlling factor of CO_2 and O_2 concentrations and hence greatly affects the physiological ability of submerged plants to continue functioning (Ram et al 2002; Jackson and Ram 2003). Plant survival under submergence is significantly higher at high light intensity and decreases with increasing depth of water (Adkins et al 1988, 1990). Palada and Vergara (1972) observed a decrease in survival of rice seedlings after complete submergence because of lower light transmission (40% of that in air).

Gas diffusion and water pH

Gases are known to diffuse 10,000 times slower in water than air (Armstrong 1979, Armstrong and Drew 2002). The concentration of O_2 in floodwater during flash floods is generally high, but floodwater may become anoxic in some environments, especially during the night when the O_2 produced during the daytime is consumed via respiration. The CO_2 concentration in floodwater during turbulent flash floods tends to be in equilibrium with that of the air due to rapid mixing (Setter et al 1987b). The importance of limited gas diffusion during submergence is clearly demonstrated by the observation that when water of submerged rice is flushed with air at high partial pressure of O_2 and CO_2, plants survive for up to 3 mo under complete submergence. Hence, poor plant growth and survival during submergence or during waterlogging are often considered a consequence of the decreased diffusion of gases, which affects photosynthesis, growth, and metabolism. Reduced O_2 supply limits respiration, reduced CO_2 supply limits photosynthesis, and reduced ethylene diffusion away from plants triggers chlorosis and excessive elongation of leaves of intolerant cultivars (Jackson et al 1987, Ella et al 2003a).

Measurements of the concentration of gases in floodwater during submergence have provided important clues about the causes of reduced growth and survival. Studies at Faizabad, Uttar Pradesh, eastern India, Bihar and Cuttack, Orissa, India, demonstrated the enormous variation in floodwater characteristics and the consequent variability in plant survival at these different locations when rice genotypes were exposed to submergence for similar durations. Oxygen concentration was found to range between 0.0 and 0.6 mol m^{-3} (air equilibrium is 0.24 mol m^{-3} at 30 ^oC) and CO_2 concentration varied between 0.28 and 1.96 (air equilibrium 0.01 mol m^{-3}; Setter et al 1995, Ram et al 1999). In Thailand, the CO_2 concentration at 0–0.02 m water depth was low, ranging between 0.003 and 0.8 mol m^{-3}, but increased with increasing water depth (Setter et al 1987b). Smith and Walker (1980) demonstrated the importance of CO_2 during submergence for aquatic species and reported that underwater photosynthesis increased until the CO_2 concentration in bulk solution reached a level above 1–2 mol m^{-3}. The concentration of O_2 also varies with the flow of floodwater, being higher and sometimes supersaturating in turbulent water while being very low in stagnant water. In the standing water of flooded fields, respiration by plants will quickly deplete the small reserve of dissolved O_2 to concentrations that are too low to sustain mitochondrial electron transport. Roots are especially vulnerable to this effect since they lack the capacity to generate photosynthetic O_2 to compensate for low O_2 in floodwater (Jackson and Ram 2003).

Measurement of CO_2 concentrations in floodwater following the Henderson-Hasselbalch equation [$pH = pKa + \log (HCO_3^-)/(CO_2)$], where pKa is 6.36 at 30 ^oC (Umbreit 1964, Ramakrishnayya et al 1999), showed that the concentrations of CO_2 depended on the pH of the floodwater. The higher the pH, the more the concentration of bicarbonate in the medium. In Bihar, India, the pH of floodwater ranged from 6.6 to 9.7 being highly alkaline (Setter et al 1995, Ram et al 1999), whereas it ranged between 4.8 and 7.4 in Thailand (Setter et al 1982), showing that the floodwater is comparatively more favorable to underwater photosynthesis in Thailand compared with India, which could result in better survival.

Floodwater temperature

In South and Southeast Asian countries, the temperature of floodwater varies from 25 ^oC to 35 ^oC and rarely drops below 25 ^oC. In Thailand, water temperature drops below 25 ^oC in December (Catling et al 1988). In India, the ‘sali’ rice of Assam and the ‘Aman’ rice of West Bengal are exposed to low solar radiation (cloudy days during the monsoon season) and thereby suffer from low photosynthetic efficiency. Boro rice grown in India and Bangladesh suffers from cold injury due to low ambient temperature rather than to cold water during the early vegetative growth stage. Plant survival during flooding is substantially affected by water temperature. Plants survive better when water is cooler, and survival decreased at about 8% per unit increase in water temperature above 26 °C (Das et al 2009).

Floodwater characteristics and plant survival: results from studies under controlled conditions

Though the role of different floodwater characteristics on survival has been described by different authors, systematic studies on the effects of variations in O_2 concentration, pH, light intensity (as caused by normal shading, cloudiness, or turbid floodwater), temperature, as well as their interactive effects on plant survival have not been sufficiently studied. We summarize here some of our recent work on these aspects.

Gaseous diffusion and pH

Oxygen availability to plants exposed to waterlogging or submergence is one of several factors that affect their growth and survival. Numerous studies have been conducted in the past on the effects of O_2 deficiency on plants (Drew 1997), but precise information on the effect of O_2 concentration in floodwater on plant survival is still scanty. Our observations showed that plant mortality increased with increasing O_2 concentration in floodwater as a consequence of higher concentration of phosphorus and algal growth, especially in sensitive cultivars (Table 2). It is possible that O_2 concentrations above anoxia and less than air saturation (0.23 m mol m^{-3} at 30 °C; gas equilibrium of 21 kPa) in floodwater would have had little effect on the survival of rice during submergence. The O_2 concentration of 0.125 mol m^{-3} was considered a reasonable threshold value required for respiration in germinating rice seeds, coleoptiles, and embryos (Taylor 1942). Ellis and Setter (1999) reported a survival rate of 100% for rice seedlings in greenhouse experiments submerged for 2 d in continuous darkness at 21, 10, or 5 kPa O_2 in floodwater but complete mortality of plants submerged under anoxic conditions (0.0 kPa O_2).

The adverse effects of low CO_2 supply were confirmed by studying the effect of different floodwater pH levels on the survival of submergence-intolerant cultivar (Table 3). When floodwater pH was lowered to 5.0, thus enhancing CO_2 availability, the survival of rice plants also increased. However, when floodwater pH was raised to 8.0, reducing the availability of CO_2, plant survival significantly decreased, especially that of sensitive cultivar IR42. Hence, where floodwater is more acidic (as in Thailand), even some susceptible cultivars may survive relatively longer durations of submergence. In India, especially in Bihar, the pH of the floodwater in general is above 8, and thus mortality of plants is expected to be higher.

Light intensity, shading, and water turbidity

Rice cultivars that contrast in their initial carbohydrate content, elongation ability under flooding, and survival percentage were compared under different levels of shading and water turbidity. Comparison of survival percentage among the different treatments showed that shade created by white cloth resulted in higher survival percentage, followed by clear water, 0.2%, and then 0.4% silted conditions (Das et al 2009). When shade was provided with white cloth, plants received lower light intensity and the temperature of the floodwater was comparatively lower (by about 1.3-1.6 °C) compared with the clear water condition without shade. This suggests that, under higher light intensity and hence greater chances for underwater photosynthesis, plants failed to survive if water temperature is relatively high. Under higher O_2 concentration, coupled with high light intensity, photorespiration may be enhanced, which might decrease the net photosynthesis; survival percentage thus decreased under clear water condition. These results also caution against the use of artificial shading for screening to simulate turbid water conditions in the field. The observation that light compensation points of *Rumex palustris* decreased under water, from 14 to 4 µ mol photons m^{-2} s^{-1} (Mommer et al 2005a, 2006), indicates that lower assimilation rates and thus lower light intensities were sufficient to compensate for respiratory demand. The reduction in the light compensation point might be the result of increased underwater assimilation rates and decreased photorespiratory losses, both resulting from decreased gas diffusion resistance (Mommer et al 2005b) and reduced rate of dark respiration (Mommer et al 2005a).

The shading effect of floodwater lowers light intensity and sometimes extinguishes it under conditions of high turbidity. Increasing the depth of water and thus the amount of shading has been shown to promote submergence injury in rice (Palada and Vergara 1972, Adkins et al 1990) and also in other species such as *R. palustris* (Nabben et al 1999). Ram et al (1999) reported variable light intensities with increasing water depths in flooded fields of eastern India having variable turbidities. At several locations, light intensity, even at 20 cm water depth, was half of the full sunlight and almost zero at 1-m depth. Low light may be injurious (Adkins et al 1990) because the resulting slower photosynthesis reduces the production of respirable assimilates and depresses O_2 production (Waters et al 1989).

Neutral or slightly acidic conditions of floodwater favor the dissociation of CO_2, which will promote growth (Setter et al 1989) and slow leaf senescence (Jackson et al 1987) and leaf extension (Raskin and Kende 1984a). In our investigation under shaded conditions created by white cloth, the pH of the floodwater was more alkaline and the concentrations of CO_2 were lower than those under silted floodwater conditions, yet leaf senescence was slower as evidenced by the extent of chlorophyll retention after submergence (Das et al 2009). Ramakrishnayya et al (1999) reported O_2 concentrations above saturation level with alkaline floodwater (pH 8.0), which decreased the survival percentage. They studied the survival percentage only under clear water conditions with variable O_2 and pH levels. However, in our investigation, the variations in floodwater in terms of pH, CO_2, and O_2 levels were due to turbidity. Hence, the shading effect caused by the use of white cloth might be responsible for such contrasting differences. Light availability under shade created with white cloth and that created with 0.2% silt was more or

Table 2. Oxygen concentration in relation to survival (%) of rice cultivars during submergence at different floodwater phosphorus (P) concentrations and with 5 ppm $CuSO_4$ to suppress algal growth. O_2 concentrations were measured at 1100 h at a water depth of 40–80 cm. The O_2 concentration of air-saturated water at 30 ºC was 0.23 mol^{-3} (7.5 ppm). Plants were submerged for 10 d, and survival was measured as the percentage of plants that survive and recover after 14 d of withdrawal of submergence. Standard errors of the means are in parenthesis.

Treatment (ppm P)	Cultivar	Oxygen concentration (days after submergence)				Survival (%)
		0	4	8	10	
0.00	IR42	0.23 (0.05)	0.25 (0.01)	0.37 (0.01)	0.36 (0.02)	17 (4)
	FR13A					100 (0)
0.00 (+$CuSO_4$)	IR42	0.20 (0.01)	0.28 (0.01)	0.27 (0.02)	0.20 (0.01)	33 (4)
	FR13A					100 (0)
0.25	IR42	0.26 (0.02)	0.29 (0.03)	0.38 (0.03)	0.37 (0.07)	0 (0)
	FR13A					100 (0)
0.50	IR42	0.27 (0.03)	0.29 (0.02)	0.41 (0.01)	0.43 (0.00)	0 (0)
	FR13A					83 (2)
0.75	IR42	0.27 (0.02)	0.31 (0.01)	0.47 (0.03)	0.46 (0.04)	0 (0)
	FR13A					83 (1)
1.00	IR42	0.27 (0.02)	0.31 (0.01)	0.57 (0.02)	0.50 (0.05)	0 (0)
	FR13A					67(4)

Adapted from Ramakrishnayya et al (1999).

Table 3. Survival of rice after 10 d of submergence at different floodwater pH levels. The CO_2 concentration in floodwater was estimated from CO_2/HCO_3- equilibrium at the specified pH based on the measured CO2 concentration in water (pH 6.4) of about 0.5 mol m^{-3} (pKa of CO_2/HCO_3- = 6.4). Values in parenthesis are standard errors of the means.

Cultivar	Treatment (pH level)	Floodwater CO_2 concentration (mol m^{-3})	Survival (%)
IR42	5.0	0.96	62 (4)
FR13A			100 (0)
IR42	6.9	0.31	17 (4)
FR13A			100 (0)
IR42	8.0	0.02	0 (0)
FR13A			100 (0)

Adapted from Ramakrishnayya et al (1999).

less similar, yet survival percentage was higher in the former. This investigation showed that water turbidity probably exerted additional adverse effects during submergence besides reducing light intensity and penetration. Under 0.4% silted conditions, plant survival was the least compared with other treatments, O_2 concentration was also low (4.23 mg L^{-1}), and light penetration was almost nil. Collectively, these factors probably caused faster senescence and resulted in higher depletion of carbohydrates. These results strongly suggest that a minimum level (88–184 µ mol m^{-2} s^{-1}) of light intensity is required to minimize chlorophyll loss and leaf senescence. Both lower O_2 concentrations (hypoxic) as well as supersaturated conditions seem to promote senescence and reduce chlorophyll retention.

A comparison of the amount of silt deposition on leaves revealed that the amount deposited on the plant surface of different cultivars was not related to the extent of survival under flooding. For example, the amount of silt deposited on the plant surface of CRK2-6 was the least, yet its survival was very low, only 12% under 0.4% silt concentration in floodwater. We observed that plants submerged in turbid water tend to lose their leaves quickly upon desubmergence, and survival depends largely on the ability to regenerate new leaves during the recovery period. This is probably why FR13A and Kusuma showed the highest survival rate despite the greater silt deposition on their leaves (Das et al 2009).

Effects of floodwater temperature

Water temperature is an important factor that affects the survival of plants during submergence. High temperature (30 °C) accelerates plant mortality, whereas low temperature (20 °C) was less deleterious. The percentage of survival is greater at lower temperature (Palada and Vergara 1972, Vergara et al 1976, Adkins et al 1990). According to Vergara et al (1976), the warmer the water, the lower is its O_2 content, subjecting rice plants to severe O_2 deficiency. High temperature decreases O_2 and CO_2 solubility in floodwater and accelerates anaerobic respiration, leading to faster starvation and subsequent plant death (Ram et al 2002). Even in intact rice plants, where O_2 required for root respiration is supplied through transport from shoots along the aerenchyma, roots experience O_2 shortage at elevated temperatures (32–33 °C), inducing ethanol fermentation. This causes faster carbohydrate utilization and thus increases plant mortality (Waters et al 1989, Vartapetian 2005).

Survival percentage was higher in plants submerged during the winter season compared with those flooded during summer (Das et al 2009). In both seasons, there was not much variation in floodwater pH and O_2 concentration; but the concentration of CO_2 and light intensity were comparatively higher in the summer season. However, the higher CO_2 concentration, as well as the higher light intensity during summer, did not improve plant survival as expected. This is probably because the floodwater was warmer during the summer season. In winter, the temperature of the floodwater was about 4.85 °C lower than that in summer. Biomass loss in warm water was also considerably faster than that in cold water (van Eck et al 2005) or in clear water without shade, resulting in lower survival percentage. These results strongly suggest that previously reported seasonal effects of flooding on species response (Klimesova 1994, Crawford 2003) are mainly due to variation in water temperature rather than in O_2 level.

High temperatures during submergence accelerate the rates of respiration, leading to faster starvation and death of submerged plants (Ram et al 2002). The relative survival of several tolerant and intolerant rice genotypes after 7 d of complete submergence indicated 100% survival in all genotypes at 20 °C but a range of 27–87% survival when floodwater temperature reaches 30 °C (Ram et al 2002). Adkins et al (1990) and Siebel and Blom (1998) also reported that, at higher temperature, plants became less tolerant of submergence, although the LD_{50} for rice was similar between 20 and 30 °C (Adkins et al 1990). It is thus clear that temperature, along with other environmental factors, plays a vital role in determining submergence tolerance of plants.

Plant hormones under flooding

Gases produced underwater during flooding (e.g., ethylene, O_2 during daytime and CO_2 at night) add to its overall concentration at the production site, whereas any gas consumed (e.g., O_2 at night and CO_2 during the day) results in a fall in concentration at the consumption site due to slow gas diffusion. Because of the slow gas movement in floodwater, ethylene reached physiologically active concentrations in plant tissues under submergence (Ku et al 1970, Konings and Jackson 1979, Stünzi and Kende 1989). In environments where submergence lasts for longer periods, rice cultivars with better elongating ability are preferred. Floating or deepwater rice plants respond to submergence with a large increase in the rate of elongation of internodes (Catling 1992). This response to submergence is known to be regulated by the interplay of ethylene, gibberellin (GA), and abscisic acid (ABA). Submergence enhances the production of ethylene (Metraux and Kende 1983, Raskin and Kende 1984a, Cohen and Kende 1987) and the activities of GA (Yamaguchi 1974, Suge 1985, Azuma et al 1990, Hoffman-Benning and Kende 1992) in the shoots or in tissues of internodes, while it decreases the level of ABA in internodal tissues (Hoffman-Benning and Kende 1992). The application of ethylene (Metraux and Kende 1983, Raskin and Kende 1984a, Suge 1985) or gibberellic acid (GA_3) (Raskin and Kende 1984b, Suge 1985, Azuma et al 1997) promotes internodal elongation in air-grown plants and in excised stem segments of floating rice. By contrast, endogenous ABA reduces the rate of intermode elongation induced by ethylene and GA_3 (Hoffman-Benning and Kende 1992). Ethylene and gibberellin act synergistically in the growth of rice coleoptile and the first leaf sheath (Jackson 1985). Metraux and Kende (1983) and Ishizawa and Esashi (1984) emphasized the important role of endogenous ethylene and CO_2 in stimulating the elongation of internodes and coleoptiles in rice. There is evidence from rice and other plants that ethylene response is GA-dependent (Musgrave et al 1972, Metraux and Kende 1983, Raskin and Kende 1984a, Khan and Seshu 1987, Takahashi 1988, Hoffmann-Benning and Kende 1992). Submergence stimulates ethylene synthesis, which accumulates in the submerged internode; it thus increases the sensitivity of the tissue to GA_3 or increases the concentration of physiologically active GA. Production of ethylene by submerged plant parts in deepwater rice fields near Ayutthaya, Thailand, was demonstrated by the presence of ethylene at a concentration of 1–2 ppm in the floodwater compared with only 0.1–0.2 ppm in the plant canopy above the water surface (Setter et al 1982). The accumulated ethylene during submergence adversely affected the antioxidant mechanism in the susceptible rice cultivars, especially after desubmergence (Kawano et al 2002). Ethylene also directly affects chlorophyll degradation and enhances chlorosis under submergence (Ella et al 2003a, b).

Essential adaptive traits in flood-prone areas

Photoperiod sensitivity

In lowland and deepwater ecosystems, submergence is a major constraint to rice production. Traditional varieties adapted to these ecosystems are generally low-yielding but sensitive to photoperiod, allowing them to avoid submergence stress at the time of flowering. Acquiring photoperiod sensitivity is beneficial in these ecosystems because of the high sensitivity of rice to flooding during flowering, where even submergence for a few days could hamper grain formation and induce spikelets to be completely sterile. For these reasons, photoperiod sensitivity needs to be incorporated into new high-yielding varieties to synchronize their flowering with the time the rainfall starts to cease.

Floods may occur any time between June and August, and almost all lowland areas of the region are prone to temporary complete inundation to which all modern varieties are sensitive. To cope with these conditions, farmers in some regions use aged seedlings for planting later in the season, when floodwater starts to recede, as in most areas of Indonesia. Photoperiod-sensitive cultivars possess high plasticity and can be planted at different ages with fewer penalties in grain yield. In a recent field survey, we observed that farmers sometimes planted seedlings that are more than 2 mo old in order to avoid complete inundation, especially in stagnant and deepwater areas. *Bolan* (i.e., double transplanting) is a traditional practice of farmers in submergence-prone areas in the northwestern parts of Bangladesh and the northeast part of West Bengal, India; here seedlings are transplanted twice to increase seedling strength and height at the time of transplanting in the field. A similar system is also being used in the swampy areas of Indonesia, where seedlings are commonly retransplanted two to three times at higher densities, waiting for the water in the field to recede to a level that can allow transplanting. Use of photoperiod-sensitive cultivars has helped in adopting these technologies.

Elongation ability versus duration of floods

Rice plants that exhibit only limited elongation during submergence mostly show tolerance for short-term complete flooding, which is referred to as flash flooding or submergence. However, for most submergence-prone areas, the ideal ideotype should combine both submergence tolerances (survival under water) together with some elongating ability (De et al 1981, Mohanty et al 2000). This is because, in most cases, floodwater tends to stagnate at higher levels (20–50 cm) for longer duration after flash floods. Typical flood patterns in these areas involve situations where water level increases and then (i) stays at that level, (ii) recedes only partly, or (iii) recedes but then rises again and stays for a longer duration. In areas where typical flash floods occur (water recedes to lower levels after complete submergence for 1–2 wk), reduced underwater elongation is beneficial for survival because elongating plants exhaust their energy reserve and tend to lodge as soon as the water level recedes. The rationale behind classifying a genotype that exhibits limited elongation during submergence as tolerant is that such a genotype is likely to use only a small quantity of available carbohydrates for elongation growth, leaving enough for survival and maintenance processes during submergence (Sarkar et al 1996, Setter and Laureles 1996, Setter et al 1997, Ram et al 2002), as well as for growth resumption after the water recedes (Ella et al 2003b, Das et al 2005). However, there are conflicting reports about the rate of depletion of carbohydrates during submergence, indicating that tolerant and intolerant varieties respire at similar rates during submergence and/or anoxia, but most variation is during the post-submergence phase (Boamfa et al 2003). The authors further reported that tolerant varieties with initial higher carbohydrates have an edge over intolerant ones in terms of survival and recovery growth.

Studies involving manipulation of elongation growth during submergence using plant hormones demonstrated the beneficial effects of growth suppression. For example, GA application to plants 48 h before submergence resulted in more elongation during submergence with the consequent reduction in plant survival. In contrast, when GA biosynthesis inhibitor, paclobutrazol, was applied, shoot elongation under submergence was reduced, resulting in higher survival percentage (Setter and Laureles 1996, Ram et al 2002, Das et al 2005). Furthermore, dwarf mutants exhibiting little or no capacity for GA biosynthesis showed submergence tolerance at par with the highly tolerant landrace FR13A, when plants of the same mass or carbohydrate contents were used in the experiment (Setter and Laureles 1996). Introduction of a genomic clone (OS-ACS5) encoding 1-aminocyclopropane-1-carboxylic acid (ACC) synthase in the modern cultivar IR36 (van Der Straeten et al 2001) rendered it more sensitive to submergence damage and the genetically engineered plants showed greater elongation, which might be due to enhanced production of ethylene resulting in accelerated depletion of reserve carbohydrates and enhanced chlorophyll degradation, with the consequent poor survival (Sarkar 1998, Almeida et al 2003).

Role of nonstructural carbohydrates and chlorophyll retention

Percentage survival of rice seedlings correlated positively with dry matter biomass, chlorophyll level, and sugar and starch concentrations of both roots and shoots (Das et al 2005, 2009). Retaining more chlorophyll during submergence enhances submergence tolerance (Sarkar et al 1996, 2001, Ella et al 2003a, Das et al 2005). Nonstructural carbohydrate contents before and after submergence are important to provide the energy needed for maintenance metabolism during submergence and for regeneration and recovery of rice seedlings after desubmergence (Sarkar, 1998, Das et al 2001, Jackson and Ram 2003). Our recent studies showed that differences in tolerance for submergence are not necessarily associated with initial carbohydrate status before submergence but rather with the ability to maintain a high level of stored energy through slow use during submergence and/or maintenance of underwater photosynthesis to ensure higher energy reserves for recovery. The initial carbohydrate level was almost the same in two genotypes, Gangasiuli and Raghukunwar, before submergence, yet Gangasiuli showed better survival, greater capacity for chlorophyll retention, and maintenance of higher nonstructural carbohydrate content during submergence. Under natural conditions, floodwater is mostly turbid, and in such situations, slow senescence and greater retention of nonstructural carbohydrate seem to be essential for survival (Das et al 2005. 2009).

Cropping patterns in flood-prone areas: past and future trends

In the forthcoming decades, South and Southeast Asia need to produce more food of better quality, with less water, and on lands of lower quality, by fewer farmers and for more people. Rainfed lowlands can thus play a central role in meeting these daunting challenges. Use of residual moisture and better management of excess water available in rainfed lowland and flood-prone ecosystems will help produce more food using these by and large wasted resources. In the past, most of these areas are monocropped with rice during the wet season using traditional low-yielding varieties. The predominantly fertile soils of this ecosystem, coupled with water availability during most part of the year, either through surface water bodies or from shallow underground bore wells, provide great opportunities for extra food production to meet this pressing demand. The progressively expanding areas devoted to dry-season boro rice in Bangladesh, Thailand, Vietnam, and India provide a good example.

Growing nonrice crops on residual moisture in lowlands following the wet-season rice depends on harvesting time of rice, availability of irrigation water after rice harvesting in the wet season, rate at which the soil dries up and becomes amenable to tillage, and sensitivity of the subsequent crops to saturated soil condition and water stagnation in the field. In general, boro rice is cultivated where field is highly saturated, with the possibility of supplementary irrigation facilities, if required, as in West Bengal, India, and Bangladesh. In many places, deepwater rice has been replaced by one rice crop during the dry season because of the ensured and better yields compared with wet-season rice. However, new challenges are now emerging in some areas where this system is being intensively practiced, such as lowering of underground water table, contamination with heavy metals, and the high expense following the upsurge in energy prices. In some parts of the Mekong Delta in Vietnam, deepwater rice has been replaced by two to three irrigated rice crops after the recent development of infrastructure for floodwater control. Short-duration pre- or post-flood rice crops are also being grown in some areas of the Chao Phraya Delta, Thailand (Puckridge et al 2001).

Depending on the profitability and suitability of the cropping system in flood-prone areas, Singh et al (2000) suggested some crop rotations for eastern India. The economic analyses of the different systems tested showed that jute-rice-lentil is the most profitable, followed by jute-rice-wheat in submergence-prone lowlands of West Bengal (Singh 2000). For the rainfed lowlands of Orissa, jute-early rice-sesame, followed by jute-late rice-mungbean was recommended. In Assam, India, the best cropping pattern was found to be rice followed by pea. In submergence- and drought-prone lowlands of Uttar Pradesh and Madhya Pradesh, rice-wheat, followed by rice-lentil and rice-linseed in Uttar Pradesh and rice-horse gram in Madhya Pradesh was suggested. In Bangladesh, the major cropping system in the flood-prone ecosystem was mainly rice-rice. Crop options for no-till farming on residual moisture are increasingly emerging. Experiments conducted at CRRI, Cuttack, showed that reduced tillage (0–5 cm surface) conserved adequate soil moisture to grow a successful crop of groundnut. Chickpea, lentil, linseed, mustard, and toria could also establish well on residual moisture in black soils with minimum tillage (Shastry et al 1998).

In the western plain of Thailand, the pre-flood period of 3–4 mo from the beginning of the wet season to the start of the flooding season provides a good opportunity to introduce a short-duration nonrice crop. Sesame, mungbean, and cowpea are the best options for the region (Kupkanchanakul et al 1988). Double cropping of rice and other cash crops has been adopted by farmers in the rainfed lowlands of Cambodia where irrigation is assured (Sarom 2004). Rice-legumes (mungbean, soybean, sesbania) are also adopted in Cambodia. In Myanmar, rice monoculture is common in deepwater areas; and when irrigation water is available, pre-monsoon jute, followed by deepwater rice, is grown. In areas where the water level recedes a little earlier, late-monsoon rice is also grown, and ‘Mayin’ rice is commonly sown when there is no standing water in the fields (Myaint 2004). Pulses and oilseeds are the other crops grown in rice-based cropping systems. The cropping system in lowland fields is rice-rice in Indonesia (Alihamsjah 2004), while in the upper or raised-bed system, farmers grow secondary crops and vegetables. In Bangladesh, deepwater aman rice is sown in March when the land is dry, raised as an upland crop until the flooding starts in June or July. Later, the crop grows with floodwater at least up to August and September. This type of rice is also grown as a mixed crop with aus, with one-third deepwater aman and two-thirds aus. The short-duration aus rice is harvested in May-June, leaving behind the deepwater aman at the vegetative stage.

Availability of water during the dry season for nonrice crop cultivation is the main limiting factor for farming during the dry season in flood-prone areas. Therefore, before choosing specific cultivars, the water use of each crop should be determined and decisions should be made on the basis of water availability, crop duration, and product marketability. The soil profile and contribution of water from the root zone during the growth period should also be considered. If winter rainfall and available residual moisture are not sufficient, then water harvested during the rainy season would particularly be useful and, depending on the water collected and crop water use, crops could be selected for greater economic returns. Use of village ponds and construction of small water reservoirs can help in this regard. Recently, the concept was demonstrated in farmers' fields in Orissa, India, and the following cropping systems were recommended (Mohapatra 2003):

a. Kharif: rice
b. Rabi: mustard/vegetables (cabbage, cauliflower, tomato, radish, cucumber)/black gram
c. Summer: oil seeds (sesame, groundnut)/pulses (green gram, black gram)/vegetables (okra, brinjal, tomato)/chili

Environmental sustainability in flood-prone ecosystem

Food production and income, through management interventions such as appropriate cropping patterns in the pre-flood period, have increased substantially in Bangladesh and eastern India due to investment in shallow tubewells. In relation to environmental protection, this kind of development was not always positive—health problems due to arsenic toxicity are reported in Bangladesh and eastern India. Increase in soil salinity and depletion of underground water further worsen the farmers' situation as productivity is reduced. Strategies for rainwater harvesting in flood-prone areas, instead of shallow tubewell installations, will be most effective and environment-friendly to improve overall productivity with minimum health concerns.

Further needs and opportunities

The first concern of the rainfed lowland farmers is food security via ensuring a 'good' rice crop, followed by an assured source of income through means other than rice cultivation. In rainfed lowlands, excess water is available but not well-distributed, prompting the need for infrastructure development to properly manage these resources. Use of residual moisture for cultivation of nonrice crops not only can generate more income but also provide employment to daily wage laborers. This will reduce the out-migration of people commonly observed in submergence and flood-prone areas. Water harvesting and its utilization for nonrice crops, especially vegetables and oil seeds, can ensure food security, nutritional balance, and better income.

Available information on soil water in rainfed lowlands suggest the suitability of this system for rice-fish farming in at least some areas. In shallow and medium deep rice-fish ecologies, the pH, temperature, and dissolved O_2 in the water remain unfavorable, whereas in deepwater and very deepwater conditions, these water quality parameters favor rice-fish farming. Dissolved O_2 concentrations below 2 mg L^{-1} do not sustain certain types of fish (e.g., white fish) but are more suitable for others (e.g., black fish), which can be easily grown (Hoggarth et al 1999, Keskinen et al 2005). Special care is needed to improve the fish culture in very deepwater environments. In West Bengal, India, we visited some flood-prone areas where farmers' communities lease their lands to fish entrepreneurs. They have identified their own local rice varieties that can be grown along with the fish during the rainy season. The fish entrepreneurs provide some income for fish farming during the rainy season and also help in harvesting excess water from the fields to ensure water supply during the boro rice season.

Besides food, nutritional quality is now a major concern in all South and Southeast Asian countries. Deepwater rice from coastal areas of Bangladesh is a source of iron and zinc. Improved rice varieties with better nutritional quality could provide better nutrition and enhance the health of even the poorest rice farmers living off these areas (Puckridge et al 2001).

Gaps in research, synthesis, and future strategies

The surface water depth in rice fields changes continuously during crop growth (Seng et al 1996). There are relatively little data available on surface hydrology and water profile for better classification of agroecosystems (Boling et al 2000). In rainfed lowland and deepwater areas, heavy rains leading to submergence, drought, and adverse soil qualities will continue to be the dominant factors affecting the productivity of this system. Emphasis should be placed on the development of rice cultivars with multiple stress tolerance. Information on floodwater characteristics is available mainly for India and Thailand but not for other countries. The information is useful not only for rice production but also for the development of nonrice crops and fisheries. Information on available groundwater, its recharge, and safety are needed to explore the possibilities of growing dry-season crops in flood-prone areas**.**

Strategic research for identification of marker traits associated with submergence and low-light tolerance and tolerance for other localized stresses, and their incorporation into popular varieties could help address the need for suitable cultivars for flood-prone areas of South and Southeast Asian countries. The maintenance of high levels of stored carbohydrates in seedling shoots prior to submergence, coupled with minimum shoot elongation and retention of chlorophyll, contributes to better submergence tolerance. Biotechnological and genetic approaches to enhance the efficiency of pathways involved in the control of these traits such as carbohydrate metabolism and regulation of plant hormones (e.g., GA and ethylene to restrict elongation and reduce chlorophyll loss under submergence) could help in developing germplasm with enhanced tolerance. Cloning and introgression of the *SUB1* gene into popular varieties provide good protection against short-term submergence (Xu et al 2006, Neeraja et al 2006; Singh et al 2009). Greater efforts are needed to further enhance tolerance for flash floods as well as for stagnant long-term flooding, which is predominant in most flood-prone areas. Besides genetic enhancement, submergence tolerance could also be manipulated through certain management practices (Ella and Ismail 2006). Proper crop and nutrient management in the nursery and main rice fields can enhance and stabilize productivity in the flood-prone ecology.

Systematic environmental characterization, along with the evaluation of germplasm for various traits including photoperiod responses under field conditions, may enable extrapolation of the research findings to other areas with similar challenges. Human health and nutrition hazards are other important concerns that need to be addressed for the well-being of poor farmers in flood-prone areas, who mainly depend on rice as the sole source of energy intake.

In general, farmers do not apply pesticides and fungicides to rice crops grown in most unfavorable rainfed lowlands because of apprehensions regarding crop failure. However, with increasing emphasis on productivity enhancement, farmers are now tempted to use more pesticides to control insect pests in rice crops, which may lead to other environmental concerns, including water pollution. To avoid this, biologically based and economical pest management strategies can be promoted. This is particularly useful for the health of fish in the rice-fish system and also for human beings. Human malnutrition is of great concern in rice-growing countries. Millions of children in developing countries suffer from anemia caused by iron deficiency and blindness caused by vitamin A deficiency. In the recent past, attempts have been made to develop high-yielding rice cultivars with high iron, zinc, and Vitamin A contents to address the malnutrition problems of rice consumers, especially in rainfed lowlands and deepwater ecosystems of South and Southeast Asia. These efforts could potentially help in enhancing the well-being of rice farmers and consumers in these areas.

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Notes

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Crop and resource management in flood-prone areas: farmers' strategies and research development

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Rice cultivation is the major farm activity in diverse flood-prone environments of South and Southeast Asia, providing food for millions of subsistence farming families. Rice productivity in these ecosystems is quite low due to the lack of high-yielding varieties tolerant of prevailing biotic and abiotic stresses, particularly the adverse hydrological conditions leading to recurrent floods and/or drought. The major constraint to low productivity is poor initial crop establishment in direct-seeded rice and poor survival upon submergence in transplanted rice. The productivity of such environments can be increased using proper crop and nutrient management strategies. Improving seedling health in the nursery through proper seed rate and nutrient management may lead to better crop establishment in transplanted rice. Robust seedlings also provide good anchorage to enable them to withstand submergence damage and show rapid regeneration after the floodwater recedes. Post-flood nutrient management, on the other hand, ensures rapid recovery and minimizes yield losses caused by submergence. The success of mitigating hunger in millions of resource-poor farming communities in South and Southeast Asia, therefore, lies on enhancing rice productivity in flood-prone environments by ensuring better crop establishment, better tolerance for recurrent floods, and rapid post-flood recovery through integrated crop and nutrient management strategies.

Keywords: crop and natural resource management, flood-prone environments, nursery management, rice, submergence

The flood-prone ecosystems of South and Southeast Asia are characterized by a great diversity of conditions, particularly timing, duration, and intensity of rainfall and floods. Soil types, topography, and prevailing biotic and abiotic stresses also vary considerably. These flood-prone ecosystems include shallow, flash-flood areas, medium (partial stagnant), deep and very deep waterlogged areas, and tidal wetlands (IRRI 1984). In South and Southeast Asia, approximately 22 million ha of rice lands are flood-prone and more than 100 million people primarily depend on this ecosystem for their livelihood (Hossain and Abedin 2004). About 13 million ha of deepwater and tidal wetland rice lands are cultivated every year in South Asia and an estimated additional 18 million ha are not being used in South and Southeast Asia because of floods (Singh et al 2004). In deepwater areas, rice is dry-seeded in April or May and the crop initially grows on limited soil water, followed by shallow flooding for a couple of months after the commencement of rain in June and July. At the later stages of growth, deepwater rice is subsequently inundated for the remaining period to a depth of more than 1 m. Deepwater rice area is found in river basins of the Ganges and Brahmaputra in India and Bangladesh, Irrawaddy in Myanmar, the Mekong in Vietnam and Cambodia, and the Chao Phraya in Thailand. Tidal wetlands are located in coastal areas where water regime fluctuates, depending on the tides, and rice in these areas experiences variable levels of submergence and even salinity in areas close to the sea.

The flood-prone ecosystem varies in flooding duration, and intensity, ranging from a short duration of 1-2 wk of flash floods to more than 6 mo of deep stagnant waterlogging. This ecosystem is also characterized by a large genetic diversity of adapted rice cultivars, holding enormous potential for crop improvement. Four different types of tolerance responses seem to satisfy the basic requirements of this ecosystem: (i) cultivars with high tolerance for submergence with minimum underwater shoot elongation, for flash-flood-prone areas where complete submergence predominantly occurs for 10–14 d, (ii) cultivars with rapid underwater shoot elongation for deep and very deep water areas, (iii) good submergence tolerance with rapid regeneration ability for repeated intermittent flood conditions, and iv) cultivars with tolerance for stagnant floods that can occur independently of or subsequent to flash floods and can result in partial submergence for longer duration. In direct-seeded areas, tolerance for flooding during germination is also required as submergence or waterlogging is often experienced as a consequence of early rains, resulting in poor germination and crop establishment (Ismail et al 2009).

In eastern India, about 13 million ha of rice lands are prone to floods, causing partial to complete submergence every year. The rice crop suffers from too little or too much water during early stages, depending on the onset of rains and time of sowing. At the later stages, mostly a couple of inundations occur due to rains in August and September. High seedling mortality and low tiller production are the main reasons for low productivity of rice in these flood-prone areas. Lack of suitable varieties with ample submergence tolerance is the other major constraint, as only a few semidwarf varieties have recently been developed for flood-prone areas. Madhukar, Barh Avarodhi, Jal Lahari, Savitri, Gayatri, and Bhudeb are some of the promising varieties grown in semi-deep water (15–50 cm depth) owing to their ability to survive 7–10 d of complete submergence. In deepwater areas where water level reaches up to 1 m, Chakia 59, Jalpriya, Panidhan, Tulasi Biraj, Suresh, and Sabita are grown because of their good elongation ability and photoperiod sensitivity. For very deepwater areas (>1 m), Jalmagna is the most suitable variety in eastern Uttar Pradesh, India. These varieties are also being used as donors for germplasm improvement programs. However, adoption of these varieties by farmers in flood-prone areas at present is still low because of their poor grain quality and undesirable agronomic traits such as yield. Recently, few submergence-tolerant lines have been identified in India, which yield about 3–4 t ha^{-1} in farmers' fields under flash flood conditions and seem to be preferred by farmers over the existing varieties. Popular varieties with *SUB1* gene introgression also became recently available and showed considerable potential for increasing and stabilizing productivity in flash-flood-prone areas (Singh et al 2009, Sarkar et al 2009).

Bangladesh is a country of rivers and flat plains, with only less than 10% of its land at more than 30 m above sea level (Yeo 1982). The Ganges-Brahmaputra-Meghna river basins form the world's largest delta (Catling 1992). About 80% of Bangladesh land is floodplain, 12% is hilly area, and 8% is terrace (FAO 1988). About 50% of the total land area is affected by floods in Bangladesh and, in exceptional years, floods may submerge 60% of the land (Karim and Iqbal 1997). Flooding in Bangladesh starts in early to mid-June in the eastern part (Meghna floodplain) and in mid-June to July in the Jamuna and Ganges floodplains of the central part. The rate of water rise is usually rapid after flooding, 4–6 cm d^{-1}, in areas where flooding occurs to a depth of 50–100 cm and about 5–8 cm d^{-1} where floods were up to 150 cm, but variable in deeper areas where floodwater reaches 150–300 cm depth (Catling 1992).

In Bangladesh, rice varieties cultivated in different ecosystems are grouped into five distinct ecotypes: (i) boro or dry-season rice, (ii) transplanted aus (T. aus), (iii) transplanted aman (T. aman), (iv) upland aus (direct-seeded aus), and (v) deepwater rice (floating rice). Boro rice is grown entirely using irrigation during the dry period (November to July), while T. aman (July to December), T. aus (April to August) and upland rice (March to July) are grown under the rainfed ecosystem. Of the total 13.8 million ha of cultivable land in Bangladesh (FAO 1988), 10.27 million ha (74.4%) are devoted to rice cultivation in the five ecosystems (BBS 1993, 1997). This area also includes tidal wetlands covering about 425,000 ha and about 3.05 million ha of coastal saline soils (Sattar 2006).

Submergence is the major abiotic stress in flood-prone ecosystems because it can substantially reduce crop stand, especially if it occurs during the early vegetative stage and if the stress is prolonged for more than 1 wk. This is a common phenomenon in many lowland areas of Asia, subject to monsoon rains, seriously affecting crop establishment and leading to severe yield losses. However, with proper germplasm and management options, it is possible to minimize yield losses caused by submergence. Management options such as improved seedling health in the nursery before transplanting, age at transplanting, nutrient management during pre- and post-floods and the timing of planting to minimize or avoid submergence damage are all found to be beneficial (Ella and Ismail 2006). High-yielding medium-duration modern varieties can effectively be grown in shallow lowland areas with proper crop and nutrient management options.

Crop establishment

Poor crop establishment is one of the major factors contributing to low productivity in flood-prone ecosystems. Successful crop establishment in these ecosystems is dependent on rainfall, land type, and rice variety. Direct seeding and transplanting are the two methods adopted by farmers for crop establishment. However, the choice of either method is dependent on the availability of rainwater and other resources.

Direct seeding

In flood-prone areas, mostly traditional tall and photoperiod-sensitive varieties, either with a reasonable level of submergence tolerance to withstand complete inundation or with elongation ability to escape submergence, are grown through direct seeding or transplanting. Farmers in flood-prone areas practice two types of direct seeding: dry and wet. Dry direct seeding is very common in India, Bangladesh, Sri Lanka, Thailand, Indonesia, Myanmar, and the Philippines (Singh et al 2004). Dry seeding is done by broadcasting seeds on dry soil in May before the beginning of the monsoon rain, which can then germinate and grow after the first showers. This type of direct seeding is risky since germination is poor and seeds are inevitably subject to damage by birds, rodents, and ants. Farmers use higher seed rates than the recommended levels to compensate for these losses.

The most successful direct seeding is in wet soils through drilling or dibbling after the first light shower, which ensures good seed germination. However, the growing crop could also suffer from intermittent early-stage drought if rains are delayed after seeding. Delayed seeding may also subject germinating seeds to waterlogging or submergence at early stages in July. A sizeable area in semi-deep and deepwater ecosystems in Orissa, West Bengal, and eastern Uttar Pradesh falls under this category.

Both systems of direct seeding have their advantages and disadvantages and can be used depending on the onset and intensity of rains. Late-sown crop after the first showers of rain can result in good germination but is prone to early-stage submergence just after germination. At times, this leads to complete crop failure. The loss in yield with delayed sowing will not be compensated for even by the use of 50% higher seed rate and nitrogen (N) fertilizer (Sharma 1994). On the other hand, a poor and uneven crop stand usually results from the use of dry seed broadcasting due to loss of seeds and staggered germination, and the resultant plants can hardly withstand eventual submergence caused by subsequent rains. Drilling of seeds at 6 cm depth and light planking are the best options in such areas (Sharma and Reddy 1992). However, in some soils, surface crusts are formed when light rains (<10 mm) occur after dry seeding, then followed by prolonged dry spells, hampering the emergence of young rice seedlings. Dry cluster dibbling/drilling of seeds is a useful technique that results in better crop establishment and also facilitates mechanical weed control and fertilizer application (Jha and Gangadharan 1989, Sharma and Reddy 1992).

The optimum seed rate for adequate crop establishment before the onset of rain is an important component of rainfed rice cultivation in flood-prone areas, where the crop initially experiences drought followed by excess water at seedling stage. These stress conditions eventually reduce germination and tiller production and increase plant mortality, and sometimes result in complete crop failure when submergence occurs for a longer duration. The optimum seeding density has been reported to be about 400–600 seeds m^{-2} for flood-prone areas at Cuttack, Orissa, and 500 seeds m^{-2} for areas prone to early-season drought as in Faizabad and Hazaribagh (Sharma 1992, IRRI 1993, Ghosh et al 1998).

The above seed rates have been reported for timely sowing conditions but can vary if sowing is delayed because of late rain or other biotic and abiotic factors. Under these conditions, appropriate adjustments should be made for seeds, fertilizers, and seedling age for planting to compensate for productivity losses. Data from a case study are presented in Table 1 from Sharma and Reddy (1992), showing that similar yields can be obtained by applying 40 kg N ha^{-1} in a late-sown crop instead of 20 kg N ha^{-1} in a timely sown crop (20th of May) in flood-prone areas. However, when sowing was further delayed (10th of June), the yield loss cannot be compensated for, even when 60 kg N ha^{-1} was applied or the seed rate is increased, indicating the importance of timely sowing in flood-prone areas, when possible.

Another traditional management practice for improving yield of dry direct-seeded rice under rainfed condition is *beushening*. This practice involves wet plowing and laddering of the field under 15–20 cm of standing water that accumulates after the rain, when the seedlings are 25–30 d old. This also helps in weed control and opens furrow for rainwater conservation. However, beushening is successful only with tall traditional varieties and is not suitable for dwarf, high-yielding varieties due to breakage of plants during plowing and laddering (Singh et al 1994). This practice is also not possible in areas where standing water exceeds 20 cm during the early growth stages or is not sufficient.

Transplanting

Transplanting is another popular method for crop establishment in flood-prone areas. This is mainly due to the shorter time period available for direct seeding and the erratic floods caused by early rains resulting in a high mortality of direct-seeded rice. The pattern of transplanting also varies at different locations in flood-prone areas, ranging from bunch planting, seedling broadcasting (throwing, parachuting) in puddled fields to double transplanting to minimize submergence damage. Seedling age is directly related to survival upon submergence; older seedlings are more tolerant of complete submergence because of higher vigor and mature tissues, lower underwater shoot elongation and high carbohydrate content than younger seedlings (Chaturvedi et al 1996, Singh et al 2005). Parvin (2005) reported that submergence tolerance increases with increasing seedling age, with shorter recovery period after transplanting and with better seedling quality, especially for submergence-intolerant varieties (Table 2). Double transplanting, known as *kalam* and s*anda* in India and *bolan* in Bangladesh, is another practice that improves seedling vigor, height, and age at the time of transplanting in the main lowland rice fields.

Seedling density

The recommended seed rate for nursery is 35–50 kg seeds for a 500–600 m^{-2} seedbed, which is sufficient for 1 ha. But farmers commonly use higher seed rates, resulting in lanky and thin seedlings. The nursery is generally unfertilized, though the application of 60 kg N and 30 kg P_2O_5 ha^{-1} as basal has been recommended for production of high-quality seedlings (Pathak 1991). In rainfed areas, nurseries are normally established after the first rain, resulting in high pressure for transplanting younger seedlings and in several cases, transplanting is delayed and farmers have to transplant older seedlings, depending on the time of sufficient rain and availability of labor and other inputs.

Table 1. Effects of sowing date and N rate on the performance of rice under intermediate deepwater conditions (15–50 cm) in India.

Sowing date and N rate	Panicles m^{-2} (no.)		Panicle weight (g)		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})	
	1988	1989	1988	1989	1988	1989	1988	1989
20 May (20 kg N ha^{-1})	91	155	2.07	1.86	1.48	2.66	4.50	4.79
30 May (40 kg N ha^{-1})	87	126	1.95	2.01	1.38	2.41	3.88	4.02
10 Jun (60 kg N ha^{-1})	22	90	2.53	1.72	0.22	1.22	0.30	2.39
SE	3.4	3.1	0.054	0.054	0.036	0.057	0.109	0.111

Source: Sharma and Reddy (1992).

Table 2. Responses of three rice varieties to submergence as affected by seedling age.

Seedling age (d)	Initial plant height (cm)	Increase in height (%)	Dry matter before submergence (mg seedling^{-1})	Submergence tolerance score[a]
FR13 A				
40	50.8	28.9	-	1
30	50.6	26.0	620	1
20	40.0	40.0	340	1
10	28.1	53.7	90	1
Pajam II				
40	59.3	48.7	590	1
30	46.3	54.4	360	1
20	38.6	73.5	210	3
10	26.9	81.4	50	9
IR20				
40	37.4	38.2	400	1
30	28.8	67.7	240	5
20	26.5	80.0	120	5
10	20.0	116.0	80	9

[a]On a scale of 1-9, where 1 is almost normal and 9 is severely damaged. Source: Parvin (2005).

Different seedling densities are used for crop establishment in rice-growing countries, depending on variety, land type, soil fertility, crop duration, and flood conditions. Higher seedling densities are generally used because of the inherent risk of plant mortality during floods and poor tillering under prolonged stagnant water regimes in flood-prone areas.

Double transplanting

Double transplanting of rice is practiced in certain parts of eastern India and Bangladesh. Known as kalam and sanda in India and bolan in Bangladesh, this type of transplanting is a little expensive and labor-intensive, but it improves survival after submergence and results in higher yield of lowland rice. In India, the seedlings are raised in the nursery in the first week of June with a normal seed rate of 40–50 kg for 1-ha planting. Twenty-one-day-old seedlings are initially planted with 4–6 seedlings hill^{-1} at a slightly closer spacing in shallow lowlands. After another 15–20 d of first transplanting, the seedlings are uprooted again and replanted in the main field with 2–3 seedlings hill^{-1} at a normal spacing of 20 × 15 cm. Sometimes, the tillers are also separated and used for planting.

This method of seedling establishment is very common in Siddarathnagar District of eastern Uttar Pradesh, India, with tall traditional variety Kala Namak, which is photoperiod-sensitive. Double transplanting reduces plant height at maturity and improves plant vigor and culm strength, enabling plants to sustain ensuing floods without substantial damage. Higher tiller number, heavier panicles, and more spikelets per panicle are the main features of the Kalam planted rice, showing an average yield advantage of 20–25% over the normal (single) transplanting system (Table 3).

A similar type of double transplanting known as sanda planting is also prevalent in certain lowland areas of Gazipur and Chandauli districts of eastern Uttar Pradesh. The method of sanda planting is similar to kalam in Siddarathnagar, except that the seed rate is much lower (25–30 kg ha^{-1}) and sown at wider spacing, producing more vigorous and sturdy seedlings. The first planting is done with 25-d-old nursery (tillers are separated and used for planting) with 4–6 seedlings hill^{-1} at normal spacing of 25 × 20 cm and the second planting in the main field is done after 15–20 d of first planting with 2–3 seedlings hill^{-1}. This method eventually results in more tillers per plant and improves seedling vigor and strength. The crop can resist lodging upon flooding. Farmers perceive a yield advantage of 25–30% over single transplanting.

Double transplanting is also common with the T. aman crop in submergence-prone northwestern parts of Bangladesh. The main purpose of bolan is to produce seedlings that are sturdy and sufficiently tall to be transplanted in the standing high water head in the main field. In this practice the nursery is raised in

Table 3. Relative performance of rice genotypes under normal (single) and kalam (double transplanting) systems in lowland fields of eastern Uttar Pradesh, India.

Genotype	Normal planting			Kalam planting			Yield advantage (%)
	Height (cm)	Sterility (%)	Yield (t ha^{-1})	Height (cm)	Sterility (%)	Yield (t ha^{-1})	
Breeding lines							
NDKN 3120	150	25.2	2.58	142	10.1	3.02	17.1
NDKN 3119	148	29.7	2.86	144	8.5	3.56	24.5
NDKN 3327	155	24.2	3.07	142	7.6	3.88	26.4
NDKN 3131	150	28.6	2.63	144	10.2	3.28	24.7
NDKN 3216	160	32.5	2.00	148	18.0	2.56	28.0
Traditional varieties							
Kalanamak	160	35.1	1.92	150	20.5	2.57	33.8
Malaysia	150	30.4	1.74	142	13.2	2.25	29.3

Source: Unpublished data of Singh et al.

high lands in wet bed condition, locally referred to as *bichonbari*. The seedlings from *bichonbari* are uprooted after 30–35 d of seeding and are transplanted densely (10 × 10 cm) with 8-10 seedlings hill^{-1} in the first high land field known as *bolanbari*. After another 25–32 d of first transplanting, the seedlings from bolanbari are uprooted and the second transplanting is done in 20 × 20 cm spacing, with 2-3 seedlings hill^{-1} in the main lowland fields locally known as *dhanbari*. Bolan transplanting improves submergence tolerance and yield of flood-prone rice by improving plant vigor, tillering, and spikelet number per unit area. The Bangladesh Rice Research Institute (BRRI) regional station at Rangpur is actively engaged in refining and validating the bolan technology for improving submergence tolerance and productivity of rice produced under this system. This includes selection of suitable varieties, optimizing seedling density in the nursery and seedling age at first and second transplanting, spacing, pre- and post-flood nutrient management, and other agronomic practices.

Research conducted at the BRRI regional station revealed that bolan produced higher grain yield (4–5 t ha^{-1}) than normal transplanting (3.0–3.6 t ha^{-1}; Table 4). However, the net income from bolan was lower than that from normal planting due to the additional labor-intensive activities. The bolan system of rice cultivation, though less profitable, is a common practice in flood-prone lowlands of Bangladesh because of the advantage of enhancing the crop's ability to withstand submergence, making it possible to transplant taller seedlings in standing water that accumulates because of early rains. Farmers can keep their seedlings for a longer duration in the first high land field to avoid devastating situations like early floods, uncertain heavy rainfall, and stagnant water in the main lowland field. Another reason for the popularity of the bolan system in flood-prone areas is the involvement of family members of medium and small farmers in farm activities, which offsets the additional cost to farmers. Adopting the bolan system seems to provide more security against floods and further increases rice production. Normal planting sometimes may result in complete crop failure if floods occur early in the season. In addition, early seeding in May produces taller bolan seedlings suitable for planting in higher depths of water in the lowlands. The bolan practice also can be used for raising post-flood T. aman rice crop, avoiding early flood damage. An example of this is in Sumatra, Indonesia, where farmers practice double and even triple transplanting in higher lands using high seeding densities. Final transplanting is then accomplished after the water in the main field recedes to lower levels at the end of the rainy season.

Table 4. Effect of sowing date and bolan (double transplanting) system of transplanting on grain yield (t ha^{-1}) of BR11 during T. aman in Bangladesh.

Establishment method	Sowing date in first nursery		
	15 May	15 Jun	Mean
Normal (single transplanting)	3.21	4.05	3.63
Bolan in high land (2nd main field in high land)	3.59	3.33	3.46
Bolan in lowland (2nd main field in lowland, usual bolan practice)	4.37	4.12	4.24
Normal transplanting in high land but 2–3 tiller separation at 30 d after first transplanting	3.35	3.71	3.53
Planting separated tillers alone in lowland	4.51	4.07	4.29
LSD (5%)		0.48	

Source: BRRI annual report (2004–05).

Nursery management for healthy seedlings and better survival

Seeding density and seedling handling

Seedlings raised conventionally in seedbeds are less vigorous and have poor establishment upon transplanting, especially when water is relatively deep. This problem can be overcome by raising healthy seedlings through proper nursery management, which involves lower seeding density, balanced nutrient and weed management, and proper seedling handling during transplanting. Efforts were made in the past to study the effects of seed density and fertilizer management in the nursery on plant survival and yield after floods in flood-prone lowlands (Hong 1995, Singh et al 2004). Lower seed density in the nursery produced healthier seedlings, which showed better survival after 7–19 d of complete submergence (Table 5), produced more filled grains, and gave higher grain yield (Singh et al 2004). The authors further reported that transplanting of older seedlings (40 d old) had better survival after submergence than younger (20 d old) seedlings and produced more but smaller panicles with lower number of filled grains.

Research conducted at the ND University of Agriculture & Technology, Faizabad, India, indicated that lower seed density in the nursery (50 g m^{-2}) produced vigorous seedlings with higher shoot biomass and high shoot carbohydrate content before transplanting, compared with seedlings produced with high-density seeding (100 g m^{-2}). Such seedlings showed better establishment upon transplanting and better survival after 10–15 d of complete submergence, and better recovery during the post-submergence period. The long-term effects of lower seed density in the nursery were evident from the higher yields relative to the higher seed density (100 g m^{-2}) in the nursery. The yield advantage ranged from 29 to 141% for different varieties and submergence conditions, with greater responses in submergence-intolerant, tall varieties such as Mahsuri (Table 6). Newly developed submergence-tolerant lines showed relatively lower responses (up to 40%) but produced higher number of filled grains and yield of up to 3 t ha^{-1}, even after 15 d of complete submergence compared with the yield of only 0.1–1.5 t from submergence-intolerant varieties (Table 6).

Seedling handling after uprooting from the nursery influences crop establishment and its survival following submergence, particularly during early growth stages. Seedling establishment after planting is negatively correlated with the time lapse after uprooting. We found that even a 24-h delay in transplanting delayed seedling establishment and reduced plant survival if submerged for 10–15 d after 15 d of transplanting.

Table 5. Percentage survival of rice as influenced by seeding density in the seedbed, seedling age at transplanting, and duration of submergence after transplanting in the field.

Seeding density	Duration of submergence (d)			
	7	11	15	19
40-d-old seedlings				
SD1a	100	100	59b	8b
SD2	100	100	85a	33a
SD3	100	100	92a	46a
SD4	100	100	100a	40a
Mean	100	100	84	32
20-d-old seedlings				
SD1	100	44bb	22a	6a
SD2	100	89a	33a	0a
SD3	100	89a	44a	2a
SD4	100	67ab	30a	6a
Mean	100	72	32	3

[a]Seeding rate in nursery: SD1 SD2, SD3, SD4 = 200 g seed m^{-2}, 100 g m^{-2}, 67 g m^{-2}, and 50 g m^{-2}, respectively. [b]Within each seedling age, means in a column followed by a common letter are not significantly different at $P < 0.05$ using Duncan's multiple range test. Source: Singh et al (2004).

Poor survival eventually decreased total biomass and grain yield (Table 6). These data contrast the findings of Singh et al (2004) who observed beneficial effects of "hardening" of uprooted seedlings by putting roots in running water for 24–36 h. Differences in response might be genotype-specific or due to the different treatments used during the hardening process (shade vs running fresh water).

Similar studies conducted at BRRI, Bangladesh, also demonstrated beneficial effects of robust seedlings produced from lower seed density in nursery. A seed density of 75 g m^{-2} in the nursery produced more vigorous seedlings relative to higher density (150 g m^{-2}). Crop establishment with robust seedlings was better and survival improved by up to 23% after complete submergence for 10 d after 7 d of transplanting. Grain yield improvement was in the range of 4–22% over higher density seeding in nursery (Table 7). From these studies, it became apparent that using low seed rate in the nursery resulted in healthier seedlings that are sturdier, richer in carbohydrates, and more tolerant of early flooding after transplanting.

Nutrient management

Soils in flood-prone ecosystems in India and Bangladesh are rich in nutrients because of deposition of sediments carrying nutrients from the upper catchments during floods. However, the benefits of high fertility are realized in the form of better harvests from succeeding post-flood crops. During the wet season, plants are normally too stressed to exploit the nutrients in floodwater and sediments due to poor crop establishment and growth caused by flooding. Sediment composition analysis in the floodplains of the Ganges, Tista, Jamuna, Kushiara, and Gomoti rivers in Bangladesh revealed that the sediments contain a reasonable amount of organic matter and are rich in N, P, K, S, Mg, Ca, Zn, Fe, and B (Idris 1999). The good harvest of black gram grown on fresh sediments at Shibganj and T. aman crop in 1998–99

Table 6. Effect of seeding density at sowing and duration between uprooting and transplanting on plant survival after submergence, and biomass and yield of lowland rice.

Treatment[a]	Genotypes				
	NDR9730018	NDR9930111	NDR9830099[b]	IR42	Mahsuri[b]
			Plant survival (%)		
D_1H_1	86±14.9	61±20.5	79.7±8.3	55±6.4	16.3±3.5
D_1H_2	75±26.5	60±12.7	75.1±3.2	50±2.1	10.0±2.9
D_2H_1	81±13.6	56±8.1	66.5±1.7	45±3.1	13.9±1.8
D_2H_2	62±16.3	53±11.4	62.7±1.2	41±2.8	9.8±1.8
			Total biomass (g plant^{-1})		
D_1H_1	26.16±0.6	25.24±0.3	11.80±0.07	21.47±1.1	8.24±0.22
D_1H_2	27.26±0.8	27.2±1.6	11.20±0.21	21.1±0.7	7.86±0.10
D_2H_1	24.22±0.6	24.2±0.8	10.27±0.20	20.33±0.5	6.86±0.08
D_2H_2	25.17±0.9	24.55±0.7	9.87±0.13	18.4±0.9	5.96±0.08
			Grain yield (t ha^{-1})		
D_1H_1	2.80±0.05	1.85±0.02	0.75±0.121	1.44±0.05	0.28±0.046
D_1H_2	2.30±0.03	1.71±0.07	0.60±0.092	1.25±0.05	0.14±0.046
D_2H_1	2.34±0.012	1.43±0.02	0.58±0.0160	1.04±0.02	0.12±0.023
D_2H_2	1.68±0.13	1.28±0.013	0.43±0.023	1.05±0.07	0.05±0.005

[a]D_1H_1 = 50 g seed m^{-2} and planting immediately after uprooting, D_1H_2 = 50 g seed m^{-2} with planting after 24 h of uprooting, D_2H_1 = 100 g seed m^{-2} with planting immediately after uprooting, and D_2H_2 = 100 g seed m^{-2} with planting after 24 of uprooting. [b]Submergence duration was for 15 d after 15 d of transplanting of 21-d-old seedlings.

Table 7. Effect of seeding rate in the nursery on plant survival and grain yield of rice genotypes submerged for 10 d after 7 d of transplanting 41-d-old seedlings. Data from experiments conducted at BRRI, Bangladesh, in the wet season of 2004.

Variety	Seed rate in nursery (g m^{-2})	Survival (%)	Grain yield (t ha^{-1})
BR11	75	83	1.53
	150	64	1.25
BRRI dhan 32	75	90	1.32
	150	74	1.27
LSD$_{0.05}$		14	0.73

following the devastating floods of July–August 1998 provided evidence of soil fertility improvement caused by deposition of sediments carried through floods.

Wet-season rice has been the major source of food in eastern India, Bangladesh, and several other countries in Asia. This warrants the need to produce more rice from the flood-prone ecosystems during the wet season, since most of these areas are used mainly for rice production. This brings a challenge before the scientific community to develop submergence-tolerant rice varieties and to match crop and nutrient management practices to reap a good harvest from the wet-season rice crop. Several submergence-tolerant rice varieties have been developed in the recent past, but they still lack true submergence tolerance and fail to reach the targeted yield. However, the International Rice Research Institute recently developed submergence-tolerant versions of a few popular rice varieties such as Swarna, Samba Mahsuri, IR64, TDK1, and BR11, by introducing the submergence tolerance gene *SUB1* through marker-assisted breeding (Septiningsih et al 2009). The validation of submergence tolerance, agronomic traits, and adaptability of these new varieties on stations and recently in farmers' fields in India and Bangladesh is currently ongoing in target locations with encouraging results (Sarkar et al 2006, 2009; Singh et al 2009). However, matching crop and nutrient management technologies are needed to further enhance the expression of the yield potential of these popular varieties and boost and stabilize rice yields in flood-prone ecosystems to meet the rising food demand.

Farmers' management practices common in flood-prone areas

Farmers in flood-prone areas either do not apply any fertilizers or apply a little amount because of inherent risks of crop failure and runoff losses during floods. They normally apply 40–50 kg N, 15–25 kg P_2O_5, and 10–15 kg K_2O ha^{-1} against the recommended rates of 60–80 kg N and 40 kg P_2O_5 (Pathak 1991). Most of these farmers do not apply fertilizers before transplanting or direct seeding because of extensive inundation during heavy rains that can break their field bunds and result in fertilizer losses. At the recession of terminal floods, several farmers broadcast only nitrogenous fertilizers at a very low rate against the recommended split dose of fertilizer (1/2 basal before planting and remaining half at panicle initiation).

Fertilizer application of 30–40 kg N ha^{-1} is optimum for deepwater areas, but farmers seldom apply any fertilizer. Deepwater rice areas normally receive sufficient organic matter and nutrients during floods and are supposed to sustain good crop growth. However, nitrogen application at the time of flowering is essential since a sizeable amount of nutrients are lost due to runoff, volatilization, and deep percolation during floods. On acid sulfate soils in Thailand, fertilizer is often broadcast onto the floodwater near the panicle initiation stage. Farmers regularly apply P and N to acid sulfate soils in Thailand and Vietnam to ensure reasonable yields. In Vietnam, highest yields on acid sulfate soils were obtained with 9 kg P + 69 kg N ha^{-1} (Zuan et al 1988). Without P, the addition of N on acid sulfate soils may not guarantee survival during years of high floods as reported in Thailand (Jugsujinda et al 1982) and, in Vietnam, N without P is reported to even decrease yields (Luat et al 1985). Since submergence in flood-prone areas affects crop establishment more seriously than other crop performance indicators, the solution lies in nursery management and "hardening" of the seedlings prior to transplanting for better crop establishment.

Nutrient management in the nursery

Submergence greatly affects N and P availability and assimilation, which can influence submergence responses and which have been implicated in differences in tolerance between cultivars. Submergence rapidly depletes the protein reserves of the plants through hydrolysis to amino acids and other soluble N-containing compounds (Yamada 1959). Palada and Vergara (1972) found the normal increase in percentage N content that occurs between 10 and 20 d after germination (from 3.1 to 4.3%) to be hindered by submergence or even reversed if the water was turbid. However, attempts to raise N levels by feeding ammonium sulfate was not beneficial and even prejudicial to survival (79% survival without vs 15% survival with ammonium sulfate application), an effect associated with 61% and 34% decrease in pre-submergence starch and total sugar concentrations, respectively (see also Yamada 1959). Furthermore, submergence-tolerant cultivars are not noticeably richer in N after prolonged submergence than intolerant lines (Mazaredo and Vergara 1982). Yet, when nitrate concentration was analyzed before submergence, the shoots of tolerant lines such as FR13A were found to be much richer in nitrate than that of sensitive types. The most tolerant lines contained more than 70 μg nitrate per plant shoot, whereas the most sensitive line contained less than 20 μg per plant. Similarly, Chaturvedi et al (1995) observed higher total N concentrations in the leaf sheath, leaf, and culm of the submergence-tolerant genotypes compared with the intolerant ones.

The nutritional status of seedlings before transplanting is also of immense importance, especially when plants are submerged during the early growth stages. Farmers' convention of applying only nitrogenous fertilizers in the nursery to get taller and greener seedlings may not have any positive consequence for flood-prone areas, since the high N content in seedlings at the time of transplanting adversely affects survival after submergence and results in poor recovery growth. However, when high N is accompanied by high P content, it seems to improve seedling vigor and tolerance to withstand ensuing submergence stress and with effectively better recovery afterwards (Jackson and Ram 2003, Ella and Ismail 2006). Singh et al (2004) also pointed out the harmful effects of high N application in the nursery when applied 1 wk before transplanting. However, application of N 10–15 d prior to planting reduced plant mortality by 50% when the soil is N-deficient. Ella and Ismail (2006) observed poorer plant survival when high N was applied late (just before transplanting) relative to early N application, irrespective of the tolerance level of the genotype. In contrast, application of P, either alone or together with N, improved the survival of plants in P-deficient soil after 12 d of complete submergence. High leaf N before submergence showed a negative correlation (R = - 0.78) with photosynthetic gas exchange during the recovery phase after desubmergence. Leaf chlorophyll content increased with application of N either alone or in combination with P, and the response was better in P-deficient soil. Late N application showed lower relative chlorophyll content during the first 3 d of recovery, with maximum recovery being noted in control plants (Ella and Ismail 2006).

Upon submergence, chlorophyll content decreased probably due to higher chlorophyllase activity; the decrease was more in IR42 than in FR13A (Ella and Ismail 2006). The authors further stressed that N application in the nursery lowered root-shoot ratio, which further decreased by about 60% with 12 d of complete submergence. Our recent study also showed that application of silicon (Si) in the soil before submergence causes similar growth stimulation as with N application and resulted in poorer survival (Table 8). During submergence, the seedlings grown in soil treated with Si before submergence had faster elongation and greater reduction in soluble sugar concentration relative to initial levels before submergence. This demonstrated that faster early-seedling growth will eventually reduce the ability of seedlings to tolerate flooding because the fast growth at this stage reduces carbohydrate storage and results in greater shoot elongation at the expense of root growth.

Table 8. Effect of silicon applied at sowing on survival, elongation, and soluble sugar content of 21-d-old seedlings submerged for 12 d. Data are means of four genotypes and four replications.

Parameter	Control	600 kg SiO_2 ha^{-1} at sowing	$LSD_{.05}$
Plant survival (%) 21 d after submergence	35.0	28.8	4.1
Shoot elongation (%) during submergence (relative to length before submergence)	107.4	119.8	8.1
Percentage reduction of soluble sugars during submergence (relative to level before submergence)	86.7	90.1	1.6

Similar approaches in nursery nutrient management have extensively been evaluated at the N.D. University of Agriculture & Technology in Faizabad, India, to study their impact on the submergence tolerance trait of popular lowland rice varieties and the newly developed submergence-tolerant lines. Enriching nursery seedbeds with N, P, and zinc, along with well-decomposed farmyard manure improved seedling vigor relative to the unfertilized control treatment (measured by plant height and shoot biomass) with about 10–30% more shoot carbohydrate concentration before transplanting (Table 9). Such seedlings showed better establishment after transplanting and survival when completely submerged for 10–15 d under natural field conditions in the 2004 and 2005 wet seasons. Plant survival in all varieties increased significantly when seedlings in the nursery were enriched with N, P, zinc, and organic manure; however, the extent of enhancement varied with variety (Table 10). Fertilized seedlings were taller before transplanting but showed lower elongation during submergence. Seedlings of submergence-tolerant varieties with proper nutrient management produced higher biomass than did those produced under control conditions after 15 d of recovery period. Shoot biomass depletion during submergence did not vary significantly among varieties and also between treatments. Higher shoot biomass before submergence seemed more useful, resulting in higher biomass and carbohydrate balance during and after submergence, which probably led to better recovery growth (data not presented).

Seedlings from well-nourished nursery beds produced higher grain yield than unfertilized control after 10–15 d of submergence. Submergence-intolerant varieties had lower absolute grain yield than the tolerant ones, but they showed greater yield improvement (up to 3.7-fold) because of proper nutrient management in nursery beds (Table 11). The beneficial effect of nursery enrichment with nutrients is probably due to lower spikelet sterility and higher tiller number per hill. The results were consistent over 2 yr, although the magnitude of yield advantage varied on the basis of variability in submergence duration, floodwater conditions, and climate variables such as temperature, sunshine, and relative humidity.

This technology was validated in two farmers' fields in Faizabad, Uttar Pradesh, in 2004 and 2005. The yield advantage, achieved by raising crops from seedlings obtained from well-nourished seedbeds, was 16–20% in one farmer's field where submergence stress was not very severe. In the other farmer's field, the benefit of nursery nutrient management was about 160%, when multiple floods occurred at three different growth stages (data not shown). This indicates that seedling health in the nursery is extremely important as it affects crop establishment and survival, especially when submergence occurs at the early stages of crop growth and also under recurrent floods. The beneficial effects of seedling health prior to transplanting seem to be more evident following severe submergence conditions and are directly related to seedling survival and rapid recovery growth after the recession of floods.

Similar studies in Bangladesh also confirmed the beneficial effects of nutrient management in the nursery on plant survival and grain yield of T. aman rice. Application of 20 kg N and P in the nursery, either alone or in combination, resulted in better survival after submergence, leading to higher grain yield (data not shown). Proper nursery management can therefore substantially help enhance and stabilize productivity in flood-prone areas, provided that balanced nutrients are used and excessive early seedling growth is avoided (Ella and Ismail 2006).

Table 9. Effects of nutrient management in the nursery on seedling height, biomass, and carbohydrate concentration at the time of transplanting (30 DAS) in contrasting rice genotypes.

Treatment[a]	NDR9830144	NDR9730018	NDR9930116	IR42	Mahsuri
		Seedling height (cm)			
Control	43.4±1.4	31.4±1.9	30.0±1.9	27.7±0.9	30.1±1.2
$N_{60}+P_{40}$[b]	43.9±0.06 (8.6)	33.8±1.1 (7.6)	33.4±0.37 (11.3)	28.6±0.7 (3.2)	38.1±1.0 (26.5)
$N_{60}+P_{40}+Zn_{20}$	45.0±1.4 (11.3)	39.6±1.2 (26.1)	38.1±0.36 (27.0)	30.9±0.1 (11.5)	40.8±1.7 (25.5)
$N_{60}+P_{40}+Zn_{20}+$ FYM (10 t ha^{-1})	46.8±1.6 (15.8)	40.7±1.1 (29.6)	42.2±0.92 (40.6)	31.2±0.4 (12.6)	45.1±1.2 (49.8)
		Shoot biomass (g 10 $plants^{-1}$)			
Control	0.39±0.02	0.49±0.02	0.47±0.02	0.27±0.01	0.33±0.02
$N_{60}+P_{40}$	0.46±0.01 (17.9)	0.60±0.02 (22.4)	0.52±0.02 (10.6)	0.32±0.01 (18.5)	0.38±0.01 (15.1)
N60+ P40+Zn20	0.50±0.03 (28.2)	0.60±0.01 (22.4)	0.57±0.02 (21.2)	0.36±0.01 (33.3)	0.43±0.01 (30.3)
$N_{60}+P_{40}+Zn_{20}+$ FYM (10 t ha^{-1})	0.56±0.03 (43.5)	0.72±0.02 (46.9)	0.66±0.02 (40.4)	0.41±0.02 (51.8)	0.48±0.01 (45.4%)
		Shoot carbohydrate (mg g^{-1} dry weight)			
Control	na[c]	39.5±2.8	37.7±1.4	na	39.5±2.8
$N_{60}+P_{40}$	na	44.1±1.6 (11.6)	38.9±0.75 (3.1)	na	44.1±1.6 (11.6)
$N_{60}+P_{40}+Zn_{20}$	na	48.5±2.2 (22.7)	42.1±1.2 (11.6)	na	48.5±2.2 (22.7)
$N_{60}+P_{40}+Zn_{20}+$ FYM (10 t ha^{-1})	na	51.5±3.7 (30.3)	44.3±0.75 (17.5)	na	51.5±3.7 (30.3)

[a]Data are means ± SE and figures in parentheses are percent increase over control. [b]N_{60} = 60 kg N ha^{-1}, P_{40} = 40 kg P_2O_5 ha^{-1}, and Zn_{20} = 20 kg zinc sulfate ha^{-1}. [c]na= data not available.

Table 10. Effects of nutrient management in the nursery on shoot elongation during submergence and survival after 15 d of complete submergence in the field. Submergence was applied after 15 d of transplanting 30-d-old seedlings. Data are means ± SE.

Treatment	Shoot elongation (%)			Plant survival (%)		
	NDR9930116	NDR9730018	Mahsuri	NDR9930116	NDR9730018	Mahsuri
Control	36.7±4.3	30.0±1.6	38.5±1.3	5.5±0.30	36.5±2.1	2.1±0.05
$N_{60}+P_{40}$[a]	26.5±1.1	21.0±4.5	28.9±1.4	25.9±4.0	46.9±1.1	4.0±0.002
$N_{60}+P_{40}+Zn_{20}$	18.9±2.3	14.9±1.7	25.6±1.4	40.5±3.0	69.9±3.2	13.0±0.05
$N_{60}+P_{40}+Zn_{20}+$ FYM (10 t ha^{-1})	13.2±1.4	10.7±1.3	24.6±1.2	45.3±4.4	74.2±2.2	23.5±1.3

[a]N_{60} = 60 kg N ha^{-1}, P_{40} = 40 kg P_2O_5 ha^{-1}, and Zn_{20} = 20 kg zinc sulfate ha^{-1}.

Table 11. Effects of nutrient management in the nursery on grain yield (t ha^{-1}) of contrasting rice genotypes as influenced by complete submergence under field conditions. Submergence was done after 15 d of transplanting 30-d-old seedlings for 10 and 15 d during 2004 and 2005, respectively. Data are means ± SE and figures in parentheses are percent increase over control.

Treatment	Wet season 2004 (10-d submergence)			Wet season 2005 (15-d submergence)		
	NDR9830144	NDR9730018	IR42	NDR9930116	NDR9730018	Mahsuri
Control	1.46±0.16	1.51±0.10	0.84±0.05	0.34±0.04	0.363±0.019	0.06±0.01
$N_{60}+P_{40}$[a]	1.71±0.10	2.00±0.21	0.95±0.06	0.54±0.03	0.852±0.031	0.06±0.004
$N_{60}+P_{40}+Zn_{20}$	1.89±0.17	2.40±0.13	1.12±0.2	0.95±0.02	1.056±0.036	0.13±0.01
$N_{60}+P_{40}+Zn_{20}+$ FYM (10 t ha^{-1})	1.93±0.14 (32.2)	2.43±0.16 (60.1)	1.13±0.15 (34.5)	1.26±0.03 (270)	1.688±0.097 (365)	0.27±0.01 (360)

[a]N_{60} = 60 kg N ha^{-1}, P_{40} = 40 kg P_2O_5 ha^{-1}, and Zn_{20} = 20 kg zinc sulfate ha^{-1}.

Nutrient management in the field

Nutrient management in the main rice fields before transplanting and also after the floods recede is also important for improving rice productivity in flood-prone ecosystems. Plant growth and yield depend not only on carbohydrate production through photosynthesis but also on mineral absorption by the roots and its assimilation. Rice crops in flooded soil absorb N both from the floodwater and the soil. Absorption of N fertilizer broadcast onto floodwater in the rice field is very rapid if fertilizer application is timed carefully to match the plant's demand. However, the N that is not absorbed rapidly is lost through gaseous emission, percolation, or runoff. Consequently, N fertilizer tends to be used very inefficiently even in irrigated ecosystems, where average recovery across Asia is less than 30% (IRRI 1998).

The rapid uptake of N from the floodwater is due to surface roots in the water and in the adjacent topsoil. These roots differ morphologically and physiologically from those in the anoxic soil bulk. The entire N in flooded soil is absorbed in the form of NH_4^+, which is the main available form of N. However, N is also absorbed as NO_3^- and amino acids in flooded rice fields, and plant growth and yield are generally improved when plants absorb N as a mixture of NO_3^- and NH_4^+ compared with either of them used separately (Kirk 2000). Kirk and Kronzucker (2005) developed a model to assess the absorption of NO_3^- by rice in flooded soil and found that about 30% of the total N uptake is accounted for by NO_3^-. The NH_4^+ assimilation was stimulated by the presence of NO_3^- arising from the oxygenation of the rhizosphere due to lateral diffusion of O_2 transported from the aerial parts. Thus, the assumption that only uptake of NH_4^+ is important in flooded rice is no longer tenable.

In flood-prone areas of eastern India and Bangladesh, nutrient management activities are mainly done after the recession of the floods because of the inherent risks of crop loss if submergence is severe. Farmers mostly apply N after the floods for rapid recovery growth of surviving rice plants. Another option followed by the researchers to facilitate the slow release of N is to apply it through urea supergranules (USG or Guti urea) or urea coated with sulfur, neem cake, and coal tar. Reddy and Sharma (1992) suggested that if the water level remains at an intermediate depth (~50 cm) in the field, 40 kg N ha^{-1} as USG or neem cake-coated or coal tar-coated urea may be applied, together with 20–40 kg P_2O_5 in the seed furrow at the time of sowing. However, if the crop is transplanted, fertilizer may be applied as basal at the time of final puddling or coated USG can be broadcast a few days later after transplanting. Singh et al (1992) reported that the placement of USG in the soil at a depth of 8–10 cm in about 15 cm of standing water resulted in higher yields than the basal application of either prilled urea or neem cake-coated urea during puddling. Recent studies conducted in Bangladesh also revealed that Guti urea is a better source of N in flooded bolan system, enhancing the yields of several T. aman rice varieties (Table 12). However, results are inconclusive and the efficacy of slow-release nitrogenous fertilizers is yet to be validated at a large scale in farmers' fields and at target locations, together with the consideration of its economic benefits.

Table 12. Effect of nitrogen management on grain yield of different rice genotypes under double transplanting (bolan) system in Bangladesh. Data are from T. Aman season in 2004.

Variety/line	Grain yield (t ha^{-1})	
	Guti urea (58 kg N ha^{-1})	Control (no N)
BR11	5.1	3.4
BRRI dhan 31	2.7	2.9
BR6187	3.3	3.1
BR6110	3.2	3.3
Mean	3.6	3.2
$LSD_{0.05}$	0.73	

Table 13. Effect of phosphorus applied as basal on shoot biomass (g plant^{-1}) of lowland rice cultivars before and after submergence. Seedlings were grown in pots for 30 d and then submerged for 7 d under field conditions. Data are means ± SE and figures in parentheses are percent decrease in shoot biomass during submergence.

Genotype	Control		Phosphorus (80 kg P_2O_5 ha^{-1})	
	BS[a]	AS	BS	AS
FR13A	0.78±0.06	0.58±0.04 (25.6)	0.96±0.03	0.78±0.04 (18.7)
Vaidehi	0.60±0.06	0.48±0.02 (20.0)	0.89±0.04	0.65±0.04 (25.9)
Jal Lahri	0.36±0.03	0.29±0.02 (19.5)	0.44±0.03	0.39±0.05 (11.4)
Sabita	0.32±0.04	0.26±0.05 (18.8)	0.38±0.02	0.30±0.01 (21.1)
IR42	0.55±0.08	0.37±0.03 (32.7)	0.65±0.05	0.56±0.04 (13.8)
Mahsuri	0.60±0.07	0.45±0.03 (25.0)	0.85±0.02	0.72±0.03 (15.2)

[a]BS = before submergence; AS = after de-submergence. Source: NDUAT Rainfed Lowland Rice Consortium (RLRRC) Annual Report 2001–02.

Table 14. Effect of phosphorus applied as basal on survival and shoot elongation during submergence of lowland rice varieties. Thirty-day-old seedlings grown in pots were submerged for 7 d under natural floodwater conditions in the field. Percentage survival and elongation were calculated relative to values before submergence.

Genotype	Control		Phosphorus (80 kg P_2O_5 ha^{-1})	
	Survival (%)	Elongation (%)	Survival (%)	Elongation (%)
FR13A	90	14.1	100	3.2
Vaidehi	93	13.9	100	6.3
Jal Lahri	54	22.5	75	18.3
Sabita	66	25.0	87	20.6
IR42	65	25.7	80	14.1
Mahsuri	60	24.0	80	11.9

Source: NDUAT Rainfed Lowland Rice Consortium (RLRRC) Annual Report 2001–02.

Submergence-induced membrane damage is one of the most serious threats to plant survival and plants need a large amount of energy for repair and maintenance processes under anaerobic stress. Supply of sufficient P might thus have positive impacts on submergence tolerance of rice plants, presumably through the maintenance of a high level of energy. Application of P at 80 kg ha^{-1} as diammonium phosphate along with 60 kg N ha^{-1} at sowing enhanced initial seedling vigor and shoot carbohydrate concentration before submergence. Plant survival after 7–10 d of complete submergence and regeneration growth during recovery were better in P-treated plants of several lowland rice varieties (Tables 13 and 14). However, P application 24 h prior to submergence did not show any beneficial effect on plant survival and recovery growth (P.C. Ram, unpubl.). Rock phosphate is a good source of P in flooded fields because of its slow release, which is further stimulated in acid soils (Thongbai et al 1988). The authors further suggested that application of 40 kg of available P ha^{-1} as rock phosphate may suffice for 4–5 yr in acid sulfate soils.

In contrast, Ramakrishnayya et al (1999) reported that addition of P to floodwater during submergence reduced rice plant survival by 35%. The adverse effects of high P concentration in floodwater were mainly attributed to enhanced growth of algae that competed with the submerged plants for CO_2 and light. Application of P should therefore be considered both in the nursery and as basal rather than in floodwater.

Post-flooding nutrient management

The response of rice to post-flood nutrient management options in flood-prone ecosystems was least studied so far, though it has a strong bearing on regeneration growth and yield of rice plants after the floods, and suitable nutrient management strategies were highly demanded. Farmers in flood-prone areas mostly broadcast small amounts of urea without any solid recommendations. Possibilities of recurrent submergence during the season are one of the reasons for avoiding nutrient application. Hence, a complete package of post-flood nutrient management is essential to enhance the productivity of flood-prone rice areas. Studies conducted in Bangladesh revealed that NPK application during the post-flood period have positive effects on growth and grain yield of T. aman rice. Nitrogen alone applied at a rate of 50 kg ha^{-1} resulted in maximum tillers and grain yield, whereas N and K applied together at 20 kg ha^{-1} each was most effective, showing a twofold increase in grain yield over unfertilized control (Table 15). However, further studies are needed to test different nutrient combinations, doses, and the proper time for their application after the water recedes. Valid recommendations can then be developed for different target sites based on local flood conditions, particularly the speed of water recession, possibility of subsequent floods, and water depth in the field following complete submergence.

Redesigning the plant type for high nutrient responsiveness

The productivity of field crops has increased significantly through improvement of the plant type (semidwarf and upright leaf) through breeding. However, the productivity of this new plant type is difficult to explain in terms of the carbon (photosynthesis-respiration) balance theory in the rainfed lowlands because of other limiting factors. The regulation of root-shoot interaction to improve the efficiency of the roots to absorb sufficient nutrients through maturity is essential to realize the full potential of high-yielding varieties. Through the use of high-yielding varieties and slow-release fertilizers, higher yields were attained by various field crops in Japan (Osaki et al 1991, 1992, 1995**.** The photosynthetic rate and root activity of high-yielding varieties remain high until maturity and the total amount of dry matter produced and the N absorbed have a linear correlation. Such plants are designated as the N-absorption type. In contrast, in traditional and low-yielding varieties, N absorption ceased at the maximum shoot growth stage; at the same time, N in nonreproductive organs started to decline followed by cessation of dry matter accumulation. These types of plants are designated as N-efficient.

Table 15. Effects of post-flooding nutrient management on tiller number and grain yield of T. aman rice in Bangladesh in 2004. Seedlings were submerged for 10 d after 1 wk of transplanting 21-d-old seedlings. Nutrients were applied 12 d after the water recedes.

Nutrient management (kg ha^{-1})	Tillers m^{-2} (no.)	Panicles m^{-2} (no.)	Grain yield (t ha^{-1})
Control	108.9	97.5	0.9
N_{20}	152.1	135.1	1.1
N_{40}	184.3	159.8	1.1
N_{50}	213.8	186.7	1.4
N_{20} + P_{10}	140.6	124.3	1.2
N_{20} + P_{20}	153.4	136.1	1.3
N_{20} + K_{10}	141.8	128.3	1.3
N_{20} + K_{20}	186.9	167.6	1.6
$LSD_{0.05}$	46.4	41.6	0.44

N = nitrogen, P = phosphorus as P_2O_5, and K = K_{20}. The number following the symbol indicates the amount of fertilizer used in kg ha^{-1}.

In high-yielding varieties, the amount of N absorbed by the plants reach about 30–40 g N m^{-2}, half of which is absorbed within only 30 d during maturation. However, in low-yielding varieties, N absorption is only 10–20 g N m^{-2} and, consequently, the plants grow by using N stored or incorporated in the leaves and stems before maturation. Root activity during maturation does not seem to play a major role. Thus, a basic strategy to achieve higher yields should involve the conversion of N-efficient types (currently common in flood-prone areas) into N-absorption types through breeding.

There is thus an urgent need to redesign flood-prone rice varieties to improve efficiency in nutrient uptake and utilization. To redesign the plant type for better nutrient use efficiency, we should focus on modifying root-shoot interaction to optimize and prolong root activity, which is strongly related to the system of carbohydrate supply to the roots during regeneration and recovery after the floods. Nodal roots also have an important role to play in nutrient assimilation from floodwater and can help sustain the growth of rice plants under flooded conditions.

Future directions

A wide knowledge gap still exists between researchers and farmers about the need and progress in rice technology development for flood-prone environments. Even the available technologies have not reached their target users because of the poor extension service networks in most of these areas. Poor characterization of the soil and hydrology of flood-prone environments also seems to limit technology development and adoption on a wider scale. One of the major constraints to rice productivity enhancement across flood-prone environments is the lack of seeds of suitable improved and nutrient-efficient and -responsive varieties. Post-flood nutrient management for better recovery growth after recession of floods is also least studied and suitable technologies are still not available. Future research should therefore focus on i) developing new varieties with a high level of tolerance for the prevailing flood type but are responsive to inputs and crop management; ii) suitable management packages at different stages of crop growth and extensive testing and validation; iii) integrating research results into extension efforts for rapid transfer to and adoption of effective practices by farmers; and iv) developing strategies to incorporate effective management practices in seed delivery and validation in farmers' fields through farmer's communities, government and other institutional agencies and dissemination as a package with improved varieties to ensure wider adoption.

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Notes

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Strategies, policies, and programs to develop rice-based farming systems for the tidal swamps and flood-prone areas of Indonesia

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Indonesia's food production relies on a total land area of about 7.8 million ha. However, the land-man ratio in Indonesia is among the lowest of the world's agrarian countries. The less favorable areas—tidal and freshwater swamps and flood-prone areas, rainfed lowland, and dryland—account for about 2.0 million, 2.1 million, and 2.5 million ha, respectively. These underexploited lands, if sufficiently explored, hold enormous potential for food production. Through modern technology, they can be converted into productive land on which various food crops can be grown, including rice. For the tidal swamps and flood-prone areas, well-adapted rice varieties that tolerate prevailing stresses such as acid soils, have been made available during the last two decades. Furthermore, water and soil management practices have been developed and practiced in these areas. Apparently, more location-specific technologies need to be developed to increase the efficiency of their application at the farm level. Sustainability problems still remain because of (i) limited access to markets, (ii) low-quality products, (iii) limited access to capital, (iv) slow technology dissemination and adoption processes, and (v) labor shortage. Based on an analysis of existing biophysical and socioeconomic circumstances, this paper attempts to provide guiding principles in the formulation of strategies and policy options, including research and development that could improve the contribution of this less favorable ecosystem to food production, farm-household income and welfare, as well as food security at the household and national levels.

Keywords: food security, freshwater and tidal swamps, less favorable agroecosystem

Agricultural development of the food crop subsector in Indonesia is dependent on a total land area of about 7.8 million ha. This land has become the sole source for livelihood of about 20 million households of landless and subsistence farmers. About 25% of these farmers rely on farming systems involving food crops on less productive agricultural land, including tidal swamps and flood-prone areas. Tidal swamps and flood-prone areas account for about 2.2 million ha, and they are concentrated mostly in Sumatra and Kalimantan islands. The land-man ratio in Indonesia is one of the lowest among agrarian communities in the world, averaging only about 362 m^2 per capita, as compared with 1,870 m^2 in Thailand and 1,300 m^2 in Vietnam. This small landholding is becoming a major constraint to improving farm household income and livelihood. Nationally, the average area per household has declined from 0.93 ha in 1983 to 0.83 ha in 1993. In the peripheral islands, average land per household has also declined from 1.38 ha to 1.19 ha. In Java, it decreased from 0.58 ha to 0.47 ha in the same period. Currently, the average household landholding is about 0.3 ha. Records show that about 43% of farm households are headed by landless farmers or farmers with landholdings below 0.1 ha.

Rice is the main staple food for about 95% of the Indonesian population, with consumption increasing at an annual average rate of about 1.6%. Besides the small landholdings, rice farmers also face other problems. Water shortage is common in some areas and, in others, both floods and droughts are experienced within the same season, causing serious reduction in grain yield. Rice in Indonesia is being grown under diverse climates and socioeconomic conditions. At present, about 65% of the total rice land is irrigated, 18% is rainfed lowland, 9% is tidal swamp and flood-prone, and 8% is upland. Consequently, grain yields vary considerably, depending on the circumstances within each ecosystem.

Java, with more fertile rice lowland with access to irrigation than the other islands, contributes about 60% of the national rice production. Irrigated rice then is given high priority in agricultural development, but the area devoted to irrigated rice has recently declined as rice lands are progressively being converted for non-agricultural uses, estimated at the rate of about 40,000 ha per year. Moreover, land is continuously being fragmented through inheritance of new generations of farming families. This causes more pressure on the land; more intensive cultivation is done by farmers to meet their food and income requirements. Consequently, soils have been degraded and their fertility decreased. Together with the lack of any soil improvement policies, these have resulted in stagnant or even declining land productivity over the years.

Swampy lands are becoming more important as a new frontier for rice production in Indonesia. Currently, the swampy area occupies about 33.4 million ha, of which 20.1 million ha are tidal swamps and 13.3 million ha are freshwater swamps and flood-prone lands (*lebak*). Tidal swamp land is directly affected by tidal water from the sea, while in the lebak area, flooding comes from the accumulation of rainwater or outflow of rivers during the rainy season. Based on the influence of tidal water, swampy areas are divided into four groups: (a) type A, land is covered by tides during spring and neap tides; (b) type B, land is flooded by spring tide only; (c) type C, land is not covered by either spring or neap tides but influenced by soil water infiltration; and (d) type D, land is not affected by spring and neap tides, and soil water table is below 50 cm depth. Types A and B are called "direct tidal swamp lands," whereas type C belongs to the "indirect tidal swamp land" category. Type D is usually referred to as "rainfed lowland" or "dry land of swampy area." Type A area constitutes about 10%, while type B and C areas are larger and mostly cultivated by farmers under "*surjan* systems" (raised and sunken bed systems). However, the implementation of the surjan system is mostly dependent on the depth of pyrite, soil water hydrology, and flooding type of tidal water. The success of traditional Buginese and Banjarese farmers of South Sulawesi and South Kalimantan, who continuously use the tidal lands along the coastal areas of Kalimantan and Sumatra for farming, provided evidence that these swampy lands hold great potential for food production. For example, in South Kalimantan, Banjarese farmers grow rice and a variety of other crops such as coconut, citrus, maize, vegetable, and sweet potato. However, farmers usually cultivate these lands using traditional methods.

Tidal swamps, including flood-prone areas, are mainly spread over Sumatra, Kalimantan, and Papua. These areas need to be effectively used for food production, especially for rice, soybean, and maize. For example, rice yield, even with existing farmers' practices, is about 3–4 t ha^{-1}. However, with use of modern management practices and suitable varieties, this yield could potentially reach 6–7 t ha^{-1}. The results discussed in this article are part of the SWAMP Program, which is an integrated swamp research and development project conducted from 1995 to 2005. The main research sites are mostly located in South Sumatra and include major agricultural commodities such as food crops (rice and secondary crops), lowland vegetable, livestock, and supporting activities (water and land management, farm machinery). The tidal swamps and flood-prone rice areas are the major focus of these research activities. Here we summarize the results of relevant research conducted on tidal swamps and also provide some discussion on the work conducted in flood-prone areas. The discussion also elaborates on the recommended strategies and policy options for future rice production, including relevant research and development programs to maximize the contribution of this ecosystem to rice production and to national food security.

Objectives of the analysis

The objectives of food crop development policy analysis of tidal swamps and flood-prone areas are to (1) formulate strategy and policy alternatives, (2) determine and analyze *entry factors*, (3) design programs and activities for the development of food crop-based agribusiness; and (4) design programs and alternatives to improve farm household income, welfare, and food security. The mid-term (5 yr) as well as longer term outputs of implementing the new policies and strategies for tidal swamps and flood-prone areas are summarized below.

Mid-term outputs

- Within the next 5 yr, productivity of common crops (rice, maize, soybean) in tidal swamp and flood-prone areas increases by 5–10% at a rate of 1–2% per year.
- Overall economic added value of each crop increases by 50–75% at a rate of 10–15% per year during the same period through horizontal and vertical diversification.
- Farm household income based on on-farm activities involving these food crops increases by 60–75% at the end of the program or between 12 and 15% per year.

Long-term outputs

- Annual farm household income reaches about US$ 2,000
- All children receive at least 9 yr of primary education or they graduate from junior high school
- Maternal and infant survival increases substantially over that of previous years
- Share of farm household consumption of nonfood commodities increases significantly compared with food consumption as a consequence of improved income

Methodology

Analytical tools

Literature review, desk study, and internet browsing were the starting tools used for policy analysis and synthesis related to the development of food crop production in tidal swamp and flood-prone areas in Indonesia. Field observations were conducted using the participatory rural appraisal approach. These approaches were carried out in order to collect primary and secondary data. The activities were conducted by a multidisciplinary team composed of a soil scientist, a water management specialist, an agronomist, a farming system specialist, and an agricultural socioeconomist. SWOT analysis was conducted to formulate strategies and policies that consisted of (1) administrative, management, and organizational aspects; (2) biophysical aspects; and (3) socioeconomic aspects (Sianipar et al 2001). Meanwhile, a logical framework approach was used to design the workplan and activities (Fardiaz 1999). The workplan for strategies and program activities was then developed to describe the initial steps and develop a roadmap to achieve each objective. The ultimate target was to optimize the use of rainfed lowlands for the production of food crops (Kaplan et al 2004).

Data and analysis

Collected data included the following: (1) land use and distribution, (2) biophysical characteristics, (3) demography, and (4) farmers' responses and perception. The data analysis and evaluation of all relevant information included empirical analysis and investment analysis. Empirical analysis output was presented in the form of a cross tabulation, while investment analysis aimed to analyze investments needed to support the development of food crops in tidal swamps and flood-prone areas. The types of investments considered were agricultural input, agricultural infrastructure, and farm machinery. Priority analysis of strategy and program activities was carried out by using a screening approach based on indicators such as feasibility, estimated cost, and anticipated risks. A decision-making analysis to determine priority crops that will be grown by farmers was done to evaluate the sustainability of producing specific food crops in the target rainfed lowland areas. This is necessary to understand, for example, how and when farmers shift from one crop to another.

Potential, opportunities, and constraints

Potential

In terms of physical and chemical soil properties, tidal swamp land and flood-prone areas in Indonesia are highly diverse. These areas were classified into four types: (a) potential land (2.0 million ha), which includes potential acid sulfate soil, where the pyrite layer is below 50 cm deep and pyrite concentration in soil solution is about 2%; (b) acid sulfate soil (6.7 million ha), which includes both actual and potential acid sulfate soils. Actual acid sulfate soil contains a high concentration of acid sulfate in the soil water and causes toxic effects on crop plants, while potential acid sulfate soil has a low concentration of acid sulfate in soil solution (2%) and with pyrite located below 50 cm of soil depth; (c) peat soil (11.0 million ha), which consists of a peat layer of 40–75 cm and peaty soil with shallower peat layer of 20–40 cm on the soil surface; (d) saline soil (0.4 million ha), which is affected by intrusion of sea water for more than 4 mo, usually during the dry season, where the concentration of Na^+ in soil solution reaches extremely high levels (Widjaya-Adhi et al 1990).

Based on the topography and depth and duration of flooding, fresh water swamp or lebak lands were classified into three: (a) shallow lebak (4.17 million ha), located along the rivers but at relatively higher elevations; floodwater depth is less than 50 cm for a duration of less than 3 mo; (b) medium lebak (6.08 million ha), located between deep and shallow lebak, with water depth of 50–100 cm and flooding duration of 3–6 mo; and (c) deep lebak (3.04 million ha), occupying relatively lower land where floodwater depth exceeds 100 cm and normally occurs either continuously or for more than 6 mo. These three lebak classes have good potential for rice production, particularly in the shallow and medium lebak areas.

Opportunities

Considerable opportunities exist in tidal swampy and flood-prone ecosystems for higher productivity of different food crops, and this could be achieved by increasing harvested area, cropping intensity, and productivity of individual crops through the use of better varieties and proper agronomic practices. The gap between farmers' yield and that obtained from research farms is substantially wide. For example, rice yields in farmers fields' average only about 2.0 t ha^{-1}, while research results show that this yield could be increased to 4.0–5.0 t ha^{-1}, merely through proper management. Land and water management technologies for these tidal swamps and flood-prone areas have been developed, but implementation at the farm level, however, is still facing some problems and constraints. In addition, the use of farm machinery such as hand tractors, threshers, water pumps for supplementary irrigation, and grain dryers has been partly adopted by farmers to solve two of the most limiting factors, labor and power.

An agricultural revitalization policy was recently initiated by the government of Indonesia. One such policy option is the expansion of agricultural land to cover about 15 million ha. Suboptimal lands such as tidal swamps and flood-prone areas, dry lands, and rainfed lowlands were specified as the main targets for this expansion. Other opportunities were also identified, and these involved adopting technology innovations such as no-tillage or zero-tillage practices, integrated crop management (ICM), and integrated food crop-livestock systems (CLS). Quality improvement and strategies to reduce the cost of production could further increase product value and benefits. Adoption of the ICM system by farmers on just 2.0 million ha of tidal swamp lands can provide an additional 4.0 million t of rice or about 7.8% increase in national rice production. Currently, a basket of suitable innovations is available, such as improved ICM for rice in the surjan system and newly released high-yielding varieties of rice and other crops such as soybean and maize. These are suitable as rotation crops after rice in tidal swamps and flood-prone areas.

Effective use of market information by farmer communities, such as the Integrated Agribusiness System Group (IASG) established by farmers in some tidal swamps and flood-prone areas, is expected to improve the farmers' bargaining power and protect the prices of their products. The establishment of IASG at the farm level, followed by the consolidation of agribusiness management through a chain of pre-production, production, and postharvest handling through marketing and distribution, is expected to provide positive economic impacts. In addition, resource allocation of land, labor, capital, technology, and agricultural infrastructure will be more efficient after the establistment and further development of IASG. However, product quality will remain the major determinant of product price and farmers' income.

Constraints

Tranplanting rice is commonly practiced by farmers in the tidal swamp and flood-prone areas, but this practice subjects the transplanted seedlings to the high risk of early floods and possible drought at maturity. These conditions often can cause severe crop losses of up to 50–75%. The surjan system may significantly increase farm household income, but this system is so difficult to adopt because of the high cost of initial land preparation. However, other opportunities exist for further diversification of this production system; one is integrating other commodities such as CLS, including rice-fish farming. The synergistic relationship among system components could improve production effciency and reduce costs, consequently enhancing farmers' income. The major challenges and constraints to improving the production of food crops in the tidal swamps and flood-prone areas can be grouped into biotic and abiotic factors. Biotic constraints include pests, diseases, rats, birds, and weeds, whereas abiotic constraints include erratic rainfall, flooding, and bad drainage. The major biophysical and social constraints are summarized below:

- Acid soils containing toxic elements; particularly a major problem in acid sulfate soils when excessive drainage causes oxidation of pyrite and the release of acids
- Malfunction of irrigation systems and other water management structure
- Pests and diseases, particularly those that are difficult to control, like birds and rats, during the dry season (due to the existence of scattered shrubs and bushes and a large area of bare land)
- Shortage or even lack of labor, machinery, and capital for intensive farming
- Lack of rural support for inputs and credit, marketing opportunities, and farmers' communities or associations
- Poor product quality and inability of local agribusinesses to influence farm gate prices of agricultural products, especially during periods of peak harvests
- Limited or even lack of accessibility to markets and high cost of transportation
- Weak or lack of coordination among related institutions, especially in providing proper inputs on time and in marketing of the products

Research achievements

Research results have shown that it is technically and economically feasible to grow two crops of rice followed by *palawija* (maize, bean, tuber crops) or horticultural crops (Ismail et al 1993). A field demonstration of tidal swamp land technology conducted in March 1997 at the Karang Agung Ulu research site in South Sumatra showed that, by integration of soil and water management and crop cultural practices, tidal swamp rice can attain yields of 4–6 t ha^{-1}, which are 200–300% higher than that currently being produced by local farmers (Ananto et al 1998).

Land and water management

Land development is based on land typology, flooding type, crop management type, and the possible impacts of new development policies on the environment (Table 1). Land with flooding type A is developed into lowland paddy fields, whereas land with flooding type B is transformed into either lowland rice field or surjan system. Land with flooding type C is developed into rainfed lowland rice fields, upland, or surjan system with gradual construction of raised beds (*guludan)* and sunken beds (*tabukan)*. Land with flooding type D is devoted entirely to upland farming or estate crops.

Shallow peat soils and peaty soils are best used for upland farming, with careful maintenance of soil moisture to avoid the irreversible drying of peat materials. However, if the shallow peat and peaty soils are exposed to flooding type A, they can be used for lowland rice production. Medium deep peat soils are best suited for estate crops. The deep and very deep peat soils are not suitable for agriculture and are left as conserved forests.

Table 1. Guidelines for tidal swamp land use in Indonesia.

Code	Land typology	Flooding type			
		A	B	C	D
Pot-1	Potential soil-1 (very deep sulfide)	Lowland	Lowland/ surjan	Lowland/ upland/ estate	Upland/ estate
Pot-2	Potential soil-2 (deep sulfide)	Lowland	Lowland/ surjan	Lowland/ surjan	Lowland/ upland/ estate
SMP	Potential acid sulfate soil (shallow sulfide)	Lowland	Lowland	Lowland	-
SMA	Actual acid sulfate-1	-	Lowland/ surjan	Lowland/surjan	Lowland/ upland/ estate
SMP-G	Peaty potential acid sulfate	-	Lowland	Estate	Upland/ estate
G-0	Peaty soil (< 0.5 m)	Lowland	Lowland/ surjan	Upland	Upland
GDK	Shallow peat soil (0.5–1 m)	Lowland	Lowland	Upland /estate	Upland/ estate
GSD	Medium peat soil 1–2 m)	-	Conservation	Estate	Estate
GDL	Deep peat soil (2–3 m)	-	Conservation	Estate	Estate
GSDL	Very deep peat soil (>3 m)	-	Conservation	Estate	Estate
D	Peat dome	-	Conservation	Conservation	Conservation

Sources: Wijaya-Adhi et al (1992), Ananto et al (1998).

Water management is implemented based on the flooding type, with the main objectives of providing sufficient water requirements, avoiding pyrite oxidation, facilitating the leaching of toxic elements, conserving peat soil moisture, and preventing saline water intrusion. Water management for lands with flooding types A and B is done by a one-way flow system to leach toxic products of pyrite oxidation, such as Fe^{2+}, Al^{3+}, and SO_4^{2-}, which are harmful to crops. In this system, the inlet canals are equipped with flap gates that open to the inward direction, while the outlet canals are equipped with flap gates that open to the outside. For lands with flooding type B, the one-way flow system is also equipped with a stop log (*tabat*) during the dry season to retain water in the canal. For lands with flooding types C and D, a tabat system is practiced. In this system, secondary canals are equipped with a stop log to retain incoming water from the rain and tides in both fields and canals in order to provide water for crops and avoid pyrite oxidation by maintaining groundwater table above the pyrite layer. The following are recommendations to enhance micro-level water management:

1. Drainage canals (primary, secondary, tertiary) should be repaired for proper functioning.

2. Micro-level water networks, such as quaternary canals, boundary ditches, and field drainage furrows should be constructed during the dry season before the start of farm activities.
3. Because of limited farm labor, subsidies should be provided for farmers to facilitate construction of micro-level on-farm water networks.
4. Farmers' communities such as water user associations (P3A) need to be functional and actively involved in water management.

Crop management

Farming systems suitable for the tidal swamp lands should be developed based on biophysical and socioeconomic nature of local farming communities. Technologies for proper crop management are location-specific and should include the following (Ananto et al 1999):

- Use of improved varieties adapted to local conditions
- Location-specific nutrient management, with the use of rock phosphate as source of P
- Soil amendments, including the use of ash and/or lime to increase soil pH, particularly on acid sulfate and peat soils
- Proper management of pests and diseases, including weeds
- Use of agricultural tools and machinery for both pre- and postharvest operations to solve labor scarcity problems, reduce yield losses, and improve product quality

Land can be prepared using hand-held tractors to soften and puddle the soil and suppress weeds. Operations during land preparation should facilitate leaching of toxic elements and enhance land leveling. The no-till system can be practiced periodically by using selective herbicides. On lands with flooding types A and B, rice is transplanted or direct-seeded and managed as lowland paddy fields, while palawija crops such as maize and soybean are planted either as dryland crops or on raised beds in the surjan system. Various crop varieties currently being used are either improved varieties or superior local cultivars that are well-adapted to tidal swamp lands. Examples are Sei Lalan, Banyuasin, Sei Dendang, Sei Batanghari, Cisanggarung, IR42, Komojoyo, and Sanapi for rice; Wilis for soybean; and Arjuna for maize. For horticultural crops, chili performed well as a commercial crop in the tidal swamps. It can even be planted on peat soils, provided there is good drainage, or on raised beds in the surjan system. Perennial crops such as coconut and coffee are commonly planted in home gardens to provide additional income.

The fertilizer use for rice on normal soils is 150 kg of urea and 100 kg KCl per ha, whereas for acid sulfate and peat soils, the amount is 200 kg of urea and 150 kg KCl per ha. Fertilizer recommendations for maize are similar to those for rice on normal soils, and for soybean, the recommended rate is 50 kg of urea and 75 kg of KCl per ha. Rock phosphate is used as a source of P at a rate of 250–350 kg per ha. Control of pests and diseases is carried out following the integrated pest management (IPM) approach and is particularly directed for major pests, such as rats, "*orong-orong*" (soil borer), armyworms, stem borers, and wild pigs. The rat control measures used are dependent on the growth stage, with mass control and fumigation carried out before planting, while baiting and a second fumigation are done during subsequent plant growth periods. The major disease of rice is blast, particularly in upland rice (types C and D).

The various technologies developed and practiced at different locations in tidal swamp lands of South Sumatra helped increase the yields of rice, maize, and soybean. The average yield increase reported by farmers following these technologies during the rainy seasons of 1997–98 and 1999–2000 ranged from 0.78 to 1.18 t ha^{-1} for rice (Table 2), 0.3 to 0.7 t ha^{-1} for soybean (Table 3), and 0.46 to 1.28 t ha^{-1} for maize (Table 4). Even higher yields were reported by other farmers who were not included in these studies. By using rock phosphate, maize yield reached 5.4 t ha^{-1} on potential (normal) soils, and a range of 2.0–2.5 t ha^{-1} on acid sulfate soils (Ananto 1999). In Karang Agung Tengah, maize farmers can grow up to three crops per year. The chili *Kriting* variety yielded 0.86–1.30 t ha^{-1} (Table 5). However, these yields are unstable across the different lands and flooding types, except for rice yield on normal soils with flooding types A and B, which is relatively more stable. This suggests that rice should be given more emphasis during the wet season in these land types.

Current yields, however, are still suboptimal for several reasons: (i) fertilizer input, particularly P and K, are not always available or applied as recommended; (ii) land development and field level water management are not properly implemented; (iii) incidences of climatic anomalies, e.g., El Niño (drought) and La Niña (excessive rainfall); and (iv) outbreaks of pests and

Table 2. Average yield of rice (t ha^{-1}) on different types of tidal lands in South Sumatra.

Typology/flooding type	WS 97/98	DS 98	WS 98/99	DS 99	WS 99/2000
Land typology					
Potential (normal) soil	3.54	3.15	4.09	1.33[b]	4.52
Acid sulfate soil	3.02	-	3.22	-	3.57
Peaty soil	2.92	-	-	-	-
Flooding type					
A	4.99	-	2.86[a]	1.33[b]	4.12
B	4.46	3.20	4.71	-	3.98
C	2.96	3.10	3.72	-	4.02
D	2.64	-	-	-	-
Av of cooperating farmers	3.43	3.15	3.84	1.33[b]	3.96
Av of non-cooperating farmers	2.65	2.40	2.66	Fallow	2.81

[a]50% rat damage; [b]90% rat damage; WS = wet season; DS = dry season. Sources: Ananto et al (1999), Djajusman et al (2000), Isbandi (2000), Nuryanto et al (2000), Saputra et al (2000), Sutriadi et al (2000), Yudarfis et al (2000).

Table 3. Average yield of soybean (t ha^{-1}) in different types of tidal lands of South Sumatra.

Typology/flooding type	WS 97/98	DS 98	WS 98/99	DS 99	WS 99/2000
Land typology					
Potential (normal) soil	1.80	0.65	0.95	1.01	1.20
Acid sulfate soil	-	0.78	-	0.49a	-
Peaty soil	-	0,54	-	-	-
Flooding type					
A	-	-	-	-	-
B	-	0.65	-	0.86a	-
C	-	0.67	0.95	0.49a	-
D	1.80	1.19	1.30	1.17	1.20
Av of cooperator farmers	1.80	0.84	0.95	0.85	1.20
Av of non-cooperator farmers	1.10	Fallow	0.88	Fallow	0.90

[a] Newly introduced. Sources: Ananto et al (1999), Djajusman et al (2000), Nuryanto et al (2000).

Table 4. Average yield of maize (t ha^{-1}) on different tidal land types of South Sumatra.

Typology/flooding type	DS 99	WS 99/2000
Land typology		
Potential (normal) soil	3.59	2.79
Acid sulfate soil	2.11	2.32
Peaty soil	2.29	
Flooding type		
B/C	1.82a	2.32a
C	3.24	2.79
Av of cooperator farmers	2.53	2.56
Av of non-cooperator farmers	1.25	2.10

[a] Flooded in 2 wk during the vegetative stage. Sources: Isbandi (2000), Saputra et al (2000), Sutriadi et al (2000).

Table 5. Estimates of contracting service system (000 Rp) in Delta Telang and Sugihan Kanan in South Sumatra, 1999/2000.[a]

Item	Farmer group Delta Telang	Farmer group Sugihan Kanan	Individual/private Delta Telang
Working days (d yr^{-1})	77.00	42.00	90.00
Working hours per day (h yr^{-1})	8.57	8.00	8.95
Working hours per area (h ha^{-1})	19.99	22.05	16.00
Capacity (ha yr^{-1})	33.01	15.24	50.34
Fixed cost (Rp h^{-1})	5,364.00	10,535.00	4,395. 00
Variable cost (Rp h^{-1})	5,116.00	4,743.00	5,984.00
Total cost (Rp ha^{-1})	209,498.00	336,888.00	166,065.00
Breakeven point (ha yr^{-1})	36.00	37.00	34.00
NPV (Rp)	-2,820,434.00	-8.362.916.00	3,502,625.00
B/C	0.79	0.38	1.26
IRR (% yr^{-1})	3.09	-	29.79
Payback period (yr)	6.32	13.14	3.97

[a] Based on a hand tractor price of Rp 13,000,000 and a contract cost of Rp 200,000 per ha. US$1 = Rp 9,500. Source: Ananto and Astanto (2000).

diseases, particularly rats, grasshoppers, armyworms, and blast disease.

Higher cropping intensity is being practiced in scattered areas, which is difficult to consolidate in one area. These scattered plantings become targets for rats, birds, and other pests during the dry season and help in building the population of these pests throughout the year. To overcome this problem, joint commitment among farmers and related agencies is needed to coordinate efforts and implement a large-scale control effort to eradicate these pests, particularly rats.

Livestock and fisheries in tidal swamp areas

Diversification is an effective strategy to increase and stabilize farm income through the integration of livestock and fish into the farming system. Generally, farmers in the tidal swamp areas prefer to raise native chickens because these can be sold easily at a good market price, thereby providing financial security to farmers in cases of agricultural crop failure. However, native chicken are still managed traditionally, allowing them to move freely with no shelter and without special feeds, increasing the chances of mortality due to pests and diseases. Technologies such as the use of locally made feeds with better quality, separation of one-d-old chicken in a brooder box, implementing vaccination programs, and construction of shelters can help increase egg production and weight and reduce mortality (Fig. 1).

Fish culture is carried out on lands with flooding types A and B, either as a monoculture or is integrated with other crops, with shelters of native chickens built above the fish ponds. This combined system of fish and chicken farming is called the *long-yam* system. *Nila* (Nile tilapia), *bawal*, and *patin* (*Pangasius pangasius* HB) are selected because of their tolerance for adverse local conditions and popularity among local consumers. During a 4-mo period, the weight of Nila can increase from 12 to 213 g, patin from 20 to 342 g, and bawal from 20 to 303 g (Slamet 2000).

Farm machinery

One of the major constraints to agricultural development in tidal swamp land is the shortage of farm labor, especially during the peak periods of land preparation, planting, and harvesting. The scarcity and high cost of labor cause longer periods of land preparation and staggered planting, affecting pest infestations and outbreaks. Besides, it results in low cropping intensity, low quantity and quality of produce, and sometimes large barren areas. To support agricultural development in these swamp lands, use of farm machinery is highly recommended. Farm machinery both for pre- and postharvest activities are required. The use of tractors for land preparation can help overcome the severe labor scarcity at that time and also help in leaching toxic elements and encouraging the adoption of other improved technologies. Manually operated row seeders (drum type) could reduce the cost and labor required for planting compared with the transplanting system, which need 40 mandays ha^{-1} (Astanto

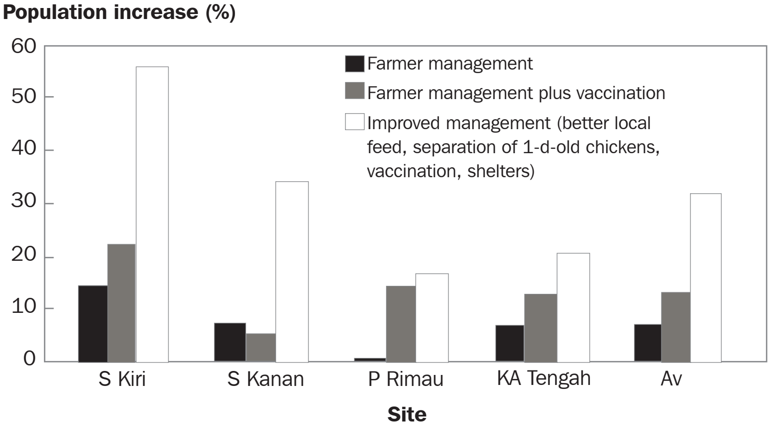

Fig. 1. Increasing population of native chickens (%) through different management practices in some locations in tidal swamp areas, October 1999-March 2000.

and Ananto 2000). However, this technology has not been demonstrated to farmers who are currently practicing direct seeding through broadcasting.

Considering the limited resources of farmers in this system, in terms of proper skills and entrepreneurship, and the high prices of farm machinery, the development of mechanization can probably be achieved through a contracting service system (*Usaha Pelayanan Jasa Alsintan–UPJA*), which can be managed either by farmer groups, cooperatives, or local entrepreneurs. In tidal swamp areas, local entrepreneurs or privately managed businesses generally perform better than farmer groups or cooperatives (Ananto et al 1996); this is true in both North and South Sumatra (Table 5). Proper training will ensure the smooth functioning and sustainability of these businesses.

Purchasing farm machinery using grants or aid should only be temporary and must be done just for starters, especially in underdeveloped areas. To ensure a sense of ownership and responsibility, the procurement of these machines should be based on a credit purchasing scheme operating under a marketing mechanism. The government could create such credit scheme opportunities for those who run such services, together with a support policy to secure the system and ensure its sustainability. For any agricultural machinery assistance program, proper arrangements and planning need to be made to avoid distortion of existing businesses of contracting service and also to train farmers in self-help and in developing their entrepreneurship. In this way, a conducive environment for contracting service businesses will be created. The establishment of local maintenance shops must also be encouraged, first by training and strengthening the existing local shops to handle farm machinery. With the existence of such local maintenance facilities, any repair and maintenance job could be done locally with lower cost and the idle time could be minimized.

Harvest and postharvest handling

The problems that most farmers face during harvest and postharvest are related to time— usually, harvesting occurs within the rainy season and when there is shortage of labor and lack of harvest and postharvest machinery. The delays in threshing and drying result in what is commonly referred to as *beras batik* (rice grains with poor quality and colorful spots that resemble a batik painting; Ananto et al 1999). The use of machinery for drying and threshing will help speed up postharvest processes and improve grain quality and market value. Using these machines in pilot studies improved the quality of milled rice, resulting in higher whole grain content, lower percentage of broken grains and gritty grain, and disappearance of greenish and yellowish grains (Table 6). Collectively, they increased the grain market price. Improvements in postharvest activities have a positive impact on farmers, as shown by the increasing adoption of drying facilities by rice millers, including the use of cemented flatbeds designed by the Indonesian Center for Rice Research (ICRR, *Balitpa*) at Sukamandi. Drying machines are now successfully being made locally; the costs are about 50% lower than the market price.

Most rice milling units are of the "single-pass type" because of their cheaper price. The "double-pass type" is not common as the machine is expensive and there is no guarantee of a continuous supply of good-quality paddy, which is required for this type of equipment. Good-quality milled rice can be produced by following the proper procedures during harvesting, threshing, and drying. The milling units should be equipped with drying facilities, where it can be used more efficiently when the supply of good grain is maintained. The units will then be able to collect rice grain during harvesting and extend the milling process through the off-season. Improving the harvest and postharvest handling operations is crucial in the development of an effective rice agro-industry. Furthermore, milled rice can further be graded to attain exclusive quality rice, while the broken portion can be processed to produce rice flour or some other products with higher selling value.

Support institutions

To guarantee a successful rice-based cropping system in the tidal swamp areas, ample support is required from social and agribusiness institutions, in particular in relation to supply of in-

Table 6. Comparison of rice grain quality (%) under different drying systems. Data are mean performance values of Sei Lalan, IR42, IR64, and Widas rice varieties.

Quality criterion	Sun-drying	Drying machine	Standards
Whole grain	34.83	64.75	Min 35
Broken grain	43.58	24.65	Max 25
Gritty grain	5.87	2.75	Max 2
Greenish/milky grain	8.29	5.01	Max 3
Yellowish grain	7.20	0.29	Max 3
Rubbish	0.19	0.00	Max 0.05
Unmilled grain	0,12	0.04	
Rendement (milled rice)	59.60	62.10	

Source: Sutrisno et al (1999).

puts, development of an effective agro-industry, and marketing. Farmgate prices of agricultural products were low, while prices of inputs were high. Apparently, some of the needed support institutions, either agribusiness or others, were already present in some locations. But most of them are not yet functioning or not performing well. Strengthening these institutions and improving the infrastructure, including transportation facilities within and between locations, will hasten the development of an effective food crop production system in the tidal swamp areas.

Social institution. To improve the performance of existing farmer institutions, water user associations and farmer groups in contiguous areas can be integrated to accelerate community efforts in operating and maintaining irrigation and drainage structures. It is critical in eliminating conflicts of interest and sustaining good water management practices. Such integration will enhance collaboration among farmers, particularly in the application of farming system technologies.

Economic/agribusiness institutions. To enhance the functioning of rural agribusiness institutions, such as millers, agricultural input vendors, and machinery owners, it is necessary to provide capital and to ensure the supply of inputs and marketing channels. These activities can actually be carried out by formal rural institutions such as the village cooperative units (KUD), but, unfortunately, most of these cooperatives are not functioning well because of weak management. This condition has become one of the main constraints to the development of farming systems in tidal swamp lands. A seed supply system of the improved varieties could be developed through the local seed production station, under the supervision of government institutions like the Seed Certification Institute. In the long run, seed management should be developed by farmer groups and local entrepreneurs or seed growers (*penangkar benih*).

A rural financial institution called *Karya Usaha Mandiri Wanita Tani* (KUM-WT) was established to provide capital services and gather and manage community funds. Its mandate is to provide services quickly and easily, with low interest within the group, and with discipline and transparency. Within 24 mo of its existence, the KUM in Sugihan Kiri and Sugihan Kanan was able to attract 885 members from eight villages, showing good performance in terms of amount of savings, credit granted, and loan repaid (Soentoro et al 2000). The total amount of savings reached Rp 74, 295,700, and the credit disbursement reached Rp 681,795,000 with unpaid loans (*tunggakan*) of only 0.2%. The loan disbursement of the KUM significantly increased the economic activity of its members by either creating new businesses or strengthening and expanding existing ones. Farming system activity increased by 36.1%, tofu and *tempe* producers by 15.8%, livestock raising by 14.7%, trade businesses by 15.0%, and home industry by 8.1%. Only 10.3% of the loans were allocated for consumption.

Development impacts

Harvested rice area and production in South Sumatra showed an increasing trend from 1996 to 1999. However, the growth rate of harvested area for 1999 was smaller than that for 1998, especially in Musi Banyuasin District, where the harvested area decreased to about 1,820 ha due to damage caused by rats, armyworms, grasshoppers, and blast disease. Fortunately, the reduction in harvested area was compensated for by the higher rice yields in tidal swamp lands. Up to 1998, the average yield of rice in these areas showed an increasing trend but still remained below that of the provincial level in South Sumatra. However, starting in 1998, rice yields consistently exceeded the average provincial yield level. The increased productivity of tidal swamp rice lands is attributed to the improved farming system technologies developed by the AARD through the Tidal Swamp Agricultural Development Project, implemented directly by farmers under the supervision of field extension staff and researchers.

Furthermore, by using a relatively low milled rice recovery of 59.6% and with a consumption rate of 117.17 kg capita^{-1} per year, there were apparent indications that South Sumatra attained a surplus rice production in 1996, 1998, and 1999 amounting to 2.2%, 6.0%, and 5.8% of total provincial production, respectively, compared with a deficit of 3.6% in 1997 (Table 7). Meanwhile, in the Musi Banyuasin (MUBA) where most rice land is under tidal swamps (75%), rice surplus was even much greater, reaching about 54.9%, 56.2%, 65.3%, and 65.3% of the total production of rice in the region, respectively, over the same period.

These developments prove that swampy lands, if properly managed, hold good potential for becoming one of the main rice production areas in the future. Such developments require farmers' participation, supported by effective rural institutions to facilitate credit, supply of inputs, and market development. In brief, tidal swamp lands could become one of the major rice- producing ecosystems in Indonesia and could simultaneously help stimulate the expansion of local businesses and rural agro-industries, subsequently increasing trading activity and enhancing economic growth in these marginal areas. Aside from increasing productivity, the impact multipliers of agricultural system development also include (1) raising knowledge and skills of farmers and field staff in effectively farming swampy lands and dealing with specific technology requirements; (2) improving the capabilities of farmer groups in planning and managing farming activities; (3) increasing the absorption of labor

Table 7. Production and consumption of rice (t) in South Sumatra Province and Musi Banyuasin District, 1996–99.[a]

Item	Region	1996	1997	1998	1999
Population	South Sumatra	7,247,212	7,328,133	7,496,438	7,708,435
	Musi Banyuasin	1,042,342	1,059,208	1,094,459	1,107,055
Grain production	South Sumatra	1,456,587	1,389,181	1,562,127	1,603,199
	Musi Banyuasin	454,763	474,999	619,402	626,288
Milled rice	South Sumatra	868,126	827,952	931,028	955,507
	Musi Banyuasin	271,039	283,099	369,164	373,268
Consumption	South Sumatra	849,156	858,637	878,358	903,197
	Musi Banyuasin	122,131	124,107	128,238	129,714
Surplus	South Sumatra	18,970	-30,685	52,670	52,309
	Musi Banyuasin	148,908	158,992	240,926	243,554

[a]Based on a milling rate of 59.6% and a consumption rate of 117.17 kg capita^{-1} yr^{-1}. Sources: Statistical yearbooks of South Sumatra Province and Musi Banyuasin District for 1996, 1997, 1998, and 1999.

in farm activities, services, and rural agro-industry development; (4) increasing collaborative activities among farmers or groups of farmers and field staff; (5) ensuring faster adoption of new technologies by farmers; and (6) effecting better coordination between relevant R&D institutions.

Flood-prone ecosystem

Research activities in the flood-prone rice ecosystem are not as intensive as those in the tidal swamp areas. The national policy was to focus R&D programs and activities on tidal swamps because the constraints in these areas are easier to tackle. However, more recently, the flood-prone areas have been given more attention and higher priority by the government.

Integrated crop management in flood-prone (lebak) areas

Demonstration plots for ICM were conducted in medium lebak (freshwater swamps) in Kayu Agung. To improve the productivity of lebak rice, the performance and yield of several rice varieties were tested in this area. Technologies that are compatible and suitable for implementation in this specific rice environment were selected. These components were made part of an ICM technology package comprising (a) improved rice varieties; (b) N management (application of 200 kg urea ha^{-1}); (c) pest management (particularly that involving golden snails); (d) and weed management.

Several lines that are tolerant of submergence and some lines with higher yield potential were included. The trial showed that IR70213 and IR70181 gave higher yields, 5.6 and 4.9 t ha^{-1}, respectively (Fig. 2); no flooding was experienced during the trial. IR42, a variety widely grown by farmers in swampy areas, was used as a check. IR70213 is one of the lines that can tolerate complete submergence. The trial was repeated in 2007, and the two submergence-tolerant lines again showed high yields. The 2-yr data showed IR70213's good potential as an important lebak rice variety because of its high yield and submergence tolerance. This line was recently released as INBPARA 3 for the lebak areas.

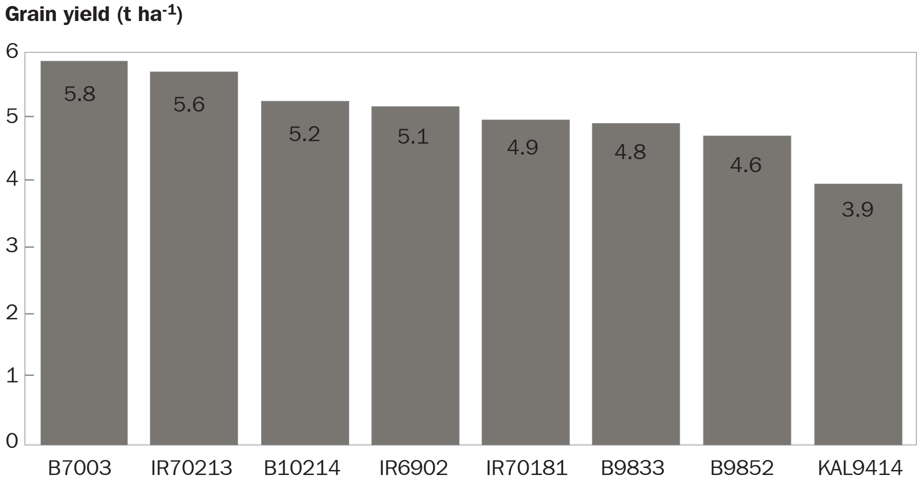

Fig. 2. Yield of several rice lines (14% moisture content) in Kayu Agung, South Sumatera, 2006 dry season.

Strategy and policy analysis for tidal swamp areas

A strategy and policy analysis of food crop development in swamp lands was prepared using the SWOT method. This involved problem identification and selection, scoring, and filtering of both internal and external factors. Three sections were identified based on existing problems: (1) administration, management, and organization (AMO) problems, (2) biophysical problems, and (3) socioeconomic problems. Six indicators have been used to determine the relevant internal (strengths and weaknesses) and external factors (threats and opportunities): (1) weighted factor (WF) for each internal and external factor, (2) supported value (SV) of each factor, (3) weighted supported value (WSV), (3) scoring for level of linkage factor, (4) average linkage value (ALV) between two factors, (5) weighted linkage value (WLV), and (6) total weighted value (TWV).

Administrative, management, and organization

Strategy

1. Intensive programs involving crop intensification and diversification to increase food crop production
2. Revitalizing the role of agricultural extension workers to meet the food sufficiency objective faster
3. Improvement in planning performance and intersector coordination to increase swamp land productivity
4. Focusing research priorities on strategic aspects and commodities based on budget availability

Policy

1. Aggressive policy to fast-track the achievement of food sufficiency, implement relevant laws, and revitalize agricultural extension
2. Diversified policy to supply mobility and communication equipment for extension workers, enhance manpower capability in planning, and enhance intersector consolidation and coordination
3. Consolidate policy for food crop R&D-based priority setting to enhance the role of the Department of Agriculture to take control of vital sectors and increase the budget for agricultural development
4. Defensive policy to construct and rehabilitate public infrastructure and facilities, balance the budget allocation to the agricultural sector, and coordinate various intersector activities to prevent pollution and environment degradation.

Biophysical aspects of tidal swamp land

Strategy

1. Optimize the use of existing improved technologies such as water management, soil reclamation and location-specific fertilizer recommendations, IPM, and introduction of high-yielding varieties to improve productivity and quality
2. Intensify food crop production to improve farm income and farm household food security
3. Rehabilitate existing water canals and construct flapgate systems for inflow and outflow to control irrigation and drainage of rice fields
4. Intensify the use of farm machinery to solve labor shortage problems and improve product quality

Policy

1. Aggressive policy to expand the improved intensification program and ICM, increase the productivity of harvested area through intensification, and apply postharvest technology for better product quality
2. Diversified policy to revitalize and improve existing water canal networks, soil amelioration, balance fertilizer application, and farm machinery service groups (MSG)
3. Consolidation policy to strengthen IPM and existing MSG
4. Defensive policy to intensify R&D programs and activities, especially those focusing on soil, water, varietal improvement, insect and pest control, and farm machinery

Biophysical aspects of flood-prone areas

Strategy

1. Optimal use of modern technology in water management, cropping pattern establishment, IPM, weed control, and varietal improvement to increase food crop productivity
2. Construction of suitable infrastructure and facilities to support food crop production
3. Development of suitable farm machinery
4. Construction of mini-polders with suitable water pumps to control flood and water depth

Policy

1. Aggressive policy to construct mini-polder systems for water management and use water pumps to control flood and water depth
2. Diversified policy to delineate flood types based on water depth and flood duration for suitable crop varietal improvement
3. Consolidation policy to strengthen IPM farmers' groups and existing MSG, and to improve water management and cropping systems
4. Defensive policy for introduction of intensive mini-polder water control system, crop varietal improvement, and effective weed control

Socioeconomic aspects

Strategy

1. Expanding the use of farm machinery for land preparation, and harvest and postharvest operations to solve

labor shortage problems and to achieve better product quality
2. Open access to soft farm credit schemes for farmers or farmers' groups to speed up technology dissemination and adoption
3. Selective subsidy of input or output price, especially for rice, to balance the increasing cost of production
4. Introduction of freshwater or brackish water fish culture and processing technology for added value and better income

Policy

1. Aggressive policy to support farm machinery and establish processing units through cooperatives and the private sector
2. Diversified policy for rural microfinance development to support farming and processing activities
3. Consolidation policy for input or output price subsidy for rice-based farming systems
4. Defensive policy to ensure open access to off-farm credit for fisheries and processing

Program and activities

Prospects for better production

The intensification program to maximize the use of marginal land aims to increase production of three main food crops—rice, maize, and soybean. This objective can be achieved using three approaches: (1) area expansion, (2) increase in cropping index per unit of land, and (3) improvement of crop yield and productivity. Two scenarios can be thought of for each commodity. In scenario I, the three approaches can be used to increase rice production, whereas the last two approaches are proposed for soybean and maize. Under scenario II, yield and productivity can be increased through technology innovation. Investments are needed to provide micro and macro water management, tractors and threshers, water pumps and water flap gates, soil ameliorants, corn fillers, rice milling unit, and the support of the public and private sectors for R&D.

Tidal swamp lands

Scenario I. Rice, soybean, and maize production is projected to reach about 1.5 million t, 72 thousand t, and 0.36 million t, respectively, when the program begins and investments are made. After 5 yr, the production of these three commodities is predicted to increase to 2.91 million t, 99 thousand t, and 0.53 million t; after 15 yr, the respective figures would be about 5.48 million t, 0.175 million t, and 0.85 million t.

Scenario II. At the start of the project, production of rice, soybean, and maize is estimated to reach 1.5 million t, 72 thousand t, and 0.36 million t, respectively. However, production will approach 2.56 million t for rice, 88 thousand t for soybean, and about 0.51 million t for maize in year 5; further increases to 3.80, 0.112, and 0.72 million t for rice, soybean, and maize, respectively, are expected by the 15th yr.

Flood-prone areas

Scenario I. Rice, soybean, and maize production in flood-prone areas will reach about 1.88 million t, 83 thousand t, and 0.25 million t at the beginning of the program. After 5 yr, the production of these crops should increase to about 2, 0.116, and 0.37 million t, respectively, and, at year 15, to 5.26, 0.173, and 0.58 million t.

Scenario II. The production of rice, soybean, and maize, which only depends on yield and productivity improvement, is projected to reach about 2.41, 0.10, and 0.32 million t, respectively, after 5 yr of the program with the same starting point. The targeted yields after 15 yr are 3.67, 0.128, and 0.43 million t.

Feasibility of investment

Tidal swamp lands

Based on scenario I, the government needs to invest at least Rp 13.58 trillion on the program in the next 15 yr to meet this target. This level of investment will provide a total production value of about Rp 2.97 trillion in the base year and Rp 7.46 trillion at year 15. Cumulatively, the total added value for production of rice, soybean, and maize is expected to reach about Rp 60.7 trillion. Therefore, the return on invesment (ROI) for these three food crops in the tidal swamp areas is expected to be 4.47. Based on scenario II, the total value of investment is about Rp 12.30 trillion for 15 yr. With this, total value of production will be about Rp 3.02 trillion in the base year and will increase to Rp 7.37 trillion at year 15. The total value of rice, soybean, and maize at year 15 will be about Rp 40.99 trillion. Considering the additional investment of Rp 11.30 trillion, this addional value of production provides an ROI of 3.33.

Flood-prone lands

With scenario I, the projected investment in the flood-prone areas is about Rp 12.88 trillion for the next 15 yr. Meanwhile, the total value of production is expected to reach about Rp 46.10 trillion, resulting in an ROI of 3.58. With scenario II, the total value of investment within the same period is projected to be Rp 12.13 trillion and the additional value of production is estimated to be Rp 27.99 trillion (ROI of about 2.31).

Programs and activities

The food crop development program for the tidal swamps and flood-prone areas consisted of (a) research and development, (b) dissemination and promotion of innovative technologies, (c) action program for production, and (d) revitalization of management and organization.

Research and development

Research on biophysical aspects is focused on the development of technologies that help overcome the major challenges of the system—biotic stresses especially insect, pest, and weed; drought spells caused by erratic rainfall; and land and water management. Research on socioeconomic aspects aims to find alternative solutions to strengthen on-farm sources of income through market-driven research activities (horizontal diversification), add value through post-harvest and processing technology innovations (vertical diversification), and develop market opportunities through demand-driven research activities. Based on these issues, R&D programs are prioritized as i) R&D on land and water management and IPM, ii) participatory breeding and varietal improvement, iii) croping pattern and integrated farming system development, and iv) priority setting for food crop-based R&D.

Dissemination and promotion of research results

Dissemination and promotion of research output aims to hasten technology adoption and diffusion and enhance on-farm application. To achieve these targets, the dissemination program includes i) dissemination and promotion of agricultural technology innovations on land and water management, ii) dissemination and expansion of harvest and postharvest technology innovation, iii) dissemination and adoption of rice-fish farming system, and iv) agricultural clinic and field laboratory to provide solutions to problems related to dissemination and adoption.

Action program

R&D outputs may not reach their target groups without effective and efficient dissemination and outscaling efforts. These efforts should be initiated at higher policy levels and brought down to the provincial and district levels and to local agricultural offices. This program should be supported, with IARRD providing technology backstop, and could include the following: i) crop intensification and quality improvement through proper ICM, ii) expansion of soil amendments and proper fertilizer application, iii) rehabilitation of water delivery and drainage networks, iv) intensification of farm machinery use for food crop production and postharvest handling, and v) construction and rehabilitation of infrastructure, especially for transportation.

Management and organization

R&D output dissemination and promotion requires strong support through an effective and efficient management and organization. This program aims to fulfill domestic needs and increase the competitiveness of agricultural products to further benefit farming communities. This could involve i) strengthening agricultural extension and farmers' organizations, ii) more balanced budget allocation for the agricultural sector, iii) input and output subsidy, and iv) control and monitoring of exported products to ensure good quality.

Roadmap toward medium- and long-term goals

The roadmap toward the achievement of medium-term goals is divided into four hierarchies, while that related to long-term goals (15 yr and beyond) consisted of five hierarchies. These hierarchies outline the goals to be achieved for food crop-based agricultural development in tidal swamp and flood-prone areas in Indonesia.

Medium-term goal

To achieve the medium-term goal, the food crop development program should start with a research assessment (Fig. 3) and should develop the component technologies of ICM for each food crop. Simultaneously, approaches to revitalize the whole agricultural system need to be developed and implemented. Location-specific technologies should be validated for each crop and their possible integration with other commodities, such as FCB-CLS, must be examined. Other commodities could include livestock, poultry, or freshwater fish. Ultimately, an ex-post analysis can be carried out to assess impact on farm household income and welfare. For the second hierarchy, as a mass action program to promote ICM for each crop, FCB-CLS is supposed to be implemented on farm. This program will speed up and sustain the adoption and diffusion of technology innovations. ICM for rice, soybean, and maize, for example, is expected to be adopted faster by farm households. The intermediate impact of this program can be realized by the third year, with the use of indicators such as increase in productivity (between 2 and 6% per yr) and increase in total production (5–10% per yr). From this targeted impact, the economic added value of production is expected to grow at 50–75% within the 5-yr period, an increase of 10–15% per yr; and net farm household's income is expected to increase by 60–75% within the same period.

Long-term goal

To achieve the long-term goal of food crop-based agricultural development in the tidal swamp and flood-prone areas, institutional, horizontal, vertical, and regional linkages and interactions are required. These linkages cannot be separated and should exist under a simultaneous action program. Such a program should be given high priority and linked to ultimate end users (Fig. 4).

Institutional linkages should focus on 1) revitalization of farmer organizations, agricultural extension systems, and rural microfinance institutions to hasten technology dissemination and adoption; (2) consolidation of agribusiness management in the form of an integrated corporate system; and (3) expansion of the partnership between agribusiness systems.

Horizontal linkages can be developed through integrated and diversified farming systems in a zero-waste crop-livestock system (ZWCLS) with basic commodities being developed with consideration of local circumstances—(1) food crop-based ZWCLS, (2) estate crop ZWCLS, or (3) horticulture ZWCLS. A delineation of the agroecosystem therefore has to be carried out to determine the most suitable combination.

Vertical linkages aim to provide added value to agricultural commodities produced in this area through expansion of postharvest technology. It can include food crops, estate crops, horticultural crops, and livestock. These activities are also expected to provide new employment opportunities in these rural areas.

Regional linkages involve zonation within each tidal swamp and flood-prone agroecosystem across provinces based on similarities of challenges. This is expected to facilitate development and boost economic benefits. Therefore, the greater application of location-specific technology should be followed

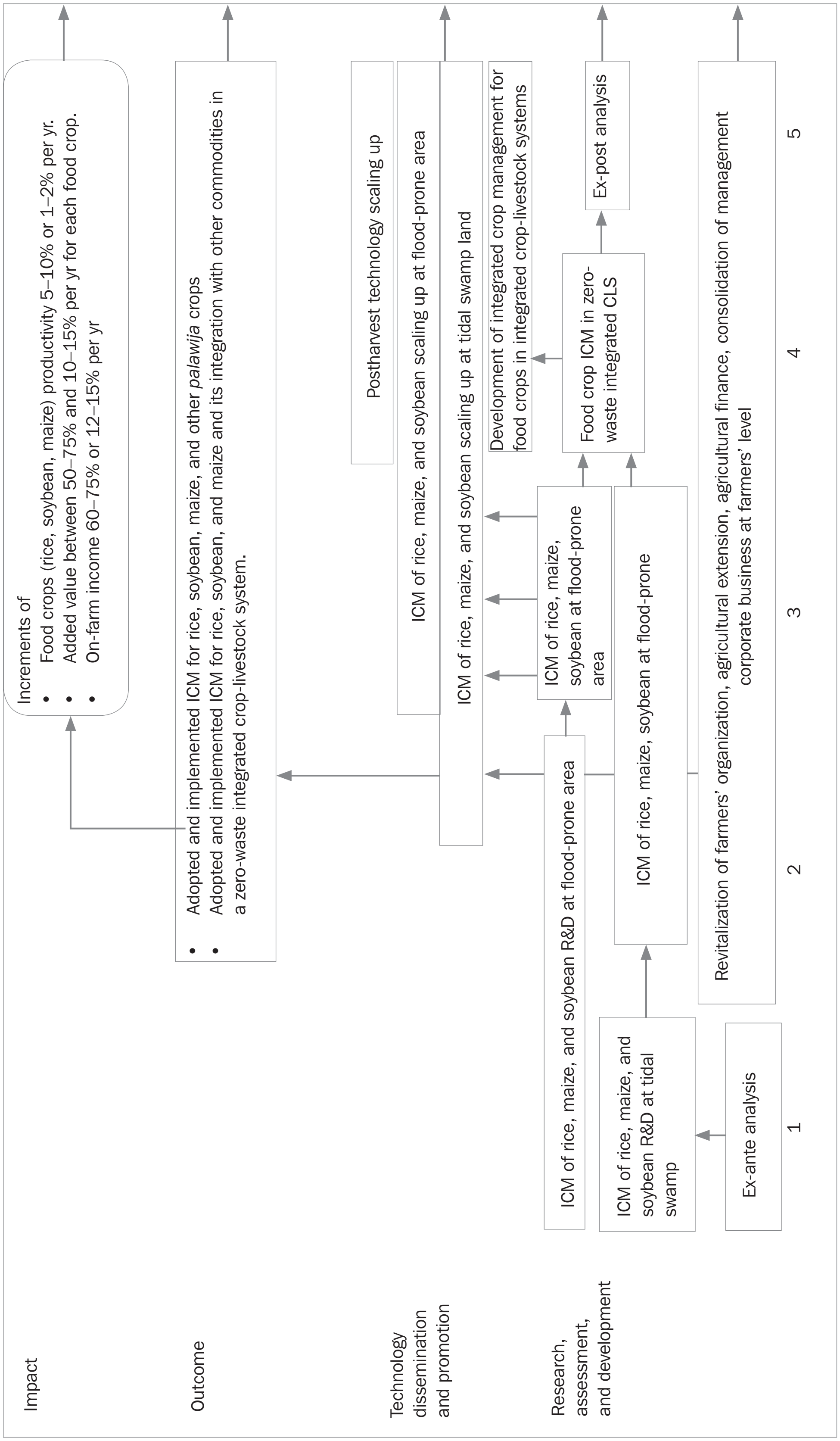

Fig. 3. Roadmap towards the achievement of the medium-term goals of food crop development in tidal swamps and flood-prone areas (2006-10).

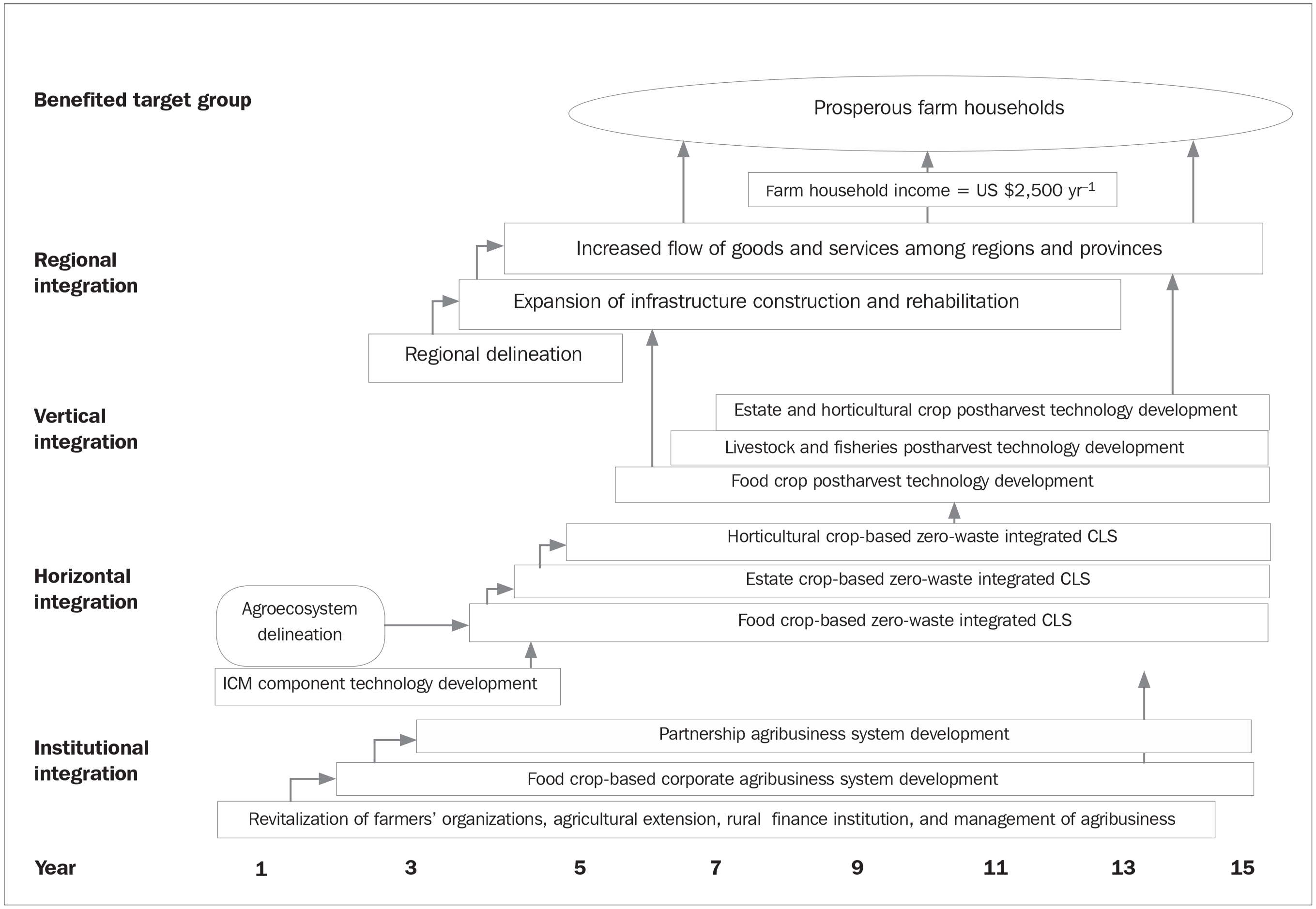

Fig. 4. Roadmap toward long-term goal achievement of FCB-CLS in tidal swamps and flood-prone areas (2006–15).

by (1) crop delineation; (2) strengthening of infrastructure, especially transportation inland or across provinces; and (3) enhancement of the flow of goods and services through the islands or provinces. Indonesia is a big country of more than 15,000 islands—great opportunities exist for domestic trade linkages that can benefit the entire nation.

Neither mid-term nor long-term strategies will be achieved if there is no political will to improve the AMO aspects. Therefore, continuous improvement of AMO is crucial and necessitates the following: (1) improvement of administrative performance at each level of the bureaucracy; (2) enhancing the quality of program planning, implementation, monitoring, and evaluation; and (3) consistent implementation of the law and regulations with balanced sanctions. The roadmap for developing the mid-term strategy within the next 5-yr period includes these four hierarchies: (1) research and assessment, (2) dissemination and social marketing of technology innovation, (3) benefit and outcome, and (4) impact of technology applications (Fig. 3).

Research and assessment aim to develop technological packages suitable for food crop development in the tidal swamp and flood-prone areas. These packages are (1) ICM for the surjan rice system, (2) ICM for beans and tuber crops, (3) ICM for maize, and (4) ICM for FCB-CLS. The activities may start with an ex-ante analysis to help obtain basic data and information needed to conduct an ex-post impact analysis. To facilitate the development of various food crop ICM schemes, revival of agriculture, especially for farmer groups, agricultural extension, corporate farming management consolidation, as well as rural microfinance organizations need to be in place.

Institutional interaction is a prerequisite to attaining the long-term goal. It involves (1) institutional revitalization such as that of farmers' organizations, agricultural extension, and rural microfinance to speed up the process of agricultural technology adoption and diffusion; (2) food crop-based corporate agribusiness management consolidation; and (3) development of agribusiness partnerships (Fig. 4). Horizontal interaction is achieved through diversified agribusiness and commodity systems by developing zero-waste FCB-CLS with location-specific commodities as basis: (1) food crops, (2) estate crops, and (3) horticultural crops. However, the choice of the main crop will very much depend on the farmers' circumstances. Optimal use of the comparative advantage of each zone and location-specific technology targeting require regional commodity delineation and the strengthening of inland island-to-island transportation infrastructure. This effort will increase the flow of goods and services between islands and regions. Goods and services will certainly flow from surplus regions to deficit regions. This trading will foster regional and national economic growth, in the end, improving farmers' income and welfare.

Achieving either mid- or long-term goals will require commitment and support from the organizations involved. It is therefore essential to improve the administrative and managerial skills of these institutions by giving enough incentives to government officials; ensuring better program planning, control, and monitoring, and consistency in program implementation at the field level; and, along with strong political support, ensuring that pertinent laws and regulations are in place.

Conclusions and policy implications

Conclusions

1. Opportunities for increasing production of rice, soybean, and maize are existing in tidal swamps and flood-prone areas; through area expansion, increase in cropping intensity and yield.
2. Clear strategy and policy options are needed to achieve the projected gains, particularly for administrative, management, and organization, biophysical, and socioeconomic aspects.
3. An integrated research and development program has to be undertaken with focus on land and water management and IPM, participatory breeding for varietal improvement, proper cropping patterns and integrated farming system development, including rice-aquaculture systems, site-specific ICM packages, and priority setting for R&D. Technology dissemination and promotion should include interventions that support land and water management and implementation of modern harvest and postharvest technologies.
4. Supporting policies and institutions must be in place, through revival and strengthening of agricultural extension systems and farmers' organizations, sufficient budget allocation for the agricultural sector, controlled input and output subsidies, microcredit finance, and monitoring and control of product quality.
5. Compared with commercial interest rates, the projected ROI shows that the development of food crops in tidal swamps and flood-prone areas remains more attractive, with ROI ranging from 3.3 to 4.5 for tidal swamps and from 2.3 to 3.6 for flood-prone areas.

Policy implications

1. To enhance national food security and improve farm household income and welfare, policy and support for developing tidal swampland and flood-prone areas need to be given higher priority, which is in line with the government's program to revive agriculture, forestry, and fisheries.
2. Policies should give emphasis to improving the performance of administration, management, and organization, both at the central and regional levels, and to develop effective and integrated strategies to jointly tackle biophysical and socioeconomic challenges.
3. The government needs to ensure the provision of sufficient funds to effectively implement a scenario of choice and should decide on an effective mechanism for budget allocation to governing bodies and other stakeholders.
4. Investment policies in these unfavorable lands should consider the development of an environment that is conducive and supportive of other investors by

providing incentives and enabling simple investment procedures, improving the quality and effectiveness of human resources for effective administration and management, developing the rural agricultural credit system; and encouraging and supporting on-farm agribusinesses to add value to the products and provide additional income.

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Salt-affected areas

Brackish water coastal zones of the monsoon tropics: challenges and opportunities

A.M. Ismail and T.P. Tuong

The tropical coastal zone ecosystem is characterized by wide variation in soil types and water and land uses and is extremely dynamic, with apparent long-term and seasonal changes. These areas are highly fragile because of the numerous natural hazards and human interventions, yet they hold massive potential for food production and other industrial uses. However, most of these areas in the tropics still remain underexploited, while mostly overpopulated with highly impoverished communities. Most soils in coastal areas are affected by salinity and other abiotic stresses, such as acidity, high organic matter, and nutritional problems. Moreover, excess water during the monsoon season causes long-term partial flooding or even complete short-term submergence, causing substantial reduction in their productivity. Livelihood sources are quite diverse and are dominated by agriculture and aquaculture/fisheries activities. Agricultural activities are normally dominated by rice farming during the wet season because of excess water and the difficulty to grow other crops, while aquaculture and fisheries constitute the second largest source of livelihoods. Conflicts among resource users are common, causing further environmental and social problems; most of them are cumulative and need to be addressed at regional levels. Major investments in infrastructure with the aim of controlling flooding and salinity intrusion demonstrated substantial impacts on the livelihoods of people in these areas when proper interventions are carefully planned and were backed with proper policies and tools that can allow monitoring and adjustments. Our present knowledge of the challenges and opportunities is still inadequate in order to formulate proper management options and policies to realize the full potential of this important ecosystem.

Keywords: aquaculture; brackish water; coastal zones; rice; salinity

Coastal inland zones constitute the interface of land and fresh water with sea ecology and saline water. This zone is characterized by extensive variation in soil characteristics and water and land uses as in river deltas, mangrove swamps, salt marches and estuaries. These ecosystems are extremely dynamic, with apparent long-term and seasonal changes, and are highly fragile because of the numerous natural hazards as well as human interventions. Nonetheless, these zones hold enormous potential for food production and industrial uses via eventual integration of agriculture and aquaculture, as well as forestry and marine products; together with the relative ease of access through the sea. Yet, these ecosystems are still underexploited in most areas despite being overpopulated by some of the most impoverished communities, particularly in South and Southeast Asia. The immediate consequences of this high population density and the limited livelihood opportunities are overexploitation of natural resources and the ensuing soil and environment degradation. The increasing incidences of natural hazards such as long drought periods during the dry season and severe flash and longer term floods during the monsoon season are causing great losses of crops, infrastructure, property, and people's lives. Moreover, land and water resources in the salt-affected coastal areas are being permanently exhausted at increasing rates due to soil erosion, land degradation, and other factors.

The coastal areas of tropical zones provide numerous essential goods such as fish, oil, gas, minerals, timber, salt, and farming. They also provide essential livelihood and ecosystem services such as shoreline protection, water quality maintenance, recreation and tourism, and transportation. The relative ease of accessibility to these areas especially through the sea makes them targets for aggregation of people for different livelihood purposes, causing human density in these already overpopulated narrow strips of land to grow even faster than inlands. It is estimated that more than half of the world's population currently live within 60 km of the shoreline, constituting most of the world's poor, and this is expected to rise to three quarters by the year 2020.

Coastal areas are preferred sites for human settlements and urbanization. However, their unique position in making up the transition between land and water, fresh and saline water, and between aquaculture and agriculture makes these areas more prone to conflicts between local resource users, which mostly leads to serious environmental and social problems as competition for land and sea resources rise, with the resulting degradation of available resources. Some of these problems and conflicts can effectively be addressed at the farm or community level; however, in most cases, an ecosystem approach at the regional level is deemed necessary. Our present knowledge of the challenges facing these important ecosystems is still inadequate to formulate proper management strategies and policies and more resources and efforts at national and regional levels are indispensable.

Biophysical characteristics and constraints in coastal zones

Salt stress

Majority of the soils in humid and subhumid coastal climates are affected by salinity and other abiotic stresses, such as acidity (acid sulfates), high organic matter content (peat soils), and nutritional problems, which render them less productive (Table 1). Saline coastal areas mainly occur in the deltas, fringes, lagoons, coastal marshes, and narrow coastal plains or terraces along the creeks. Salinity in these areas could be inherent, caused during the process of soil formation, or most commonly due to marine influence and the subsequent periodical floods with tidal saline water. It can result from frequent inundation of land during high tides and ingress of seawater through drains, creeks, and rivers, particularly during the dry season. Water table is normally shallow and, during dry periods, saline water moves to the soil surface through capillary rise, which then evaporates, leaving the salt in the surface soil to accumulate to toxic levels. Secondary salinization can also take place in coastal areas where poor-quality irrigation water is used for irrigation during the dry season, coupled with improper or, in most cases, lack of drainage.

Soil and water salinity constitutes one of the major problems facing agriculture in tropical coastal zones. However, the extent of affected soils is not yet well documented, and various figures are presented in different reports. For example, a total of about 27 million ha were reported to be affected to some extent by salt stress in coastal areas of South and Southeast Asia (Ponnamperuma and Bandyopadhyay, 1980). Of this area, about 3.1 million ha are in India, 2.0 million ha are in Bangladesh, and 2.1 million ha are in Vietnam. With the availability of new means such as high-resolution GIS maps, more accurate data will probably be available in the near future. Majority of these areas are not currently in use for agricultural production; however, most of these soils in humid tropics are suited for rice production as well as for other crops. These soils are often highly saline or have other soil problems that limit their productivity (Singh et al 1994).

Table 1. Abiotic stresses encountered in coastal rice production areas in Asia

Major problem	Deficiencies	Toxicities	Other stresses
Acid and acid sulfate	P, N	Acidity, sulfate, Al, Fe, salinity	Inhibition of nutrient uptake, stagnant and flash flooding
Peat (Histosols) soils	N, P, K, Zn, Mo, Cu and B	Acidity, Fe, H_2S, organic substances	Waterlogging, low thermal conductivity
Salinity	P, Zn, N	Salts (Ca, Mg, Na)	Submergence, stagnant and flash flooding, drought

Source: Ponnamperuma , 1994; FAO Problem Soils Database http://www.fao.org/ag/agl/agll/prosoil

Salinity in coastal areas is also more dynamic and varies with the season, being very high during the dry season with the peak around April-May, as a result of high evaporative demand with the consequent high concentration of salts at the soil surface due to capillary movement of saline underground water. Salinity level in the soil and water then decreases progressively with the onset of monsoon rains between June and September, reaching levels close to normal conditions later in the season (Fig. 1). Apparently, this dynamic nature and fluctuation of salinity in coastal areas make it difficult to handle through management options involving long-term soil reclamation. However, some of these problems could partially be solved through major infrastructural developments, which require heavy capital investments. Management options at the farm level can also help mitigate the effects of salt stress such as continuous farming and avoidance of fallows (Fig. 2), and use of salt-tolerant varieties coupled with nursery and field management options (Mahata et al, this vol).

Water level and discharge

In the humid tropics, coastal areas are also characterized by heavy annual rainfall, most of it occuring during the monsoon season from June to September. These heavy rains, together with the poor or nonexisting proper drainage facilities, normally create serious waterlogging conditions and sometimes complete flooding. Moreover, heavy rains are likely to occur during the month of July and could cause serious losses to transplanted rice in these areas. Rainfall is mostly erratic during most of the year and is less frequent during the dry season, which necessitates supplementary irrigation. Early rainfall during the month of April or May during harvesting of dry season crops such as vegetables also causes severe losses. Humidity is relatively high during most of the year in coastal tropics, which sometimes aggravates problems of pests and diseases. However, this high

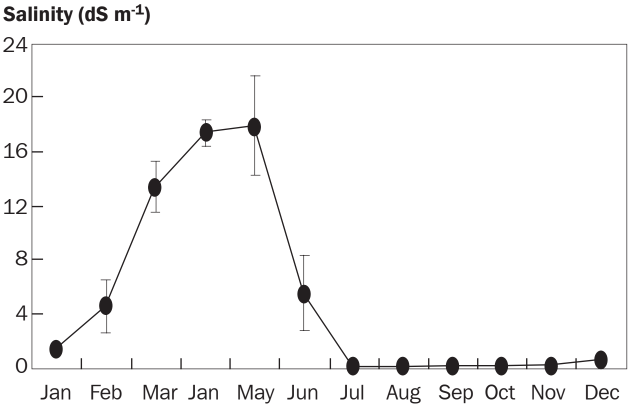

Fig. 1. Monthly salinity level in Kazibachha River measured at Kismat Fultola Village, Khulna District. Data are averaged over 1997 – 2004 and vertical bars indicate ±SE of eight monthly values; each of which was the average of 10-20 daily measurements. Data are from Mondal et al (2006) with permission.

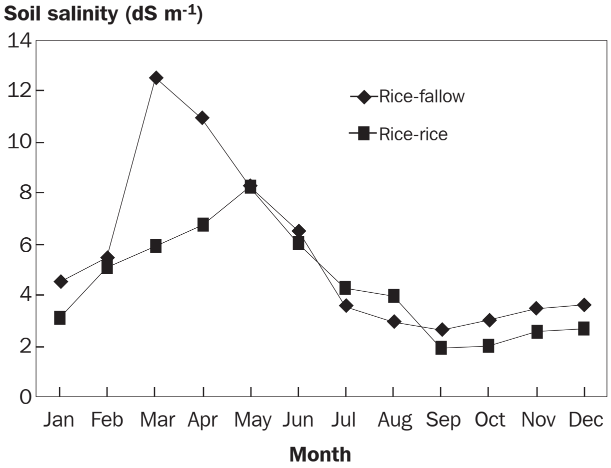

Fig. 2. A typical soil salinity pattern in a rice-rice and a rice-fallow system, Batiaghata, Khulna, Bangladesh. Data are average of 7 years from 1998 too 2004.

humidity also helps reduce evapotranspirational water losses and conserve soil water, particularly during the dry season. The cloudy weather during the monsoon season also reduces the number of sunshine hours, affecting photosynthetic activity and hindering productivity, as reflected by the low yield of rice during the wet season compared with the dry season.

Because of this high rainfall and impeded drainage during the monsoon season, one major constraint for agriculture in tropical coastal zones is the excess water stress during the wet season, resulting in water stagnation of up to 50 cm for most of the season, and, in some cases, complete submergence. Prolonged waterlogging constitutes a serious problem during the wet season, annually affecting about 3 million ha in India and more than 1 million ha in coastal Bangladesh. Modern rice varieties are not adapted to these conditions and their yield is severely reduced because of lower tillering, reduced panicle size, and high sterility. This is probably one of the main reasons modern rice varieties are not widely adopted in these areas and farmers still grow their local low-yielding landraces. Breeding and management options for improving productivity in these areas must, therefore, consider the effects of long-term water stagnation beside salt stress and other adaptive and agronomic traits.

Because of excess water problems and high humidity, most of the coastal areas are entirely under rice monocropping during the monsoon season. Local rice varieties have some level of tolerance for these conditions, including water stagnation and short-term complete inundation, but their productivity is very low. During the rest of the year, the area mostly remains fallow due to high soil and water salinity and lack of good-quality irrigation water, high saline water table, and relatively high evaporative demand. These challenges vary widely with location, suggesting that amendments and mitigation strategies as well as proper cropping patterns should essentially be different and mostly specific to each target area.

Water level and salinity in rivers and soils

In coastal areas and particularly in deltas, water levels in rivers and their tributaries are determined by rainfall in upper catchments, which fluctuates seasonally, as well as by the diurnal tidal movements. Water level is normally high during the monsoon season but decreases substantially during the dry season, causing ingress of saline water through rivers and canals. During high tides, the high-density saline water pushes fresh water to rise to levels that cause transient floods (Fig. 3). This dynamic movement of tidal waves is sometimes being used to control fresh water levels in irrigation canals and for irrigation as is the case in the Telang area in North Sumatra, Indonesia.

Soil properties in coastal areas

Soils in coastal areas vary substantially both in chemical and physical characteristics. Generally, they vary from being neutral to extremely acidic, particularly where acid sulfates and pyrites are predominant in the parent material, such as in coastal Vietnam and Indonesia. They also vary with respect to the extent of salt accumulation based on location and season and could be extremely saline during the dry season due to the ingress of tidal saline water and/or rise of saline underground water. These soils also vary in their organic matter content—from being extremely

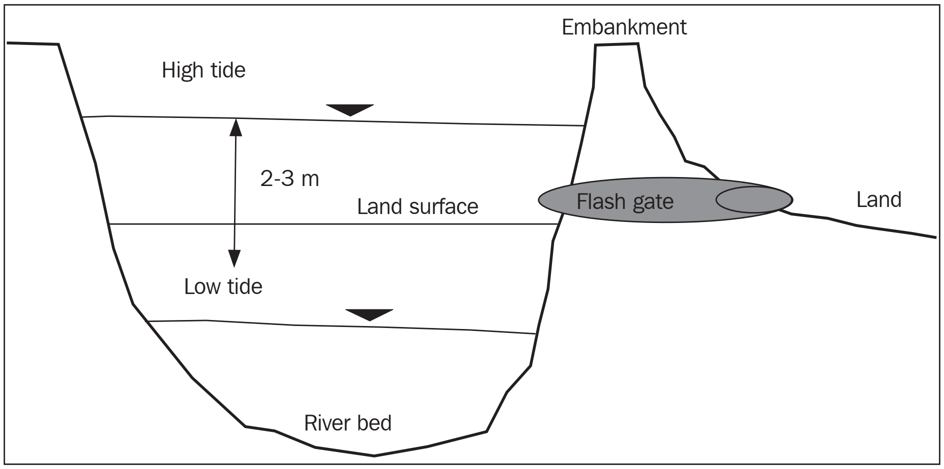

Fig. 3. A schematic river section showing high and low tides. Through controlled sluice gates, this tidal power is used to deliver water from rivers to irrigation canals during high tide.

deficient as in sandy soils to highly organic as in peat soils. Nutrient contents also vary dramatically from being deficient (P, Zn, K) to being toxic, when the concentration is too high, as in the case of aluminum and iron in acid sulfate soils (Table 1). These extreme conditions cause instability and tremendous reduction in productivity of these soils and, in some cases, hinder their agricultural use, particularly during the dry season when these problems are further aggravated by drought. Effective use of these lands entails enormous resources and efforts to integrate genetic tolerance for prevailing stress into adaptive high-yielding varieties (Ismail et al 2007), coupled with effective mitigation and management options.

Natural disasters

Coastal zones feature a wide range of natural hazards from hurricanes and severe storms to floods and landslides, earthquakes and tsunamis, shoreline erosion, and land subsidence. All of these hazards threaten lives, property, and natural resources, and are becoming more imperative with the progressive increase of human populations in these coastal areas and the unfavorable trend in climate changes. Hurricanes and typhoons are probably the most frequent disasters, particularly in rice-growing coastal areas of South and Southeast Asia. Examples are the devastating "super cyclone" that passed through Orissa, India, in October of 1999, seriously affecting more than 15 million people; the catastrophic cyclone that hit Bangladesh in April of 1991, leading to the loss of 138,000 lives; and, more recently, the Sidr cyclone claiming close to 4000 lives in November of 2007. Earthquakes and tsunamis are extremely dangerous natural hazards that threaten the coasts and inland areas. The 2004 Indian Ocean earthquake and tsunami increased international awareness of these devastating and disastrous nature perturbations. The earthquake triggered a series of lethal tsunamis on December 26 that killed approximately 275,000 people, displaced more than one million, and caused billions of dollars in property and infrastructural damages. Some side effects of these disasters are the long-term ecological impacts on the habitat of affected areas such as destruction of shrubs and trees, loss of livestock, and deposition of salt in agricultural soils, among others. In most cases, the soil structure will change due to the deposition of sand and sediments brought by sea water,

Besides these natural disasters, coastal areas are generally prone to other more frequent tribulations that can vary from one location to another as well as with the season. These include, tidal water inundation during high tides and heavy spells of rainfall causing severe floods. Drought incidences are frequently experienced in some coastal areas even during the monsoon season, and this normally results in massive crop loss.

Impacts of climate change

Climate change is expected to cause gradual rise in sea levels and increase in storm incidences, making the coastal zones particularly under threat from these changes (Peltier and Tushingham 1989, Pessarakli and Szabolcs 1999, Wassmannn et al 2004). Most of these areas are highly populated and low-lying lands such as the large deltas of the Gangus-Bhamabutra in Bangladesh, Ayeyarwady in Myanmar, and Mekong Delta in Vietnam. Other low-lying areas in the Philippines, Malaysia, and Indonesia are also at high risk. The economic and social impacts of these changes will extend beyond coastal areas to major cities and ports, with the unfavorable effects on commercial fisheries and agriculture, with particular effect on rice farming that dominates these areas. Millions of people could be displaced from these areas with even a modest rise in sea level, and enormous investments are needed to formulate favorable response plans to avoid any devastating impacts.

Livelihood strategies in the coastal tropics

Coastal zones are regarded as highly populated areas, with higher levels of poverty than most other ecosystems. For example, in Bangladesh and Vietnam, the national poverty levels are about 40% and 23%, whereas the levels in coastal areas are 49% and 40%, respectively. Poor infrastructure and development, together with high poverty and population density, create enormous pressure on the existing national resources.

Current livelihood means are quite diverse in coastal areas (Fig. 4). These sources are dominated by agriculture and aquaculture/fisheries activities. Agricultural activities are normally dominated by rice farming during the wet season, (for example, constituting about 38% in south Vietnam), and only about 2% of livelihood is attributed to other crops. This is because of excess water during the monsoon season and the difficulty to grow other crops due to persistent flooding or waterlogged conditions. Aquaculture and fisheries constitute the second largest source of livelihoods, amounting to about 30%. Resource-poor and landless farmers in these areas rely mostly on open access resources such as open water fishing, as well as on employment. For example, in south Vietnam, about 26% of the poor depend in their livelihood on open water fishing and 25% work as laborers in shrimp culture and other on-farm activities (Fig. 5).

Recent developments and impact on rice farming

Mangrove ecosystems are important coastal habitats in tropical regions, directly or indirectly supporting subsistence and commercial fisheries. In the past, these forests were the primary features of the coastlines throughout the tropics and subtropics. However, these ecosystems are progressively becoming under threat in developing countries, where land is being cleared to accommodate a variety of human activities. An estimated area loss of 1% per year is occurring in Asia and the Pacific, with some areas already losing more than 70% of their original mangrove habitats. Due to continued disturbances, altered soil conditions and limited dispersal, natural recovery may be slow. Restoration of these coastal areas is becoming more important as a tool for maintaining coastal ecosystem health, particularly in developing countries, and priorities should be given to incorporating restitution projects and their evaluation into coastal management plans.

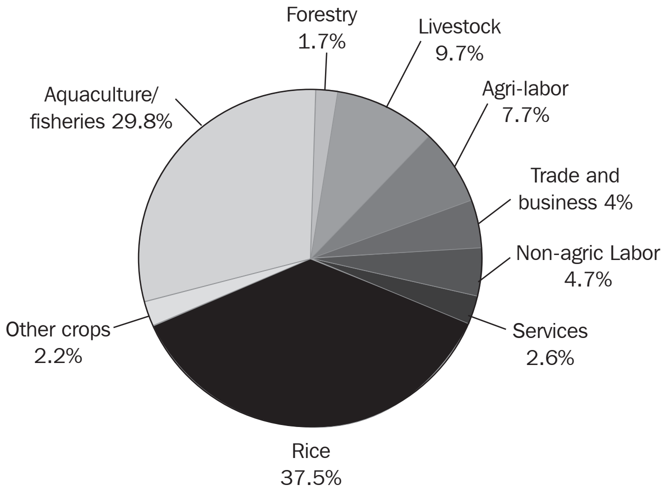

Fig. 4. Means of livelihood in coastal areas: Sources of income by employment. (Total income (US$) = 1,486 and per capita income (US$) = 292).

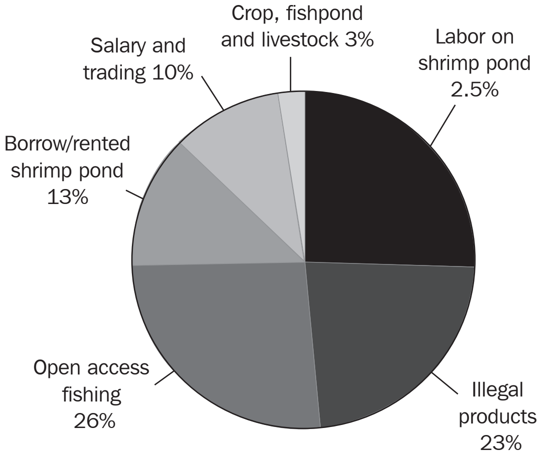

Fig. 5. Sources of livelihood in coastal saline areas: example from southern Vietnam.

Substantial areas of mangrove forests are still found in Bangladesh, India, Indonesia, Malaysia, Myanmar, Philippines, Thailand, and Vietnam. These forests used to cover a vast area in coastal zones a few centuries ago; however, the areas under mangroves are now considerably reduced. For example, in the eighteenth century, the total area in India and Bangladesh was about 16,700 km^2, but this area decreased to only about 10,000 km^2 in recent years (Islam and Wahab 2005). These forests are sources of a variety of renewable resources and play a significant role in the livelihood of people living in coastal areas as well as for the national economy. In India and Bangladesh, more than 10 million people in coastal regions are directly or indirectly dependent on mangroves for a variety of purposes, such as agriculture, fishing, fuel, and food. Moreover, these forests play an important role in global environmental balance and constitute natural barriers for windstorms and cyclones.

With increasing human pressure in recent years, exploitation of mangroves was progressively intensified. Some of these forests were converted for other land use purposes in recent decades, resulting in irreversible changes in the natural balance and loss of sustenance. The most significant conversion has been to shrimp farming (Fig. 6), with the consequent detrimental effects on the ecosystem (Gowing et al 2006, Karim 2006). Other uses were for salt production or even for growing agricultural crops such as rice. Overexploitation and conversion of these natural forests, however, have resulted in serious environmental and social consequences (Islam and Wahab 2005, Hoanh et al 2006).

Besides the overexploitation of these natural coastal forests, various land use changes are taking place in the coastal tropical zones. These changes include the enormous expansion in aquaculture and particularly shrimp farming in recent years as driven by the market economy (Fig. 7), extensive embankments and control sluices to control the intrusion of saline water during high tides in the dry season, and more intensive cropping patterns involving rice, rice-other crops and rice–aquaculture systems. Some examples from south Vietnam and south Bangladesh are presented below.

Developments in southern Vietnam

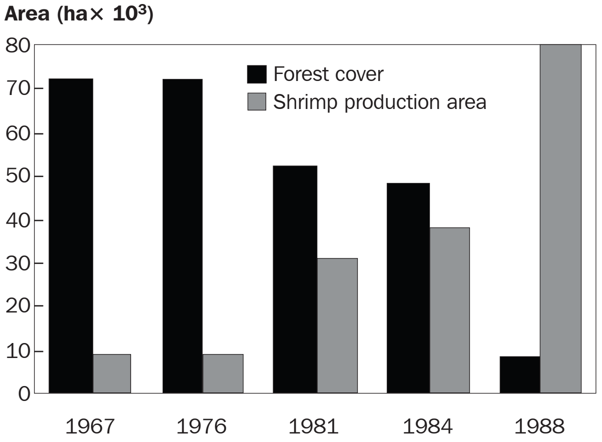

Fig. 6. Encroachment of shrimp farming on mangrove forests. Example from Sunderban mangroves in South Bangladesh

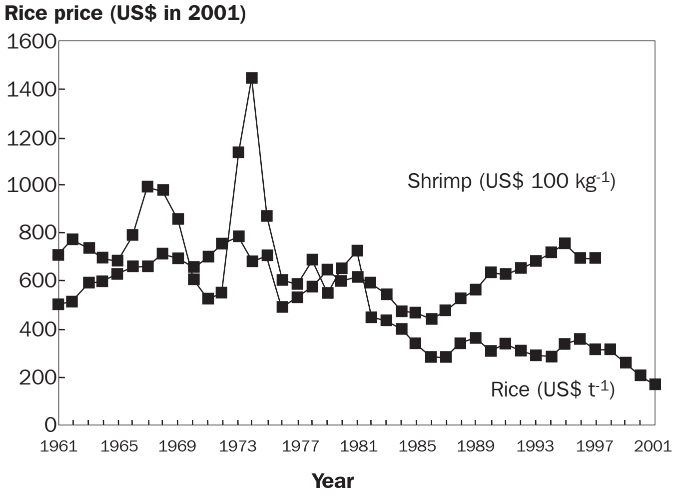

Fig. 7. Global trends in real prices of shrimp and rice (1961-2001).

The Ca Mau Peninsula at the extreme southern tip of the Mekong Delta in Vietnam witnessed tremendous modifications in recent years, with consequent impacts on natural resource use, livelihoods, and the environment (Hoanh et al 2003, Tuong et al 2003). These changes followed the phased construction and operation of extensive sluice systems during 1994-2000, to control seawater intrusion and increase rice production as driven by the severe food shortage and higher prices of rice. A total of about 160,000 ha of land were protected to some extent, and this was initially anticipated to improve cropping intensity with the consequent enhancement of food security and farmers' income.

Following this construction, canal water salinity decreased rapidly upstream of the sluices, which allowed intensive rice cultivation, resulting in doubling or even tripling of the annual rice area in some of the eastern parts of the peninsula, the consequence of freshwater availability throughout the year. However, in the western parts, farmers did not benefit from these interventions at the beginning, and their livelihoods even worsened. This is because most people in these areas were equally dependent on shrimp farming in low-lying acid sulfate soils and on rice in higher lands. Brackish water supply for shrimp farming was hindered and the acid sulfate soils predominant in these areas posed problems for rice farming. The opening of these areas for rice cultivation increased acid pollution and excess aluminum contamination in the farms as well as in the surrounding areas (Tuong et al 1998). Because of the increased acidity and reduced salinity in canal water, landless and poor farmers were even more affected because of the sharp decline in fisheries resources on which they depend as source of income, It is clear, however, that this policy did not recognize the diversity of the livelihoods of the populations in different areas affected by these changes, particularly the importance of fisheries and aquaculture, and the presence of extensive deposits of acid sulfate soils, particularly in western parts that are more suited to shrimp farming than to rice cultivation.

The adverse effects of these modifications and the ensuing popular pressure prompted the local authorities to rethink the rice focus policy in favor of a land and water policy for balanced rice and aquaculture production. This was achieved through an analytical process to identify alternative solutions, and a major policy shift designating rice and shrimp zones and seasonal patterns in an attempt to establish more balanced cropping systems was formulated and implemented (Hoanh et al 2003). A water management infrastructure was established and, together with effective analytical means, was expected to further enhance productivity and accommodate the land-use decisions of local people. Particular attention was devoted to addressing the requirement of landless farmers whose livelihoods depends entirely on open-water resources (Fig. 5), and the long-term effects of the sluices on the buildup of acidity, with subsequent adverse effects on aquatic life outside the protected areas (White et al 1996). Apparently, both natural resources and the environment in these coastal lands seem to be extremely fragile and sensitive to external interventions. A clear understanding of the environmental and socioeconomic impacts of any interference is crucial to help plan strategies that can enhance farmers' conditions without negatively impacting the environment. Intensification of rice as the sole crop involves relatively less risk to farmers but results in relatively lower income compared with rice-shrimp or a sole intensive shrimp system. However, shrimp production requires that brackish water supply should be maintained, with the potential to increase income but at higher risks and indebtedness (Gowing et al 2006) and additional consequences to the environment.

Developments in southern Bangladesh

The coasts of Bangladesh are rich in natural resources and hold enormous potential for development, but these are vulnerable to natural and man-made misfortunes, which contribute to the current limited progress in developing these areas compared with the case in other countries as south Vietnam. These areas are characterized by frequent cyclonic storms and tidal surges with the consequent high degree of loss in human life, property, and natural resources. Large areas that are relatively rich in nutrients and are highly productive are progressively being accreted. These lands are officially government property and are initially intended to be planted with mangrove forests. But this is normally not the case—and the accreted land is commonly possessed by the people. In the late 1970s, a project on erosion control and development of accreted land was supported by the Government of the Netherlands to develop these newly formed lands. Cyclone shelters and life-saving infrastructure were also developed in high-risk areas through different projects, with the objective of maximizing their use during non-cyclone periods (e. g., for schools or other community uses). Similar strategies were also followed in areas devastated by the super cyclone in 1998 in coastal Orissa, India.

About 250,000 ha were estimated to have good potential for coastal aquaculture in south Bangladesh, of which 180,000 ha are suitable for shrimp culture (Khan and Hossain 1996). Over the last two decades, shrimp cultivation in these coastal zones considerably increased and contributed progressively to the national economy. However, this increase was achieved principally through area expansion rather than through increased productivity, and this unregulated expansion resulted in substantial reduction in productivity of other crops and in soil degradation, raising concerns regarding its adverse effects on traditional agricultural systems and on the social and environmental aspects. Most of the soils became unusable for rice production after a few years of shrimp culture because of the accumulation of salinity and other toxins due to improper drainage and rotations. Shrimp farming also disproportionately benefited selected groups of the population but negatively impacted the livelihoods of landless and marginal farmers (Karim 2006). Measures are needed to move towards modern and more intensive systems to increase productivity while reducing the area under shrimp farming. This will minimize further degradation of the soil, increase rice productivity, and further halt the notable decline in natural vegetation cover due to the encroachment of shrimp ponds towards homestead and mangrove forests.

Embankments and sluices were being built in the coastal areas of Bangladesh since the 1960s, through the Coastal Embankment Project and subsequent efforts through other aid agencies. The main objectives were to protect loss of life and crops from tidal surges and to control salt intrusion (Fig. 8). Coastal zone management in Bangladesh has evolved through a number of steps since its independence in 1971, for the most part, to provide further protection and promote agricultural development with particular emphasis on rice production. These developments involved the construction of small-scale polders to control salinity intrusion and tidal flooding and providing opportunities for controlled irrigation and drainage. The ultimate goal was to facilitate a shift from the heavily censured brackish water shrimp farming towards the more secured and environmentally sound rice-based systems.

A recent study was conducted to assess the impact of these small-scale polders on rural households and to identify emerging trends both in the embanked areas as well as in neighboring unprotected areas (Chowdhury et al 2006). In both areas, a shift towards rice farming was evident because of the investments in shallow tube wells to provide freshwater for dry-season rice. The embankments substantially enhanced the productivity of wet-season rice by providing protection against salinity and better water management, and this was reflected in an increase in farmers' income and the ensuing reduction in poverty. However, this positive impact was not reflected in rice productivity during the dry season. This is possibly because the protected areas were deprived of the regular silt deposits from floodwater that replenish plant nutrients and restore soil fertility, and farmers in these areas have to invest more in fertilizers and other inputs. As a consequence, the net return from dry-season rice was higher in the areas outside the embankments. Farmers in the unprotected areas also continued to grow brackish water shrimp and fish during the dry season, whereas farmers within the polders mainly grew freshwater fish and prawn in low-lying areas. As expected, the productivity of aquaculture was higher in the unprotected areas. However, given the risks of shrimp and fish culture and the relatively high costs involved, the net returns are lower than that obtained from the more secured dry-season rice, which is a good incentive for farmers to switch to this system. This study again demonstrates the importance of careful gauging of the potential social and environmental consequences when planning major interventions in these highly vulnerable coastal zones. Careful assessment of these consequences is imperative before following such interventions in order to facilitate policy adjustments and ensure that intended benefits go to the ultimate users.

One of the major problems in expanding rice cultivation during the dry season in south Bangladesh is the lack of fresh water resources, particularly in areas where underground water is saline. As a consequence, more than 1 million ha is being grown to a single crop of wet-season, low-yielding traditional rice varieties, with the land essentially left fallow during the dry season. A recent study conducted in these target areas showed enormous

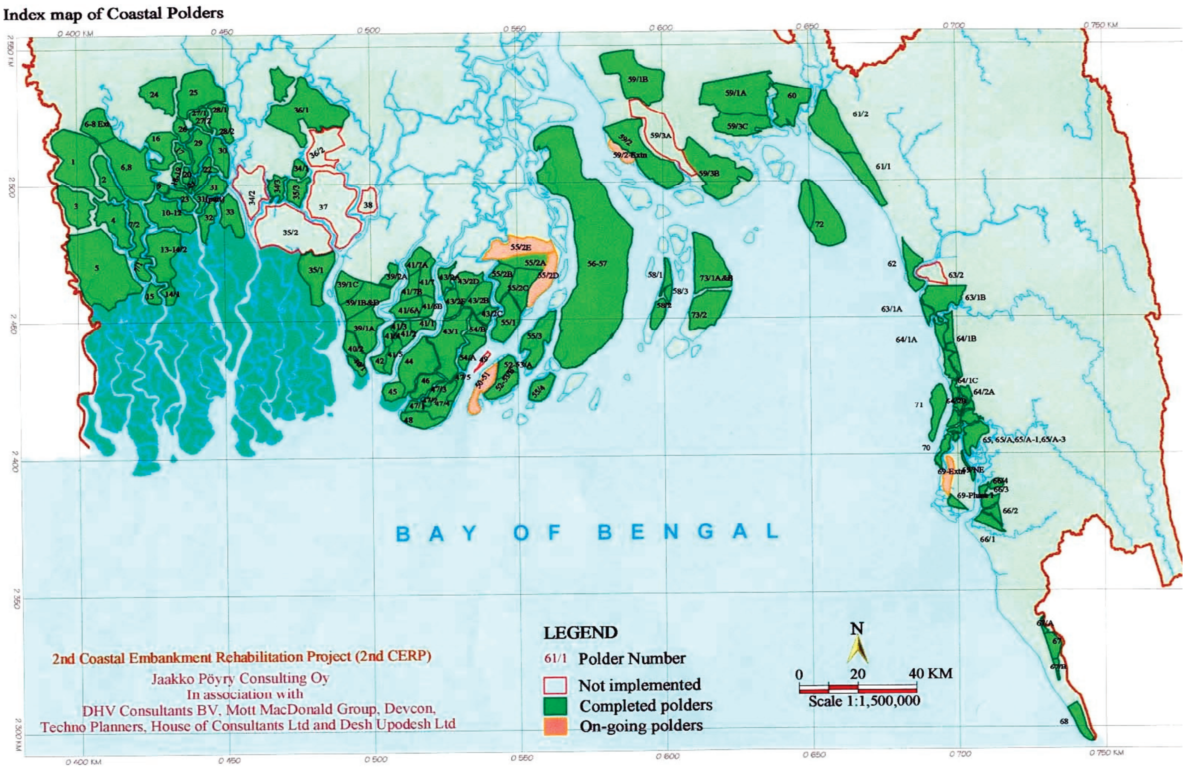

Fig. 8. Agricultural development and salinity control in south Bangladesh.

potential for increasing productivity of rice in these areas by harvesting fresh water in the on-farm irrigation canal network just before the river water from becomes too saline (Mondal et al 2006). The new system involves the use of relatively short -maturing, high-yielding rice varieties during the monsoon or T. aman season, followed by short-maturing, dry-season varieties. The latter can then be irrigated with river fresh water until about mid-February when river water starts to become saline. River water is then stored in on-farm canal networks during high tide, and used to supplement irrigation through maturity. This new cropping pattern resulted in a two- to threefold increase in annual rice yield and about 1.5- to 2-fold increase in farmers' income compared with the traditional system, with no apparent impact on the environment. Farmers seem to prefer this system over the fragile rice-shrimp system because it is relatively more secure. However, successful implementation of this system in coastal areas entails proper excavation of the irrigation canal networks to provide sufficient storage capacity and proper monitoring of salinity in river water, both of which require the involvement of local authorities.

Conclusions

Coastal zones of the tropics are unique in being extremely diverse and dynamic, with enormous potential for development. Substantial resources are available for agriculture, aquaculture and fisheries, and even forestry, most of it far from being fully exploited. Moreover, these areas are highly populated with predominantly resource-poor farming communities, which often results in conflicts among resource users, creating further environmental and social problems. Even though some of these problems and conflicts could be addressed at the individual farm or community level, most are cumulative and can only be addressed at the regional level through better planning involving ecosystem approaches and the entire beneficiaries. The few case studies of the major developments occurring in some of these areas in south Vietnam and Bangladesh demonstrate substantial enhancement in the livelihoods of people in these areas when proper interventions are carefully planned and backed by proper policies and tools that allow monitoring and adjustments. Our present knowledge of the actual challenges facing these tropical coastal zones is evidently inadequate to formulate proper management options and policies and more efforts are needed. Conscientious consideration should be given to the interactions between various land use options and the long-term impacts on the environment, coupled with strategic impact assessments and formulation of sustainability indicators for this fragile ecosystem. Adequate methodologies and techniques are, however, necessary to more precisely estimate and monitor the capacity of this ecosystem to cope with current and future interferences.

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Crop and natural resource management for high and stable productivity in coastal saline areas

K.R. Mahata, D.P. Singh, and A.M. Ismail

Coastal areas support a large proportion of world food production, industrial raw materials, and ecosystem services. In South and Southeast Asia, the coastal zones are dominated by rice monocropping. Salinity fluctuates with the season: it is high during the dry season and decreases during the wet season with the onset of the monsoon. The coastal ecosystem is predominantly rainfed, but some areas are irrigated with groundwater or harvested rainwater during the dry season. Farmers are mostly resource-poor with marginal to small landholdings. The productivity of coastal areas is currently very low because of several abiotic stresses (salinity, drought, and submergence) and frequent cyclones and storms. To improve farmers' livelihoods and ensure food security, it is imperative to enhance crop productivity and cropping intensity through crop diversification and provision of alternate sources of income in an integrated system approach, making the most effective use of existing land and water resources. Some of these possibilities are reviewed in this chapter. Reclamation of the coastal saline soils is difficult and expensive; however, use of salt-tolerant crops and crop varieties is cost-effective and feasible. Good progress has been made in developing salt-tolerant rice varieties and research efforts are continuing to further enhance the level of salt tolerance as well as tolerance for other abiotic stresses through trait and gene pyramiding. Management options such as application of organic and green manure, biofertilizers, and soil ameliorants, and use of robust and healthy seedlings have great potential for increasing wet-season rice productivity. Recent on-farm studies in India showed that substantial yield improvement can be achieved by combining salt-tolerant varieties with matching management practices. Most coastal areas suffer from shortage of irrigation water during the dry season; harvesting and use of rainwater and judicious use of marginally saline water are therefore important for crop intensification. Furthermore, use of less water-requiring nonrice crops helps expand the cropping area during the dry season. Increasing and stabilizing the yield of wet-season rice is a prerequisite for food security in these areas as rice is the only crop that can survive excessive monsoon rains. Using a more integrated and diverse farming system by including more remunerative enterprises such as aquaculture, agroforestry, and farm animals could help increase and stabilize the income of the poor farming communities living off these lands.

Keywords: coastal zone, crop and nutrient management, rice, salinity

Coastal areas provide home for more than 40% of the world's population and support a large proportion of world food production, industrial raw materials, and ecosystem services. In South and Southeast Asia, the coastal zones are predominantly used for aquaculture and agriculture, with the latter dominated by rice monocropping and, to a lesser extent, by rice-based farming systems. The major constraints to food production in these coastal areas are excess salinity and water stress (excess water and drought), as in coastal India, Bangladesh, and Vietnam. Salinity from salt intrusion renders the soil unproductive and unsuitable for rice farming. The extent of salt stress fluctuates with the season, being high during the dry season because of salt accumulation in the surface soil through capillary rise from shallow groundwater and tidal inundation, but decreasing with the onset of the monsoon season. This dynamic nature of salinity makes it difficult to handle through reclamation or long-term infrastructure modifications.

These areas are predominantly inhabited by impoverished communities with fewer opportunities for food security and livelihood. Rice is often the most suitable crop because it can grow under flooding, a condition needed for dilution and leaching of harmful salts, in addition to its high potential for genetic improvement of tolerance for excess salt and water. Nevertheless, rice productivity in these areas is currently very low, less than 1.5 t ha^{-1}, but it can reasonably be raised by at least 2 t ha^{-1} (Ponnamperuma 1994), providing food for millions of the poorest people living off these lands. Recent studies in some affected areas revealed that farmers' adoption of salt-tolerant rice varieties alone can help provide sufficient food for the whole year, instead of the current 6-mo food supply (Paris et al unpubl.). Furthermore, great opportunities exist for increasing and stabilizing productivity in coastal areas through integrated management strategies at the field and farm levels. In this chapter, we will review some of these possibilities with emphasis on progress made in coastal India where more information is currently available.

India is bounded by the Arabian Sea in the west, the Bay of Bengal in the east, and the Indian Ocean in the south; the coastline extends over a length of 8,129 km. The east coast is low-lying with lagoons, marshes, beaches, and deltas rich in mangrove forests, whereas the west coast has a wide continental shelf and is marked by backwater and mud flats. The coastal saline soils are spread over an area of more than 3.0 million ha and mainly occur in the vicinity of creeks, rivers, deltas, and estuaries. The entire coastal belt, except for north Gujarat, is humid with an average annual rainfall of more than 1000 mm, but it could be as high as 2500 mm in the west coast. About 80% of the annual rainfall is received during normal monsoon season (June-September), except in coastal Tamil Nadu, where maximum rainfall occurs in October-November.

Salinity develops because of seawater intrusion during high tides into low-lying agricultural lands and aquifers, causing salinization of the soil and ground/river water and the shallow water table that contributes to salt accumulation in soil surface during the dry season. There is a wide seasonal variation in salinity levels, depending on soil wetting and drying and also the extent of dilution by rainwater during the wet season. In general, salinity is low (EC_e up to 5.0 dS m^{-1}) during the wet season, but it increases considerably during the dry season, reaching its maximum (EC_e >30 dS m^{-1}) in May. Soils are mostly alluvial, red loam, red sandy loam, sandy clay, sandy, and black clay in the east coast and laterites/lateritic, clay loam, gravelly clay, sandy loam, and sandy in the west coast. Most of these soils belong to the orders Entisol, Alfisol, and Inseptisol and are mostly saline, with small patches of sodic soils in the south and west coasts. Acid sulfate soils are found in Kerala, Andaman and Nicobar Islands, and the Sunderban areas of West Bengal. Dominant cations and anions present in the coastal saline soils, in descending order, are Na^+, Ca^{2+}, Mg^{2+} and K^+, Cl^- and SO_4^{--} . The pH ranges from below 4 in acid sulfate soils to above 9 in sodic soils. In acid sulfate and lateritic soils, Fe and Al toxicities are common problems. P and Zn deficiencies are observed in acid sulfate and alkaline soils, respectively. In coarse-textured soils, K^+ and Ca^{2+} are generally present in low amounts. The important characteristics of some typical coastal saline soils are presented in Table 1.

Agriculture in the coastal ecosystem is predominantly rainfed, although some areas are irrigated by pumping fresh groundwater when available or using harvested rainwater. The coastal saline areas in India are largely used for rice production during the wet season. Crop productivity is generally low because of several abiotic stresses—salinity, submergence, and waterlogging due to poor drainage conditions, and drought due to erratic rainfall, coupled with the frequent occurrence of cyclones and storms. Farmers are mostly resource-poor with marginal to small landholdings. To improve farmers' livelihoods and ensure food and nutrition security in these poor and underdeveloped areas, it is essential to enhance crop productivity and cropping intensity and engage in diversification to provide alternative sources of income.

Management of coastal saline soils

Soil reclamation

Unlike inland saline soils, reclamation of coastal saline soils is difficult and expensive due to the seasonal pattern of salt accumulation in soil and water. Intrusion of seawater can be prevented by constructing protective embankments along the rivers and creeks (with a 1.0-m free board above the high-tide level and a side slope of 3:1 on the riverside and 2:1 on the inland; CSSRI 1985). One-way sluice gates are constructed in the embankments to allow draining of excess field water during low tides but prevent intrusion of seawater during high tides. Plantations of trees, shrubs, and grasses strengthen the earthen embankments against erosion and tidal effects. Construction of dikes across the creeks with unidirectional sluice gates also helps in preventing the inflow of saline water into the creeks during high tides. Excavation of drainage canals for surface drainage facilitates washing of salts and their leaching by lowering the water table. Surface drainage from waterlogged areas of Kushabhadra and Bhargavi '*doab*' in Orissa has increased agricultural productivity by about 30% (Nanda et al 2001). Construction of peripheral bunds around catchments for regulating the inflow of excess water and control of flow between zones helps control salinity and submergence. The excess rainwater from different zones is diverted to the outlets of drainage canals used for field draining (Singh and Sharma 2001). These measures require huge infrastructure development that must be supported by local governments and other agencies.

High rainfall, undulating topography, hill slopes, storms/cyclones, and deforestation usually cause severe soil erosion and pose a threat to the security and stability of the shoreline eco-

Table 1. Physicochemical characteristics of some typical coastal saline soils of India.

Characteristic	West Bengal (Kamalpur)	Orissa (Balimunda)	Kerala (Arikalam)	Gujarat (Mundra)	Tamil Nadu (Vettikaran Iruppu)
pH (1:2)	6.5-8.0	6.1-7.9	3.5-4.8	7.4-8.6	7.0-8.7
EC_e (dS m^{-1})	7.0-10.5	9.3-19.7	8.4-43.6	1.4-12.9	0.5-5.5
Organic C (%)	0.26-0.78	0.65-0.92	2.4-4.8	0.13-0.59	0.3-0.5
CEC [cmol (p+) kg^{-1}]	19.7-21.6	25.7-28.9	14.7-69.2	12.7-46.9	8.3-11.9
ESP	10.9-15.2	4.7-19.2	5.8-20.5	5.9-21.3	7.0-33.7
SAR	10.5-12.1	12.9-31.7	-	11.7-23.7	4.0-15.3

Sources: Singaravel and Balasundaram (2001), Maji et al (2004), Polara et al (2004).

system, particularly in the west coast. Soil needs to be protected and conserved by encouraging the planting of suitable trees such as mangroves, shrubs, and grasses. Casuarinas, cashew nut, and coconut trees are extensively planted along the coasts of Orissa and West Bengal, acting as wind and shelter breaks and protecting the sandy seashores.

Mitigation options

Cultivation of salt-tolerant crops and crop varieties is the most economical and feasible mitigation option in most salt-affected coastal areas. Substantial progress was made in developing salt-tolerant rice breeding lines and some of them were released as varieties in coastal areas (Gregorio et al 2002, Senadhira et al 2002, Sen et al 2006, Salam et al 2007). Management options such as application of organic manure, inorganic fertilizers, and ameliorants such as lime, rock phosphates, and calcium-rich oyster shell powder in acid sulfate/lateritic soils and sand, rice husk, and straw in heavy-textured soils (Bandopadhyay 1988, Sen and Bandopadhyay 1984, CSSRI 2006) help in reducing the effect of salt stress**.** The toxic effects of Na^+ on rice plants could be mitigated by mixing cheap Ca^{2+} sources in soil/irrigation water and dipping seedlings in CaO slurry or $CaCl_2$ solution (Quadar et al 1980). In P-deficient acid sulfate soils, rice yield can be increased by adding *Sesbania* green manure and using a higher rate of P application in combination with lime at half the recommended rate (CSSRI 2006). Subba Rao et al (1994) reported that surface drainage to remove soil salinity and leaching salts beyond the root zone, followed by green manure or incorporation of rice straw, efficiently reduced the effects of initial salinity in sandy soils. Continuous ponding of water in rice fields during both wet and dry seasons helped in leaching the root zone profile and significantly improved grain yield. Combining genetic tolerance with management and amendment options was found to be more effective than either option alone. This is probably because tolerant cultivars are subjected to lower levels of internal stress, rendering them more responsive, particularly to nutrients.

Water management in coastal saline areas

Most coastal areas suffer from severe waterlogging due to flat topography, siltation of drains, and rising water level in rivers, creeks, and drainage canals following heavy rains and seawater backflow. In some areas such as the west coast and the southern part of India's east coast, there is acute shortage of water because of inefficient rainwater management and overexploitation of groundwater. Steep sloping topography and uncontrolled deforestation accelerate runoff losses. About 70% of rainwater is lost as surface runoff to the sea. Excessive use and inadequate recharge of groundwater cause a lowering of the water table with the consequent ingress of seawater, leading to intense salinization of soil and water. During the dry season, the acute shortage of freshwater restricts crop production to limited areas with good irrigation water quality.

Harvesting of rainwater as in dugout farm ponds in India and using it to irrigate dry-season crops is one of the most effective approaches for improving crop production, increasing cropping intensity, and encouraging aquaculture in these coastal saline areas. The Central Soil Salinity Research Institute (CSSRI) Regional Research Station at Canning, India, has recommended the conversion of 20% of individual farm areas to on-farm reservoirs (CSSRI 1996). Although this technology is expensive, the payback period of investment is estimated to be 3–4 yr. In lowlands with problems of severe waterlogging and marginal crop productivity, the raised bed-pond system in a ratio of 1:2.7 was found beneficial (Sahu et al 2004). A case study in Dankuni Basin, West Bengal, showed that farmers were able to grow more remunerative crops like vegetables on raised beds using stored pond water during both wet and dry seasons. Micro-watershed management—for controlling runoff losses and soil erosion and storing water for irrigation during dry periods in areas with hill slopes as in the west coasts of India, and undulating lands as in the east coast—is important for augmenting and stabilizing agricultural production. In sand belts along the coast, a unique feature of shallow groundwater is the formation of fresh water lenses (rainwater directly enters through sand layers) floating over saline water that intruded from the sea. Farmers dig pits and use the accumulated seepage water for irrigation during the dry season. This system of skimming perched water is called '*Doruvu*' in India. The Doruvu technology has been improved by installing perforated pipes at 2-m depth radially from collection pits (Raghu Babu et al 1999).

Groundwater suitable for irrigation is found at a depth of 300–400 m in most coastal areas, and its exploitation is very expensive and difficult (CSSRI 1996). Groundwater at shallow depths can be easily exploited but it is of poor quality (EC >2 dS m^{-1}) and its use for irrigating dry-season crops may aggravate salinity problems, particularly in heavy-textured soils. However, the saline groundwater can be used in conjunction with fresh water at relatively tolerant growth stages, while fresh water has to be applied at sensitive stages (Rao et al 2001). The exploitation of saline water requires a better understanding of the magnitude and interaction of various components of water and salt balances under field conditions (Kijne 2003). On-farm trials conducted by CRRI under the Challenge Program on Water and Food-funded project (CPWF PN7) on salinity showed that marginally saline water (ECe of 2.4–3.1 dS m^{-1}) could be safely used for 4 wk during rice vegetative growth stage (20–48 d after transplanting) without substantial reduction in rice yield during the dry season under high salinity condition (Fig. 1). Also, providing irrigation with fresh water 2 d after the disappearance of standing water during the vegetative stage (10 d after transplanting to panicle initiation) did not significantly reduce grain yield and resulted in considerable water savings. Mixing of saline groundwater with fresh water and then using it for irrigation are not practically feasible.

Crop and nutrient management for coastal saline soils

In the wet season, rice is the only crop largely grown in the coastal saline areas due to excessive rainfall. To date, most of the coastal areas are covered by traditional rice varieties with

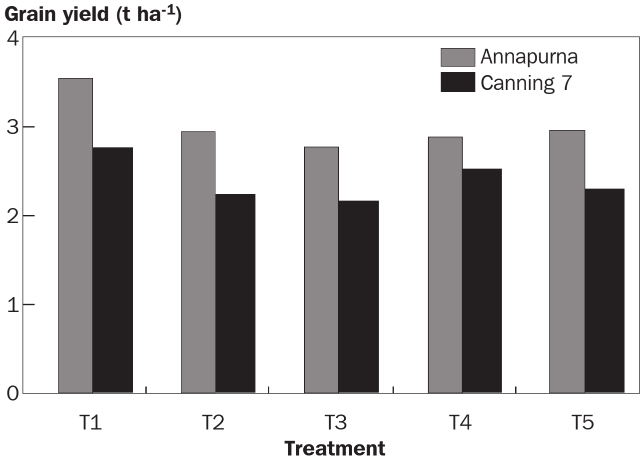

Fig. 1. Grain yield of two rice varieties irrigated with moderately saline water (EC 2.4–3.1 dS m^{-1}) for a particular duration and grown on saline soils (soil ECe 12–14 dS m^{-1}) during the 2005 dry season at Ersama, India. Treatments: T_1-irrigation with freshwater throughout (control); T_2-irrigation with moderately saline water for 1 wk (41–48 d after transplanting; DAT); T_3-irrigation with moderately saline water for 2 wk (34–48 DAT); T_4-irrigation with moderately saline water for 3 wk (27–48 DAT); and T_5-irrigation with moderately saline water for 4 wk (20-48 DAT). $LSD_{0.5}$: varieties = 0.23, treatments = ns.

low yield potential, low grain quality, and poor response to fertilizers. In the dry season, most of the lands remain fallow due to the scarcity of irrigation water. However, short-duration rice varieties are grown in small pockets in areas where adequate water is available, and certain nonrice crops are grown in areas with limited water availability under low to medium salinity.

In coastal Orissa, India, an inventory of farmers' current crop management practices was prepared to assess their technology needs and to identify improved technologies that can further be validated, refined, and disseminated. In the wet season, productivity is low because farmers mostly grow traditional rice varieties, with low yield potential and are sensitive to most abiotic and biotic stresses, coupled with a minimum use of inputs. In the dry season, rice is grown on a limited scale with harvested rainwater using short-duration rice varieties to escape salinity damage. Staggered planting and indiscriminate use of fertilizers and pesticides are followed. On-farm trials showed that, during the wet season, use of older (50 d old) well-fertilized robust seedlings, transplanted at closer spacing (15 × 10 cm), and with proper nutrient management (*Sesbania* green manure (GM) + prilled urea (PU) and Sesbania GM + *Azolla* for shallow lowlands and *Sesbania* GM for intermediate lowlands), along with improved salt-tolerant rice varieties enhanced rice yield remarkably (Fig. 2a). In the dry season, use of salt-tolerant rice varieties, with advanced transplanting (by Jan 15) and *Azolla* + PU were found promising, with considerable yield improvement (Fig. 2b).

In lowlands subjected to waterlogging, farmers generally grow long-duration, tall, traditional varieties with low yield potential during the wet season. Breeding efforts in the past have led to the development of a number of salt-tolerant rice varieties with high yield potential. Varieties found promising at the CSSRI Regional Station, Canning, India, for different hydrological situations during the wet season and for the dry season under different salinity levels are listed in Table 2. Recently, another promising rice variety, Bhutnath, for the shallow lowlands, has also been released by this station. Results from on-farm trials conducted by CRRI, Cuttack, in saline coastal areas of Orissa showed that Pankaj (shallow lowlands) and SR26B, Lunishree (intermediate lowlands), together with few other lines developed at CRRI for the wet season, and Annapurna, Canning 7, and CSR4 for the dry season, were promising (Sen et al 2006). Under high salinity, Annapurna was significantly superior to Canning 7. A salt-tolerant line, IR72046-B-R-3-3-3-1, was found promising, even under high salinity condition during the dry season, both in Orissa and West Bengal coastal regions.

Rice in coastal areas is mostly transplanted using aged seedlings after the soil is sufficiently washed and the salt is diluted by rainwater. In some areas, direct seeding is occasionally practiced but the crop often suffers from drought and salinity stresses in the event of scanty rainfall. However, in few other areas, "dibbling" is practiced, where seeds are placed deeper in the less saline moist soil layers. For transplanted rice, seedlings are raised in less saline areas. The main crop is grown mostly with no fertilizers and pesticides because of the low productivity and the high risks brought by multiple abiotic stresses and natural hazards. Plowing the fields soon after the harvest of wet-season rice or after the first showers during summer helps in reducing salt accumulation in the surface soil. Wilson et al (2000) reported that electrical conductivity and Cl^- concentration in the top 2.5 cm of the soil under tillage were lower than those in no-till soil, although salt distribution beyond this depth was similar in both. Mulching with rice husk/straw, particularly in fallow fields soon after the harvest of wet-season rice, reduces evaporation and salt accumulation and improves the leaching of salts during the monsoon season (Bandopadhyay and Sen 1977). Farmers in most areas raise their nursery without any fertilizers. However, transplanting with robust seedlings raised using reduced seed rate, together with application of an adequate amount of fertilizers and organic manure, resulted in better crop establishment and higher productivity under salt stress conditions (CRRI 2006). In Pokkali areas of Kerala, raised mounds

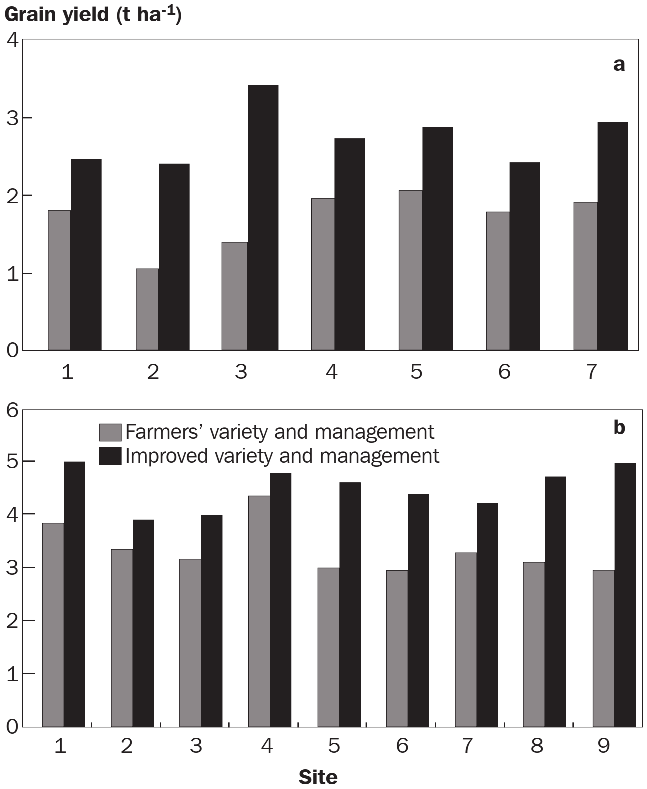

Fig. 2. Comparison of grain yield of rice at Ersama, India, using farmers' variety and farmers' management versus improved variety and improved management (a) during the 2006 wet season, SE ± 0.35, and (b) during the 2007 dry season, SE ± 0.38.

Table 2. Rice varieties developed for different hydrological conditions during wet and dry seasons in coastal saline ecosystems of India.

Season/water regime	Salinity level	Varieties
Wet season		
Water depth 0–15 cm	Medium to high (EC$_e$ 6 to >8 dS m^{-1})	*Early duration*: CSR4, Canning 7, CSRC(S)7-10-10-2-0, and IET144 *Medium duration*: CST7-1, Jaya, CSR1, CSR2, and CSR3
Water depth 0–30 cm	Low to medium (EC$_e$ up to 8 dS m^{-1})	*Medium duration*: CSR6, SR26B, CSRS(S)5-2-2-5, CSRC(S) 2-1-7, IR16294 CS 9-1-30, Dudheswar, and CSRC(S)11-5-0-2 *Late duration*: NC1281, NC678, Matia, Hamilton, Najani, Jhingasail, Gavir Saru, Gopal Bhog, C340-22-5, C340-22-17, and C300 BD 50-11
Water depth 0–50 cm	Low to medium (EC$_e$ up to 8 dS m^{-1})	*Medium duration*: CSRC(S) 2-1-7, SR26B, CSR6, IR16294, and CS9-1-30 *Late duration*: C300 BD50-11, C340-22-17, C340-22-5, NC 1281, Matia, Hamilton, Asfal, and Gavir Saru
	Acid sulfate soils (pH 4.0–5.5) with medium salinity (EC$_e$ 6–8 dS m^{-1})	*Medium duration*: Mahsuri, Canning 7, SR26B, and K.D. Mali
Flash flood		CAC615, CSR6, and SR 26B
Dry season	Low to medium (EC$_e$ up to 8 dS m^{-1})	CSR4, Canning 7, CST7-1, and CSRC(S) 7-10-4-0-1

Source: CSSRI (2003).

(1.0 m length × 1.0 m breadth × 0.5 m height) are prepared with surface soil before the onset of the monsoon and seeds are sown on the top surface after sufficient washing of salts by rain. Seedlings are uprooted along with the soil and transplanted. The raised seedbed technique is useful and can be extended to other coastal saline areas.

Use of robust and aged seedlings and closer planting are likely to improve crop establishment, survival, and yield of wet-season rice under stress situations. Dargan et al (1974) reported increased rice yield with increasing plant density in highly saline sodic soils. Application of fertilizers in waterlogged situations is not feasible and causes lodging in traditional varieties mostly grown in these areas. With the introduction of the high-yielding modern varieties, there is a greater need for more nutrition through application of fertilizers and organic manure. Nitrogen is the most limiting nutrient for crop production in saline soils that have low organic C content. Major losses of applied N occur through ammonia volatilization (25–65%), which is further aggravated by high salt concentration, high pH, and low nitrification rate (Rao and Batra 1983, Sen and Bandopadhyay 1987). Ammonia volatilization can be reduced by placement of urea briquettes or use of sulfur-coated urea. P uptake by plants under high salinity is affected by the reduced root growth and competitive inhibition by Cl^-. Although coastal alluvial saline soils are rich in available P and K, long-term studies have shown significant crop responses to application of P but not K (Bandopadhyay et al 2004). However, plants grown under high salinity may show K deficiency because of the antagonistic effect of Na on K absorption (Bandopadhyay et al 1985). Soils with low clay content may also require application of K fertilizers. In acid sulfate soils, response to P application is high because of P deficiency caused by its precipitation in the form of Al and Fe phosphates (Bandopadhyay and Maji 1999). Application of P fertilizers also increases the threshold limits for the crop's salinity tolerance (Chauhan et al 1991). The doses of N, P, and K fertilizers are location-specific and dependent on rice variety, soil characteristics, salinity level, and hydrological situation.

Addition of organic matter increases microbial biomass and mineralization of macro- and micronutrients during its decomposition, improves soil physical condition, and facilitates the leaching of salts. Consequently, it improves soil fertility and enhances and stabilizes productivity in the long term. Slow mineralization of organic matter in saline soils (Rietz and Haynes 2003) may be advantageous because the released nutrients are not readily lost. The use of chemical fertilizers, along with organic manure and biofertilizers, on saline soils increases fertilizer use efficiency (Kroeck et al 1988, Patil et al 1991). Among organic sources, farmyard manure (FYM), compost of organic wastes (including city compost), *Sesbania,* forage legumes, green leaf (*Gliricidia*, *Ipomoea,* and *Leucaena*) manure, and biofertilizers such as *Azolla* and blue-green algae have been extensively tested in studies on integrated nutrient management for different land situations and water regimes. In saline-sodic soils of Tamil Nadu, organic amendments such as composted coir pith, *Casuarina* needles, and press mud are reported to significantly reduce salinity and sodicity and increase the yield of the succeeding rice crop (Singaravel et al 2001).

The extensive root ramification of *Sesbania* improves soil aggregation and permeability and liberates CO_2 and organic acids, which help in reducing sodicity and salinity (Somani and Saxena 1981). On-farm trials on integrated nutrient management conducted by CRRI, Cuttack, in coastal saline soils in the last 4–5 yr have shown that *Sesbania* green manure during the wet season and *Azolla* during both wet and dry seasons resulted in 21–34% and 10–20% higher grain yield of rice, respectively, besides saving 30–40 kg of N ha^{-1} of chemical fertilizer (Tables 3 and 4). *Azolla* nurseries were commonly established in village ponds to ensure easy and cheap availability of *Azolla* inoculum, which has greatly helped in disseminating the biofertilizer technology. However, *Azolla* could not be used during the wet season in fields likely to face problems of drought or flash floods/excessive waterlogging. Similarly, there are problems of poor germination and establishment of *Sesbania* due to high salinity and drought in the event of scanty premonsoon rain. If the monsoon season is delayed for longer periods, its incorporation is difficult because of the lack of adequate water in the field. Application of blue green algae is reported to decrease Na absorption and reduce the demand for N in rice-based cropping systems (Jain and Kaushik 1989). However, while blue-green algae could be used successfully in alkaline soils, their growth is generally poor in acidic soils.

In the dry season, farmers generally grow short-duration, high-yielding rice varieties, which perform well under low to medium salinity but are not suitable for high salinity condition. Seedlings are generally raised in wet puddled seedbeds using a high seed rate. Allowing some time for sufficient leaching of salts before sowing and reducing the seed rate may help produce robust seedlings in the nursery, with better tolerance for salt stress upon transplanting. On-farm trials conducted by CRRI, Cuttack, have shown that advanced transplanting during the first week of January under high salinity considerably improves crop survival, recovery, and yield (Fig. 3). Delayed transplanting substantially reduces grain yield and the crop transplanted on February 5 or later does not survive because of increased salinity. Under low to medium salinity, transplanting could be delayed up to the first week of February. *Azolla* dual cropping with rice gives a supplement of about 30 kg N ha^{-1} in the dry season, thereby giving significantly higher grain yield. Ponding of water in puddled fields for a few days before transplanting to leach down the salts may be useful under high salinity conditions, provided adequate water is available. Harvesting of rainwater and the conjunctive use of marginally saline water will widen the scope for growing dry-season rice.

Rice-based cropping patterns for coastal saline areas

The cropping intensities in the east and west coasts of India are only 134% and 125%, respectively. The major parts of the coastal tracts of West Bengal, Orissa, and southern Andhra Pradesh—comprising nearly 50% of the cultivated coastal saline areas where rice is largely grown under rainfed condi-

Table 3. Effects of integrated nutrient management with *Sesbania* on rice grain yield during the wet season in coastal saline areas, Ersama, India.

Treatment	Grain yield (t ha^{-1})
Sesbania green manure + prilled urea (30 kg N ha^{-1})	5.0
Urea briquette (60 kg N ha^{-1})	4.9
Prilled urea (60 kg N ha^{-1})	3.8
No-N control	2.6
LSD$_{0.05}$	1.0

Source: CRRI (2005).

Table 4. Effect of integrated nutrient management with *Azolla* on rice grain yield during the wet and dry seasons in coastal saline areas, Ersama, India.

Season	Treatment	Grain yield (t ha^{-1})
Wet season (eight sites)	Prilled urea (60 kg N ha^{-1})	4.8
	Azolla + prilled urea (30 kg N ha^{-1})	5.4
	LSD$_{0.05}$	0.4
Dry season (nine sites)	Prilled urea (90 kg N ha^{-1})	4.2
	Azolla + prilled urea (60 kg N ha^{-1})	4.7
	LSD$_{0.05}$	0.3

Source: CRRI (2005).

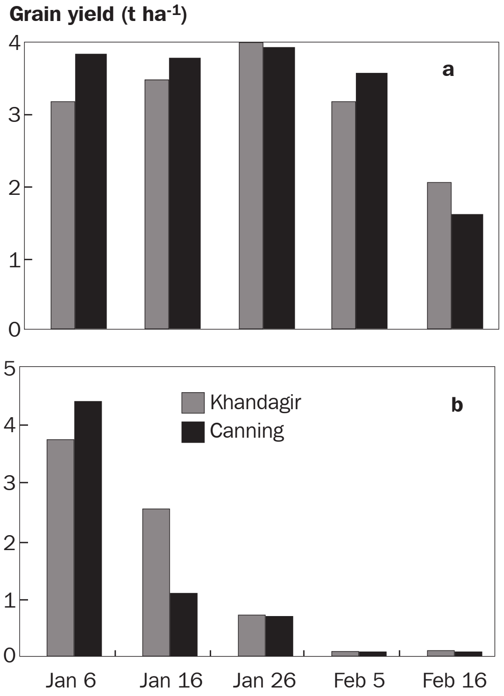

Fig. 3. Effect of date of transplanting on grain yield of two rice varieties at (a) low to medium and (b) high salinity sites during the 2005 dry season, Ersama, India, SE ± 0.31.

tions—constitute the low-productivity rice belt in India. To increase cropping intensity and ensure food and economic security in the coastal saline areas, efforts must be focused on developing diversified rice-based integrated farming systems by including in the cropping pattern low water-requiring, salt-tolerant nonrice crops, including horticultural, plantation, medicinal, and aromatic plants of high market value. These areas are ideal for commercial aquaculture, animal production, betel vine and mushroom cultivation, and agroforestry, which could provide alternate sources of income to poor households, particularly during the dry season.

A diversified farming system could provide more steady and assured income and minimize risks from crop losses and price fluctuations. However, not much research has been done on this aspect, particularly for the salt-affected coastal areas. Some of the cropping sequences found promising under different salinity levels are presented in Table 5. In on-farm trials conducted in Orissa by CRRI, Cuttack, sunflower, chili, and *Basella* under high salinity (EC$_e$ 9.3–14.6 dS m^{-1}) and watermelon, okra, pumpkin, and groundnut under low to medium salinity (EC$_e$ >7.0 dS m^{-1}) showed good promise (Singh et al 2006). Growing these less water-requiring crops not only can expand the cropping area during the dry season but also can increase land and water productivity substantially. Sunflower and *Basella* could be grown even with saline irrigation water (EC 4.1–7.0 dS m^{-1}). Negligible yield reduction due to the use of saline irrigation water (EC 8.0 dS m^{-1}) through a sprinkler system is reported in onion and spinach (AICRP 2002). The relative salt tolerance and productivity of some important crops at varying soil salinity levels are given in Tables 6 and 7, respectively. Fertilizer requirement varies with the crop, soil fertility status, and level of salt stress. The recommended doses of N, P, and K for some important crops in the coastal saline areas of West Bengal, India, are shown in Table 8. Tropical root and tuber crops such as cassava, sweet potato, elephant foot, yam and yam bean, with their inherent tolerance for abiotic stresses and high carbohydrate content and calorie value, can serve as alternate food crops and source of raw materials for industries that deal with commercial production of alcohol, starch, and glucose. However, the extent of salinity tolerance and the adaptability of these crops under different coastal agroclimatic conditions need to be evaluated. On-farm trials conducted by CRRI in coastal Orissa, India, showed that sweet potato varieties CIP440127, CIP40038, Samrat, and Pusa Safed produced tuber yields of 10.8–17.3 t ha^{-1} under medium salinity and 6.0–8.9 t ha^{-1} under high salinity.

Fruit crops such as guava and sapota are relatively tolerant of salinity and could be grown even with moderate to low saline water (EC 3–4 dS m^{-1}). Sapota can grow well under high soil salinity values of up to 10 dS m^{-1}, whereas guava survives well under moderate levels (EC$_e$ of up to 5.6 dS m^{-1} (CSSRI 2004*a*). Plantation crops such as coconut, areca nut, oil palm, cashew nut, and cocoa and spices like cumin, coriander, fennel, fenugreek, and black pepper are high-value commercial crops that are widely grown in some coastal areas. Certain shade-loving spices could be intercropped with coconut and areca

Table 5. Cropping sequences suitable for different salinity levels in coastal saline environments.

Soil salinity level	Crop sequence
Medium to high (ECe 6 to >8 dS m^{-1})	Rice-barley and rice-sugar beet
Low to medium (ECe up to 8 dS m^{-1})	Rice-rice, rice-wheat, rice-linseed, rice-mustard, rice-sunflower, rice-groundnut, rice-watermelon, rice-chili, rice-cabbage, rice-ladyfingers, rice-tomato, rice-forage sorghum, rice-cowpea, and rice-cotton

Sources: Somani (1998), CSSRI (2003), Gangwar et al (2004).

Table 6. Classification of different crop species based on tolerance for salt stress.

Type of crops	Tolerant	Moderately tolerant	Sensitive
Field crops	Barley, sugar beet, rapeseed, and cotton	Rye, wheat, oat, rice, sorghum, maize, sunflower, castor, safflower, soybean, pearl millet, linseed, cluster bean, pigeon pea, cowpea, sesame, and groundnut	Black gram, bengal gram, green gram, and lentil
Vegetable crops	Garden beets, asparagus, spinach, and *Amaranthus*	Bitter gourd, bottle gourd, brinjal, tomato, cabbage, pea, ladyfingers, onion, potato, carrot, turnip, sweet potato, dolichos, sponge gourd, watermelon, muskmelon, chili, fenugreek, and garlic	Radish, celery, green bean, coriander, cumin, and mint
Forage crops	Salt grass, Bermuda grass, Rhodes grass, and birdsfoot	Perennial rye grass, dallies grass, sudan grass, alfalfa, orchard grass, and blue grama	Meadowfortale, red clover, and burnet
Fruit crops	Date palm	Pomegranate, guava, fig, grape, ber and kagzi lime	Pear, apple, orange, plum, peach, mango, and avocado

Source: Somani (1998).

Table 7. Yield of some important crops at different soil salinity levels relative to that under control conditions.

Crop	Soil EC$_e$ (dS m^{-1})											
	1	2	3	4	5	6	7	8	9	10	11	12
Cotton	Relative yield (% of control)											
	100	100	100	100	98	93	88	83	78	83	67	62
Sugarbeet	100	100	100	100	94	88	82	76	71	65	59	53
Safflower	100	100	100	100	100	100	97	90	85	80	75	-
Wheat	100	100	100	100	100	100	93	86	79	71	64	-
Sorghum	100	100	100	100	98	90	84	78	70	63	56	-
Tomato	100	100	95	85	75	65	55	46	36	26	16	-
Cabbage	100	98	88	79	69	59	50	40	30	20	11	-
Rice	100	100	100	88	76	63	51	39	27	15	2	-
Chili	100	100	100	100	95	85	70	50	33	20	-	-
Ladyfingers	100	100	100	100	96	90	75	47	30	20	-	-
Brinjal	100	100	100	100	90	80	65	48	35	15	-	-
Sweet potato	100	95	84	73	62	51	40	29	18	7	-	-
Cucumber	100	100	94	81	68	55	42	29	16	3	-	-
Soybean	100	100	100	100	80	60	40	20	-	-	-	-
Potato	100	96	84	72	60	48	36	24	12	-	-	-
Cowpea	100	90	76	61	47	33	19	4	-	-	-	-
Carrot	100	86	72	58	44	30	15	1	-	-	-	-
Onion	100	87	71	55	39	23	6	-	-	-	-	-

Source: Bandopadhyay et al (1999).

Table 8. Fertilizer recommendations for important crops grown in the coastal areas of West Bengal, India.

Crop	Nutrient requirement (kg ha^{-1}) under different soil fertility levels								
	High			Medium			Low		
	N	P	K	N	P	K	N	P	K
Rice	30	9	17	40	9	17	60	13	25
Chili	80	22	50	80	22	50	100	26	66
Watermelon	80	17	33	100	22	42	120	26	50
Vegetables	100	22	42	120	26	50	150	35	66
Cotton	40	9	17	40	9	17	40	9	17
Sunflower	30	13	25	40	17	33	60	17	33
Wheat	80	17	33	100	22	42	120	26	50
Mustard	60	13	25	80	19	36	100	22	42
Sugar beet	80	17	33	100	22	42	120	26	50

Source: Bandopadhyay et al. (1999).

nut. In Gujarat, *isabgol* (*Plantago ovata*) and opium poppy are commercially grown for medicinal use. Palmarosa, vetiber, and lemongrass have also been found promising. *Sulvadora persica*, a facultative halophyte, is a good source of fatty acids with immense application in the soap and detergent and pharmaceutical industries and is of great economic importance (Rao et al 2003). The highly saline black soils that remain fallow could be brought under cultivation using certain halophytic grasses such as *Aeluropus lagopoides* and *Eragrostis*, which can be grown even with highly saline water (EC up to 30 dS m^{-1}) (CSSRI 2005). Apparently, a large number of different crop species can be successfully grown during the dry season to improve the profitability of the predominantly rice-based cropping system in coastal saline ecosystems.

Many rice lands in coastal India (Andhra Pradesh and West Bengal), South Vietnam, and Bangladesh are being converted into commercial fish and shrimp farms because of severalfold higher income from these enterprises compared with that from rice, and, in some cases, because of the high salinity and lack of fresh water sources during the dry season. However, the selling of land by small farmers renders them landless proletariat and the displacement of agricultural labor and salinization of neighboring rice fields are some of the issues related to shrimp/fish farming that are not yet sufficiently addressed. In a case study at CSSRI Regional Station, Canning, India, the salinization effect of brackish water fisheries on adjoining fields was limited to a 50-m distance (CSSRI 2006). In this context, rice-fish/shrimp farming has greater potential but should be carefully planned and managed to avoid local conflicts and further land degradation. At CRRI, Cuttack, an integrated rice-fish farming system model for the lowlands, which involves additional components of fruit and vegetable crops, floriculture, plantation crops, and duck farming, has been developed and is being popularized (Sinhababu 2001). This system has increased farm productivity fivefold and income tenfold over rice monocropping, besides generating additional employment (Sinhababu et al 2005).

Milk and egg production is the main livestock-related activity in the coastal ecosystem (Varma 2001). Integration of animal husbandry and livestock production in the farming system will substantially contribute to the production system and generate additional income. For this, better cattle feed and fodder will be needed. Forage grasses such as Karnal grass and *Dichanthium annulatum* and halophytes such as *A. lagopoides* and *Eragrostis* sp. could be grown under saline conditions during the dry season for green fodder purposes. Furthermore, there is ample scope for increasing meat production through farm animal rearing. Backyard poultry and duck rearing were introduced in coastal Orissa by the Central Aviation Research Institute Regional Center, Bhubaneswar. Different breeds were provided to mostly small farmers and landless laborers, and the beneficiaries could earn a net profit of about $8/bird (Anonymous 2005).

Rehabilitation and expansion of mangrove forests

The depletion of mangrove forests through overexploitation is a serious threat to the ecology of the coastal agroecosystem because these forests act as barriers against cyclones, typhoons, and tidal waves, prevent soil erosion, and serve as natural habitat for fish and other marine organisms, as well as sources of timber and fuel. Species of *Heritiera* are used for making boats, planking, and fuel; *Aegiatilis* are used for extraction of high-grade salt after burning; and *Exocoecaria* are used for making matchboxes. Thus, restoration and conservation of mangrove ecology are immensely important and require concerted efforts from different government agencies. In places with high salinity and shallow water table, tree species such as *Casuarina glauca*, *Tamarix reticulata,* and *Prosopis juliflora* perform well (CSSRI 2004*b*). Casuarinas and coconut-based agroforestry is also prevalent in the coastal areas.

Synthesis and recommendations

Increasing and stabilizing the productivity of wet-season rice is of paramount importance for improving farmers' livelihoods and ensuring food security in the coastal saline ecosystem, as rice is mostly the only source of their calorie intake and subsistence. In this context, development of suitable varieties with adequate tolerance for prevailing abiotic stresses is a prerequisite. Improved rice varieties developed in India, Bangladesh, the Philippines, and Vietnam so far perform well under low to medium salinity but they suffer from drastic yield reductions under higher salinity levels and from other abiotic stresses. When rainfall distribution is erratic, the crop experiences drought (mostly at seedling and later at reproductive stage) and submergence/waterlogging (mostly at vegetative stage), which are common features of this highly fragile ecosystem. Thus, it is imperative to reorient and integrate rice breeding programs that incorporate higher levels of salt tolerance by pyramiding different salt-tolerance genes and combining these with genes for tolerance for other prevalent stresses such as drought, waterlogging, and submergence, apart from tolerance for major insect pests and diseases. This approach is important for stabilizing yield, but achieving these complex objectives requires intensive and concerted research efforts. Use of advanced biotechnological techniques and tools could be handy in the near future and efforts toward these directions are ongoing, both at the national and international levels. For dry-season rice, short-duration varieties with high salinity tolerance need to be developed, as varieties developed so far have moderate tolerance and do not perform well under high salt stress. Besides, the development and extensive on-farm evaluation of salt-tolerant varieties of nonrice crops are also important, particularly as dry-season crops, in areas where sufficient fresh water resources are not available for rice production. Furthermore, suitable management options and cropping patterns need to be developed and sufficiently tested in the context of the newly developed salt-tolerant rice varieties. Selection of salt-tolerant crops and crop varieties and improved crop and natural resource management technologies is highly location-specific, which entails the need for detailed micro-level biophysical and socioeconomic characterization of these coastal saline agroecosystems. Promising rice-based cropping systems for different locations must be developed, validated, and adjusted for wider adoption.

Most of the soil and water management strategies discussed earlier are expensive and can be adopted only with full support from local governments and other funding agencies. However, individual farmers with small landholdings can resort to micro-watershed management/on-farm rainwater harvesting and use the harvested water for growing rice and nonrice crops during the dry season to increase cropping intensity and farm productivity. For dry-season crops, use of saline water at growth stages that are relatively less sensitive and use of fresh water at sensitive stages would help in expanding the cropping area and improving productivity. Mulching and plowing the land soon after harvest of wet-season rice should be practiced where possible to reduce salt accumulation by preventing capillary rise of saline underground water and facilitating rainwater infiltration. This will help achieve better establishment of dry-season crops and green manure such as *Sesbania,* with subsequent benefits to the following wet-season rice. When possible, land should not be kept fallow during the dry season. Acid soils could be amended by application of lime along with P fertilizer, preferably after the leaching of salts.

Integrated nutrient management using chemical and organic nutrient sources in coastal saline soils is very important for improving rice establishment and productivity. Topdressing of N fertilizers is not feasible under waterlogged situations during the wet season; however, placement of urea briquettes is useful, but its use is restricted by the lack of suitable cost-effective application tools. Farmyard manure (FYM) and organic wastes could be sources of organic amendments, but their limited availability and the demand for rice straw for other uses greatly restrict their use in coastal saline ecosystems. Furthermore, the occurrence of cyclones and the lack of forage and crop residues (because of rice monocropping) contributed to the diminishing cattle population in these ecosystems. Rice straw, which is more abundant, is mostly used for thatching and as cattle feed. Further, FYM and compost available in limited amounts are used mostly for crops other than rice. Green leaf manure does not seem promising because of limited availability, large biomass requirements, and high costs of collection, transportation, and incorporation. Nevertheless, whichever organic manure is available locally should be used. The most promising organic sources for the coastal ecosystem are *Sesbania, Azolla,* and blue green algae, which can generate enough biomass in a short period of time. While *Sesbania* is suitable only in the wet season, *Azolla* can be used during both wet and dry seasons in areas with favorable water regimes (Mahata et al 2006).

To ensure better crop establishment during the wet season, robust seedlings that can survive higher salinity upon transplanting should be used. This could involve the raised-seedbed technique, use of lower seeding rate, and combining organic and inorganic fertilizers in the nursery. Closer transplanting with aged seedlings is also important for better seedling survival, crop establishment, and productivity. In the dry season, early and closer transplanting and use of *Azolla* biofertilizer, along with chemical fertilizers, help increase rice yields.

Growing dry-season rice with limited fresh water restricts the cultivated area under nonrice crops. However, farmers still prefer rice over other crops for subsistence, since rice production in the wet season is poor and uncertain. If production of wet-season rice can be made stable through the use of suitable varieties with appropriate management practices, there will be less compulsion to grow dry-season rice. This will eventually help in expanding the area under the more remunerative and less water-requiring nonrice crops. In this context, research on the development and validation of location-specific, salt-tolerant varieties of promising nonrice crops and good agronomic practices that can enhance land and water productivity need special attention. To improve farmers' livelihoods and achieve food and economic security, integrated rice-based farming systems, which incorporate different components based on socioeconomic and market needs and resource availability, should be encouraged, with the active support of local administrative bodies. The following are some of the immediate needs that need to be addressed:

- Further biophysical and socioeconomic characterization of the coastal saline ecosystems at the macro and micro levels and assessment of research opportunities and farmers' needs
- Development of suitable salt-tolerant rice varieties with optimum maturity classes and with built-in tolerance for other abiotic stresses during wet and dry seasons
- Development and evaluation of location-specific, salt-tolerant varieties of promising nonrice crops, identifying best agronomic practices for both rice and nonrice crops, and establishing suitable rice-based cropping systems
- Promotion of integrated farming systems by including profitable agricultural enterprises such as aquaculture, animal production, and agroforestry
- Participatory validation, refinement, and dissemination of improved crop varieties with matching management technologies for rice-based cropping systems
- Rehabilitation and expansion of agroforestry and mangrove forests for ecological and economic benefits

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Resource management through agronomic manipulation and genetic tolerance in rice-based cropping systems in sodic soils

G. Singh and D.K. Sharma

Land degradation and diversion to nonfarm purposes seriously affect food, employment, and environment security. Per capita land availability is shrinking at a fast pace, especially in developing countries. Salt-affected soils occupy 953 million ha throughout the globe; about 50% of it is sodic. In India, 6.74 million ha are salt-affected and more than 50% are sodic. Sodic soils are characterized by high pH (>8.5) and high exchangeable sodium (>15%), low organic C and available nutrients, and poor physical conditions. Since their characteristics vary widely from region to region, reclamation and management strategies have to be location-specific. To reclaim sodic soils, replacement of exchangeable Na^+ by Ca^{++} through suitable amendments is a prerequisite. Among the chemical amendments, gypsum has been the most popular, followed by low-grade iron pyrites in India. The Central Soil Salinity Research Institute (CSSRI), in Karnal, India, developed a package of practices comprising proper land leveling, improved agronomic practices, and use of rice as a first crop, followed by wheat in winter and Sesbania green manure in summer. Transplanted rice is preferred because it needs submergence, thereby accelerating the reclamation process. Salt-tolerant varieties of rice (e.g., CSR10, CSR13, CSR23, CSR30, and CSR36) have synergistic interaction with gypsum and their use leads to a marked reduction in gypsum requirements. Improved nutrient and water management techniques further improve the yields of rice and wheat. Resource conservation technologies such as zero tillage, direct seeding of rice, planting rice-wheat in ridge-furrow geometry, laser land leveling, and broadcasting Sesbania for weed control in direct-seeded rice were developed and these options proved beneficial in saving water and increasing rice and wheat productivity. After 4–5 yr of reclamation, other remunerative crops can be included in the cropping sequence. With adoption of these improved technologies, more than 1 million ha of sodic lands in the Indo-Gangetic Plain were reclaimed; producing an additional 8 million t of food grains annually, besides generating additional employment. Alternative land uses such as agroforestry systems have shown good promise for communities living on sodic lands. Further research is needed to speed the reclamation and management of sodic soils in order to meet the growing needs for food and to maintain the natural resources.

Key words: crop management, reclamation, resource conservation, salt-tolerant varieties, sodic soils

One of the principal constraints to achieving the desired growth rate in food grain production is human-induced land and water degradation. Salt-affected soils cover roughly 10% of the land surface in more than 100 countries. Based on the FAO/UNESCO *Soil Map of the World*, a total of 953 million ha (Table 1), which covers about 8% of the land surface, is affected by this malady (Szabolcs 1979), more than 50% of which is sodic. The salt-affected soils are reported to occupy 42% of the land area of Australia, 21% of Asia, 7.6% of South America, 4.6% of Europe, 3.5% of Africa, 0.9% of North America, and 0.7% of Central America (El-Mowelhey 1998). Australia has the world's largest area of sodic soils, equivalent to 33% of the continent's area (Rangasamy and Olasson 1991).

Depending on the source, agency, and methodology used, estimates of salt-affected areas in India vary from 6.74 to 26 million ha (Table 2). According to Singh (1994), salt-affected soils in India cover about 8.6 million ha, of which nearly one-third is sodic. As per recent estimates, Gujarat, followed by Uttar Pradesh, has the maximum area of sodic soils (Singh 1989). The Central Soil Salinity Research Institute (CSSRI) is in the process of reconciling figures given by different agencies.

Excess salt stress is adversely affecting the productive capacity of about one-third of the potential arable land in the world, which is either lying barren as merely poor grazing ground or has very low productivity due to unfavorable environment for plant growth. In nearly 2.3% of the total geographical area or about 4% of the total cultivable area in India, crops either do not grow or they yield poorly because of excess salts in the root zone. The problem is becoming more acute with expanding irrigation. The nature and severity of the problem vary from region to region, depending on the topographical situation, hydrological and climatic conditions, drainage availability, and land use and cultural practices, among others. Accurate data on the extent and severity of these problem soils are of vital importance in formulating sound reclamation strategies and in assigning priorities for resource allocation. Good progress was made in the first half of the 20th century and is presently generating information on the relative salt tolerance of different crop plants, methods of sodic soil reclamation, and drainage of waterlogged saline lands. CSSRI was established in 1969 as a followup of the recommendations of an Indo-American team assisting ICAR in developing a comprehensive water management program during its Fourth Five-Year Plan. In a short span of nearly 37 years, CSSRI has developed into one of the foremost international centers of excellence in salinity research. Detailed reviews of

Table 1. Regional distribution of salt-affected soils in the world (million ha).

Region	Solonchaks/ saline	Solonetz/ sodic	Total
North America	6	10	16
Mexico and Central America	2	--	2
South America	69	60	129
Africa	54	27	81
South and West Asia	83	2	85
South and East Asia	20	--	20
North and Central Asia	92	120	212
Australasia	17	340	357
Europe	--	--	51
Total	--	--	953

Sources: Szabolcs 1979, 1980.

Table 2. Extent and distribution of salt-affected soils in India.

State	Area (million ha)
Gujarat	2.23
Uttar Pradesh	1.37
Maharashtra	0.61
West Bengal	0.44
Rajasthan	0.38
Tamil Nadu	0.37
Andhra Pradesh	0.27
Haryana	0.23
Bihar	0.15
Punjab	0.15
Karnataka	0.15
Orissa	0.15
Madhya Pradesh	0.14
Andaman & Nicobar Islands	0.08
Kerala	0.00
Total	6.74

Sources: Reconciled figures of NRSA, CSSRI, and the National Bureau of Soil Survey and Land Use Planning, 2006.

research achievements of the institute had been published before (Tyagi and Minhas 1998, Singh et al 2007).

Characteristics of salt-affected soils

From the management standpoint, salt-affected soils are divided into two broad categories—(1) sodic (alkali) soils and (2) saline soils, though at places saline-sodic soils are also common. However, the management of saline sodic soils will be more similar to that of sodic soils. Such soil needs extra fresh water for leaching of soluble salts before the application of any amendments. The sodic soils have a higher proportion of sodium in relation to other cations in soil solution and on the exchange complex. Growth of most crop plants on sodic soils is adversely affected because of impairment of physical conditions, disorder in nutrient availability, and suppression of biological activity due to high pH, exceeding even 10 in severe cases, and exchangeable sodium percentage of up to 90 % or so. Salt solutions contain a preponderance of sodium carbonates and bicarbonates capable of alkaline hydrolysis, thereby saturating the absorbing complex with sodium. The sodic soils of the Indo-Gangetic Plains are generally gypsum ($CaSO_4$•$2H_2O$)-free but are calcareous, with $CaCO_3$ increasing with depth, which is present in amorphous form, in concretion form, or even as an indurate bed at about 1 m depth. The accumulation of $CaCO_3$ generally occurs within the zone of a fluctuating water table. The dominant clay mineral is illite. Processes that target the dissolution of $CaCO_3$ have a significant role in the reclamation of alkali or sodic soils. These soils are deficient in organic matter, available N, Ca, and Zn. Certain micronutrients present problems of either deficiency or toxicity. Toxicities of Al, Mn, and Fe sometimes pose problems for wheat when it is overirrigated and result in yellowing of the crop.

The major factors responsible for the formation of alkali soils in the Indo-Gangetic region include irrigation, with groundwater containing excessive quantities of carbonate and bicarbonate ions, rise in groundwater due to the introduction of canal irrigation and salt-laden runoff from the adjoining areas and undrained basins. The inland saline lands are widespread in the canal-irrigated arid and semiarid regions. These soils are characterized by the presence of excess neutral soluble salts like chlorides and sulfates of Na, Ca, and Mg. Sodium chloride is the dominant salt. High soil salinity is often accompanied by high water table, often within 2 m of the soil surface. Subsoil water is generally salty and, therefore, its use for irrigation presents major constraints to crop production. In general, these soils have good physical properties but poor natural drainage. The formation of saline soils is generally associated with the rise in water table due to the introduction of irrigation but with inadequate drainage.

Management strategies for sodic soils

There are basically two approaches for getting a good crop stand and yield on sodic soils. The first could be achieved through improvements in soil conditions to meet the crop requirement; the second is to select tolerant crop species and cultivars suitable for problem soils. However, in most cases, particularly when the stress is severe, a combination of the two is deemed more successful. A list of promising crops and varieties is given in Table 3. The relative performance of various cropping patterns for these soils can be judged on the basis of crop productivity, net economic return per unit land area, and energy return. Since crop species differ widely in their performance on sodic soils, proper selection of crops in the initial stage of reclamation is of crucial significance. Considerable research has been conducted on this aspect in India and elsewhere in the last few decades.

Table 3. Relative tolerance of crops and grasses for soil exchangeable sodium (ESP).

Tolerant ESP, 35-50	Moderately tolerant ESP, 15-35	Sensitive ESP <15
Karnal grass (*Leptochloa fusca*)	Wheat (*Triticum aestivum*)	Gram (*Cicer arietinum*)
Rhodes grass (*Chloris gayana*)	Barley (*Hordeum vulgare*)	Mash (*Phaseolus mungo*)
Para grass (*Brachiaria mutica*)	Oat (*Avena sativa*)	Chickpea (*Cajanus cajan*)
Bermuda grass (*Cynodon dactylon*)	Shaftal (*Trifolium resupinatum*)	Lentil (*Lens esculenta*)
Rice (*Oryza sativa*)	Lucerne (*Medicago sativa*)	Soybean (*Glycine max*)
Dhaincha (*Sesbania aculeata*)	Turnip (*Brassica rapa*)	Groundnut (*Arachis hypogea*)
Sugar beet (*Beta vulgaris*)	Sunflower (*Helianthus annuus*)	Sesamum (*Sesamum oriental*)
Teosinte (*Euchlaena mexicana*)	Safflower (*Carthamus tinctorus*)	Mung (*Phaseolus aureus*)
	Berseem (*Trifolium alexandrinum*)	Pea (*Pisum saccharatum*)
	Linseed (*Linum siuqatissimum*)	Cowpea (*Vigna unguiculata*)
	Onion (*Allium cepa*)	Maize (*Zea mays*)
	Garlic (*Allium sativum*)	Cotton (*Gossypium hirsutum*)
	Pearl millet (*Pennisetum typhoides*)	
	Cotton (*Gossypium hirsutum*)	

Physiological studies revealed that avoidance of Na^+ uptake and maintenance of high K^+-Na^+ ratio in the shoot portion is crucial for tolerance (Setter et al 2004). Among the agricultural crops, rice is considered most ideal as it has relatively greater tolerance for sodicity, an extensive shallow root system, minimal amendment requirements, and tolerance for waterlogging, which is normally encountered in sodic soils due to lower permeability. In view of these benefits, rice is recommended as the first crop to start with upon soil reclamation, to be grown in the monsoon season (Chhabra and Abrol 1977). Rice as a first crop increases the solubility of applied gypsum and helps in leaching through standing water in the field (Table 4).

Choice of suitable salt-tolerant crops and varieties

To identify promising germplasm, the limits of sodicity tolerance in different crops, halophytes and glycophytes, have been studied in the field and under controlled conditions in pots and microplots (Setter and Waters 2003). The choice of tolerant varieties within a crop is essential for better production and economic returns from sodic soils. Such varieties have been identified and further improved through selection and hybridization, as in rice, wheat, mustard, barley, and sugar beet. Some of the promising varieties recently released or are in the pipeline for release for sodic soils are listed in Table 5.

The characteristics of rice varieties released by CSSRI, India, over the last few years for sodic soils (CSR10, CSR23, CSR27, CSR30, and CSR36) are presented in Table 6. Of these varieties, CSR30 is the first fine-grained basmati-type rice variety developed with a high level of tolerance for salt stress. This has been released for cultivation in sodic soils (pH_2 8.8–9.5) of northwestern districts of Uttar Pradesh, Punjab, and Haryana, India. This variety yields about 20% higher than the national check (Taraori Basmati) and is comparable with it in all aspects of grain quality. It has long, slender (7.12 mm), highly scented grains with good head rice recovery (59%), high kernel elongation upon cooking (KLAC), intermediate gelatinization temperature (GT), and intermediate amylose content (23%), which is at par with Taraori Basmati. In a panel test, it was rated as one of the best varieties, on account of its attractive flakiness, aroma, and fine elongation of cooked rice. CSR30 is relatively tall under nonstress conditions (155–160 cm) with moderately strong culms, but has intermediate height (120–125 cm) under

Table 4. Soil properties as affected by growing rice, which hastens the reclamation process.

Original soil		After the experiment				
pH_2	ESP	Without rice		With rice		Na^+ removal by rice cultivation (kg ha^{-1})
		pH	ESP	pH	ESP	
10.3	93.6	9.6	68.6	8.9	28.6	163
9.5	46.0	8.9	26.3	8.3	1.2	80
9.0	29.9	8.4	9.5	8.2	0.6	19
8.4	10.5	8.1	1.8	7.2	0.2	3

pH_2= soil : water (1:2); ESP = exchangeable sodium percentage.

Table 5. Important crops and varieties for sodic and saline soils (based on stress level with less than 50% reduction in grain yield).

Crop	Level of stress	Varieties	Remarks
Rice	pH_2 <10.2 and EC_e <10 dS m^{-1}	CSR10, CSR11, Try1, IR4630-22-2-5-1-3, CSR-13, and CSR19	Dwarf, early-maturing (120 d) and high-yielding salt-tolerant varieties
	pH_2 <9.9 and EC_e <7 dS m^{-1}	CSR-21, CSR23, CSR27, CSR31 and CSR 42	CSR21 is a long, slender variety
	Medium tolerant pH_2 < 9.6	CSR 30	Basmati-type variety
Wheat	Tolerance pH_2 <9.6 EC_e <8.5 dS m^{-1}	Kharchia 65, KRL 2-10, KRL 19, and WH157	Wheat varieties cannot grow economically beyond pH_2 9.3
	Medium tolerance pH_2 <9.3 EC_e <6.5 dS m^{-1}	KRL 1-4, KRL 19, PBW 65, and Raj 3077	
Barley	Up to pH_2 9.3 EC_e 11.0 dS m^{-1}	CSB1, CSB2, CSB3, DL200, Ratna, BH97, DL 348	Hulled barley varieties. Economic yield can be obtained up to pH_2 9.6.
Mustard	pH_2 9.2 and EC_e <8 dS m^{-1}	CS-52 and CS614-4-1-4, Pusa Bold, Varuna, and Kranti	Economic yield can be obtained up to pH_2 9.2
Sugar beet	pH_2 9.5 to 10.0 EC_e 10 dS m^{-1}	Ramonskaya 06, Polyrava-E, Tribal, and Maribo-Resistapoly	Highly tolerant of alkalinity up to pH_2 10.0

Table 6. Salient features of salt-tolerant rice varieties released by CSSRI in the recent past.

Character	CSR10	CSR23	CSR27	CSR30	CSR36
Plant height	85 cm	115 cm	115 cm	155 cm	110 cm
Maturity	120 d	130 d	120 d	155 d	135
Grain type	Short & bold	Long & slender	Long & slender	Basmati-type	Long & slender
Salinity tolerance	Up to 11.0 dS m^{-1}	Up to 9.0 dS m^{-1}	Up to 10.0 dS m^{-1}	Up to 7.0 dS m^{-1}	Up to 11.0 dS m^{-1}
Alkalinity tolerance	Up to pH_2 10.2	Up to pH_2 9.9	Up to pH_2 9.7	Up to pH_2 9.5	Up to pH_2 9.8
Grain yield (normal soils)	>6. 0 t ha^{-1}	>6.5 t ha^{-1}	>6.5 t ha^{-1}	>3.0 t ha^{-1}	>2.6 t ha^{-1}
Grain yield (salt-affected soils)	>3.0 t ha^{-1}	>4.0 t ha^{-1}	>4.0 t ha^{-1}	>2.0 t ha^{-1}	>1.6 t ha^{-1}

sodic soil conditions. Less height under stress condition is an added advantage, which prevents lodging even with intensive use of inputs.

Chemical amendments

As the nature and intensity of the problem of sodic soils vary, depending on topography, hydrological and climatic conditions, drainage availability, land use, soil texture, calcareousness, and other features, the methods of amelioration and management have to be location-specific. Sodic soils require application of an amendment before most crops can subsequently be grown. The results of various experiments conducted using different amendments (such as gypsum, pyrite, sulfuric acid, nitric acid, press mud, ferrous sulfate, and farmyard manure [FYM]) proved that gypsum, followed by pyrite, are the most useful sources because they are easily available, easy to handle, and less expensive. Furthermore, field studies have shown that pyrite was much less effective than gypsum (Swarup 2004). Experiments on highly sodic soils showed that a single application of gypsum at a lower dose before the first crop of rice is as effective as higher and repeated applications with respect to their effectiveness on crop yields in subsequent years (Swarup 2004). These field studies clearly ruled out the need for repeat application of gypsum in sodic soils. The dose of an amendment required for reclaiming sodic soil is governed by the soil's initial exchangeable sodium percentage (ESP), tolerance level of the crops to be grown, texture, mineralogy of the soil, and depth to be reclaimed. It also depends on the nature of the soil, the extent of deterioration, and the crops to be grown. Field experiments further showed that, for initiating the reclamation of sodic soils and for cultivation of shallow-rooted crops like rice, wheat, barley and berseem, application of 50% of the gypsum requirement (GR), which amounts to 10–15 t ha^{-1} in the 0–15 cm soil depth, is probably sufficient, and mixing of gypsum in shallow depths was more beneficial than deeper mixing (Khosla et al 1973). Mixing limited quantities of gypsum in deeper layers results in their dilution and reduces their effectiveness for soil reclamation. Field experiments also showed a better efficiency of pyrite when it was placed on the soil surface than when it was mixed in shallow soil depth, probably because of a better environment for oxidation. Furthermore, keeping the soil moist for 10–15 d increases pyrite efficiency by further improving its oxidation (Sharma and Swarup 1990).

Gypsum is commonly used as a chemical amendment for the reclamation of sodic soils in India, and a sizeable area of alkali soils has been reclaimed in the Indo-Gangetic Plain by its application. The gypsum was made available to farmers through reclamation corporations at highly subsidized rates (50–75%); however, this subsidy has gradually declined in recent years. Furthermore, legal implications on gypsum mining in the near future may substantially impact the availability of gypsum for soil reclamation. Application of recommended doses of gypsum for reclamation is beyond the economic means available to the small and marginal farmers. Hence, to develop a low-cost technology to minimize GR by the introduction of salt-tolerant varieties of rice and wheat seems quite promising for resource-poor farmers. Studies were initiated at the Lucknow center of CSSRI to find out the timeframe for substitution of salt-tolerant varieties with other high-yielding varieties following soil reclamation. The 4-yr data indicated that cumulative benefit-cost ratio was higher with 25% GR when combined with salt-tolerant varieties of rice and wheat, as compared with application of a double dose of gypsum with salt-intolerant rice varieties. It was noted that salt-tolerant varieties of rice can be replaced only after 3 yr when gypsum is applied at 50% GR. The replacement of salt-tolerant wheat varieties with high-yielding varieties may be considered after 2 yr if the gypsum is applied at 50% GR. However, even without the use of amendments, salt-tolerant varieties of rice and wheat could still produce a reasonable grain yield of 2–3 t ha^{-1} for rice and 0.5–1.5 t ha^{-1} for wheat, in sodic soil with pH 9.8 and 9.4, respectively, when almost no yield is expected from intolerant varieties. In general, varieties developed for normal soils have high yield potential compared with salt-tolerant varieties when planted in normal soils (pH <8.5).

The organic matter content of sodic soils is often very low. Organic manure, which includes FYM, composts, and green manure, has long been known to be effective in accelerating alkali soil reclamation. Incorporating organic materials in the soil, followed by leaching with ponding water, proved to be successful (Swarup 2004). Decomposition of organic matter results in the release of carbon dioxide and organic acids, lowering of soil pH, and release of cations by solubilization of $CaCO_3$ and other soil minerals. This will consequently increase the electrical conductivity of the soil solution, enhance the replacement of exchangeable Na by cations like Ca and Mg, and thus lower the ESP (Chhabra and Abrol 1977). Organic materials, together with inorganic amendments, further hasten the reclamation of sodic soils (Dargan and Chiller 1980). Experiments conducted on a highly sodic soil showed that application of FYM can help reduce the GR to half that needed in the absence of manure. Application of press mud (a by-product of the sugar industry) also proved to be highly effective in lowering soil pH and increasing organic C content of sodic soils (Singh et al 1999).

Water management

The presence of excess exchangeable sodium imparts poor physical properties, resulting in compaction of top layers, destruction of soil structure, and creation of extremely low transmission characteristics. Due to the dispersed soil structure, the infiltration rate of sodic soils is drastically lower than that of normal soils. Higher depths of water application are likely to cause damage to standing crops, especially wheat, due to prolonged water inundation on the soil surface, which affects root aeration. During drying, the few centimeters of surface soil dry quickly, whereas there may not be any change in water content of layers below 15 cm depth (Acharya and Abrol 1991). Due to these properties, rice is the principal crop grown on these soils. These problems indicated that water management strategies in sodic soils are quite different from those applied in normal soils. In soils that are affected by high sodicity, precision leveling enhances the leaching of salts and surface drainage, which are critical to higher crop productivity. The distribution efficiency obtained with various depths of application (4–12 cm) showed that distribution was more uniform (> 90 %) in plots with an average leveling index of 0.75 cm and poor (<50 %) in plots with an index of 6.75 cm (Tyagi 1984). High irrigation frequency with low irrigation depths has been found to improve the yield of most crops grown on sodic soils. Rice is a semi-aquatic plant; its water relations are very different from those of other grain crops as it requires flooded conditions for best growth. If moisture stress develops beyond a threshold value, the growth and yield of the crop are adversely affected. Singhandhupe and Rajput (1989) reported that irrigation of rice after 1 d of disappearance of ponded water produced as much yield as that with continuous shallow submergence, but further delay to 4 d after disappearance of ponded water significantly reduced grain yield. These agronomic manipulations could potentially save a substantial amount of irrigation water. These practices also help save the rice crop during years of water shortage (Samra and Singh 2002).

Sharma et al (1985) reported that, compared with 21 d in normal soil, the first irrigation of wheat should be given at 30 d after sowing in sodic soil (ESP = 28–50). The maximum yield of wheat was recorded when five irrigations were given at different crop growth stages in a rice-wheat system (Table 7). The three irrigations at crown root initiation, tillering, and milk stages or irrigation at 1.0 IW-CPE (irrigation water-cumulative pan evaporation) ratio gave significantly higher grain yield of wheat than the three irrigations given at other crop growth stages (Sharma et al 1990). The authors also reported that seasonal evapotranspiration (ET) of a crop with 1.0 IW/CPE was 335 mm, of which 72 mm was extracted from the 0–15-cm soil profile. A maximum water use efficiency of 6.5 kg grain mm^{-1} of water was recorded when irrigation was given at 1.0 IW/CPE. Sharma and Singh (1992) noted that, to obtain the maximum yield of mustard under a rice-mustard cropping system in sodic soils, water stress at rosette and siliquae (fruit) formation stages must be avoided. Strategies for judicious use of poor-quality water for crop production in alkali soils have been established before (Minhas and Samra 2004). Sodic underground waters can safely be used in a mixed and cyclic mode with good-quality canal water (Sharma et al l994).

Table 7. Yield and water use efficiency of wheat as influenced by different water management treatments in sodic soil. Treatments refer to the number and stage at which irrigation water was applied.

Treatment[a]	Grain yield (Mg ha^{-1})	% yield compared with yield with five irrigations	Water use efficiency (kg ha^{-1} mm)
Rainfed	0.44	14.8	2.65
One (CRI)	1.18	39.7	5.38
Two (CRI+F)	1.72	58.0	6.24
Three (CRI+J+M)	2.16	72.8	6.57
Three (CRI+T+M)	2.50	84.6	7.53
Three (CRI+T+F)	2.19	74.0	6.70
Four (CRI+T+J+M)	2.77	93.5	7.23
Four (CRI+J+F+M)	2.66	88.5	6.96
Five (CRI+T+J+M+D)	2.96	100	6.78
CD at 5%	0.153	-	0.12

[a] CRI = crown root initiation, T = tillering, J = jointing, B = booting, M = milk formation, D = dough stage.

Nutrient management

High pH, excess exchangeable Na, higher amounts of $CaCO_3$, negligible to low organic matter content, and the harsh physical conditions of alkali soils influence the transformation and availability of native and applied nutrient fertilizers. Black alkali soils are known to be deficient in both available N and P, whereas alluvial alkali soils are deficient in N but medium to high in available P. The efficiency of N fertilizer is generally low in alkali soils partly due to volatilization losses as NH_3 and partly due to suboptimal plant growth. Bhardwaj and Abrol (1978) observed that nearly 32–52% of applied N was lost through volatilization in sodic soils. To compensate for these N losses, it is recommended that crops should be supplied with 20% extra N than in normal soils (Rao and Batra 1983, Tiwari and Sharma 1989). Owing to the rapid enzymatic hydrolysis of urea in alkali soils, the released NH_3 tend to escape into the environment. These losses could be reduced to a large extent by using neem-coated urea (NCU, 35.4% N) or phospho-gypsum urea (urea G, 36.8% N). Maximum yield of paddy in alkali vertisols was obtained by the use of urea G (Deshmukh and Tiwari 1996). To achieve higher efficiency, split application of N in rice and wheat is recommended (Singh 1986, Singh 1987). Studies conducted on N requirement of rice and wheat in sodic soils indicated that during the initial years of reclamation, 150 kg N ha^{-1} is the optimum dose. Application of N to rice and wheat in three doses, half or one-third at transplanting/sowing, and the remaining applied in two equal splits at 3 and 6 wk after sowing/transplanting is better than other schedules. Due to sensitivity of soil microorganisms to soil sodicity, symbiotic N_2 fixation is also suppressed in sodic soils. *Rhizobia* was reported to survive and multiply in sodic soils with pH of up to 10.0, but the host plant was sensitive at this high sodicity level (Rao 1998).

The availability of P in sodic soils and its subsequent uptake by plants are largely governed by the pH and $CaCO_3$ content of the soil. In gypsum-amended sodic soils, octa-calcium phosphate is reported to be the dominant form of P, which results in decreased available P levels. Responses to applied P in sodic soils are governed by the nature of amendment used. In a long-term experiment at Karnal, Haryana, India, it was observed that 15 cm of the soil surface lost 24 kg ha^{-1} of soluble P through leaching in the initial years of cropping. Due to the inherently high soluble P content of the soils, rice and wheat grown in rotation did not respond to P application during the initial 3–5 years of cropping. Singh (1998) reported that the rice crop starts to show symptoms of deficiency when P levels in surface soil fall below 7.5 kg ha^{-1} (using Olsen's method). The wheat yields did not decline at this critical level in the following few years. This indicates that P application in sodic soils that undergo reclamation should be based on soil tests for available P. Application of P to either one or both crops significantly increased the grain yield of rice only after 5 years of cropping; yield of wheat increased after 11 years (Singh 1994).

The clay fraction of the Indo-Gangetic alluvium is dominated by illite, which has a good reserve of K in these soils. The rate of K release and its uptake are not ordinarily affected in sodic soils. As the water-soluble and ammonium acetate-soluble K^+ fractions are at high to very high levels in these soils, no responses to applied K have been reported. To maintain the optimum K^+:Na^+ balance in sodic soils, it is always necessary to maintain high K^+ levels. Sodic soils generally contain less than 0.6 mg kg^{-1} of DTPA extractable Zn because Zn precipitates as hydroxides and carbonates in sodic soils owing to the high pH, presence of $CaCO_3$, high soluble P, and low organic matter content (Katyal et al 1980). Rice, though fairly tolerant of sodicity, is sensitive to Zn deficiency, which may appear 15–20 d after transplanting, resulting in stunted growth with rusty brown spots and ultimately significant reduction in yield. Singh et al (1987) and Singh (1998) recommended the application of 20–40 kg Zn ha^{-1} during the reclamation phase of sodic soils. Even high levels of pyrites with fertilizers, in the absence of Zn, did not show the yield advantage possible with an additional application of $ZnSO_4$ at 50 kg ha^{-1} (Tiwari and Sharma 1989). Application of zinc sulphate to rice and berseem significantly improved their yields. Application of Zn without P was reported to be more effective than the combined application. Field experiments to standardize Zn requirements of different crop species showed that application of 10 kg $ZnSO_4$ ha^{-1} to each crop of rice and wheat or 20 kg $ZnSO_4$ ha^{-1} to rice increased the grain yield significantly over the no-Zn control (Singh and Abrol 1986). Application of Zn is reported to play an ameliorative role in alkali soils by enhancing the absorption of Ca and K and improving the Ca^{++}-Na^+ and K^+-Na^+ ratios in plants. Furthermore, the integrated use of organic and inorganic sources of nutrients was found to be more beneficial than the sole application of inorganic chemical fertilizers, in terms of sustainability of the rice-wheat system on sodic soils.

Crop diversification options for sodic soils

The choice of crops to be grown in alkali soils is restricted by the adverse physical and chemical properties of these soils. A rice-wheat cropping sequence has been recommended during the initial years of reclamation after application of gypsum. As the reclamation proceeds, there is continuous improvement in soil properties in both surface and subsurface layers, with the reclamation being faster in the surface than in the subsurface layers. Growing rice for 3 yr is reported to lower soil pH level from more than 10.0 to about 9.0, so that it becomes possible to profitably grow less tolerant crops such as wheat, berseem, and mustard. Of the four crop rotations tried in farmers' fields, paddy-wheat-*Sesbania* and paddy-berseem proved to be more remunerative (Sharma et al 1984, Tiwari and Sharma 1989). There is a distinct possibility to diversify cropping systems in the reclaimed alkali lands after 3 yr of amendment application. Depending on soil pH in the 0–15 cm layer, the crops that can be successfully grown in these soils are listed in Table 8.

Table 8. Possibilities of crop diversification options from rice-wheat system as determined by soil pH and number of years after reclamation.

Soil pH (0–15 cm layer)	Expected years after reclamation	Crops	
		Kharif (wet season)	Rabi (dry season)
9.2–9.3	3–4	Cotton, sorghum, and pearl-millet	Mustard, rapeseed, Persian clover, and berseem
8.9–9.0	5–8	Sugarcane, groundnut, pigeonpea, and soybean	Sunflower, safflower, gram, pea, and linseed
8.5–8.8	After 8 – 10 yr	Green gram and all other crops	Potato, onion, garlic, and tomato

Rice-wheat cropping systems for sodic soils

Rice-wheat is the dominant cropping system in sodic soils and this system is the world's most important cropping sequence, providing staple food for almost two billion people in South Asia alone. In China and four South Asian countries (India, Pakistan, Bangladesh, and Nepal), this system occupies 28% of total rice area and 35% of wheat area, predominantly in the subhumid subtropics, covering 22.5 million ha. This rotation is reportedly being practiced on 12 million ha in South Asia, out of which, nearly 10 million ha is in India. The major rice-wheat growing states of India are Uttar Pradesh, Punjab, Haryana, Bihar, West Bengal, and Madhya Pradesh, where sodic soils also exist. These systems increased cereal grain production dramatically during the first 3 decades of the Green Revolution, but this resulted in natural resource degradation and brought out environmental issues. CSSRI and the national agricultural research systems of Bangladesh, India, Nepal, and Pakistan have been working to identify and overcome constraints to sustained production and to increase input use efficiency of this important cropping system in order to better meet animal and human food and nutritional requirements.

Productivity and sustainability of rice-wheat system on sodic soils

Attempts were made to determine indicators of long-term productivity and sustainability of rice-based cropping systems in sodic soils in the Punjab, Haryana, and Uttar Pradesh states of India. The results indicated wide spatial and temporal variations among the three states. Although output growth and crop yields were much higher in Punjab, followed by Haryana and Uttar Pradesh, productivity growth was higher by only a small margin. The intensification, especially in the wheat-rice system, resulted in greater resource degradation in both Punjab and Haryana than in Uttar Pradesh. Concerns have been expressed about resource degradation, shrinking land and water resource base, environmental quality, and declining profitable margin from most of the highly productive areas in the country. Issues of groundwater decline and pollution, deteriorating soil quality, depleting organic matter, multiple deficiencies, in particular micronutrients, and widening NPK ratio (owing to imbalance in fertilizer use) need introspection. There is a felt need to apply more inputs to sustain yield levels and/or to further improve current yields. As seen in Uttar Pradesh, late planting and poor crop establishment also cause lower productivity. Long-term experiments showed a declining trend in rice productivity and, obviously, more inputs are required to obtain the same yield levels as before. More input-responsive varieties with pest and disease resistance need to be developed and nutrient depletion in various cropping systems need to be monitored. Farmers also have to be educated on efficient nutrient and water use strategies. A declining trend in groundwater table was observed in most parts of the rice-wheat belt due to overexploitation through tubewells. The cost of pumping water by tubewells has increased and replacement of cavity tubewells (centrifugal) by deep submersible tubewells may create some socioeconomic problems. This calls for the development of rice varieties and agronomic practices that will slow down the process of groundwater depletion and upgrade and conserve the resource quality in the Indo-Gangetic basin. A number of farmers in Punjab and western Uttar Pradesh now grow two crops of rice between May and November. Planting of short-duration rice varieties (90–100 d) in May has a drastic impact on groundwater depletion. In areas where groundwater is showing declining trends, rice cultivation in May should be discouraged.

Resource quality under the rice-wheat farming system

A decline in soil nutrient status leading to poor soil health was observed in the rice-wheat belt in both normal and reclaimed sodic soils. The proper use of green manure was found to be beneficial for improving soil health and saving on chemical fertilizers in these soils. Sodic soils are highly deficient in organic matter, which is a storehouse of essential nutrients, particularly N. Therefore, efficient management and maintenance of soil organic matter assume greater significance. Results have shown that long-term balanced fertilizer use under a rice-wheat system helps in maintaining the organic C status of the soil as compared with a control plot. The results further suggest that sodic soils have a great potential for C sequestration. Green manuring with *Sesbania* helps to build up organic matter in sodic soils. Field studies showed that use of green manure (*Sesbania*) during summer gave as much increase in grain yield of the succeeding rice crop as with field application of 75–80 kg ha^{-1} of nitrogenous chemical fertilizers, thereby saving almost half of the dose of N in the rice crop. Subsequent studies proved that incorporation of 50-d-old green manure crop before transplanting provided about 100 kg N ha^{-1} into the soil. To avoid NH_3 volatilization losses in sodic soils, CSSRI has recommended that rice should be transplanted immediately after the incorporation of green manure crops. Cultivation of summer mungbean after wheat harvest (between April and June) improves the resource quality and increases the yield of the following rice crop. In addition, the farmers obtain additional income ranging from Rs 10,000 to Rs 15,000 per acre. When sodic soils are being reclaimed by amendments and by growing rice under flooded conditions, Olsen's extractable P in surface soils tend to decrease because of its movement toward the lower subsoil layers, uptake by the crops, and increased immobilization (Chhabra et al 1980), suggesting that additional P is probably necessary during this reclamation process. Reclamation of alkali soils also helps in reducing runoff and flood hazards, in minimizing drainage needs, and in augmenting groundwater recharge (Narayana et al 1986).

Resource conservation in reclaimed and partially reclaimed sodic soils

The factors responsible for the success of a rice-wheat system in reclaimed sodic soils are minimum support prices, good economic returns, available marketing infrastructure, and less risk associated with the cultivation of these crops. Therefore, the rice-wheat system is becoming increasingly popular among farmers. In parts of Haryana, Punjab (where basmati- type rice is grown) and central and eastern Uttar Pradesh, the late harvest of rice results in delayed sowing of wheat. Poor infiltration rate of partially reclaimed sodic soils delays wheat sowing by 10–30 d in these states. Similarly, wheat sowing is also delayed in critically and semi-critically waterlogged areas, resulting in poor crop stand and grain yield. Moreover, considerable time and energy are being spent on preparing the land for wheat after the harvest of rice. To overcome the problem of late sowing of wheat and to reduce energy requirements for field preparation, zero tillage was developed. Research showed that zero tillage shows promise in saving time and energy needed for growing wheat after rice.

Zero tillage

Considerable amount of fuel is spent to prepare fields for growing wheat after rice harvest. Experience at CSSRI and in farmers' fields showed that wheat does not require any preparation for a fine seedbed, and that the main factors responsible for higher wheat productivity are use of improved varieties, timely sowing, good crop stand, and sufficient nutrient and water supply. By adopting zero tillage, sowing of wheat can be advanced by 10–15 d. It also reduces the cost involved in field preparation for sowing wheat. The tillage cost for growing the wheat crop by zero tillage is hardly 10% of the cost involved in normal field preparation being employed by farmers. Experiments conducted at Lucknow on reclaimed sodic soils (pH_2 9.0) indicated that seed germination was completed in 8.2 d under zero tillage, while it took 10.3 d with conventional tillage. The grain yield obtained using zero tillage was significantly higher than that coming from a tilled field (Table 9). The major contributing factors to the better performance of zero tillage with regard to grain yield were accelerated germination and notable gains in yield-attributing characters, particularly number of panicles m^{-2} (Sharma and Lal 2005). Zero tillage generated a total profit of Rs 4015 ha^{-1}.

Table 9. Comparison of performance of wheat grown under zero and conventional tillage in reclaimed sodic soils.

Variable	Zero tillage	Conventional tillage
Plowings (no.)	0	7
Time taken to emergence (d)	8.2	10.3
Ears m^{-2} (no.)	305.7	295.6
Grain yield (t ha^{-1})	3.51	3.28
Total monetary gain (Rs ha^{-1})	4015	-

The other resource-conserving technologies experimented in reclaimed sodic lands included direct seeding of rice, planting rice-wheat in ridge-furrow geometry, laser land leveling, and broadcasting *Sesbania* for weed control in direct-seeded rice. Most of these options proved beneficial in saving water and increasing productivity of rice (Table 10).

Environmental consequences of sodic soil reclamation

The important social benefit of sodic land reclamation is the improved quality of the environment. Use of rainwater by reducing surface runoff and consequent soil erosion during the rainy season is an important aspect of sodic land reclamation. About 40% of the total irrigation requirement of the newly reclaimed areas of rice and wheat is met from rainwater conservation. This ultimately results in an increase in groundwater recharge and improvement of soil quality. It further helps control flood hazards by reducing peak runoff during heavy rainstorms. Another important environmental benefit is the change in landscape after reclamation.

Table 10. Comparative advantages of resource conservation options on paddy yield and water productivity.

Treatment	Paddy yield[a] (Mg ha^{-1})	Applied irrigation water (cm)	Water productivity (kg m^{-3})
Direct-seeded (DSR) with shaper machine (SP) (HRK47)	5.93	55	0.53
DSR sown with line machine (HRK 47)	5.66	47	0.59
Transplanting on ridges (HR 47)	5.24	22	0.73
Transplanting in unpuddled condition (HRK47)	5.51	70	0.46
Transplanting in unpuddled condition (CSR30)	2.47	69	0.20
Transplanting in puddled condition (HRK47)	5.82	70	0.49
Transplanting in puddled condition (CSR30)	2.52	55	0.25

[a]Yield of paddy taken at 12% moisture content.

Alternate land use of sodic soils

Most sodic land possessed by individual farmers has been reclaimed through conventional techniques and has become productive under the rice-wheat system. However, a sizeable area constituted village community land and government and private land reserved for specific purposes. CSSRI has developed special techniques for reclamation and management of such sites for other uses. The most promising forest species identified for planting in highly alkaline soils are *Prosopis juliflora*, *Acacia nilotica, Casuarina equisetifolia,* and *Tamarix articulata* (Table 11). A package of cultural practices such as irrigation, fertilization, spacing, and pruning schedules for promising species such as *P. juliflora* and *A. nilotica* has been developed and standardized (Singh et al 1994). Long-term studies at Karnal further suggested that prolonged occupation of sodic soils, particularly by trees such as *Prosopis* and *Acacia,* may restore the productivity of these abandoned soils much above the present agricultural production levels (Singh et al 1998).

Table 11. Biomass accumulation of selected trees grown on highly alkaline soils for 10 yr.

Tree species	Biomass production (kg $tree^{-1}$)		
	Bole weight	Branches + leaves	Total
Prosopis juliflora	113	43	156
Acacia nilotica	85	44	129
Casuarina equisetifolia	84	28	112
Eucalyptus tereticornis	66	24	90

In addition to biomass production, growing of trees on sodic soils results in amelioration of these soils, by improving their physical, chemical, and biological properties. Long-term field studies at several locations showed that growing leguminous trees such as *Prosopis*, *Acacia,* and *Casuarina* reclaim these soils at a much faster rate than growing of nonleguminous trees because of the buildup of organic matter and the recycling of important nutrients (Table 12). It has also been proven that highly sodic soils reclaimed through tree plantations can be successfully used for growing other agricultural crops, including rice, after these trees are harvested (Singh and Gill 1992).

Table 12. Reclamation effects of tree plantations on alkali soils.

Species	Original (before planting)		After 20 yr	
	pH_2	Organic C (%)	pH_2	Organic C (%)
Eucalyptus tereticornis	10.3	0.12	9.18	0.33
Acacia nilotica	10.3	0.12	9.03	0.55
Albizia lebbeck	10.3	0.12	8.67	0.47
Terminalia arjuna	10.3	0.12	8.15	0.58
Prosopis juliflora	10.3	0.12	8.03	0.58

Earlier, it was considered difficult to raise fruit trees in sodic soils of pH_2 >10.0. But recent experiments at CSSRI, Karnal, and Lucknow, India, with some salt-tolerant species of fruit trees have shown that some fruit tree species can successfully be grown in highly sodic soils after proper site preparation and through the use of higher amounts of organic and inorganic amendments. The promising fruit species identified include aonla (*Emblica officinalis*), karonda (*Carissa carandus*), ber (*Zizyphus mauritiana*), and guava (*Psidium guajava*). A special planting method, called the pit-augerhole technique, has been developed and standardized for raising these fruit trees in sodic soils (Singh et al 1996). This planting technique consists of making pits of 60 cm × 60 cm × 60 cm dimensions and in the center of each pit, an auger bore of 20–25 cm diameter and 140–160 cm depth (to pierce through the *kankar* pan) is made using tractor-mounted augers. These pits-cum-auger bores are filled back with a mixture of original soil + 8–10 kg of gypsum +10 kg of FYM + 20 kg of river sand. A field trial on the identification of intercrops with fruit plantations showed that, if the pH_2 of the soil is less than 9.5, aromatic and medicinal crops such as *babuna* (*Matricaria camomila*) and *isabgol* (*Plantago ovata*) can successfully be grown in association with fruit trees.

The performance of rice-wheat, rice-berseem, and pigeonpea-mustard crop rotations in association with eucalyptus (*Eucalyptus tereticornis*), babul (*Acacia nilotica*), and poplar (*Populus deltoides*) was studied in a partially reclaimed soil for 5 yr (Singh et al 1997). The results indicated that association of trees with rice-wheat and rice-berseem was a better option in terms of sustainability of agriculture on reclaimed sodic soils. The organic C and available N contents were markedly improved when trees were grown in association with these crops. Various components of this model and its benefits are depicted in Figure 1.

A number of success stories involving sodic land reclamation throughout India have demonstrated the tremendous impact of this program. The socioeconomic status of the villages involved has changed considerably after adopting the sodic land reclamation program, with financial help from national and international development agencies. The villagers were mobilized for group action to reclaim their sodic land by applying gypsum, along with a package of practices that includes rice as the first crop. The social impact of sodic land reclamation is quite visible in terms of employment, food production, farm

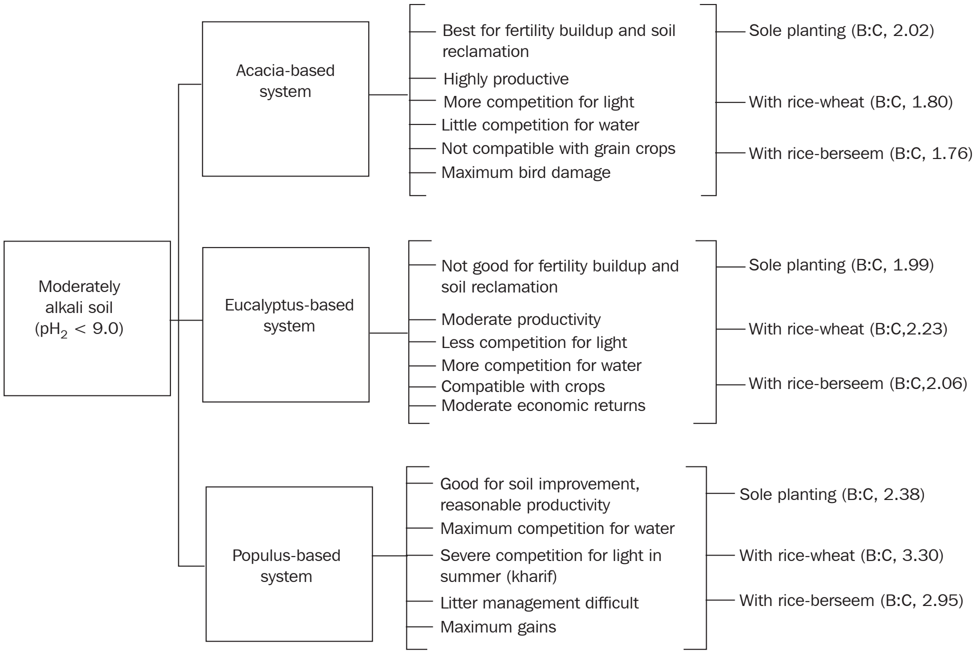

Fig. 1. Agroforestry model for commercial farming of tree crops, potential benefits, and benefit-cost ratio (B:C) when intercropped with other annual crops.

income, resource use efficiency, farm assets, capital formation, land value, improvement in soil properties, and improvement in the quality of life and the environment. It helps in eliminating poverty and inequity within and among rural societies. Social indicators such as literacy levels, birth and death rates, and life expectancy also reflected better changes. These social benefits are discussed in the following section.

Additional food grain production

In the late sixties and early seventies, there was a rapid increase in production of rice and wheat in Haryana and Punjab. Additional annual food production of rice and wheat on sodic land after reclamation was estimated to be 5 and 2.5 t ha^{-1}, respectively, after the 3rd year of reclamation. This indicates that reclamation of sodic land played a key role in augmenting agricultural production in the states of Punjab, Haryana, and Uttar Pradesh. Estimates are that, more than 1 million ha of sodic land have been reclaimed for rice and wheat production so far and about 8 million t of food grains are being added annually from these lands to the food basket of the country. It is estimated that, between 1976-77 and 1980-81, land reclamation has contributed to a 26.7% increase in rice production in Punjab, 13.8% in Haryana, and 11.5% in Uttar Pradesh (Tripathi et al 2004).

Additional employment

The reclamation of sodic soils has generated additional employment for marginal farmers as well as for landless laborers in the rural sector. Employment of roughly 165 man-days ha^{-1} could be generated in the first year of reclamation. The employment potential was estimated to be 30 man-days ha^{-1} in bunding, leveling, and gypsum application, and 94- and 41 man-days ha^{-1} in rice and wheat cultivation, respectively. In subsequent years, nearly 135 man-days ha^{-1} would be employed for the rice-wheat cropping system on farmer's field (Joshi and Agnihotri 1984).

Enhancement in land value

Reclamation of sodic soils substantially increases land value due to better resource quality and increased production potential and income. The Uttar Pradesh Sodic Land Reclamation Project executed in 10 districts in the state showed tremendous increment in the value of land over a period of 7 years from 1993 to 2000. The value of reclaimed land increased by about 48% in the B^+ category, by 108% in class B, and by 317% in class C.

Poverty alleviation

The sodic land reclamation program provided unique opportunities for alleviation of poverty, particularly among marginal and small farmers, who were delimited by the vicious circle of poverty— i.e., low investment–low output–low savings. Project interventions in Uttar Pradesh resulted in a decline of the number of households below the poverty line, following soil reclamation. Thus, a sizable number of participants have crossed the poverty line and some households have moved upward.

Gaps and future research needs to further exploit sodic land

With the rapid expansion of irrigation projects, many fertile areas are being affected by secondary soil salinization, particularly in the arid and semiarid regions. There is an urgent need to develop proper technologies for reclamation and management of these sodic soils under shallow water table conditions. In this direction, suitable farming system technologies should be put in place to increase land and water productivity and to generate year-round employment opportunities and income for small and marginal farmers. Experimental evidence shows that salt-affected lands offer ample opportunities for profitable production of tolerant high-value agricultural crops, forest species, fruit trees, grasses, agroforestry systems, and aromatic and medicinal plants. Research and development efforts must be promoted to further develop and extend these interventions.

Proper post reclamation management is essential to avoid reversion of soil sodicity/salinity and to ensure sustainability of these costly reclamation programs. Periodic monitoring of changes in soil properties after initiation of reclamation programs is indispensable to facilitate timely corrective measures. Intensive research is needed to work out feasible practical methods relating to optimum depth, number and time of flushings prior to amendment application, and also for treating and recycling drainage water and using other marginal water resources for safe irrigation of sodic soils, as in Uttar Pradesh. Research agenda should focus on the use of locally available, cheaper amendments to lower reclamation cost so that it becomes affordable and within the resources available to marginal and small farmers. This is also high time to find an alternate amendment for gypsum as legal implications on gypsum mining may affect cost and availability in the near future. Research should be strengthened to explore phospho-gypsum as a potential substitute for gypsum. Accurate prediction models need to be standardized to monitor and prevent further soil salinization and sodification in areas prone to such problems. Government-initiated, time-bound, well-planned, and adequately supported action programs will go a long way in ensuring profitable rehabilitation and sustainable management of vast tracts of salt-affected soils in India and other countries, thereby promoting food security, environmental safety, and national prosperity. Future research plans should particularly focus on the following:

- Sustaining the productivity of reclaimed soils through groundwater recharge, diversification, residue management, and adoption of resource conservation practices
- Dryland salinity management and exploiting genetic potential for biosaline agriculture
- Increasing water productivity through multi-enterprise agriculture: saline aquaculture in coastal areas integrating rice and fisheries
- Strategies for safe use and disposal of water with marginal quality
- Exploiting biotechnology and genetic engineering tools for enhancing salt tolerance through

  - identification and transfer of genes associated with tolerance for salt stress, e.g from halophytic species like *Prosopis* and *Leptochloa* to rice, wheat, and other crops
  - heavy metal remediation
  - introduction of tolerance for toxicities associated with Al, Mn, Fe, and Bo under waterlogged conditions
- Alternate affordable reclamation options for resource-poor farmers
- Location-specific, problem-oriented, participatory efforts in network modes to provide feasible solutions.

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Coastal saline ecosystems in India

S. Saha, D.P. Singh, and K.R. Mahata

India is bounded by sea on three sides with an 8,129-km coastline. The coastal ecosystem, which comprises the deltas, lacustrine fringes, lagoons, marshes, and narrow plains and terraces along the rivers and creeks, can broadly be classified into two zones: the eastern coastal plain and the western ghats and coastal plain. The west coast is dominated by steep slopes, whereas the east coast is more stable, flatter, wider, and more suited to farming. The climate varies from hot arid to hot and humid. Storms and cyclones are more common in the east coast. Of the 10.78 million ha in the coastal area, about 3.09 million ha are saline. Soils are predominantly saline, with patches of sodic, saline sodic, and acid sulfate soils. The dominant ions are Na^+, Mg^{++}, Ca^{++}, K^+ , Cl^-, SO_4^-, and HCO_3^-. Saline soils generally have low organic C and N, medium to high available P, and adequate K. However, there are some location-specific nutrient deficiencies and toxicities. Soil salinity shows wide spatial and temporal variability, depending on the distance from the seacoast, intrusion of brackish water, soil type, groundwater depth and salinity level, rainfall, season, and cropping patterns. It is low during the wet season but sharply increases during the dry season, reaching its maximum in May. Surface and groundwater salinity follows a similar trend. Rainfall is often erratic and the bulk of rainwater is lost through surface runoff. The coastal saline areas are mostly monocropped with rice in the wet season. In the dry season, rice and certain salt-tolerant nonrice crops such as barley, cotton, chili, sunflower, sugar beet, and watermelon, are grown in small areas using harvested rainwater. Productivity is low, owing to several abiotic stresses (salinity, drought, waterlogging), natural hazards, lack of suitable varieties, and poor adoption of improved agronomic and natural resource management practices. Continued efforts are needed to develop and deploy stress-tolerant varieties and improved management practices. Crop intensification and diversification integrated with small-scale agri-enterprises is necessary for sustainable food, nutrition, and economic security. Cultivation of horticultural and plantation crops, aquaculture, and raising of farm animals need to be promoted. Construction of embankments and sluice gates for preventing brackish water intrusion, rainwater harvesting, improvement of drainage system for reducing water stagnation, and reforestation of shoreline are important measures for the overall development of the coastal saline ecosystem.

Keywords: climatic variability, coastal zones; rice-based cropping system, soil salinity, water quality

The coastal agroecosystem in India plays a significant role in maintaining the overall ecological balance and in meeting livelihood requirements of the largely agriculture-based dense populations living in these areas. These coastal areas hold tremendous scope for production of many high-value commodities but are beset with many production constraints, including salinity, water stress, and natural hazards such as cyclones and coastal storms. The Indian coastline runs a distance of 8,129 km and has a continental shelf of 50,000 km^2 distributed along nine states: Gujarat, Maharashtra, Karnataka, Kerala, and Goa in the west coast; and Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal in the east coast; and two union territories of Pondicherry and Daman Diu, besides Lakshadweep, Andaman, and Nicobar Islands. The peninsular region is bounded by the Arabian Sea on the west, the Bay of Bengal on the east, and the Indian Ocean on the south. The latest division of coastal agroecosystem into subregions is broadly based on a few soil and climatic parameters (Velayutham et al 1998). However, there is a need for a more systematic study to delineate the coastal zone based on a set of well-defined scientific indices.

The total coastal area in India is estimated to be 10.78 million ha, of which 3.09 million ha is-salt affected. Agricultural productivity of the coastal areas lags far behind that of the inland areas. The situation is still worse in coastal saline areas, which are mostly rainfed and monocropped with rice during the wet season. In the dry season, lands largely remain fallow primarily due to lack of good-quality irrigation water and moderate to high soil salinity. The major abiotic constraints to crop production in these areas are salinity, early and terminal drought, and waterlogging due to heavy rainfall and poor drainage.

The coastal ecosystem is apparently widely variable with respect to climate, physiography, soil, vegetation, habitat, and socioeconomic conditions. This paper attempts to discuss the important features of coastal saline ecosystems in India and the current major constraints to agricultural production. We also outline some strategies to overcome these constraints to ensure food security and improve the livelihoods of the mostly poor rural communities living in these areas. Extensive studies on micro-level characterization of the coastal saline ecology have not been made and our discussion is based on the limited information presently available.

General features of the coastal saline ecosystem

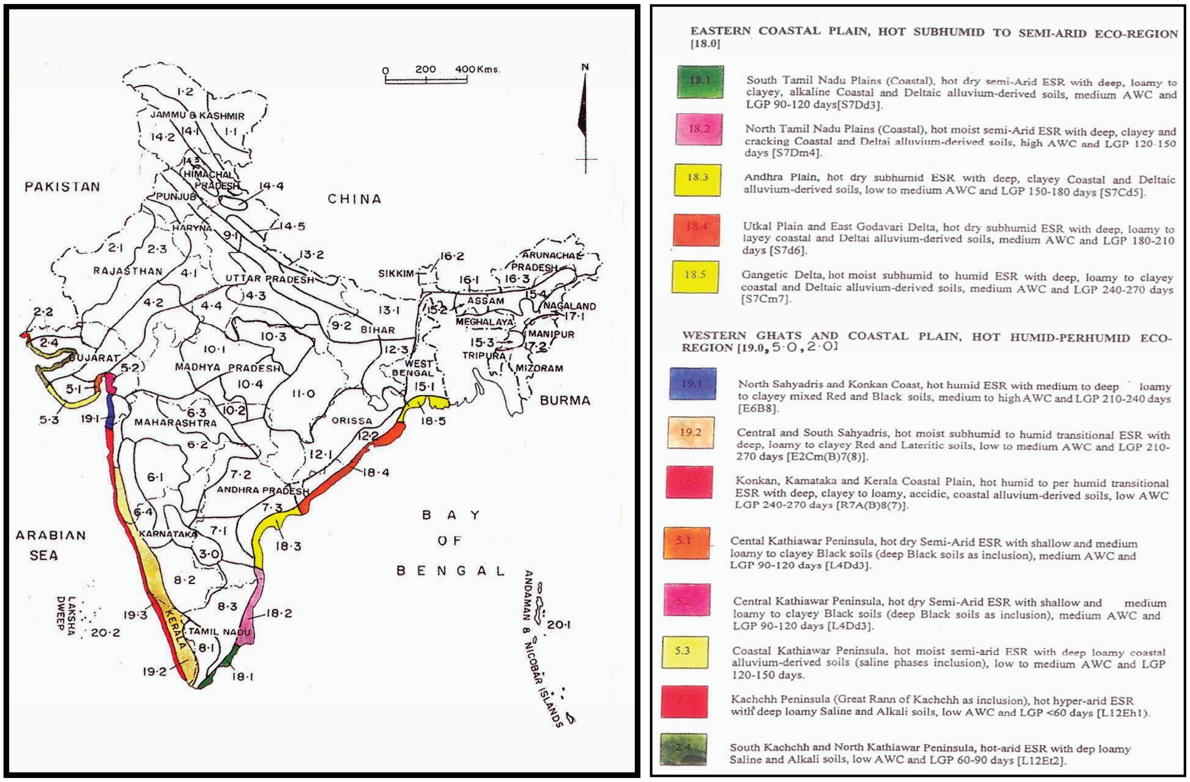
Physiographic features. The coastal ecosystem comprises the deltas, lacustrine fringes, lagoons, marshes, and narrow plains and terraces along the rivers and creeks. It also includes hinterlands, which have varied geometric and topographic features of mountains, valleys, coastal plains and riverine systems, different soils, water bodies, and vegetation ranging from tropical rainforests to coastal mangroves. The coastal zone represents the transition zone between terrestrial and marine influences, comprising the shoreline ecosystem, upland watersheds, and the near-shore sublittoral ecosystem. The coastal wetlands comprise both agricultural land and nonagricultural land with or without vegetation. Vegetated land includes mangroves, tidal swamps, and marshes, whereas nonvegetated land consists of mudflats, beach, spit and sandbars along the lagoon estuaries, and deltaic regions. The west coast is dominated by steep slopes resulting in well-drained hinterlands; the east coast is more stable, flatter, wider, and relatively more suited to farming than the west coast (Subba Rao 2001). The main geomorphic subunits of the alluvial and deltaic plains are lower alluvial plain, deltaic flood plains, marshy/inundated areas, and coastal sand dunes.

Agroecological classification and climate. According to the National Bureau of Soil Survey and Land Use Planning, the Indian coastal ecosystem can be broadly classified into two zones—the Eastern Coastal Plain and Western Ghats and Coastal Plain (Sehgal et al 1992). The Eastern Coastal Plain extends from the Cauvery delta to the Gangetic delta and occupies 2.5% of the country's total land area. It is further divided into five agroecological subregions: South Tamil Nadu Plain; North Tamil Nadu Plain; Andhra Plain; Utkal Plain and East Godavari Delta; and Gangetic Delta. Similarly, the Western Ghats and Coastal Plain (3.0% of total land area) are divided into seven subregions: North Sahyadris and Konkan Coast; Central and South Sahyadris; Konkan, Karnataka, and Kerala Coastal Plain; Central Kathiawar Peninsula; Coastal Kathiawar Peninsula; Kachchh Peninsula; and South Kachchh and North Kathiawar Peninsula. The climate is hot hyperarid in Kachchh Peninsula (annual rainfall is 300 mm and cropping season <60 d); hot arid in South Kachchh and North Kathiawar Peninsula (400–500 mm and 60–90 d); hot dry semiarid in South Tamil Nadu Plain and Central Kathiawar Peninsula (750 mm and 90–120 d); hot moist semiarid in North Tamil Nadu Plain and Coastal Kathiawar Peninsula (1000 mm and 120–150 d); hot dry subhumid in Andhra Plain and Utkal Plain and East Godavari Delta (1000–1500 mm and 150–210 d), hot moist subhumid to humid in Gangetic Delta and Central and South Sahyadris (1500 mm and 210–270 d); hot humid in North Sahyadris and Konkan Coast (2500 mm and 210–240 d); and hot humid to perhumid in Konkan, Karnataka, and Kerala Coastal Plain (2500 mm and 240–270 d; Figs. 1 and 2). The average maximum temperature is within the 25–35 ^{o}C range and the average minimum temperature rarely falls below 20 ^{o}C.

Devastating cyclones are common, resulting in ecological disasters. The east coast is relatively more vulnerable to damage from storms because of its lower slopes and the greater frequency of wind and rain storms compared with the west coast. In the Bay of Bengal, four to five tropical storms are experienced every year and two to three of them could be as severe as the ones that occurred in Andhra Pradesh, Orissa, and West Bengal (Ramakrishna et al 2001). Andhra Pradesh is most prone to tropical storms and more than 60 cyclones have occurred since 1900. Sometimes, high-intensity rainfall received during a short period, coupled with impeded drainage, causes prolonged waterlogging in several areas. The tidal flow repeatedly inundates the soil and impregnates them with salt. On the eastern coast in Sunderbans (West Bengal), the highest tides would inundate the coastal lands to a water depth of up to 2 m. Based on the influence of the tides, the coastal saline zone can be divided into four: (i) the strip closest to the sea and subjected to daily tides, (ii) the strip lying up to several kilometers away from the sea and subject to only unusually high tides, (iii) the areas where tidal influence is only through rivers and creeks, and (iv) the areas that are free from tidal influence (Chatterjee and Maiti 1981).

Soil characteristics. The soils of the coastal saline areas in India exhibit wide spatial variability and complete characterization requires exhaustive site-specific studies. Most of the published reports deal with profile characterization from a limited number of sites that may not truly represent the variability of the entire area. Soils in the east coast are derived predominantly from deltaic alluvium, although red loam, red sandy loam, coastal sand, and black soils are also found in some areas. In the west coast, soils are lateritic, gravelly clay, mixed red and black, and coastal sand. The important physicochemical properties of salt-affected soils in the major coastal states of India are presented in Tables 1, 2, and 3. Soil texture varies from sand to clay, but majority of the soils are sandy loam to clay loam. Sandy soils generally occur near the sea coast and clay soils are mostly found in low-lying areas. The pH of most soils is slightly acidic to neutral, although alkaline soils are found in some parts of Gujarat, Maharashtra, Andhra Pradesh, Tamil Nadu, and Pandicherry. Acid sulfate soils are found in low-lying areas of Kerala, Andaman, and Nicobar Islands and in some places in West Bengal. Salt-affected soils extensively occur in both east and west coasts and are predominantly saline, with patches of sodic, saline sodic, and acid sulfate soils. Most salt-affected soils have low organic C and N, medium to high available P, and adequate K. However, acid sulfate soils are rich in organic C and highly deficient in P, with problems of Fe, Al, and B toxicity in some cases (Bandyopadhyay and Rao 2001). Sandy soils have very low organic C and low nutrient contents. Saline soils are usually adequate in micronutrients, although Zn and Mo deficiencies are occasionally observed. The coastal organic soils are mostly deficient in N, P, Zn, Cu, and Mn and toxicities of Fe, H_2S, and organic substances are sometimes experienced (Ponnamperuma and Bandyopadhyay 1980).

Water resources. Most of the coastal saline areas in India are rainfed and receive relatively high rainfall, except for major parts of Gujarat in the west coast and some parts of Tamil Nadu in the east coast. This rainwater, if evenly distributed and properly managed, is sufficient to support agriculture.



EASTERN COASTAL PLAIN, HOT SUBHUMID TO SEMI-ARID ECO-REGION [18.0]

18.1	South Tamil Nadu Plains (Coastal), hot dry semi-Arid ESR with deep, loamy to clayey, alkaline Coastal and Deltaic alluvium-derived soils, medium AWC and LGP 90-120 days[S7Dd3].
18.2	North Tamil Nadu Plains (Coastal), hot moist semi-Arid ESR with deep, clayey and cracking Coastal and Deltai alluvium-derived soils, high AWC and LGP 120-150 days [S7Dm4].
18.3	Andhra Plain, hot dry subhumid ESR with deep, clayey Coastal and Deltaic alluvium-derived soils, low to medium AWC and LGP 150-180 days [S7Cd5].
18.4	Utkal Plain and East Godavari Delta, hot dry subhumid ESR with deep, loamy to layey coastal and Deltai alluvium-derived soils, medium AWC and LGP 180-210 days [S7d6].
18.5	Gangetic Delta, hot moist subhumid to humid ESR with deep, loamy to clayey coastal and Deltaic alluvium-derived soils, medium AWC and LGP 240-270 days [S7Cm7].

WESTERN GHATS AND COASTAL PLAIN, HOT HUMID-PERHUMID ECO-REGION [19.0, 5·0, 2·0]

19.1	North Sahyadris and Konkan Coast, hot humid ESR with medium to deep loamy to clayey mixed Red and Black soils, medium to high AWC and LGP 210-240 days [E6B8].
19.2	Central and South Sahyadris, hot moist subhumid to humid transitional ESR with deep, loamy to clayey Red and Lateritic soils, low to medium AWC and LGP 210-270 days [E2Cm(B)7(8)].
19.3	Konkan, Kamataka and Kerala Coastal Plain, hot humid to per humid transitional ESR with deep, clayey to loamy, accidic, coastal alluvium-derived soils, low AWC LGP 240-270 days [R7A(B)8(7)].
5.1	Cental Kathiawar Peninsula, hot dry Semi-Arid ESR with shallow and medium loamy to clayey Black soils (deep Black soils as inclusion), medium AWC and LGP 90-120 days [L4Dd3].
5.2	Central Kathiawar Peninsula, hot dry Semi-Arid ESR with shallow and medium loamy to clayey Black soils (deep Black soils as inclusion), medium AWC and LGP 90-120 days [L4Dd3].
5.3	Coastal Kathiawar Peninsula, hot moist semi-arid ESR with deep loamy coastal alluvium-derived soils (saline phases inclusion), low to medium AWC and LGP 120-150 days.
2.2	Kachchh Peninsula (Great Rann of Kachchh as inclusion), hot hyper-arid ESR with deep loamy Saline and Alkali soils, low AWC and LGP <60 days [L12Eh1).
2.4	South Kachchh and North Kathiawar Peninsula, hot-arid ESR with dep loamy Saline and Alkali soils, low AWC and LGP 60-90 days [L12Et2].

Fig. 1. Coastal agroecological subregions of India (Velayutham et al 1998).

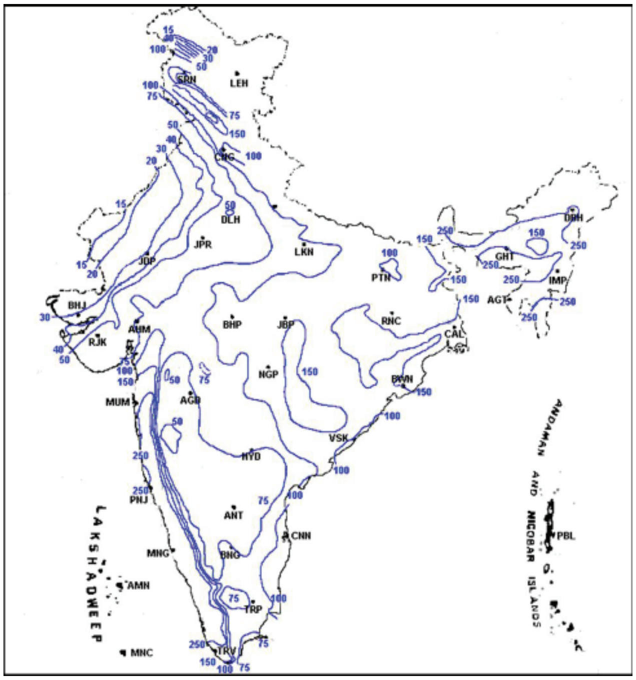


Fig. 2. Average annual rainfall (cm) in different coastal agroecological subregions of India (Indian Meteorology Department, New Delhi).

Table 1. Some important characteristics of coastal saline soils of India.

State	Texture	pH	EC (dS m^{-1})	Dominant salts
West Bengal	Silty clay and clay loam	5.5 – 7.0	4 – 53	NaCl and Na_2SO_4
Orissa	Sandy loam, clay loam, and clay	5.0 – 7.5	2 – 50	NaCl
Andhra Pradesh	Sandy loam, clay loam, and clay	6.0 – 8.8	0.5 – 17	NaCl and Na_2SO_4
Tamil Nadu	Sandy loam and clay loam	6.0 – 8.2	2 – 10	NaCl and Na_2SO_4
Kerala	Sandy loam, loam, and clay	3.5 – 5.5	1 – 20	Na_2SO_4
Maharashtra	Clay loam and clay	7.0 – 8.5	4 – 14	NaCl
Gujarat	Sandy loam and clay loam	7.5 – 8.5	9 – 20	NaCl
Karnataka	Sandy loam and clay loam	5.0 – 7.5	3 – 10	NaCl
Goa	Silty clay and clay loam	5.0 – 6.0	4 – 15	NaCl
Pondicherry	Sandy loam and clay loam	6.5 – 8.5	1 – 50	NaCl and Na_2SO_4

Sources: Ponnamperuma and Bandyopadhyay (1980), Velayutham et al (1999).

Table 2. Important physicochemical characteristicsa of salt-affected soils in major coastal states of India.

State	District (sites)	Texture	pH (1:2)	ECe	SAR	ESP	CEC	OC	Source
West Bengal	South 24 Parganas (17)	Sandy loam to silty clay (acidic to alkaline)	4.7-8.0 (5.9)	2.0-9.6 (4.5)	6.1-12.1 (8.6)	4.6-14.7 (9.4)	4.3-28.7 (18.1)	0.33-1.67 (0.76)	Bandyopadhyay et al (2003)
	South 24 Parganas (4)	Silty clay loam to silty clay (strongly acidic)	4.0-4.4 (4.2)	6.6-12.3 (9.5)	4.7-8.2 (7.0)	11.0-14.8 (13.4)	12.8-17.0 (15.8)	0.60-2.17 (1.47)	
	North 24 Parganas (6)	Sandy loam to clay loam (acidic to neutral)	4.6-7.2 (5.7)	2.4-7.2 (5.1)	3.2-10.0 (6.1)	6.4-13.4 (9.4)	11.1-20.3 (15.5)	0.25-1.61 (0.74)	
	North 24 Parganas (5)	Sandy clay loam to clay loam (strongly acidic)	4.1-4.3 (4.3)	5.9-13.9 (9.0)	4.0-8.3 (6.7)	7.0-14.3 (10.1)	12.7-21.3 (16.5)	0.63-1.86 (1.31)	
Gujarat	Kuchchh (9)	Sand to sandy loam	7.0-8.8^b (8.0)	0.5-46.0 (8.1)	6.3-22.9 (13.0)	3.4-33.9 (11.3)	-	0.06-0.86 (0.40)	Polara et al (2004)
	Surendranagar (3)	Sandy loam to clay loam	7.6-8.5 (8.1)	27.3-57.3 (40.3)	54.2-98.4 (77.2)	50.2-54.4 (51.8)	9.6-28.6 (18.8)	0.19-0.41 (0.33)	Dubey and Sharma (1987)
Orissa	Balasore (2)	Sandy clay loam and clay	5.7 and 6.1 (5.9)	6.9 and 9.7 (8.3)	16.2 and 20.9 (18.6)	6.4 and 4.7 (5.6)	15.9 and 25.7 (20.8)	0.63 and 0.92 (0.78)	Maji and Bandyopadhyay (1996)
	Puri (2)	Loam and loamy sand	5.3 and 6.0 (5.6)	6.1 and 66.4 (36.2)	22.3 and 64.4 (43.3)	26.6 and 48.8 (37.7)	10.9 and 7.4 (9.1)	0.52 and 0.35 (0.43)	Sahu and Dash (1993)
Tamil Nadu	Nagapattinam (3)	Sand to sandy loam	7.0-8.7 (7.7)	0.4-5.5 (2.1)	4.0-15.3 (8.2)	7.0-33.7 (16.6)	6.2-11.9 (8.8)	0.20-0.50 (0.33)	Singaravel and Balasundaram (2001)
Maharashtra	Konkan (9)	Sandy loam to silty loam	6.0-8.5^b (7.9)	6.9-16.1 (9.6)	24.5-47.1 (40.1)	-	-	1.2-2.9 (2.1)	Powar and Mehta (1999)
Kerala	Calicut and Alleppey (2)	Clay and clay loam	4.4 and 4.1 (4.2)	43.6 and 2.9 (23.3)	41.2 and 6.4 (23.8)	6.2 and 2.1 (4.2)	18.7 and 19.2 (19.0)	4.8 and 3.1 (4.0)	Bhargava and Abrol (1984)
	Cannanore and Ernakulam (2)	Clay and clay loam	6.5 and 7.0 (6.7)	29.4 and 44.5 (37.0)	33.9 and 48.7 (41.3)	28.5 and 25.8 (27.2)	31.6 and 39.6 (35.6)	2.8 and 3.0 (2.9)	

^{a}EC$_e$=electrical conductivity of saturation extract (dS m^{-1}); SAR=sodium adsorption ratio; ESP=exchangeable sodium percentage; CEC=cation exchange capacity [cmol (P+) kg^{-1}]; OC=organic carbon (%). Figures in parentheses are mean values. ^{b}pH (1:2.5).

Table 3. Water-soluble ions in salt-affected soils of major coastal states of India.

State	District (sites)	Water-soluble ions (meq L^{-1})							Source
		Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	SO_4^{--}	HCO_3^-	
West Bengal	South 24 Parganas (17)	8.9-82.4 (38.0)	0.1-3.1 (0.9)	1.2-21.2 (6.1)	0.9-29.9 (13.2)	1.8-74.9 (21.3)	1.5-41.5 (15.7)	0.5-3.2 (1.3)	Bandyopadhyay et al (2003)
	South 24 Parganas (4)	58.8-84.7 (72.0)	1.3-2.0 (1.6)	8.5-20.4 (14.5)	15.4-62.3 (42.2)	38.9-70.9 (49.9)	26.5-54.6 (44.2)	0.5 (0.5)	
	North 24 Parganas (6)	6.8-71.3 (42.0)	0.3-2.6 (1.0)	1.7-14.6 (8.1)	4.6-26.0 (14.1)	8.4-48.1 (30.2)	1.7-46.8 (21.6)	1.3-3.0 (2.1)	
	North 24 Parganas (5)	51.7-89.1 (70.9)	1.0-4.3 (2.3)	11.0-22.7 (18.5)	19.4-89.1 (53.1)	21.6-93.0 (51.6)	30.5-114.5 (64.5)	0.5-2.6 (1.7)	
Gujarat	Kuchchh[a] (9)	2.0-74.6 (13.7)	0.1-0.8 (0.3)	0.2-25.6 (2.4)	0.2-16.8 (1.8)	0.8-74.3 (12.8)	0.1-15.3 (2.2)	1.0-6.6 (2.7)	Polara et al (2004)
	Surendranagar (3)	315.0-787.0 (488.2)	-	24.0-90.0 (58.1)	7.5-38.0 (21.2)	276.0-811.4 (471.8)	60.0-128.0 (96.7)	1.6-2.1 (1.9)	Dubey and Sharma (1987)
Orissa	Balasore (2)[b]	54.3-91.0 (74.4)	0.5-1.4 (0.9)	4.0-8.0 (5.8)	3.6-13.5 (9.7)	54.0-98.0 (79.2)	7.9-9.8 (8.2)	Trace - 1.4 (0.5)	Maji and Bandyopadhyay (1996)
	Puri (2)	48.9 and 788 (418.4)	0.4 and 5.9 (3.1)	5.4 and 119.8 (62.6)	4.2 and 179.7 (91.9)	48.8 and 1020 (534.4)	8.5 and 73.9 (41.2)	1.1 and 3.0 (2.1)	Sahu and Dash (1993)
Tamil Nadu	Nagapattimam (3)	5.2-28.4 (13.7)	0.7-1.4 (1.0)	2.2-4.6 (3.2)	1.2-2.3 (1.6)	4.1-18.6 (9.4)	2.5-12.0 (5.9)	1.9-3.4 (2.6)	Singaravel and Balasundaram (2001)
Maharashtra	Konkan (9)[b]	110-270 (190)	-	16-43 (29.5)	34-67 (50.5)	116-464 (290)	9-29 (19)	6-17 (12)	Powar and Mehta (1999)
Kerala	Calicut and Alleppey (2)	321.7 and 16.2 (179.0)	6.7 and 1.6 (4.2)	30 and 4.6 (17.3)	92.8 and 8.2 (50.5)	354 and 21.2 (187.6)	102 and 7.3 (54.7)	2.0 and 0.5 (1.3)	Bhargava and Abrol (1984)
	Cannanore and Ernakulam (2)	244.3 and 384.7 (312.5)	5.6 and 10.4 (8.0)	26.4 and 26.0 (26.2)	77 and 78 (77)	218 and 448 (333)	131.9 and 70.0 (100.9)	2.2 and 1.0 (1.6)	

[a]Values are based on 1:2.5 dilution; [b]in cmol kg^{-1} soil.

However, rainfall distribution is often erratic and the bulk of water is lost through surface runoff. For example, in certain parts of Kerala with more than 3000 mm annual rainfall, about 70% of rainwater is lost mainly through surface runoff and per capita availability of fresh water is less than that in some dry parts of Rajasthan (Yadav 2004). In the Konkan coast, dry spells are common, despite very high rainfall because the bulk of it is received during July-August and a large portion is lost as surface runoff (Powar and Mehta 1999). The runoff losses can be reduced to some extent by constructing field bunds and embankments along the rivers and creeks. Estimates of annual rainfall and potential evapotranspiration suggest that most of the coastal areas have excess rainfall, which could be stored and used for irrigation during dry periods. Rainwater harvesting through on-farm reservoirs and off-farm storage structures (like dugout pond) is useful but expensive and needs some support from local governments.

Most of the coastal areas, particularly in the east coast, have a network of rivers, rivulets, and creeks through which most rainwater flow into the sea. The backflow of brackish water during high tides makes the river water saline and unfit for irrigation during dry periods. Construction of sluice gates across the rivers and creeks not only prevents the inflow of seawater but also helps store fresh rainwater for irrigation purposes, but this again is very expensive. Wherever such sluice gates have been constructed, plenty of fresh water is available for irrigation during the dry periods.

The unconfined groundwater in the upper layers is generally saline and unfit for irrigation. The groundwater in some confined aquifers is fresh and commonly used for irrigation with the help of shallow tubewells. However, its overexploitation leads to the lowering of groundwater table and ingress of seawater, causing a gradual increase in groundwater salinity. Continuous use of saline groundwater for irrigation leads to a buildup of soil salinity (Prasad and Prasad 2001). The problem is more severe in areas with less rainfall and poor recharge of groundwater. The hydrologic and hydrogeologic analysis of groundwater basin in Balaore, Orissa, has indicated that the current groundwater withdrawal for irrigation is about 70% more than the safe yield, and it is now severely contaminated by seawater intrusion within a 4–5-km tract along the coastline, rendering the groundwater unsuitable for drinking and irrigation (Rejani et al 2003).

Socioeconomic condition. In India, nearly 82% of farmers are small and marginal with landholdings of <2.0 ha; this proportion is gradually increasing with land fragmentation due to the increase in population. The average landholding size has decreased from 2.3 ha in 1970–71 to 1.41 ha in 1995–96. The situation is worse in majority of the coastal states. The proportion of marginal and small farmers is 90.0–98.6% in Tamil Nadu, Goa, Pondicherry, West Bengal, and Kerala; 83.8% in Orissa and 82.7% in Andhra Pradesh, based on data from the Ministry of Agriculture, Government of India, in 2000–01. A benchmark survey conducted by CRRI in the coastal saline areas of Jagatsinghpur District, Orissa, revealed that 88% of the farmers are small to marginal. Based on 2003–04 data, per capita income in primarily agriculture-dependent coastal states such as Orissa, Andhra Pradesh, and West Bengal is below the national average of Rs 11,799 (US$272), although the income in more industrialized states such as Gujarat and Maharashtra is higher than the national average. The proportion of indebted farm households in Andhra Pradesh, Tamil Nadu, Kerala, and Karnataka is 62–82%, as against the national average of 48.6%. Even in the other coastal states, barring Orissa, the indebted farm households constitute 50.1–54.8%. This clearly reflects the farmers' poor economic condition in the coastal areas. Although no separate data are available for the salt-affected areas, the situation there is more distressful. These areas have poor infrastructure and communication facilities and lag behind in the developmental activities.

The yield of rice, the major and, in some cases, the only crop grown in coastal saline areas, in nearly 60% of the Indian coastal districts is below 2.5 t ha^{-1}; one-fourth of them produce less than 2.0 t ha^{-1} (Fig. 3). These estimates are based on yields of both nonsaline and saline areas and the yield in saline areas is much lower due to various abiotic stresses and natural hazards. A baseline survey conducted by CRRI under IRRI's Consortium of Unfavorable Rice Environments (CURE) activities indicated that the yield in salt-affected areas of Jagatsinghpur was 1.89 t ha^{-1} as compared with the district average of 2.05 t ha^{-1}.

Livelihood strategies. The poor economic condition of the rural households in the coastal saline areas of India is the consequence of the predominance of small landholdings and the large number of landless families, rice monocropping, and low and unstable crop yields. Rice may help in improving the food security situation, but it cannot ensure economic uplift. The people have to depend on many other on-farm and nonfarm activities for their livelihoods. Fresh and brackish water aquaculture is one of the most promising enterprises for employment, income generation, and supply of supplementary food (Rao and Ravichandran 2001). Commercial aquaculture is practiced by a few rich farmers because of the high initial investment, while lots of people earn their daily living from open fisheries from the sea, estuaries, rivers, and creeks. The landless families also engage in sharecropping and work as farm laborers. In Orissa and West Bengal, some people grow betel vine for additional income. People living near the mangrove forests earn their livelihood by collecting and selling firewood and honey. The rearing of livestock such as cattle, goats, pigs, poultry, birds, and ducks is also an additional source of household income for many people.

Characteristics and seasonal variation of salinity

There is no sharp demarcation of coastal saline tracts in India. However, marine influences with typical flora and fauna exist roughly up to a distance of 50 km from the shoreline. Of the total 10.78 million ha of coastal area in India (Velayutham et al 1999), saline soils are spread over an area of 3.09 million ha, of which 2.52 million ha are agricultural land and 0.57 million ha are under mangrove forests (Table 4). The east coast accounts for more than 60% of agricultural land and 76% of this is distributed

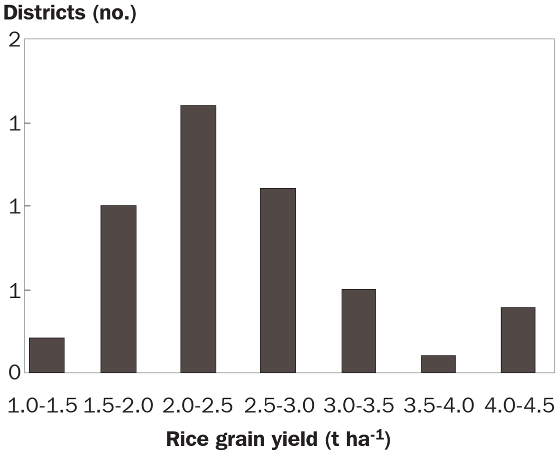


Fig. 3. Distribution of rice yield in coastal districts of India (2003-04) (Ministry of Agriculture, Government of India, New Delhi).

Table 4. Total area of salt-affected soil in coastal states of India.

State/union territory	Area (in ‘000 ha)
Andhra Pradesh	276
Goa	18
Gujarat	714
Karnataka	86
Kerala	26
Maharashtra	63
Orissa	400
Tamil Nadu	100
West Bengal	820
Andaman and Nicobar islands	15
Pondicherry	1
Mangrove forest (all states)	574
Total	3093

Source: Yadav (2001).

in West Bengal and Orissa. Of the remaining area in the west coast, Gujarat alone accounts for nearly 80%. Salinity in coastal soils is either inherent since the time of soil formation under marine influence or occurs due to periodical inundation with tidal water or both. In lowlands near the sea, high water table and saline groundwater also contribute to salinity buildup.

The problem of salinity is highly complex and dynamic in nature. Soil salinity shows wide spatial and temporal variability, depending on the distance from the sea coast, intrusion of brackish water, land situation, soil type, depth of groundwater table, groundwater salinity, cropping pattern, rainfall, and season. Some data on important soil salinity parameters for major coastal states of India are summarized in Tables 1, 2, and 3. However, any generalization and comparison among the states based on the limited information may not be dependable because of the differences in time and place of sampling, land situation and hydrology, soil type, protection against brackish water, and cropping history. The problem of salinity appears to be more severe in Gujarat, Orissa, and West Bengal than in the other states. High soil EC values have been observed in areas close to rivers and creeks, particularly in unprotected areas subjected to brackish water intrusion. NaCl and Na_2SO_4 are the predominant salts present in the coastal saline soils. Major cations and anions in decreasing order are Na^+, Mg^{++}, Ca^{++}, K^+ and Cl^-, SO_4^-, HCO_3, but soils having free $CaCO_3$ have more of Ca^{++} than Mg^{++}.

Soil salinity is generally low during the wet season and sharply increases during the dry season, reaching its maximum in May (Bandyopadhyay et al 2003). In almost the entire salt-affected coastal areas in India, high rainfall received during the wet season from June to September causes salt dilution and washing. However, late onset or early cessation of the monsoon and long dry spells considerably increase the salinity levels. With the receding monsoon and drying of fields, the soil becomes increasingly saline from November onwards. Depth of groundwater table and salinity of groundwater also show similar variability and seasonal fluctuations commensurate with the rainfall pattern. As the dry season progresses, depth of groundwater table and groundwater salinity increase gradually in response to higher atmospheric evaporative demands (Fig. 4). In most of the coastal areas, shallow groundwater is encountered at a depth of 1–2 m below the ground level in the dry season and rises above the soil surface during monsoon season. The salinity of groundwater ranges from less than 2 dS m^{-1} during the monsoon period to 20 dS m^{-1} or more during summer months (Burman et al 2005). Salinity levels in different water sources such as estuaries, creeks, ponds, and wells also undergo similar seasonal fluctuations (Sahu and Dash 1993). Sometimes, seawater enters the fields directly or through breaches of river/creek embankments during high tides and cyclones, resulting in an increase of salinity to such an extent that farmers are forced to shift to shrimp farming.

Crops and cropping systems

About 44% of the area in the east coast and 38% in the west coast of India are being cultivated, with a cropping intensity of 134% and 125%, respectively. The important crops and cropping systems prevalent in the coastal agroclimatic zones in the different states of India are listed in Table 5. During the wet season, rice is the main crop grown under different hydrological situations. The crop is mostly transplanted randomly after the accumulation of sufficient rainwater and dilution of salts. In the ‘Pokkali’ areas of Kerala, surface soil is heaped into mounds (1.0 m long × 1.0 m wide × 0.5 m high) before the onset of the monsoon for washing and leaching of salts by rainwater (Tomy 1981). Rice seeds are then sown on top of the mounds and seedlings are uprooted along with the soil for transplanting in the main field. In low-lying submergence-prone areas, the use of older and taller seedlings is a common practice to reduce damage due to waterlogging. Sugarcane is also tolerant of water stagnation and is grown in certain low-lying areas of Andhra Pradesh, Tamil Nadu, Karnataka, Gujarat, and Orissa. Cotton, sorghum, and pearl millet are grown in low-rainfall areas

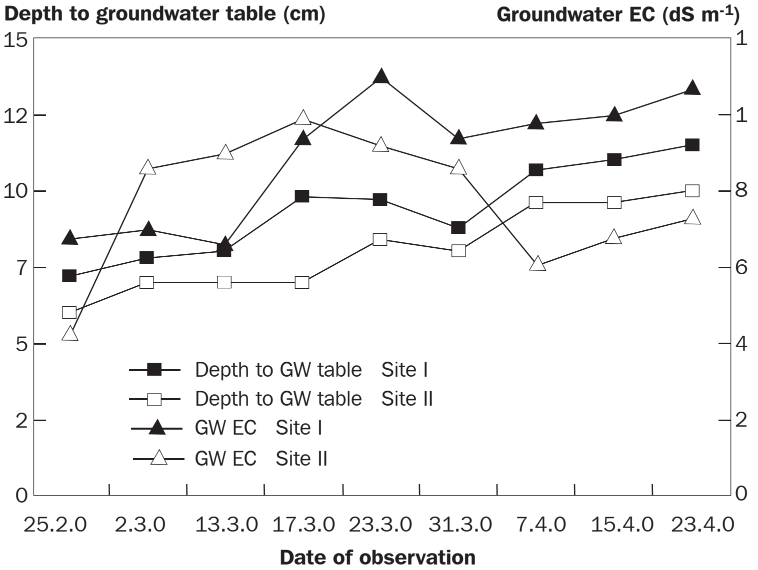


Fig. 4. Variability in depth to groundwater table and salinity during the dry season at Ersama, Orissa (Singh et al, unpubl.)

Table 5. Important crops and cropping systems found in coastal areas in different states of India.

State	Field crops		Plantation crops/spices	Prevalent cropping system	Source
	Wet season	Dry season			
Andhra Pradesh	Rice, cotton, sugarcane, tobacco, groundnut, pearl millet, sorghum	Black gram, green gram, horsegram, groundnut, sesamum, chili	Coconut	Rice-based Sugarcane-based Groundnut-based	Rastogi (1991a)
Gujarat	Rice, cotton, groundnut, sugarcane, sorghum, pearl millet	Sorghum, pearl millet, groundnut, chili	-	Rice-based Groundnut-based Cotton-based	Saxena (1991)
Karnataka	Rice, groundnut, sugarcane, pigeon pea, horsegram	Fingemillet, chili	-	Rice-based	Rastogi (1991b)
Kerala	Rice, tapioca, yam, cassava	Rice, sweet potato, sesamum	Coconut, areca nut, rubber, black pepper, cashew nut	Rice-based Coconut-based	Gangopadhyay (1991a)
Maharashtra	Rice, finger millet, sorghum	Groundnut, niger, black gram	Coconut, areca nut, clove, black pepper,	Rice-based	Singh (1991)
Orissa	Rice, sugarcane, jute	Rice, black gram, green gram, groundnut, sunflower	Coconut, cashew nut	Rice-based	Gangopadhyay (1991b)
Tamil Nadu	Rice, sugarcane, sorghum, pearl millet, tapioca	Rice, groundnut, cotton	Coconut, cashew nut	Rice-based	Gangopadhyay (1991c)
West Bengal	Rice, jute	Rice, barley, lathyrus, sunflower, sugarbeet, chili, watermelon	-	Rice-based	Gangopadhyay (1991d)

of Gujarat and Maharashtra in the west coast (Chatterjee and Shrivastava 1990). Groundnut is also grown in certain parts of Andhra Pradesh, Gujarat, and Karnataka. In Andhra Pradesh, tobacco and cotton are grown in areas free from water stagnation. Jute is cultivated mainly in West Bengal and Orissa. In the high-rainfall zone of Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu, plantation crops such as coconut and oil palm are grown extensively (Sunitha and Varghese 2005). Cultivation of black pepper (intercropped with coconut or oil palm), cassava, sweet potato, tapioca, elephant foot yam, turmeric, and ginger is also prevalent in Kerala and Karnataka (Dhandar et al 2001).

During the dry season, rice is grown in certain parts of Tamil Nadu, Orissa, West Bengal, and Andhra Pradesh where adequate irrigation water is available. Groundnut is grown in areas with limited irrigation at many places in Orissa, Tamil Nadu, Andhra Pradesh, Gujarat, and Maharashtra. Then, there is chili in Andhra Pradesh, West Bengal, Gujarat, and Karnataka; sunflower in Orissa and West Bengal; pulses like black gram, green gram, and horsegram in Andhra Pradesh, Orissa, and Maharashtra; cotton in Tamil Nadu; and watermelon and sugar beet in West Bengal. The above information is for the coastal ecosystem as a whole and only a few reports are available on salt-affected soils. Most of the coastal saline areas are generally rainfed and monocropped with rice. In the dry season, land mostly remains fallow due to lack of fresh water and high salinity. However, rice and certain salt-tolerant nonrice crops are grown in pockets using rainwater harvested in surface bonds. Crops such as barley, cotton, chili, sunflower, sugar beet, and watermelon are grown in a few places, depending on soil and climatic conditions. Under low salinity, groundnut and pulses such as black gram, cowpea, and green gram are grown in many areas. On-farm trials conducted by CRRI showed that sunflower, *Basella*, chili, watermelon, ladyfingers, and pumpkin are promising nonrice crops for coastal saline soils of Orissa; some of them are being adopted by farmers (Singh et al 2006).

The mangrove forests in India are spread over an area of about 0.5 million ha, mostly in the states of West Bengal, Gujarat, Andaman and Nicobar Islands, Andhra Pradesh, Orissa, Maharashtra, and Tamil Nadu. The east coast supports extensive mangroves because of the intertidal slope and heavy siltation. The largest mangrove forests are located in the Sundarbans of West Bengal. In Andaman and Nicobar Islands, forest coverage is nearly 88% of the total land area. These forests provide a favorable habitat for a variety of marine fishes, crabs, snails, mussels, and many other important organisms. Besides protecting the shorelines and river banks, the forests serve as the source of honey, timber, fuel wood, poles, tannin, resins, dyes, and useful medicine. Some of the useful tree species are *Heritiera fomes* for making boats, *Excoecaria agallocha* for matchbox, *Aegialitis rotundifolia* for high-grade salt, *Xylocarpus granatum* for pencils, and *Ceriops decandra* for timber (Yadav 2001, Bandyopadhyay et al 2003).

Problems of agriculture in the coastal saline ecosystem

Coastal regions suffer from a complex array of climate-, soil-, and water-related problems and agricultural productivity is low and unstable. Most of these areas, except for parts of Gujarat and Tamil Nadu, receive high rainfall, but the distribution is often erratic, resulting in early- and late-season droughts and frequent waterlogging, particularly in low-lying areas with poor drainage system. The problem is further aggravated by the frequent occurrence of cyclones and storms, especially in the east coast, sometimes causing heavy losses to crops, livestock, and human lives. In 1999, a super cyclone in the Bay of Bengal, with a windspeed of 250-300 km h^{-1}, ravaged 13 districts of Orissa and inundated vast tracts of land with seawater up to a distance of 20 km from the coast (Singh et al 2001). Low solar radiation due to cloud cover during the wet season adversely affects crop productivity. Soil erosion, particularly in the west coast with steep slopes, is also a serious concern.

High soil salinity, coupled with shallow and saline groundwater table at many places, is a major constraint to agricultural production, particularly during the dry season. The problem is aggravated by frequent intrusion of tidal brackish water in the land and aquifers, particularly in unprotected areas. Even in protected areas, breaching of embankments sometimes leads to soil and groundwater salinization. Besides, there are a number of location-specific soil problems such as Fe and Al toxicities and P deficiency in acid soils, Zn deficiency in alkaline soils, low fertility in sandy soils, and N, P, Zn, Cu and Mn deficiencies and Fe and H_2S toxicities in organic soils. In many coconut-growing areas of south India, deficiency of B is commonly observed. Increasing deforestation for purposes of fuel wood, crop cultivation, and human settlement is leading to soil degradation and ecological imbalance. Rice productivity in the wet season is low (1.5–2.0 t ha^{-1}) because the crop frequently suffers from drought, coupled with salinity at the seedling and reproductive stages in the event of a delayed onset or early cessation of monsoon and water stagnation, mostly at vegetative stage under high rainfall and poor drainage. Another problem, particularly in the east coast, is cyclonic disturbances that cause severe crop losses. Lack of suitable varieties with multistress tolerance and poor adoption of improved agronomic and natural resource management practices also contribute to low productivity. Breeding efforts in the past to incorporate high yield potential with tolerance for various soil and environmental stresses have made limited success due to the prevailing harsh and diverse ecologies that require location- and constraint-specific varieties (Siddiq and Shivkumar 1998). In the dry season, the limited availability of fresh water restricts crop intensification. For food security, farmers prefer to use the available fresh water mostly for growing a second crop of rice instead of the less water-consuming nonrice crops because of the high risks they face during the wet season. However, the progressive increase in salinity with time during the dry season due to high temperature, along with high wind velocity at the reproductive stage, leads to high sterility and poor crop yield.

Use of horticultural and plantation crops is limited to farmers with large landholdings, while small and marginal farmers have to grow rice and other field crops for their household food security. Aquaculture, dairy, poultry, goat rearing, and piggery are potential enterprises for income generation but these have not yet been developed in these coastal areas, mainly due to poor resource base, high risks, and inadequate infrastructure. The lack of awareness about different technology options as a consequence of poor extension and communication services, low profitability, and limited credit and marketing opportunities are some of the other socioeconomic constraints. Shrimp farming is highly remunerative and is gaining popularity in certain areas, but it may lead to salinization of groundwater and neighboring lands, rendering them unsuitable for growing other crops (Alagarswami 1995). Marine fishery is affected by excessive fishing in shallow shore areas, brood stock and juvenile fishing, particularly in the breeding grounds and ingress points in estuaries and mangroves, which result in the depletion of the fish catch.

Prospects for improving agricultural productivity in coastal areas

Improving rice productivity is the primary concern for ensuring household food security of the predominantly poor and subsistence farmers in coastal saline areas. Continued efforts have to be made to develop and deploy multistress-tolerant varieties. This must be accompanied by improved crop and natural resource management practices for enhancing crop survival and productivity and for stabilizing yields under stress. Introduction of location-specific, rice-based cropping systems that integrate oilseeds, vegetables, and pulses with proper soil and water management could considerably contribute to increasing crop production, improving farmers' income, and ensuring food and nutritional security. Cotton, sugar beet, barley, and watermelon are the other potential crops for certain areas. Tropical tuber crops such as cassava, tapioca, sweet potato, and yams are widely grown, particularly in south India, as alternate sources of food. However, there is immense potential for commercialization and value addition, as these crops serve as raw materials for starch and pharmaceutical industries. Cultivation of fruit crops such as guava, sapota, mango, jackfruit, and banana; plantation crops such as cashew nut, coconut, areca nut, and oil palm; spices such as black pepper, cardamom, ginger, turmeric, cumin, coriander, fennel, and fenugreek; and certain medicinal plants needs to be promoted, particularly for farmers with large landholdings, for better income and additional employment.

Animal husbandry and livestock production need to be strengthened not only for meeting the food and nutrition requirements but also for bringing in sustainability to the production system. Improving the livestock population and providing better cattle feed and fodder are needed to increase milk production. Furthermore, there is ample scope for increasing meat production through goat and poultry rearing with the establishment of hatcheries and broiler farms. This calls for sustained efforts of both government and nongovernment agencies.

Production from inland fisheries can be increased by bringing more areas under aquaculture with diversification from single species to composite culture of different prawn species, oysters (including pearl oysters), mussels, and crabs. Mariculture is now being practiced on a small scale in enclosed backwaters and estuaries in Andhra Pradesh, Kerala, Karnataka, and West Bengal. Rice-shrimp farming is also promising, particularly in areas where high salinity during the dry season prohibits cultivation of other crops. The system has been standardized and widely adopted in some countries such as Vietnam and Thailand and can be tried in similar areas of India.

Policies and infrastructure need to be developed for conservation, transport, and marketing of the surplus agricultural produce and by-products after value addition, which will provide additional employment and income to rural communities. As demand for high-value products like shrimp is increasing, processing infrastructure for value-added products such as cooked, ready-to-eat products, and canned food has to be strengthened by providing processing facilities.

Synthesis and recommendations

The coastal saline ecosystem of India is widely variable with regard to climate, soil, water resources, and socioeconomic conditions, which determines the choice of crops and crop varieties, cropping systems, and other associated enterprises. Crop and natural resource management also has to be tuned to the specific agroclimatic conditions of different locations. Salinity, which depends on climate, soil type, land situation, position and quality of groundwater, brackish water intrusion, and cropping pattern, shows large variations not only between locations but also within a given location. Therefore, extensive soil and groundwater characterization at the micro level is a prerequisite for site-specific system production planning. This is a huge task and requires concerted efforts from various research organizations. Rice is the main crop during the wet season in most of the areas and its productivity is low due to multiple and complex constraints, including salinity, drought, waterlogging, and natural disasters. Enhancing and stabilizing the yield of wet-season rice is the key to household food security, and this can be achieved by developing appropriate varieties and practices. On-farm trials conducted by CRRI have shown that even the available salt-tolerant, high-yielding varieties with improved management have the potential to double grain yield. The yield advantage could be further enhanced with improved stress tolerance and proper management.

In the dry season, only limited areas are planted to rice, depending on the availability of fresh water. Presently, short-duration varieties are grown in less saline areas using harvested rainwater. The development of varieties with high levels of salt tolerance is important for increasing yield under salinity stress and a few such lines developed by IRRI and CRRI have been found promising. While cultivation of rice is possible in areas where relatively more fresh water is available, crop diversification using less water-requiring, salt-tolerant, nonrice crops should be given priority in areas where fresh water is scarce. This will help expand the cropped area in the dry season and increase land and water productivity. These crops must be carefully selected on the basis of their suitability to local agroclimatic conditions, profitability, and farmers' preferences. Harvesting of rainwater through appropriate infrastructure and optimizing water use through proper water-saving technologies should be given greater attention. A wide variety of fruit and plantation crops, spices, and medicinal plants are promising for commercial exploitation, particularly on highlands in Kerala, Karnataka, and Andhra Pradesh. Shrimp farming is highly profitable if carefully and properly practiced.

The overexploitation of groundwater causes intrusion of seawater into the freshwater aquifers, deforestation of mangroves disrupts the food chain and threatens the existence of several aquatic species, and brackish water aquaculture causes salinization of soil and groundwater. Therefore, sustainable management of natural resources is of utmost importance in ensuring the stability of the production system. Research should provide the knowledge needed to maintain a balance between agricultural development, natural resource conservation, and socioeconomic growth to halt further degradation of the environment. Construction of embankments and sluice gates to prevent brackish water intrusion, rainwater harvesting to increase fresh water availability, improvement of drainage systems to reduce water stagnation, and afforestation to protect the shoreline are important considerations for the overall development of the coastal saline ecosystem. However, these measures are cost-prohibitive and can be implemented only through government support. The following are some of the important recommendations for consideration of researchers, policymakers, government officials, and extension agencies.

Researchable issues

- Complete site-specific characterization of soil, including spatial and temporal variability of salinity, for proper assessment of the different components of the production system
- Extensive characterization of water from different sources such as estuaries, rivers, creeks, ponds and groundwater and monitoring of seasonal fluctuations of water quality
- Inventory of existing crops/crop varieties, cropping systems, and farmers' practices in different agroecological zones for designing need-based technologies
- Development of better salt-tolerant varieties of rice and nonrice crops and location-specific management practices for increasing productivity and profitability of rice-based cropping systems
- On-farm testing, refinement, and dissemination of improved technologies through active participation of different stakeholders

Developmental issues

- Development and strengthening of irrigation and drainage systems to minimize crop losses due to abiotic stresses and natural calamities
- Construction of embankments, sluice gates, and water-harvesting structures to prevent soil and groundwater salinization and increase fresh water availability
- Promotion of location-specific fruit and plantation crops and other enterprises such as aquaculture, apiculture, mushroom cultivation, and animal husbandry for income generation and value addition
- Development of infrastructure and marketing facilities

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