Herbicides in Asian rice: transitions in weed management

EDITED BY ROSAMOND NAYLOR

STANFORD UNIVERSITY
INSTITUTE FOR INTERNATIONAL STUDIES

IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE

DEDICATION

To Keith Moody
WEED SCIENTIST

As an agronomist and leading weed scientist at two major centers in the CG System—the International Rice Research Institute (IRRI) from 1975 to 1995 and the International Institute of Tropical Agriculture (IITA) from 1969 to 1975—Keith Moody has played a critical role in designing strategies for weed management as part of the Green Revolution for rice. He has worked with scientists in nearly all countries of Asia and West Africa where rice is grown, and he has published more than 200 research papers in internationally refereed journals. His professional memberships include International Weed Science Society (president, 1984-88), Asian-Pacific Weed Science Society (treasurer, 1984-90), and Weed Science Society of the Philippines (president, 1984-85; vice-president 1983-84, member of the board of directors, 1976-86 and 1988). His professional service includes *Weed Abstracts* (editorial advisory board member), *Crop Protection* (international editorial board member), and *Journal of Plant Protection in the Tropics* (panel of reviewers-members). He coordinated IRRI's weed science training short course and guided more than 30 degree candidates and research fellows.

Keith Moody has challenged weed scientists throughout Asia and Africa to pay close attention to farmers and their traditional methods of weed control. He has sought to develop an integrated weed management strategy for rice production that is scientifically sophisticated, compatible with traditional pest management practices, profitable for farmers, and nondamaging to the environment. His knowledge of farmers' behavior and field conditions with respect to weeds is unsurpassed. It is to his excitement for weed science and to his deep concern for the welfare of rice farmers and the health of rice-based ecosystems that this volume is dedicated.

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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of 16 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). Its membership comprises donor countries, international and regional organizations, and private foundations.

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FOREWORD

Weeds have been a persistent problem in rice since the beginning of settled agriculture. For Asia as a whole, weeds cause an estimated 10-15% reduction in rice yields-equivalent to about 50 million tons of rough rice annually.

Traditionally, rice farmers have managed weeds primarily through water control and by hand labor. Now, rice farming is undergoing rapid change. Labor costs are increasing as labor supplies in the rural sector dwindle, and the availability of water for agriculture is decreasing. Farmers are turning to new rice culture techniques-direct seeding instead of transplanting and reduced use of water for early weed suppression. With these new ways of growing rice, weed control relies heavily on herbicides. The increasing use of herbicides, while lowering production costs, also poses risks to the environment and human health. Perhaps most worrisome for the future stability of rice agriculture is the potential buildup of herbicide resistance in weeds where herbicides are overused or used inappropriately.

Research on weed ecology and management in Asian rice systems is at a watershed. Ensuring the sustainability of rice production systems calls for much broader, more integrated weed management strategies. The challenge for IRRI and national rice research programs in Asia is to increase the cultural, chemical, and biological methods available for weed management; to expand knowledge and understanding of weed ecology; and to integrate knowledge, understanding, and new methodology into realistic weed management systems for farmers. This effort requires the cooperation of both private and public sectors, and the participation of policy makers, national and international research communities, and, of course, rice farmers themselves.

Immediate attention needs to be directed to the benefits and risks of herbicide use and misuse in rice, without repeating the shortcomings of Asia's 20-yr-old experience with insecticides. Two decades ago, the intensification of rice production to increase the food supply for an additional 600 million people in Asia pressured changes in rice insect pest populations. Over reliance on pesticides to control the new levels of harmful insects caused adverse responses in insect communities. These responses, characterized by repeated cases of pesticide resistance, generated new areas of research, which led to a better understanding of the rice-refuge-pest-predator relationships. That understanding makes it possible to manipulate and reestablish the natural resilience of rice ecosystems at higher levels of productivity.

While most herbicides are much less toxic and persistent than the majority of the insecticides applied in Asian rice production, widespread use of herbicides in densely populated areas—especially when the chemicals are misused—is cause for concern. It is time for researchers and their farmer partners to undertake work to better understand the changing ecology of weed pests as a basis for developing tactics for environmentally sound weed management. New weed management is needed that allows farmers to profit from rice farming in our changing world.

The question of how to manage rice herbicides appropriately in Asia was addressed by a conference held at Stanford University in 1994. Scientists from several national research programs in Asia, science and policy researchers from academic institutions and private agrochemical industries, and scientists from IRRI presented discussion papers. The conference was an outstanding forum for these knowledgeable individuals to discuss current trends in herbicide use, the direct and indirect costs-benefits of herbicide use over time, and the research needed to develop viable weed control strategies. One important outcome was a fundamental shift in the perceptions of participants as to the scope, importance, and potential impacts of expanding herbicide use in Asian rice production.

Herbicides in Asian rice: transitions in weed management grew out of a series of papers that were presented at that conference. The chapters that follow define the links between the economics of weed control, herbicide use, and weed ecology. We hope this book will provide a basis for developing a much broader array of weed management tools from which integrated weed management strategies can be designed. Understanding the linkages and developing rational methods are critical in efforts to achieve greater sustainability of rice production.

KENNETH S. FISCHER
Deputy Director General for Research
International Rice Research Institute

PREFACE

Asia is entering the 21st century on a wave of unprecedented economic growth that, in much of the region, is fundamentally transforming agriculture. High rates of industrialization are diminishing the relative importance of agriculture in the economy, drawing away labor and driving up wages. Most Asian countries can no longer be characterized by labor surpluses and economic stagnation in the countryside.

Although rural underemployment still exists in some slow-growth countries, such as Cambodia, Myanmar, and Bangladesh, farmers in the rapidly industrializing countries, such as Korea, Thailand, and Indonesia, are having increasing difficulty securing labor at affordable prices. At the same time, there is rising pressure on agricultural systems throughout the region to increase productivity, in order to feed expanding populations and generate marketable surpluses for urban growth.

For a region that is home to more than half the world's population—an ever larger proportion of them living in cities—a major challenge looms: how to increase agricultural production to meet rising food demands, at prices that will be affordable to both rural and urban residents. This challenge is particularly pressing in Asia's rice-based economies. Rice continues to be the primary staple in the Asian diet, accounting on average for more than one-third the total calories and one-fourth the protein intake. Over the next 30 years, rice demand in Asia, estimated conservatively. will increase by 1.5% a year. Meeting that demand will require world rough rice production to increase from 525 million tons per year to more than 800 million tons per year.

Virtually all of the needed rice supplies must come from higher yields; few opportunities exist to expand the high-productivity cropping area. The amount of prime agricultural land area in most Asian countries is actually declining in the face of urbanization, industrial growth, and the expansion of rural settlements. Moreover, increases in yield are beginning to taper off in several high-productivity rice systems.

The need to raise yields and maintain profits on a progressively limited land base has paved the way for expanding the role of herbicides in Asian rice production. Farmers are left with little choice but to cut labor and production costs, in particular for the most labor-intensive tasks such as planting and weeding. Herbicides increasingly are being substituted for manual labor as a method of weed control. This trend is being reinforced by the adoption of direct seeding in many wetland rice areas.

Direct-seeded rice offers a high potential for yield increases in the near term. Indeed, the new rice type being developed at the International Rice Research Institute (IRRI)—a so-called "super rice" cultivar that promises to increase yields by 20% or more—will result in varieties that will be primarily direct-seeded, in much denser stands than transplanted rice. As this new set of green revolution technologies spreads throughout Asia early in the 21st century, herbicides will become an integral component in intensive rice production systems.

Herbicides have long been used in the more industrialized countries of Asia, such as Japan and Korea. Now their use is spreading rapidly in the less developed countries in the region, including Malaysia, Vietnam, and India. They will surely become important in even the lowest income countries in the next few decades as agricultural chemicals become more available and affordable.

The steady emergence of herbicides as a preferred technology for weed control in Asian rice systems follows a 20-year period of widespread growth in insecticide use that is just beginning to subside. Asian farmers now realize that their dependence on insecticides has often been unnecessary, expensive, and sometimes even dangerous. Although herbicides are thought to be a less serious problem than insecticides in terms of acute toxicity to humans and crop damage to rice, the inevitable question arises: 20 years from now, will Asian societies regret having gone down the herbicide path?

This volume reflects one of the first comprehensive attempts to address this question. It is comprised of a series of papers by economists, agronomists, biologists, plant breeders, soil scientists, and agricultural policy specialists that focus on the growing use of herbicides in Asian rice systems and the implications of that use for rice productivity, rural incomes, human health, and ecosystem viability. While the focus is primarily on rice and rice technology in Asia, the content seeks to develop a much broader perspective of technological change than is common in the agricultural literature. Agricultural technology does not develop in a vacuum, nor is agriculture isolated from other economic sectors. Its evolutionary path is influenced by governments, private companies, and millions of individual farmers.

The extent to which new agricultural technologies are appropriate depends on the economic and social, as well as biophysical, dynamics operating in an agricultural system as a whole. The main objectives of this volume are to describe and analyze these dynamics in an effort to determine the optimal role of herbicides—in terms of both private and social well-being—in Asian rice systems.

Because of the wide variation in herbicide use throughout Asia and the growing importance of herbicides in many Asian countries, there is clearly a need for a few basic rules on weed management that can be applied broadly at the farm level, the national level, and the level of international research. The search for simple solutions to complex problems requires extensive knowledge on herbicides and weed management that spans a number of disciplines. This volume attempts to impart the knowledge that is needed to develop the basic rules that can guide the development of sensible policies on the future use of herbicides in Asian rice systems.

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Any volume that draws from an international conference and involves 25 authors from around the world requires exceptional effort and dedication of many people and institutions. I would especially like to thank Robert Herdt and Gary Toenniessen at the Rockefeller Foundation for generous support of the conference and subsequent publication efforts. I would also like to thank Klaus Lampe and Kenneth Fischer at the International Rice Research Institute (IRRI), and Walter Falcon and Donald Kennedy at the Institute for International Studies (IIS) at Stanford University for providing both intellectual and physical auspices for the conference. Without the enthusiasm of these people and institutions, the diverse group of participants would never have met to discuss the important transitions that are now occurring in weed management throughout the Asian rice economy and to collaborate on the volume.

The authors and other participants of the conference were presented with a large challenge. They were asked not only to think about weed management in the context of their individual disciplines, but also to push their ideas forward to help create an integrated strategy for weed management in Asian rice systems that was scientifically feasible, profitable to farmers, beneficial to human health and the environment, and compatible with private and public sector goals. The discussions at the conference reflected innovative and deep thinking. It was in the spirit of those wide-ranging conversations that this volume was created. I would like to thank all of the participants, and especially the authors, for contributing their expertise and for emphasizing an integrated approach throughout this volume.

The conference and the volume would not have taken place without the help and hard work of many people behind the scenes. I would particularly like to thank Joan Parker and Kathleen Cain at IIS, and my research assistant, Phoenicia Vuong, for their help in organizing and providing logistical support for the conference and the subsequent publication. I would also like to thank Robert Huggan, head of IRRI's Information Center, and Gene Hettel and Tess Rola of IRRI's publication staff for seeing the volume through to its present form. Most importantly, I would like to thank LaRue Pollard, the production editor for the volume, for endless hours of editing for consistency, rewriting, and communicating with the authors. To all of the above and a host of others go my heartfelt thanks.

ROSAMOND NAYLOR
Stanford, California
September 1996

Overview

HERBICIDE USE IN ASIAN RICE PRODUCTION: PERSPECTIVES FROM ECONOMICS, ECOLOGY, AND THE AGRICULTURAL SCIENCES

R. Naylor

Herbicides now appear to be an inescapable fixture in Asian rice economies. But an essential concern remains: how best to govern their use. Addressing this issue requires knowledge—f the economic determinants of herbicide use, of the potential effects of herbicides on society and ecosystems, of the options for integrating herbicides into a broader weed management strategy, and of appropriate roles for the public and private sectors within different countries.

Although herbicide use in Asian rice production is still at an early stage of evolution, it is progressing at an extremely rapid rate. Understanding the dynamics and potential consequences of widespread herbicide applications on the ricefields of densely populated regions of Asia is therefore critical, if long-term damage that could accrue from overuse or misuse of these chemicals is to be avoided.

ECONOMIC DETERMINANTS OF HERBICIDE USE

Weeds are the most severe and widespread biological constraint to rice production (Herdt 1991 ; Moody 1990, 1991). Potential yield reductions caused by uncontrolled weed growth throughout a crop season have been estimated to be in the range of 45-95%, depending on the cultural system; cropping season; plant spacing; amount of fertilizer applied; ecological and climatic conditions; and duration, time, type, and amount of weed infestation (Moody 1991, Ampong-Nyarko and De Datta 1991). Even using a more conservative estimate of a 10-15% yield reduction in well-managed fields (Ampong-Nyarko and De Datta 1991, Baltazar and De Datta 1992), losses caused by weeds in Asian rice systems amount to approximately 50 million tons of rough rice, valued at more than US$ l0 billion in 1995 (World Bank 1996).

Traditionally, weeding of rice in Asia has been done by hand. The availability of inexpensive, unskilled workers in rural areas made labor-intensive agricultural practices cost-effective for farmers and a source of income for millions of laborers. Now, as more lucrative, full-time job opportunities become available in nonagricultural activities, Asian farmers are finding it increasingly difficult to hire seasonal workers for transplanting and hand weeding rice. The current movement of labor from agricultural to nonagricultural sectors in the less developed countries of Asia is characteristic of a more general process of structural transformation that occurs at varying rates and degrees in all developing economies. The process is defined broadly by a diminishing role of agriculture in national income and aggregate employment as an economy grows. A relative decline in the agricultural labor force occurs in the early to middle stages of structural transformation; in later stages, the absolute number of workers in agriculture also falls (Timmer 1988). The process of structural transformation is already well advanced in several Asian countries (Table 1).

One consequence of this structural transformation is that, in many Asian countries, real wages for agricultural labor have increased relative to real rice prices (Table 2). In 1995, the world price of rice, adjusted for inflation, was roughly half what it was in 1970 (World Bank 1996). In a number of regions, that higher cost-to-return ratio has induced the adoption of herbicides as a substitute for hand weeding (Table 3).

Herbicides offer one of the most effective means by which rice farmers can reduce labor costs for two reasons. First, labor inputs for hand weeding are extremely high, accounting for up to half the total preharvest labor hours in some irrigated rice systems of Asia (Naylor 1994a). Second, effective use of herbicides permits direct seeding of rice, which further economizes on labor. Experimental data from IRRI show that labor costs average 1.8 person days per hectare for direct-seeded rice and

Table 1. Economic indicators for selected Asian countries, 1965-90.

Country	GNP capita^{-1}	Annual GNP growth (real)		GNP from agriculture (%)		Labor force in agriculture (%)	
	1990	1965-80	1980-90	1965	1990	1965	1990
Nepal	170	2.3	4.6	65	60	94	92
Bangladesh	210	2.4	4.3	53	38	84	68
India	350	3.8	5.3	47	31	73	66
China	370	6.4	9.5	39	27	81	68
Pakistan	380	5.2	6.3	40	26	60	50
Sri Lanka	470	4.0	4.0	28	26	56	52
Indonesia	570	7.9	5.5	56	22	71	48
Philippines	730	5.9	0.9	26	22	58	47
Thailand	1,420	7.4	7.6	35	12	82	64
Malaysia	2,320	7.3	5.2	28	na	59	32
Korea, Rep.	5,400	9.5	9.7	39	9	55	24
Singapore	11,020	10.2	6.4	3	0	6	0
Hongkong	11,490	8.5	7.1	2	0	6	0
Japan	25,430	6.3	4.1	9	3	26	6

Sources: World Bank, various issues; IRRI (1995); UNDP (1990).

Table 2. Growth in agricultural wages and rice prices in selected Asian countries, 1970-90.

Country	Growth in constant prices (1985=100 [a]) (annual average % change)		Nominal wage rate (US$ d^{-1}) 1990
	Wage	Rice price	
India	1.0	-0.7	1.00
Indonesia	2.0	0.6	1.14
Sri Lanka	4.5	1.9	1.18
Philippines	0.7	-0.1	2.12
Korea	7.3	3.6	18.68
Japan	1.9	0.4	35.40

[a]Agricultural wages and rice prices are deflated by the consumer price index in each country. Source: IRRI (1995).

25 person days per hectare for transplanted rice (IRRI 1990). In addition to savings in direct production costs, switching from transplanted rice to direct-seeded rice lowers the transaction costs of labor search and monitoring and increases the timeliness of planting (Erguiza et al 1990). The reduction of labor and management costs with direct-seeded rice has motivated a large and growing number of farmers throughout Asia, especially in regions where labor shortages exist at peak periods, to switch from transplanting to direct seeding (De Datta and Nantasomsaron 1991).

The interaction between herbicide availability and direct-seeded rice technologies is important in terms of technology adoption and in terms of the potential spread of herbicide use throughout Asia. Direct seeding of rice is viable in high-productivity irrigated systems only if cost-efficient herbicides that can effectively kill dominant grass weeds are available. Weed growth is encouraged in direct-seeded rice because seed germination and crop plant establishment require nonflooded conditions. Rice and weeds germinate simultaneously when the soil is exposed during initial crop growth stages (De Datta and Bernasor 1973, De Datta 1989). Also, age similarities and morphological resemblances of grass weeds and rice seedlings make it difficult for hand weeders to differentiate weeds from rice, increasing the probability of significant weed infestation and consequent yield loss. Roughly three times more labor is needed to hand-weed direct-seeded ricefields than to hand-weed transplanted ricefields (450 vs 150 labor hours per hectare in experimental fields [De Datta 1988]). This makes hand weeding direct-seeded rice crops prohibitively expensive, especially if real wages are rising much faster than real rice prices.

Data on the extent of direct seeding of rice in Asia are extremely difficult to obtain. In areas where direct seeding of rice is adopted by a few farmers, it tends to spread quickly and uniformly. Table 4 presents recent estimates of direct-seeded rice area. Widespread adoption of direct-seeded rice technologies is already in progress in many regions of South and Southeast Asia, including parts of Thailand, Malaysia, the

Table 3. Herbicide use in rice production in selected Asian countries, 1991-94.[a]

Country	Weed control practice
Bangladesh	Herbicides are not used. Virtually all rice area is hand-weeded twice a season.
China[b]	Herbicides were first introduced in the mid-1960s and are now used on 30-40% of total rice area.
India[c]	Herbicides are not used much in the traditional rice areas in northeast and south India, but they have become popular and are steadily growing in the nontraditional irrigated rice areas, such as Punjab, Haryana, Western Uttar Pradesh, Jamu, Kashmir, Tamil Nadu, Andhra Pradesh, and parts of Orissa and Madhya Pradesh.
Indonesia[d]	Herbicides that have been used since the mid-1970s in North Sumatra and South Sulawesi are just beginning to be introduced in Java. Approximately 20-25% of rice farmers on Java now use herbicides.
Japan	Rice area treated with herbicides increased from 2 to 233% between 1949 and 1970, reflecting the fact that most crops receive more than two applications per growing season.
Philippines	About 50% of rice area is currently treated with herbicides. Consumption of herbicides more than doubled between 1967 and 1990, and area applied with herbicides is steadily rising.
Korea, Rep.	Between 75 and 100% of rice is treated with herbicides.
Sri Lanka	Herbicides are not used to any significant degree. Most rice area is hand-weeded twice a season.
Taiwan	By 1979, more than 90% of rice area was treated with herbicides; by 1990, herbicides were applied at least once a season on virtually all rice crops.
Vietnam[e]	Herbicides are widely used in the Mekong Delta, where 50% of the country's rice is produced. In other regions, hand weeding is still the most widespread form of weed control.
Thailand	Herbicides are applied to 80% of direct-seeded flooded rice, 10% of transplanted rice, and less than 10% of deepwater rice.

[a]Most of the information in the table comes from Moody (1991) and De Datta (1989), unless otherwise specified. The information reflects observed weed control practices as of 1991 and should be Interpreted as approximate information only. [b]Personal correspondence with K. Li, Asia-Pacific Regional Research and Training Center for Integrated Fish Farming, Wuxi City, People's Republic of China; H. Tang, Institute for Plant Protection, Shanghai, People's Republic of China, 1994. [c]Updated data were obtained from personal correspondende with V.M. Bhan. National Research Center for Weed Science, Jabalpur. India, 1994. [d]Personal correspondence with C.P. Mamaril, IRRI, Bogor, Indonesia, 1994, and information from Naylor (1992) and Sumaryono and Soedarsan (1987). [e]Information from Chin and Sadohara (1994).

Table 4. Estimated area of direct-seeded rice in 1994 in selected Asian countries.

Country	Area of direct-seeded rice (%)
China [a]	Of 33 milllion ha of rice area sown in China, only about 5-10% are direct-seeded. More than 50% of total rice area is transplanted by hand, the remainder is transplanted by machine.
India [b]	Approximately 70% of India's 42.1 million ha sown to rice are direct-seeded, most of the remaining 30% is transplanted by hand.
Japan [c]	Less than 0.5% of Japan's 2.14 million ha of rice are direct-seeded, the remaining 99.5% area are machine transplanted.
Thailand [d]	Thirty-three percent of 8.8 million ha of rice are direct-seeded.
Vietnam [e]	Direct-seeded rice covers about 94% of the total rice area in the Mekong Delta, which accounts for 50% of rice production in Vietnam.
Indonesia [f]	Direct seeding is practiced on 3.5% of total rice area (on and off Java) confined to rainfed and upland ecosystems in the wet season. There is virtually no direct-seeded rice in irrigated areas.
Philippines [g]	About 30% of irrigated rice area is direct-seeded in the dry season.
Malaysia [h]	More than 80% of total rice area in Peninsular Malaysia and more than 60% of rice area in the country as a whole is direct-seeded.
Myanmar [i]	Almost 50% of total rice area is direct-seeded in the dry season.

Sources: [a] K. Li, pers. commun.. 1994, Asia-Pacific Regional Research and Training Center for Integrated Fish Farming, Wuxi City, PRC: and H. Tang, Institute for Plant Protection, Shanghai, PRC. [b] V.M. Bhan, pers. commun.. 1994, National Research Center for Weed Science, Jabalpur, India; and D.N. Sen, Department of Botany, University of Jodhpur, India. [c] H. Shibayama. pers. commun.. 1994, Marine and Highland Bioscience Center, Saga University, Japan. [d] P. Vongsaroj, pers. commun., 1994, Botany and Weed Science Division, Department of Agriculture. Bangkok, Thailand; Vongsaroj (1994); Sittisuang (1994). [e] D.V. Chin, pers. commun., 1994, Cuu Long Delta Rice Research Institute; Chuong and Yamauchi (1994). [f] C.P. Mamaril, pers. commun.. 1994, IRRI, Bogor. Indonesia. [g] Garcia et al (1994), Pandey (1994). [h] Supaad and Cheong (1994). Jaafar et al (1994). [i] Tin and Hia Min (1994), Yamauchl et al (1994).

Philippines, and Vietnam (De Datta 1989, De Datta and Nantasomsaron 1991). The data suggest that direct seeding is not suitable for all rice-growing regions. Direct seeding requires effective weed control as well as efficient water control and level fields for adequate seed germination.

Herbicides are now used extensively in Asian rice production systems primarily because they are profitable to farmers. Experiments on weed control practices for both transplanted and direct-seeded flooded rice indicate that the benefit-cost ratios to farmers are most favorable when herbicides are used (Ampong-Nyarko and De Datta 1991, De Datta 1989). The benefit-cost ratio measures net returns to rice production with different weed control practices in relation to returns without weed control (Naylor 1994a). The research shows that the benefit-cost ratio of controlling weeds with herbicides in transplanted rice is 16:1; the benefit-cost ratio for hand weeding is only 3.3:1. The benefit-cost ratio for direct-seeded rice in some cases exceeds 25:1 with complete chemical control (De Datta et al 1989, De Datta 1986).

Current data suggest that herbicides are important for lowering total variable costs through reduced labor inputs, although yields in transplanted systems might actually be half a ton greater with careful hand weeding (Naylor 1994a). Given the relative magnitude of labor costs in these systems, however, the yield advantage from hand weeding does not make up for the potential savings on labor with herbicide use. For a representative group of Asian countries, labor costs as a whole account on average for almost 50% of total variable costs and more than 25% of gross revenues in rice production (Table 5). With such high relative costs, the yield advantage in many Asian rice systems would have to be on the order of 1-2 t to justify hand weeding on the basis of private farm profits (Naylor 1994a).

Asia now accounts for a vast majority of the global rice herbicide market (Table 6). Japan alone accounts for more than 50% of the value of all herbicides sold for rice production; its large share is attributed to labor scarcities in agriculture as well as to its use of the higher priced, premium herbicides used in single-application formulations (Shibayama 1996). Other countries in Asia also are beginning to buy larger amounts of herbicides and more expensive products as their economies grow. Taken together, the Asian rice economies excluding Japan bought almost US$300 million of herbicides in 1993, more than twice the amount sold in the United States, and almost five times the amount currently sold in Europe.

Moreover, the share of the world's rice herbicides sold in Asia will almost surely continue to grow. Not only will sales rise in response to the continued increase in demand by Asian rice farmers, but trade in agricultural chemicals will be facilitated by the recent revision of the General Agreement on Tariffs and Trade (GATT) that seeks to reduce domestic subsidies and trade barriers for agricultural products and inputs. Multinational agrochemical companies will be looking to take advantage of a

Table 5. Share of labor in rice production budgets in selected Asian countries.

Region	Labor costs (%)	
	Variable costs	Gross revenues
Bangladesh (1987-88)	44	24
Cambodia (1988-89)	75	60
Indonesia (1987-88)	65	23
Pakistan (1988)	43	33
Philippines (1988)	39	15
Thailand (1987-88)	49	23
Vietnam (1990)	25	17
Av	49	28

[a]Data derived from farm budgets for irrigated wet-season rice crops. Source: IRRI (1995).

Table 6. Global rice herbicide market, 1993.

Country/region	Total sales ($ milllon)	Total market (%)
India	23	2.0
China	80	6.9
Indonesia	6	0.5
Thailand	18	1.5
Brazil	55	4.7
Colombia	25	2.1
Vietnam	6	0.5
Myanmar	5	0.4
Bangladesh	5	0.4
Philippines	11	0.9
Japan	659	56.3
Korea, Rep.	110	9.4
USA	100	8.6
Europe	55	4.7
Others	15	1.1
World	1170	100

Source: IRRI (1995).

more liberal trading climate in Asia, especially as U.S. and European markets become increasingly restricted by environmental and health regulations on agricultural chemicals. The process of registering new agrochemicals and maintaining existing products in the U.S. market, for example, has now become so burdensome that many US-based multinational companies are finding it more cost-effective to market existing herbicides abroad (John Killmer, Monsanto Agricultural Group, pers. commun., 1994; Kent Reasons, E. I. Dupont of Nemours and Co., Agricultural Productions Group. pers. commun., 1994). Some herbicides currently sold in Asia are either banned or restricted in the United States and many countries of Europe (Pingali and Roger 1995), which raises questions about the ethical basis for such trade. Virtually all less developed countries in Asia have much more lenient health, safety, and environmental regulations than the United States, most European countries, and Japan.

Literally hundreds of herbicide products are emerging in the Asian market, a large number of them the same formulations under different labels. This enormous and increasingly complex set of products is originating both inside and outside the region and is becoming accessible to farmers in even the poorest regions with slow economic growth. Like earlier experiences with insecticide marketing in Asia. both private chemical companies and governments are responsible for the distribution and sale of herbicides. The availability of individual herbicides in each location is thus dictated as much by relations between private companies and governments as by agronomic, health. environmental, and other social criteria. Health and environmental criteria, however, are extremely important to society, especially as herbicides spread throughout the densely farmed and densely populated areas characteristic of Asia's rice bowls.

Social costs

Among the most important social issues associated with the spread of herbicides in Asian rice production systems is its impact on the displacement of unskilled labor and the consequent effect on rural communities. The creation of employment often is considered to be in itself an objective of agricultural policy, particularly in densely populated, poor areas with high levels of unemployment and underemployment. In regions undergoing rapid economic growth, however, where there is a high opportunity cost of labor (if labor has a high value in its next-best use), workers may be quite happy to discard the arduous task of hand weeding and gain time for leisure or other forms of employment. Rice farming will need to require less drudgery to become a more attractive enterprise, particularly to young people who are increasingly migrating to the cities to look for work.

The impact of herbicide adoption on rural labor markets must be considered in a broad social and economic context. In the short run, the potential for labor displacement throughout Asia is substantial, and could worsen income distribution in rural areas. Field studies on Java show that certain groups of people, such as women over the age of 50 who are unskilled and relatively immobile, are particularly vulnerable to displacement by herbicides (Naylor 1992). Strong economic growth is required to absorb displaced workers and compensate for the negative equity effects. Sustained economic growth is especially important in the long run, since the adoption of technologies to relieve drudgery tend to be irreversible. Once farmers have adopted herbicides, they are not likely to go back to hand weeding, even if real wages fall.

Furthermore, the availability of effective and inexpensive herbicides might induce farmers in some countries with slow economic growth, such as Bangladesh, Laos, and Cambodia, to adopt chemical weed control, even though large supplies of underemployed labor exist in the rural areas. In this case, the interaction between technological development and factor market dynamics is critical. Development of technologies that reduce farmers' private costs (variable input and transaction costs) might significantly raise social costs in some regions, especially if the adoption of those technologies results in millions of unemployed laborers. When economic growth is slow, laborers often welcome even drudgery tasks as a source of subsistence income.

In extremely stagnant or declining economies that have very limited employment opportunities outside the rice sector, labor costs measured in social prices are close to zero. In these cases, the social benefits of labor-intensive farm practices are relatively high. As the opportunity cost of labor rises, the social benefit-cost ratio of hand weeding in relation to chemical weed control falls. Naylor (1994a) used cost-benefit analysis of experimental data on rice production and market wages for 1990 to show that the social price of labor would have to be 25% of the market wage in the Philippines and 50% of the market wage in Indonesia to make hand weeding as profitable socially as herbicides.

Social price assumptions of 25-50% of the market wage are unreasonable for the Asian rice economy as a whole, but they may be quite reasonable for regions where employment opportunities for rural unskilled labor are limited. In the Philippines, the social price of labor is probably greater than 25% of the market wage, although the economy has been growing slowly and real wages have remained stagnant for several decades (Table 2). Field surveys of employment opportunities for unskilled workers on Java suggest that the opportunity cost of labor is close to the market wage (Naylor 1991). However, the older women who do much of the weeding in the Java rice economy may have a lower opportunity cost, and the social value of their labor could fall significantly if the economy turns down (Naylor 1994b). For Asia as a whole, this means the assumption that herbicide use will be profitable to farmers both privately and socially (in terms of reduced drudgery) rests heavily on the continuation of strong economic growth and structural transformation throughout the region.

In reviewing the equity implications of herbicide use, it is important to balance the potential negative impact of labor displacement against the positive effects of lower rice prices in the market which could result from reduced input costs. Sixty percent of Asia's labor force is still employed in agriculture (IRRI 1995), and the proportion of poor households employed primarily in agriculture is even higher. Agricultural production in general, and rice production in particular, thus plays a large role in the level and distribution of rural income in Asia. Many of the households that are employed in the rice sector, however, are actually net consumers of rice. In very poor regions, households spend 80% or more of their total budgets on food, and up to 35% of their budgets directly on rice and other cereals. This means that production technologies that lower the price of rice can have a positive impact on the real income of poor households.

An empirical analysis of the effects of herbicide use on rice prices and income distribution has yet to be done for the less developed countries of Asia. Japan, where rice herbicides have been used for decades, in principle could serve as a model for such a study. In practice, however, production subsidies and price supports would distort the results (due to national price and trade policies, market prices of rice in Japan have been up to ten times the world price). Given the relative newness of herbicide use in many other rice-producing regions of Asia, the verdict on herbicide-rice price interactions and their effects on income distribution is not yet in.

Ecological and health risks

In addition to the potential displacement of unskilled workers, the costs of herbicide use include potential ecological and health damage that is not valued in the market. Current research indicates that most herbicides are less toxic and persistent than the majority of insecticides used in Asian rice production (Pingali 1992, Antle and Pingali 1994). But all pesticides are toxic to some degree, and it is often their misuse, particularly in the handling of the chemicals, that is the main source of problems. In addition, with widespread herbicide use, large concentrations of herbicides could accumulate in soils and in water tables. How such accumulations in densely populated areas would affect human health and the ecology are not well understood.

Three broad categories of risks associated with extensive and long-term use of herbicides in Asian rice systems warrant further study: potential damage to rice productivity and to the productivity of other farm enterprises, such as livestock and aquaculture; potential damage to the health of laborers and residents both on and off the farm; and potential external damage to surrounding ecosystems. Some of the specific environmental and health risks include

- health risks to workers who apply herbicides and to others who come into contact with agrochemicals in the process of transportation and storage;
- chronic health and environmental risks associated with the contamination of ground and surface water through runoff and seepage;
- risks associated with the movement of herbicide residues through the food chain to consumers of rice and to livestock that obtain feed from ricefields;
- risks associated with increased mortality of aquatic vertebrate and invertebrate organisms (such as fish, frogs, and shrimp) that play both economic and ecological roles in ricefields;
- risks associated with alterations in the populations of microorganisms in ricefield soil and water that help sustain soil fertility;
- ecological risks associated with potential resistance of weeds to herbicides and increased incidence of perennial grass weeds; and
- risks associated with the elimination of weeds that play an important role as alternate hosts to certain insect pests.

Where any of these factors are significant, private profits earned from rice production systems that use herbicides may exceed net benefits to society. Society may even suffer a net loss.

During the 1960-70 decade, a large share of the herbicides used in Asian rice systems were in the "moderately hazardous" category 2. These chemicals included the phenoxy acid compounds such as 2,4-D. The proportion of herbicides used in the region has increasingly shifted to chemicals in the less toxic "products unlikely to present acute hazards in normal use" category 4 (Rola and Pingali 1993). The less toxic chemicals include the acetamide compounds such as butachlor, pretilachlor, and oxadiazon. Many farmers now use a combination of phenoxy acid and acetamide compounds for preemergence and postemergence applications. The safety ratings applied to these chemicals, however, are based only on acute toxicity ratings for oral, dermal, and inhalation exposure. Chronic toxicity is not considered.

Epidemiological studies currently support the view that, while irritation from the use (and misuse) of pesticides is common, most herbicides have low acute toxicity, especially when they are absorbed dermally. The research conducted by Pingali and Marquez (1996) and Rola and Pingali (1993) suggest, however, that use of phenoxy acid compounds is linked to the incidence of pterygium (eye irritation), bronchial asthma and other pulmonary disorders, low hemoglobin, and polyneuropathy. These studies also show that acetamide compounds are highly correlated with eye irritation in particular because these herbicides tend to be applied with higher frequency and at larger active ingredient concentrations than the phenoxy acid compounds. Moreover, the reported incidence of pterygium, which diminishes visual acuity and can significantly lower the productivity of farm workers, is five to seven times greater among users than among nonusers of herbicides in rice production.

When the full extent of potential health costs associated with herbicide applications are accounted for, Pingali and Marquez show that these costs are more than offset by the reduction in labor costs in Philippine rice production systems, especially in direct-seeded systems. Their study also confirms the more general view that it is the misuse, rather than the use, of herbicides that is most threatening to health. Most families surveyed practice extremely unsafe methods of storage, disposal, and application of all pesticides. These practices have led to increased incidence of accidental exposure to the chemicals and to contamination of the water canals that surround ricefields.

Although the direct health risks associated with judicious herbicide use in rice systems are thought to be low, some herbicides, such as alachlor and atrazine, are important ground water contaminants and are carcinogenic to animals (McConnell 1994). A number of herbicides are toxic to fish (Table 7). Toxicity to fish is especially a problem in ricefields when heavy rainfall accumulation overflows the irrigation

Table 7. Toxicity to fish of selected herbicides.[a]

Common name	Trade name	Toxicity to fish[b]	Manufacturer
Bensulfuron	Londax	Low	DuPont
Bentazon	Basagran	Low	BASF
Butachlor	Machete	Moderate	Monsanto
Cinosulfuron	Set-off	Low	Ciba-Geigy
2,4-D	Numerous	Low-moderate	Numerous
EPTC	Eptam	Low	Stauffer
Fenoxapro p	Whip	Moderate	Hoechst
Fluorodifen[c]	Preforan	High	Ciba Geigy
MCPA	Numerous	Low	Numerous
Metsulfuron	Ally	Low	DuPont
Molinate	Ordram	Moderate	Stauffer
Oxadiazon	Ronstar	Moderate	Rhone-Poulenc
Pendimethalin	Stomp/ Herbadox	High	Cyanamid
Pretilachlor	Sofit	Moderate	Ciba-Geigy
Propanil	Stam F-34	Moderate	Rohm & Haas
Pyrazosulfuron	Sirius	Low	Nissan
Quinclorac	Facet	Low	BASF
Thiobencarb	Saturn	Moderate	Kumiai

[a]Source: Moody (1990). [b]Low-LC_{50} >10 ppm; moderate-LC_{50} 0.5-10 ppm; high-LC_{50} <0.5 ppm. [c]No longer in production, use, or development in Canada and the United States. Weed Science Society of America (1989).

bunds from the field into canals and other waterways (Moody 1990). Research by Cagauan (1990) suggests that butachlor, which is used by more than 80% of the farmers in Pingali and Marquez's survey region in the Philippines, is highly toxic to tilapia, a fish often cultivated in ricefields as a form of aquaculture. Studies on fish mortality from pesticides used in the Sacramento Delta of California (Finlayson and Lew 1983) also showed that two other herbicides widely used in Asia — thiobencarb and molinate — can be highly toxic to carp, another fish that is common in Asian aquaculture.

Li and Li (1996) demonstrate that herbicides can damage aquaculture systems through direct toxic effects on fish and through indirect effects on the water environment. Indirect effects include impacts on levels of dissolved oxygen, pH, and ammonia in the water and a buildup of toxic chemicals in the sediment. The primary, undisputed problem with fish mortality in Asian rice systems is that an important source of food and income is lost to farmers. A more contentious issue, and thus one that deserves long-term field analysis, is whether toxicity in aquaculture systems poses a danger to consumers through the food chain (Ocampo et al 1990, Li and Li 1996).

The on-farm effects of herbicide use in irrigated rice, including residues in the ricefield soil, water, rice plant, and grain, are not thought to be significant as long as the chemicals are applied at the recommended rates and times. Tropical flooded ricefields provide an ideal environment for rapid detoxification of most of the herbicides known to persist in nonflooded fields and other aerobic systems (Roger and Kurihara 1988, Sethunathan and Siddaramapa 1978). Crosby (1996) shows that the main factors that reduce the toxic risk of herbicides to the environment include both physical factors (such as dissolution, adsorption, and volatilization) and biochemical factors (such as photodegradation by sunlight, biodegradation by microorganisms in the soil and water, and mineralization). These factors are offset to some extent by factors that increase the toxic risk, such as bioconcentration. Both sets of processes interact in ways that affect the rice ecosystem directly and the surrounding aquatic and terrestrial ecosystems indirectly. The environmental impacts of herbicides on natural ecosystems are especially difficult to predict, measure, and control in areas where there is chemical drift caused by wind or water movement.

The most significant impact of herbicides on the environment is on plants; herbicides are specifically designed to affect the surrounding flora. Weed populations and their vigor and biomass are reduced by herbicides, although there may not be a direct effect on the total number of plant species (Mahn and Helmecke 1979). Some of the indirect effects of herbicides on the ricefield environment, such as the loss of habitats resulting from altered water flow, water temperature, sunlight intensity, and hiding places, may have larger impacts on species composition (Way and Chancellor 1976). The aggregate effect of herbicides on the environment over time and space depends ultimately on the method and types of herbicides applied. Most of the newer formulations demonstrate low persistence; the older, inorganic compounds, including the phenoxy acid compounds, have higher persistence. Currently, both sets of chemicals are available in Asian markets, without many restrictions, or at least without enforced restrictions (Rola and Pingali 1993, Moody 1996b).

Continuous use of pesticides, broadly classified to include the hazardous category 1 and 2 chemicals, tends to decrease biodiversity within rice ecosystems. Continuous use also leads to the adaptation and possible blooming of individual microorganisms, especially those residing in energy-poor environments in the soil (Racke 1990). This means long-term herbicide use could change the microbiology of the soil as well as the ecology of weed populations. Research by Roger and Simpson (1996) shows that herbicides applied on soil at recommended levels tend to have little impact on microbial populations in the short term. The limited studies that exist, however, indicate the relationship between pesticide use and biological variables may not be consistent over long time periods. Although short-term studies are valuable in elucidating the effects of herbicides on microflora in the soil, it is clear that additional field studies are needed to assess more precisely the long-term impact of continuous herbicide use on microbial systems and soil fertility.

A more serious threat to rice productivity is that continuous herbicide use can promote shifts in the weed population and the emergence of herbicide-resistant weeds (Dowler et al 1974, Kim et al 1975, Mahn and Helmecke 1979, Moody 1991, Ho et al 1992). Ecological shifts of weed species from annuals to perennials have occurred in areas where herbicides have been used continuously in rice for a number of years, such as in Japan and Korea (Shibayama 1996, Moody 1991, Ueki 1983, Vega 1988). Examples from the Philippines and Malaysia (Ho et al 1994) indicate that continued use of postemergence herbicides, such as 2,4-D, to suppress a number of easily controlled broadleaf weeds and sedges have led to complete dominance by grass weeds, which are much harder to control. Similarly, use of grass weed killers, such as pretilachlor, molinate, propanil, and oxadiazon, over a long time has increased the dominance of broadleaf weeds and sedges. This empirical evidence indicates that, although herbicides can eliminate dominant weeds in rice at any given time, chemical weed control that relies over an extended time on the use of a single herbicide or group of herbicides with the same mode of action will not be effective.

The emergence of new weed types creates a continuing competition for nutrients, water, and sunlight—the principal resources of agricultural production. Weeds tend to be more effective competitors than rice in ricefield ecosystems for three reasons: they have lower dry weight, they require less water and nutrients for growth, and they produce more seeds. The physiological interactions between weeds and rice can be modeled to predict the probable extent of competition in any given rice ecosystem. These models can be useful in estimating potential yield loss and in designing more effective weed management programs (Weaver 1996, Kropff and van Laar 1993).

A fine line exists between the evolution of weed types in intensive rice systems and the buildup of resistance to herbicides in weeds. Controlling weeds with a single herbicide can lead over time to the evolution of herbicide-resistant weeds, through the selection of naturally occurring herbicide-resistant biotypes or through genetic mutation. Even if herbicide mixtures are used, weed strains with multiple resistance can develop over time. Mutation frequencies of weeds treated by sulfonylurea herbicides, for example, indicate that a small percentage of plants have a semidominant mutation in the acetolactate synthase target site that is resistant to the herbicide (Kim 1996). Sulfonylurea resistance appeared within 3-5 yr of limited use, and now the emergence of resistant weed biotypes is being widely reported in California rice systems where sulfonylurea is used extensively (Hill 1996). The evidence suggests that resistance has been increased by intense selection pressure caused by use of the same mode-of-action herbicide on the same crop in the same fields over successive years. It is not known whether any resistant biotypes against sulfonylurea have evolved in Asia or not, although this chemical is being used increasingly in herbicide mixtures throughout the region (Kim 1996).

Red rice, a weed now appearing in parts of Asia, can reduce yields by 80% or more if unchecked. This is the type of weed that is likely to become more dominant with the spread of direct-seeded rice (Moody 1996a). Once a resistant weed strain develops, it can spread easily across farms via multiple pathways, including wind, water, rice seeds, and agricultural machinery. As farmers rely increasingly on herbicides, weed resistance and weedy rice problems will surely increase, just as overuse of antibiotics has encouraged disease resistance. If this occurs, the huge price advantage experienced by farmers who first use herbicides will quickly disappear.

The combined evidence on ecological and health risks associated with widespread herbicide use in Asian rice systems underscores the need for careful management practices. Potential threats to human health appear to be greater in terms of immediate personal safety than in terms of chronic exposure, although little data exist on the contamination of water wells and of groundwater by herbicide application and by the cleaning of spraying equipment in irrigation canals. If handled correctly, most modern herbicides dissipate relatively quickly and thus pose little danger to human health and ecosystems. If handled incorrectly, herbicides have potentially severe ecological and health effects, both on and off the farm. The outcome depends on the amount and type of herbicides used at any given time, and on whether a single herbicide or combination of herbicides with the same mode of action is used over a long time within a region. The buildup of weed resistance to herbicides, and the potential loss in yields and revenue that resistance implies for farmers, is one of the greatest risks of extensive and unregulated herbicide use in Asia.

OPTIONS FOR A BROAD WEED MANAGEMENT STRATEGY

Evidence on the emergence of resistant weed biotypes and ecological changes in weed populations alone make it clear that yields, and therefore total returns to production investment, cannot be maximized unless a combination of weed control practices is used to curtail all of the various weeds. Integrated weed management (IWM) that uses limited quantities of low-cost chemicals in combination with other control techniques, including hand weeding, may be the best approach from agronomic, economic, and environmental points of view (Akobundu 1987, De Datta 1981). This approach can be broadened to include biological controls and other technologies that favor a crop's resistance to relatively benign herbicides and that improve the competitiveness of rice over weeds in ricefield ecosystems.

Experience with integrated pest management (IPM) targeted primarily at insect control in Indonesia, Malaysia, and the Philippines underscores the potential yield gains that can come from understanding the dynamic interactions between the economics and ecology of cultivated rice systems (Teng 1994). In all cases where IPM practices have been broadly substituted for prophylactic control of pests using insecticides, rice yields have risen rather than fallen (FAO 1988, IRRI 1992, Rola and Pingali 1993). The adoption of IPM programs sets a precedent for exploiting such ecological principles as predator-prey relationships in preference to short-term technological fixes. Like IPM, IWM implies a movement away from a component-based system to a knowledge-based system of pest control.

IWM involves both cultural and technology-driven methods of weed control (De Datta and Baltazar 1996). The most widely used cultural methods include hand weeding, hoeing, and interrow cultivation, with limited use of herbicides. These often are complemented by other cultural controls, such as good tillage and land preparation, careful timing of fertilizer applications (so that the nutrients go to the crop and not the weeds), flooding to suppress weed growth, and crop rotation. The extent to which each method is used depends on farm-specific agronomic conditions (for example, the rice culture used and the dominant weed types), local factor market conditions (including the availability and cost of labor and machinery), and regional ecological and agroclimatic conditions (such as rainfall patterns and water availability for flooding). Most rice farmers in Asia who use these cultural methods already practice IWM to some extent. The tendency to perceive herbicides as a cure-all for weeds, however, has increased with rising labor and management costs and the increasing availability of herbicides in the market (Moody 1996b).

An alternative method to control weeds in rice is beginning to appear-the use of biological agents, including insects, plant pathogens, and herbivores. Cother (1996) indicates that an inundative approach using plant pathogens, especially fungal pathogens (mycoherbicides), is currently the most promising biological control method for restricting the growth of rice weeds. The inundative approach essentially introduces a new pathogen or augments natural background populations of pathogens that kill or severely limit the growth of weeds. The inundative approach can be used to control almost any weed if a naturally occurring organism with sufficient destructive attributes can be identified. Grasses are among the most difficult targets for biological control because pathogens that attack grass weeds tend to have very broad host ranges that often include the cereal crop being protected. Even so, progress is now being made in identifying a number of specific plant pathogen control agents for grasses (Gohbara and Yamaguchi 1992, Smith 1992, Watson 1993), and the potential range of candidate plant pathogens for controlling grass weeds in rice is being expanded (Hokkanen and Pimentel 1984, Hokkanen 1985, Cother 1996).

Research on biological control in Asian rice systems is at an early stage. Investments by the private sector have been especially slow to develop; biological control is site-specific, involving greater aggregate costs for product development and marketing than do chemical herbicides applied to wider areas. Commercial applications of a given mycoherbicide require, for example, that it can be cultured and produced in abundant and durable form, that it is genetically stable and specific to the target weed, that it can kill or suppress the target weed over a wide range of environmental conditions, that it has a limited ability to spread or survive in nature (thus creating the need for continuing sales), and that it can be patented so that development costs can be recovered (Peter McEvoy, Oregon State University, pers. commun., 1994). Cother (1996) maintains that these conditions are by no means out of reach, that the lack of investment by the private sector may be due more to attitudinal problems than to technological or scientific constraints.

Another form of biological control still in the development stage is the use of allelopathic rice cultivars and allelochemicals to reduce weed growth. Allelopathy in this context can be defined as any direct or indirect harmful effect by one plant on another through the production of chemical compounds released into the environment (Olofsdotter 1996). Khush (1996) defines plant allelochemicals or allelopathic chemicals more broadly, as secondary plant metabolites that play an important role, both beneficially and detrimentally, in plant-plant, plant-microorganism, and plant-insect interactions, and that act as important ecological factors influencing plant dominance, succession, and crop productivity. Allelopathy is a mechanism by which weeds restrict crop growth that occurs widely in natural plant communities (Whittaker and Feeny 1971). Rice cultivars having allelopathic activity against certain aquatic weeds have been identified in the United States and Japan (Smith 1992, Fujii 1992), and a few allelochemicals that are effective in restricting the growth of dominant rice weeds have been isolated and identified in Korea (Kim 1992).

Fujii (1992) screened almost 200 rice cultivars, using lettuce as the assay crop. He noted that improved japonica varieties show little allelopathic activity, while traditional tropical japonica rice cultivars and red rice strains show stronger indications of allelopathic activity. The Agricultural Research Service of the U.S. Department of Agriculture is evaluating approximately 14,000 rice germplasm accessions for allelopathic properties to ducksalad, a common aquatic weed in U.S. rice systems (Dilday et al 1996). Of the accessions screened so far, about 4% have demonstrated allelopathic activity. Most of them are from China/Taiwan, China, and from India/Pakistan. Germplasm from China appears to be a good source of allelopathy to ducksalad for medium-grain japonica rice. Germplasm from Pakistan could contribute allelopathic properties to long-grain indica rice.

In the long run, the use of biological controls, including both plant pathogens and allelochemicals, presents a lower risk to human health and the environment than the use of herbicides. Like herbicides, however, biological control can cause changes in the weed ecology, with a buildup of weed resistance over time. The use of exotic organisms as biological control agents also could, if they became invasive, alter natural and cultivated ecosystems (Harris 1990, Howarth 1991). Because of their ecological interactions, these practices should not be considered in isolation as a form of weed control, but rather be evaluated as components of an integrated and continuously evolving strategy of weed management.

The use of plant breeding to improve the competitiveness of rice over weeds is likely to become an important component of the evolving weed management strategy, especially with the spread of direct-seeded rice cultivars. Several traits for weed competitiveness in rice can be identified, including early seedling emergence, seedling vigor, increased growth rates and longer growth duration, increased plant height, and greater root volume (Minotti and Sweet 1981, Berkowitz 1988). Other traits that improve competitiveness include the following:

- Tolerance for anaerobic conditions, so that pregerminated seeds can be sown into standing water.
- Allelopathic activity that restricts the growth of dominant weeds.
- Tolerance for parasitic weeds.

Khush (1996) suggests that it is possible to use plant breeding to select for rapid seedling emergence, early seedling vigor, faster growth rates, and higher root biomass. The potential for developing varieties capable of emergence in standing water under tropical conditions is high for direct-seeded rice. It may not be possible, however, to select for high tillering, greater plant height, and longer growth duration. because these traits are in direct conflict with the traits currently being compiled into a plant type designed for high yield potential (a so-called "super rice" cultivar). As in any varietal improvement program, selection for traits that impart weed competitiveness requires energy that would otherwise be used for different plant processes, and selection of one trait can have a significant opportunity cost in terms of desirable traits that may be foregone.

A vastly different technological approach to weed management is the use of biotechnology in developing herbicide resistance in rice cultivars (Toenniessen 1996). This approach can make it possible to increase the number and variety of herbicides that can be used in a given field without damaging the rice crop, which is important in mitigating ecological shifts in the weed population and the emergence of resistant weed biotypes. It also can be used to select for herbicides that are toxicologically and environmentally safer than other herbicides. One danger is that private chemical companies may develop rice varieties resistant to their own chemicals, regardless of whether or not their herbicides are safe to human health and the environment (Goldburg et a1 1990).

Genetically engineering plants for herbicide tolerance has been one of the earliest and most widely employed applications of biotechnology. Several transgenes for herbicide resistance have been developed in rice, including resistance to the broad-spectrum herbicides glufosinate-ammonium (Basta) and glyphosate (Roundup) (DeGreef et al 1989, Della-Cioppa et al 1987). Most herbicide-resistant varieties have been developed and patented in industrialized countries, although the number of agricultural field trials of transgenic plants being screened for herbicide resistance has been steadily increasing in less developed countries. It is likely that biotechnology will be used to develop other traits for weed control in rice as well, such as allelopathic activity and anaerobic tolerance, and to increase the effectiveness of plant pathogens for biological control of rice weeds (Toenniessen 1996).

POLICY IMPLICATIONS

The wide array of cultural, biological, and technological options that now exists for weed control in rice makes the design of an IWM strategy increasingly complex. Three sets of decision processes must be evaluated in determining the appropriate role of herbicides in such a strategy:

- Farm-level weed management decisions that focus on input costs and crop productivity.
- Regulatory decisions by a government that focus on the social costs of weed control practices, including potential labor displacement, health damages, and environmental effects.
- Strategic research program decisions by international and national agricultural programs that focus on the use of varietal improvement and biotechnology.

Development of an overarching strategy for managing herbicides in Asian rice systems is further complicated by the fact that decisions by farmers, governments, and national agricultural research systems differ widely among countries. For example, weed management choices in Japan, where wages are high and agricultural research and development well established, may be very different from those in Cambodia and Myanmar, where wages are low and agricultural research and development more limited. Similarly, the strict regulatory environment for herbicide registration and use in the United States cannot be expected to be transferred directly to Japan, let alone to less developed countries like Bangladesh (Shibayama 1996, Hill 1996).

Moreover, current research on herbicide use in Asian rice systems remains focused primarily on cultural and technological options for weed management. What appears to be lacking is a focus on institutions. A strong commitment by the governments of Asian countries is needed to ensure that herbicides are used safely and in combination with other weed control practices, in order to minimize labor displacement and environmental and health-related risks. Although herbicides are being marketed aggressively by private chemical companies in many rice-producing areas, their use has not been incorporated consistently into extension recommendations (Ho 1996). As a result, the misuse of herbicides is common, posing health and environmental risks that might not otherwise exist. A combination approach to weed control which uses labor, chemicals, and natural resources efficiently may not be forthcoming solely from the private sector. A successful IWM strategy will most likely depend on coordination between the public and private sectors, to design herbicide recommendations and, ultimately, to define the appropriate use of herbicides.

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WEED COMMUNITY DYNAMICS IN RICEFIELDS

K. Moody

Since the introduction of organic herbicides, research on weeds in rice has concentrated primarily on developing and using herbicides to control weeds, to minimize their economic impact on a rice crop. Over the last three decades, this emphasis has resulted in significant advances in herbicide technology and widespread adoption of herbicides. Yet weeds continue to pose problems in ricefields. Some intractable weeds cannot be contained; herbicide use over time invokes floristic shifts, often to species or ecotypes inherently more difficult to kill; increasing costs are impacting the profitability of herbicide use.

As research became more and more preoccupied with weed control, research into weed ecology was relegated primarily to the category of academic interest. Now, whether because of a belief that increased understanding of biological mechanisms will lead to better control or because of heightened academic curiosity, research on weed ecology is increasing (Cousens and Medd 1994).

At first glance, a rice ecosystem may appear to be a simple system made up primarily of rice plants. Closer examination, however, reveals a highly diverse complex of organisms. This diversity occurs in spite of the drastic interventions undertaken to prepare a ricefield for planting. A ricefield can be colonized by terrestrial, semiaquatic, or aquatic plants, depending on the type of rice culture and on the season (Fernando et al 1980). In rainfed rice, all three communities will occupy the same field at different times of the year (Moody 1983). During cultivation, a ricefield is subjected to flooding, plowing, and turning up of the substrate, followed by a period of rice monoculture (Fernando et al 1980). This period of monoculture is usually short because the field will be rapidly invaded by weeds (Moody 1983).

With knowledge about the population dynamics of a weed, it is possible to determine the factors that govern weed abundance, to define the conditions and times most suitable for imposing control measures, and to predict the weed's response to various control measures and cropping programs. Knowing how weeds interact in different rice environments and how they respond to control measures is important in deriving long-term strategies for weed management. The challenge becomes one of gaining an understanding of the ecological basis of the reaction of weeds to the crop environment in order to take advantage of weed interference with the crop community in developing control methods that reduce the need of external inputs (Gliessman 1989).

WEED-CROP INTERACTIONS

Four major components are involved in weed-crop ecology: the weed species, the crop, the natural environment, and humans. The combination creates a dynamic system called the weed-crop ecosystem (Aldrich 1984). A plant species does not exist alone; it always occurs in association with other plant species and may affect those other species directly or indirectly (Connell 1990). Burkholder (1952) listed 10 types of interactions that might occur among plant species growing together. Of these, three common negative interactions—competition, amensalism, and parasitism-are most important (Radosevich and Holt 1984).

WEED COMMUNITY COMPOSITION

The composition of a weed community on arable land reflects the production and management practices that have been imposed on that land. The weed community in a cultivated ricefield changes constantly. Cultivation practices affect some species favorably, some adversely. A small advantage for one species during seedling establishment can result in a significant advantage in competition with other species later in the season.

In agricultural production, the habitat of a cultivated field is managed intensively and disturbed regularly to create a beneficial environment for a crop and to maximize productivity. Many of the major agronomic weeds adapt to this kind of environment and benefit from the same activities, such as irrigation, fertilization, and pest control, which are intended to benefit the crop. They exhibit “ruderal” or “competitive-ruderal” growth habit characteristics (Grime 1979). In general, because these weeds lack the ability to tolerate shade and to invade and survive in established vegetation, they are not considered strong competitors from the botanical point of view. From an ecological and evolutionary point of view, they are similar to domesticated crops (Patterson 1985).

Competitiveness is not an intrinsic property of any particular weed or crop, and is only measurable in comparison with another species. Some characteristics of plants, however, tend to be associated with competitiveness. In an agroecosystem, plant traits associated with resource exploitation, which leads to rapid development of adsorptive surface area and a preemption of both above- and belowground space, are more important than such characteristics as shade tolerance and the ability to invade established vegetation (Patterson 1985).

The composition of a ricefield's plant community will change with the type of agricultural practices that are applied. Modifying crop management inputs will alter the competitive environment, and the morphological and physiological traits that confer plant success will shift — the type of agricultural activity influences the type of weeds found.

WEED MANAGEMENT

Weed management can be defined as the manipulation of an agroecological environment to create a situation favorable for crop growth but unfavorable for weed survival. Continuous application of a particular cropping practice can contribute inadvertently to a shift in dominance and distribution of rice weeds. In formulating a weed management program, it is important to systematically manipulate recommended production practices in synchronization with the current location-specific farming activities (Ho et al 1994).

Factors affecting composition of weed flora

Better understanding of the mechanisms of interaction between the different species in an agricultural field population can lead to more effective weed management practices. Most crop-weed communities, especially those predominantly composed of annual species, exist in simplified, disturbed habitats. Weeds are well adapted to such conditions (Gliessman 1989). Adoption of direct seeding, increased herbicide use, intensified crop rotations, and other modifications of crop production practices alter the environment. This means the morphological and physiological traits that confer the success of weeds will shift.

Most plant species are tolerant of a wide range of soil types, and soil factors are not a major limitation to plant distribution. The primary factors that encourage weed communities to coexist with rice are habitat, water status of the field, and crop planting method (Tiwari and Nema 1967). The weed species found often will reflect the history of agricultural activity in the field, not the soil type.

Broader understanding of the influence of chemical and nonchemical weed control treatments on weed population dynamics would enable us to predict ecological changes. This would facilitate adjusting treatments to prevent the weed population shifts that make control more difficult (Shaw and Jansen 1972).

Landscape position. In the Muda area of Malaysia, the composition of the weed flora is strongly influenced by landscape position. The higher ponding potential of the coastal areas that have a higher water table favors growth of aquatic weeds such as *Ipomoea aquatica* Forssk., *Nymphoides indica* (L.) O.K., *Blyxa auberti* Rich., *Hydrilla verticillata* (L.f.) Royle, *Ottelia alismoides* (L.) Vahl, and *Nelumbo nucifera* Gaertn. In the inland areas with lower water ponding potential, a lower water table favors *Cyperus iria* L., *C. babakan* Steud., *Scirpus supinus* L., and *Melochia concutenata* L. (Soo 1972).

Soilfertility. Monochoria vaginalis (Burm. f.) Presl is a typical weed in nitrogen-rich soils; *Fimbristylis miliacea* (L.) Vahl is prevalent in phosphorus-poor soils (Vongsaroj 1994).

Water management. Water management plays a major role in determining the weed flora found in a cropped field. Saturated soil conditions favor the germination of *Echinoclzloa crus-galli* (L.) P. Beauv., *Sphenoclea zeylanica* Gaertn., and *C. difformis* L. (Vongsaroj 1993). Field capacity is ideal for germination of *Leptochloa chinensis* (L.) Nees, *Eclipta prostrata* (L.) L., *C. iria,* and possibly *E. colona* (L.) Link. *M. vaginalis, Scirpus juncoides* Roxb., and *Limnocharis flava* (L.) Buch. can germinate under flooded conditions.

In Thailand, farmers try to reduce the severity of *E. crus-galli* infestations in wet-seeded rice by maintaining a longer dry period after planting, but this results in the replacement of *E. crus-galli* by *L. chinensis, C. iria, F. miliacea, E. colona,* and *Ischaemum rugosum* Salisb. (Vongsaroj 1993).

Ali and Sankaran (1984) reported that the dominant weeds under puddled conditions were *E. crus-galli, C. difformis, E. prostrata, Ammannnia baccifera* L., and *Marsilea quadrifolia* L. *E. colona, C. iria,* and *E. prostrata* were dominant under nonpuddled conditions. Unchecked weed growth caused 53% reduction in grain yield in puddled conditions and 91% reduction in nonpuddled conditions.

Pablico et al (1994) reported that when pregerminated rice seeds were sown on well-drained puddled soil, with the field flooded to a depth of 5 cm 7 d later, grasses and sedges were codominant, accounting for 85% of the total weed weight. When water was not introduced until 15 d after seeding, sedges dominated, accounting for 81% of total weed weight. Weed growth was also highest in this treatment. But when rice was seeded into water, broadleaf weeds became dominant, comprising 85% of the weed biomass. The weed flora was least diverse in the water-seeded plots.

This indicates that different weed control strategies are needed for each crop establishment method. For example, lower herbicide rates or a different, possibly cheaper, herbicide might be adequate to control weeds in water-seeded rice.

Planting method. The current shift from transplanted to direct-seeded rice in Asia has resulted in dramatic changes in the types and intensity of weeds and in their distribution in ricefields. Studies in Malaysia clearly show that direct-seeding techniques cause weed populations to shift from less competitive broadleaf weeds to more problematical grasses. Weed surveys in the Muda area in the late 1970s, when direct seeding was new (less than 1% of the planted area), found 21 weed species belonging to 13 families. The hierarchical order of dominance was *M. vaginalis* > *Ludwigia hyssopifolia* (G. Don) Exell > *F. miliacea* > *C. difformis* > *L. flava* (Ho and Zuki 1988). In the first season of 1989, when 82% of the area was direct seeded, 57 weed species belonging to 28 families were recorded. The order of severity was *E. crus-galli* > *L. chinensis* > *F. miliacea* > *Marsilea minuta* L. > *M. vaginalis* (Ho and Itoh 1991).

In Cho Moi District, An Giang Province, Vietnam, weed populations have shifted as the method of planting has changed from transplanting to wet seeding. There are more sedges in transplanted rice, more grasses in wet-seeded rice. This has resulted in a change in the herbicide used, from 2,4-D to pyrazosulfuron ethyl.

Van de Goor (1950) reported that the *Eleocharis atropurpurea* (Retz.) Presl, *S. supinus,* and *C. difformis* present in transplanted rice almost disappeared in dryseeded rice. The reverse was observed with *C. rotundus* L. In transplanted rice, E. *crus-gall;* was present; in dry-seeded rice, *E. colona* abounded. *L. chinensis* frequently was found in dry-seeded rice. Misra et al (1990) also reported that *E. colona* and *L. chinensis* were dominant in dry-seeded rice, *E. crus-galli* in wet-seeded and transplanted rice.

Farmers may change the method of rice establishment as a tactical response to temporal variations in climatic conditions and pest infestations. For example, in Iloilo, Philippines, after several years of wet seeding, farmers switched to transplanting to reduce weed buildup (Pandey 1994). Farmers in Myinmu township, Sagaing Division, Myanmar, alternate wet-seeded rice with transplanted rice to reduce weed problems. In Malaysia, some farmers have switched back to transplanting to overcome the problem of weedy forms of rice in direct-seeded fields.

Planting season. Seasonal succession of species can be expected to occur in most habitats which undergo cyclic climatic changes. In Thailand, the problem in wet-seeded rice in the rainy season is broadleaf weeds, such as *S. zeylanica,* and sedges, such as *C. difformis.* But in the dry season, the problem weeds are grasses, such as *E. crus-galli* and *L. chinensis* (Vongsaroj 1987).

Herbicide application. Application of herbicides may contribute significantly to ecological perturbations in rice and, in fact, may tend to mask rice's true stability in tropical environments. Herbicides move an agroecosystem toward low species diversity, in contrast to the high species diversity of a natural ecosystem (Moody 1991).

Although herbicides are a crucial component in weed management, continuous use of the same or related compounds can cause changes in weed composition and species dominance (Dowler et al 1974). Reliance on a single herbicide could result in quantitative changes in the structure of a weed population in as short a time as 5 yr (Mahn and Helmecke 1979).

In Korea, 140-150% of the irrigated rice area (100-120% of the total rice area) has been treated with herbicide annually since 1980, with high reliance on a single herbicide. From 1975 to 1989, butachlor accounted for more than 50% of the total herbicide used, peaking in 1986 at 80%. This resulted in undesirable weed shifts (Kim 1994).

In Malaysia, continuous application of molinate controlled *E. crus-galli* and *E. colona* but created favorable conditions for invasion by other grasses, such as *L. chinensis* and *I. rugosum* (Ho et al 1990). In west Java, Indonesia, with continuing use of 2,4-D and metsulfuron-methyl for broadleaf weed control, *E. crus-galli* is increasingly an important problem in transplanted rice (Moody 1991).

Such problems could be avoided by an integrated system of weed management, possibly involving rotation of chemicals as well as rotation of crops. Lo (1990) advocated using herbicides with different grass control spectra alternately over seasons to prevent the development of tolerant weeds.

Herbicide mixtures also may help prevent the shifts in weed populations associated with the use of a single herbicide. These shifts include the emergence of weed species tolerant of (not initially controlled) and resistant (initially controlled) to a single herbicide. It is possible, however, that the use of herbicide mixtures could lead to the development of weeds resistant to multiple herbicides (Barrett 1993).

Crop rotation. Patterns of land use may have a direct bearing on whether a weed species persists at low levels or becomes sufficiently abundant to cause economic damage. For the last several years, farmers near Pyinmana, Myanmar, have been growing two crops of rice (transplanted rice - wet-seeded rice) where previously they had grown an upland crop after transplanted rice. This monocropping has resulted in increased weed problems in transplanted rice, caused by a reduction in time for land preparation and a change from a long-duration, more competitive rice cultivar (Inmayebaw) to a short-duration, less competitive cultivar (Manawthukha). Before the introduction of the wet-seeded rice crop, *Commelina diffusa* Burm. f. and *Echinochloa* spp. were the major weeds in transplanted rice. Since then, *Isachne globosa* (Thunb.) O.K. has increased in importance.

Rice and wheat are grown in rotation on about 12 million ha in South Asia. This rotation is highly productive and very profitable. However, weed problems in wheat have increased with the adoption of the new production technology. *Phalaris minor* Retz. and *Avena fatua* L. are particularly troublesome (Malik et al 1984). Planting alternate crops, such as Egyptian clover (*Trifolium alexandrinum* L.), potato (*Solanum tuberosum* L.), and sugarcane (*Saccharum officinarum* L.), reduces *P. minor* infestation, but farmers are reluctant to adopt less profitable cropping sequences (Fryer 1981).

CONCLUSION

Weed populations in cultivated fields can be complex. Each population is composed of individual species at different growth stages, interacting with each other and with other species. Weed complexes may vary considerably within a country, among countries, and among rice ecosystems.

Weeds will continue to plague modern crop production systems because of the diversity and plasticity of plant communities. It is important that weed scientists be able to predict weed population shifts, to use in evaluating the feasibility of new production systems, in matching control strategies to the weed spectrum, and in exploring new management methods (Buhler 1995).

Although considerable data on weed control exist, there is little ecological information for most weeds in most crops. The paucity of such basic knowledge hampers efforts to develop ecologically sound weed management strategies (Cousens and Medd 1994).

Weed control should be undertaken as part of the management of a total farm and of a regional agroecosystem, rather than limiting research and control strategies to a single weed in a single crop. An agroecosystem approach to weed control will involve rotating crops and rotating the herbicides used on crops, as well as using combination herbicide treatments, sequential treatments, and mixtures of herbicides. Chemical control must be integrated with cultural practices and ecological techniques (Shaw and Jansen 1972).

Because biological systems are dynamic, farmers must vary their strategies for controlling weeds to maintain cropping viability and achieve sustainable production. To manage weeds as effectively as possible involves the development and integration of a much wider variety of control methods than are now available.

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HERBICIDES IN UNITED STATES RICE PRODUCTION: LESSONS FOR ASIA

J.E. Hill and L.S. Hawkins

Rice was introduced into the United States in 1647, and by the early 1700s had become a well-established commercial crop on plantations of the Atlantic seaboard of North Carolina, South Carolina, and Georgia. The rice crop was hand-seeded in shallow trenches, intermittently flooded to suppress weeds, and drained at midseason to allow hoeing and hand weeding. Grass weeds such as barnyardgrass *Echinochloa crus-galli* were major problems.

The highly labor-intensive planting and weed control practices disappeared following abolition of slavery in the 19th century, and the U.S. rice industry gradually migrated west, first to southwest Louisiana, then to Arkansas. Labor shortages and the industrial revolution rapidly led to mechanization. In these new areas, technologies for mechanical planting and harvesting of rice were adapted from those being used in traditional midwestern crops. Rice continued to be direct-seeded and grass weeds remained a serious problem, only partially solved by plowing, water management, and preventive hand weeding where infestations were low (Knapp 1899).

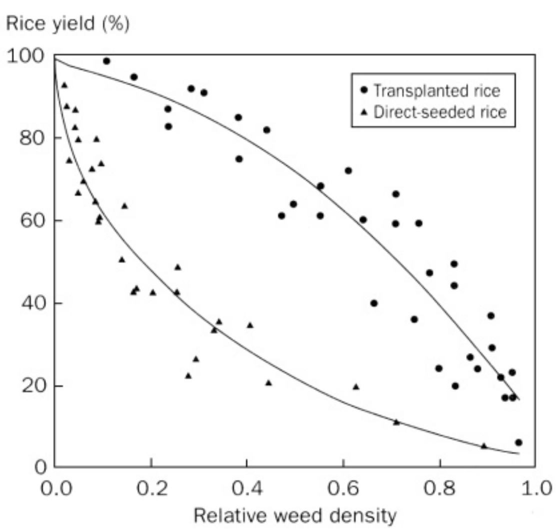
In California, rice was first grown commercially in 1912, as a dry-seeded crop. As in other dry-seeded areas, barnyardgrass flourished. Despite hand weeding and cultural practices for weed control, fields seeded to two or more consecutive crops of rice became so infested with barnyardgrass that further rice production on the same land was not profitable.

Weeds have played a significant role in determining cultural practices in direct-seeded rice in the United States Experiments by Dunshee and Jones (1924) on the influence of water depth on barnyardgrass suppression led to a change from dry seeding to sowing rice directly into water. Water seeding suppressed *Echinochloa* spp. and *Leptochloa* spp. grass weeds, although other large-seeded *Echinochloa* spp. and a complex of less competitive aquatic weed species subsequently invaded. Similar cultural problems undoubtedly led to transplanting in Asia (Matsunaka 1983).

Today, rice is produced in three principal areas of the United States, the Mississippi Delta/Arkansas Grand Prairie, the Gulf Coast of Louisiana and Texas, and the Pacific Area of California. All the rice hectarage is direct-seeded, either by drill or broadcast dry seeding, or by water seeding (Hill et al 1991a, IRRI 1993). The crop is predominantly dry-seeded in the Mississippi Delta, both dry- and water-seeded in the Gulf Coast, and almost entirely water-seeded in California. Weed species vary, depending on planting method. Grass weed species are dominant in dry-seeded systems, both aquatic weeds and large-seeded *Echinochloa* spp. infest water-seeded rice.

The cultural practices currently used to control weeds are largely preplanting activities or related to irrigation management. Hand weeding is limited to controlling small infestations in rice grown for seed; in-crop cultivation is almost nonexistent, even in drill-seeded rice (Smith et al 1977). Weed germination before rice is seeded is prevented by cultivation, but weeds and rice germinate together after seeding. This means direct-seeded rice must compete with weeds from the onset of the crop.

Transplanted rice is much more effective in competing with weeds than is direct-seeded rice because the advanced size and plant stage of the rice seedlings at transplanting provide a competitive edge (Matsunaka 1983). When Hill and others (1990a) compared studies on *Echinochloa* spp. competition in rice, they noted that the relative weed density that caused a 20% yield loss in transplanted rice caused a 70% loss in direct-seeded rice (Fig. 1). As rice farmers in Asia change to direct seeding on a larger scale, weed problems can be expected to increase.



1. *Echinochloa* spp. competition in transplanted and direct-seeded rice.

US. rice farmers rank weeds as their number one pest problem. In 1981, Chandler estimated that weeds caused 17% losses in rice, with losses ranging from 12% in California and Missouri to 34% in Texas (Table 1). Total losses have been estimated to exceed US$250 million (Chandler 1984).

While economic loss due to weeds is primarily the effect of their impact on yield, weeds also interfere with other aspects of rice production. They restrict the flow of irrigation water, harbor insects and diseases, slow harvest operations, increase grain drying costs, and reduce grain quality (Smith et al 1977, Smith and Hill 1990). These problems increase on-farm energy consumption and production costs, and may reduce land values based on yield history.

Weed species differ in their ability to compete with rice (Smith 1968). Relative yield losses from season-long weed infestations were estimated for several weed species using data from experiments on drill- and water-seeded rice (Table 2). The weeds

Table 1. Estimated average annual losses caused by weeds in rice 1975-79 in selected U.S. states.

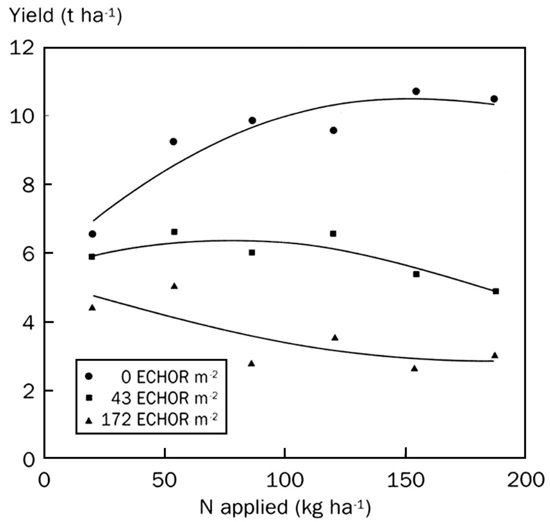
State	Production loss	
	Reduction (%)	Quantity (t ha^{-1})
Missouri	12	6
Arkansas, Mississippi, Louisiana	17	650
Texas	34	573
California	12	160

Sources: Adapted from Chandler (1984).

Table 2. Yield losses in dry-seeded irrigated rice due to season-long interference by different weed species.

Weed	Yield loss [a] (%)
Red rice	82
Barnyardgrass	70
Bearded sprangletop	36
Broadleaf signal grass	32
Ducksalad	21
Hemp sesbania	19
Spreading dayflower	18
Northern jointvetch	17
Eclipta	

[a] Rice densities were optimum (160-215 plants m^2) and weed densities were high. Source: Smith (1988).



2. Interaction of nitrogen and watergrass competition in rice.

red rice (*Oryza sativa* L.) and barnyardgrass (*Echinochloa crus-galli*) caused greater losses than bearded sprangletop (*Leptochloa fascicularis* [Lam.] Gray) or a number of broadleaf weeds. A 50% yield loss was caused by 19, 57, and 148 plants m^{-2} for red rice, barnyardgrass, and bearded sprangletop, respectively, but even densities as low as 1-3, 5-10, and 15-30 plants m^{-2}, respectively, were sufficient to justify implementing weed control practices (Smith 1988).

Cultural practices—method of direct seeding, nitrogen management, and water management—influence weed competition. For example, Smith (1988) estimated that losses from barnyardgrass were greater in drill- than in water-seeded rice. Nitrogen fertilization increased watergrass competition, and even reduced rice yields when watergrass populations were high (Fig. 2, Hill et al 1985).

HERBICIDE USE IN U.S. RICE

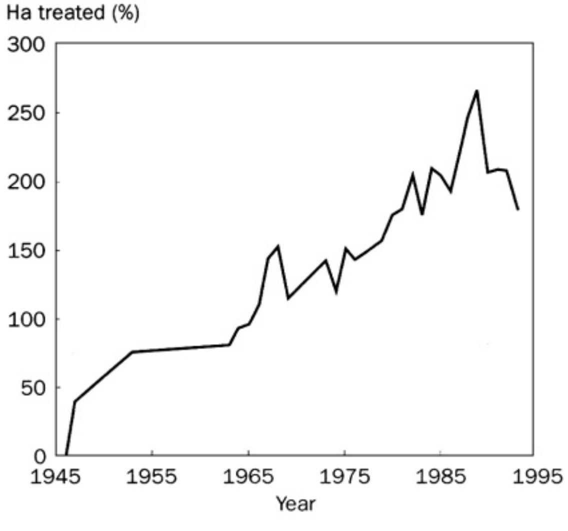
Herbicide use and costs

The post-World War II introduction of 2,4-D, followed by other phenoxy herbicides for selective broadleaf weed control, initiated a period of rapid adoption of herbicides in U.S. rice. As early as 1947, nearly 40% of California rice was treated with 2,4-D By the mid-1950s, 40% of the rice in Louisiana and 60% in Arkansas (Smith 1956), and 75% in California (Miller and Brandon 1979) was treated with phenoxy herbicides. In the 1960s, herbicides for the selective control of barnyardgrass and other grass weeds in rice were introduced and rapidly adopted. These herbicides included propanil, which remains the backbone of weed control programs in the southern United States, and molinate, the principal grass herbicide used in California. In 1990, Smith and Hill estimated that more than 95% of U.S. rice received one herbicide treatment per hectare and 80% received two, usually one for grass and one for broadleaf weed control. Herbicide use in California was especially high, peaking in 1988 at 2.6 treatments per hectare (Fig. 3).

Herbicide costs range from US$45 ha^{-1} to as much as US$168 ha^{-1} in dry-seeded rice (Chaney et al 1989) and from US$61 ha^{-1} to nearly US$200 ha^{-1} in water-seeded rice (Wick et al 1992). Few growers include cultural practices in their weed control budgets, but when costs of relevant practices are added to the costs of herbicides, the total cost for weed control may exceed US$200 ha^{-1} in both dry- and water-seeded rice.

Weed control and rice yield gains

Rice yields in the United States have nearly tripled since 1950 (Fig. 4). Several technologies have contributed to this increase, including the introduction of herbicides for broadleaf and grass weed control; application of nitrogen fertilizers, with more efficient nitrogen management in flooded soils; adoption of semidwarf rice varieties; and availability of laser-directed field leveling. Some of these technologies, in turn, have exacerbated weed problems, most notably the adoption of semidwarf varieties. The short-statured rice varieties currently planted are less competitive against weeds than their taller predecessors, and the practices used to grow short-statured rices—nitrogen fertilization and low floodwater depth—often intensify weed problems. Use of



3. Herbicide-treated rice hectarage in California, 1946-95.

semidwarf varieties probably has increased dependency on herbicides for successful weed control, at least in direct-seeded rice cropping systems.

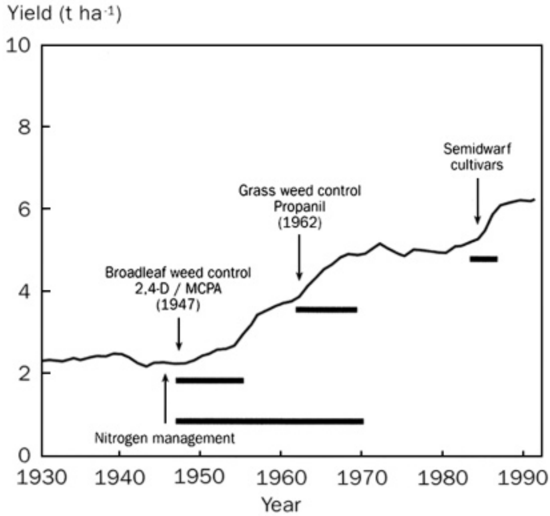
One measure of the return on herbicides applied in direct-seeded rice production can be estimated by comparing herbicide-treated to untreated research plots. In California, in 17 on- and off-station experiments from 1986 to 1993, herbicides for broadleaf weed control increased yields of semidwarf varieties 162% and herbicides for grass weed control increased yields 178%. With combined grass and broadleaf herbicides, yields increased 201%. Average yields from the 17 experiments were 4.8 t ha^{-1} where plots were untreated, compared with 7.7, 8.5. and 9.6 t ha^{-1}, respectively, where broadleaf, grass, and both broadleaf and grass herbicides were used. This makes a farmer's investment in herbicides for weed control cost effective, even at US$200 ha^{-1}. Similar increases in yield were reported for broadleaf control with MCPA/2,4-D in the 1950s.

In a study of the relative significance of technological changes in maize production, Cardwell (1982) estimated that hybrids contributed 58%, nitrogen 47%, and herbicides 23% to gains in Minnesota maize yield (other changes caused reductions, accounting for a total of more than 100%). We do not attempt here to analyze and separate the relative contribution of changes in technology to U.S. rice yields. However, the introduction of 2,4-D and other phenoxy herbicides for broadleaf weed control undoubtedly contributed to gains in U.S. rice yields. Yields, which had increased only slightly in the previous four decades, both nationwide and in California, increased substantially during the 1950s (Figs. 4 and 5). U.S. rice yields, which were slightly above 2 t ha^{-1} in 1945-50, increased by more than 60%, to 3.2 t ha^{-1}, by 1960. California rice yields followed the national trend, increasing by about 1.5 t ha^{-1}.

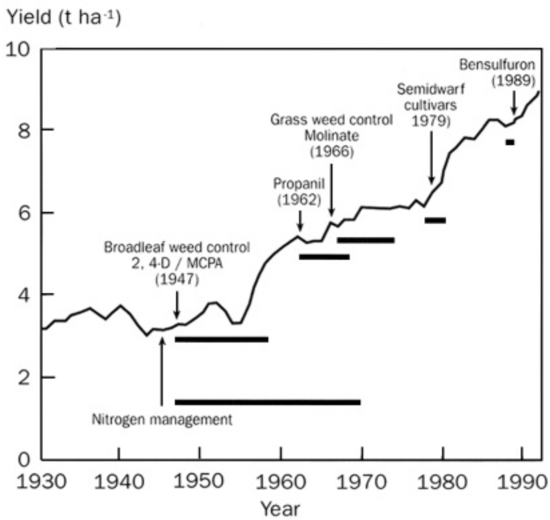
Weed control continued to improve in the 1960s, with the introduction of selective grass herbicides. Dry-seeded rice in the southern states benefited especially from the discovery and registration of propanil in 1961. The 30% increases in U.S. rice yields during the 1960s is believed to be due in large part to selective grass control (Fig. 4). In the water-seeded rice of California in the decade following the adoption of herbicides for barnyardgrass control, yield gains were about 15% (Fig. 4). U.S. rice historians refer to the 1950s and 1960s as the decades when broadleaf and grass weeds were finally brought under control (Miller and Brandon 1979).

The very rapid adoption of bensulfuron on nearly all California rice hectarage in 1989, to replace previous broadleaf herbicides, is thought to be largely responsible for recent increases in yield (Fig. 5). Bensulfuron controls weeds at earlier stages than the herbicides used previously and is less injurious to rice than the phenoxy herbicides (Hill et al 1990b).

The improvements in yield of the 1950s and 1960s cannot be attributed entirely to the introduction of rice herbicides; herbicides were only one component in an integrated package of new technologies. The use of nitrogen fertilizer in U.S. crop production also increased rapidly during this period, and may be inextricably linked to advances in weed control. For example, experiments with nitrogen fertilizers before



4. U.S. rice yields and adoption of new rice technology, 1930-90.



5. California rice yields and adoption of new rice technology, 1930-90.

the advent of rice herbicides showed that nitrogen-induced weed growth often led to decreases in yield (Nelson 1931), making herbicides necessary to achieving the maximum nitrogen use efficiency in direct-seeded rice. Varietal improvement cannot explain the yield gains of these decades either. Although substantial and much heralded yield gains from semidwarf varieties were made in the United States in the 1980s, the gains were on the same order as those of the 1950s and 1960s (Fig. 4).

The conclusion is that the introduction of herbicides for weed control appears to have contributed substantially to the yield gains in U.S. rice of the 1950s and 1960s, and more recently in California. How much of the increase can be attributed to herbicides alone is less important than is their contribution to maximizing the package of technologies adopted by U.S. rice farmers.

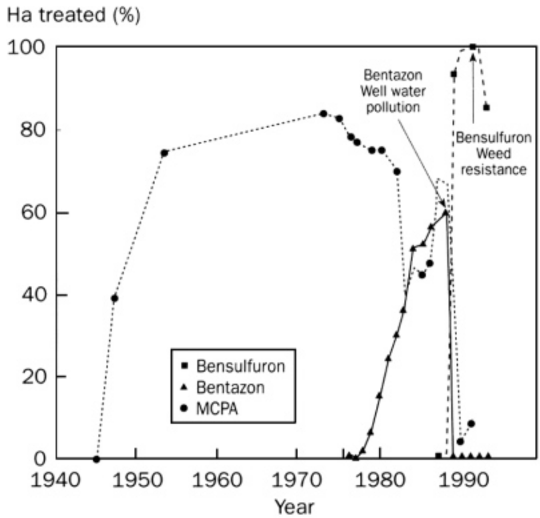
PROBLEMS WITH HERBICIDES

Herbicides have contributed substantially to improved weed management in U.S. rice, but as large urban populations develop, more and more social and environmental concerns are being articulated about the relationship of chemical use and environmental quality, particularly in California. Extensive herbicide use also has raised questions about overreliance on a single strategy for weed control. Although herbicides were adopted rapidly, U.S. rice farmers continue to integrate preventative and cultural practices with chemical weed control. These practices include weed-free seed, crop rotation, land leveling, cultivation, water management, and fertilizer management.

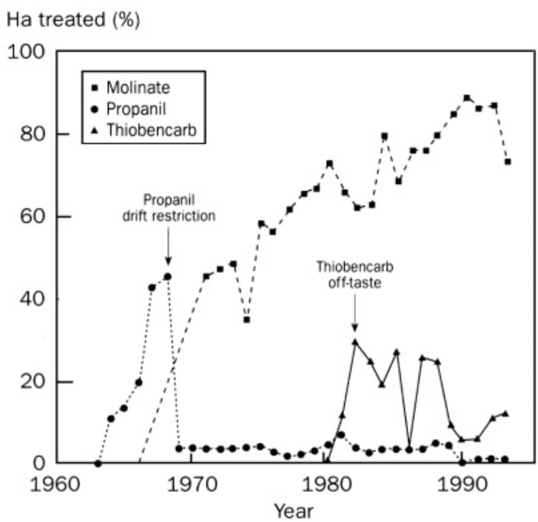
Environmental overload and misuse of herbicides can cause problems. Damage to other sensitive crops from herbicide drift of both the phenoxy herbicides and propanil has occurred in all U.S. rice areas (Smith et al 1977. Barbe and Hillis 1969). In California, rice herbicide residues have been found in well water and agricultural drains and rivers (Cornnachia et al 1984). Continuous use of herbicides with the same mechanism of action has led to the evolution of herbicide-resistant weeds. A number of U.S. rice herbicide registrations have been canceled, for a variety of reasons. The phenoxy herbicide 2,4,5-T was deregistered in 1983 in response to concerns about a highly toxic contaminant, dioxin. More recently, registration of bentazon, a broadleaf herbicide, was canceled in California after it was detected at low concentrations in well water. These problems and increasing regulatory costs have reduced the availability of existing herbicides and slowed development of new herbicides for U.S. rice production. Figures 6 and 7 show how herbicide use has changed in California, with an explanation of the changes.

Herbicide drift

U.S. rice often is grown adjacent to other crops that are sensitive to rice herbicides. In the Mississippi Delta and Gulf Coast regions, cotton and soybean, as well as home garden crops, have been damaged by herbicide drift. In California, where cropping diversity is far greater than in the southern United States, rice herbicides have been



6. Use of herbicides to control broadleaf weeds in California ricefields and problems associated with herbicide use, 1940-90.



7. Use of herbicides to control grass weeds in California ricefields and problems associated with herbicide use, 1960-90.

responsible for injury to several crops. To avoid herbicide drift onto nontarget crops, regulatory agencies in the rice states restrict the use of aerial and ground applications of rice herbicides. In Arkansas, for example, phenoxy herbicides cannot be applied within 6 km of cotton, virtually eliminating their use on 70% of Arkansas rice hectarage. In 1969, use of propanil was restricted to less than 10% of the rice hectarage in California (Fig. 7) because of long-range drift and excessive damage to deciduous orchards (Barbe and Hillis 1969, Elmore et al 1970). Drift from herbicides other than the phenoxys and propanil has been far less extensive, but all herbicides have the potential to cause damage to other crops. In the southern United States, drift from applications of propanil, quinclorac, and triclopyr have injured nontarget crops.

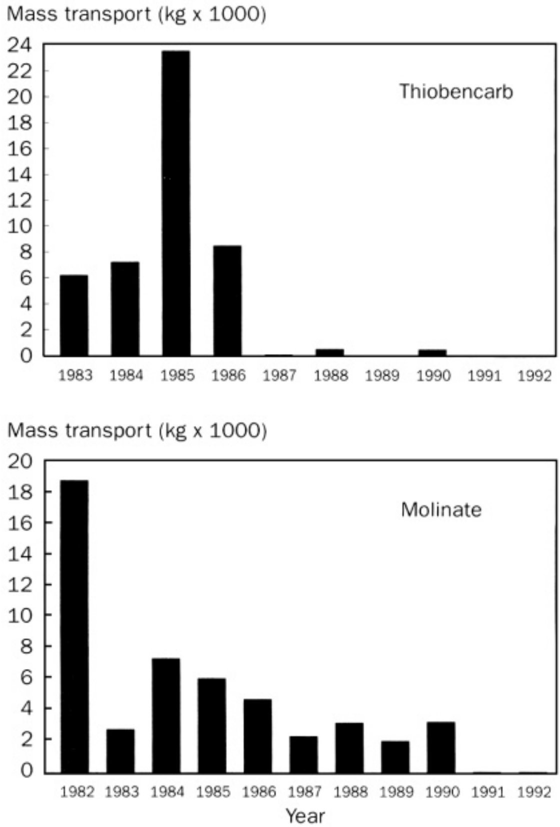
Various adjuvants have been used for drift control, with mixed results. Ground applications generally drift much less than aerial applications. On small hectarages where herbicides can be applied by backpack sprayers or ground-driven applicators, drift can be minimized. More selective herbicides and improvements in application technology are needed to solve the problem of rice herbicide drift and injury to sensitive crops.

Water quality

Fish kills in the agricultural drains of California rice production areas in the 1970s and off-tastes in potable water in 1981-82 were attributed to the herbicides molinate and thiobencarb, respectively. The fish kills were found only in agricultural drains downstream from rice production areas, not in the Sacramento River or its natural tributaries. While only nongame fish species of carp *Cyprinus carpio* were affected, concerns were raised immediately about the implications for highly valued anadramous species, such as salmon *Salmo salar,* bass *Perca fluviatilis,* and shad *Alasa sapidissima,* that spawn in the river systems, as well as for the health of aquatic species in general. In Asia, where rice-fish cropping systems are common, herbicides will need to be tested and monitored to protect these important food production systems.

At nearly the same time as the fish kills caused by molinate, a sulfoxide metabolite of thiobencarb was implicated as causing an off-taste in the municipal drinking water of the City of Sacramento (Cornacchia et al 1984). The metabolite was not detected in municipal drinking water, but the herbicide itself was found in the Sacramento River at the intake of the treatment facility. The appearance of the herbicide and the off-taste water followed peak thiobencarb use in rice. A taste panel evaluation of metabolite-spiked water samples provided additional evidence that thiobencarb was responsible. Thiobencarb use subsequently was restricted to less than 25% of California rice hectarage (Fig. 7). Current state regulations set very low residue limits for molinate (10 ppb), thiobencarb (1.5 ppb), and other pesticides in public waters.

Through the early 1980s, California rice growers continued to use conventional, flow-through irrigation systems developed before the advent of herbicides and other pesticides. Little thought was given to the consequence of applying herbicides in a ricefield during the time tailwater was flowing from the field. When downstream



8. Thiobencarb and molinate transport at the Sacramento River, 1982-92.

surface water pollution became an issue, the principal strategy to mitigate herbicide runoff was to lengthen water-holding time in ricefields, to allow for increased herbicide degradation. To better control water management and further control off-site pollution, California rice farmers began installing recirculating irrigation systems and developing other. somewhat novel, static or tailwater recapture systems (Hill et al 1991b). Within the last decade, voluntary and regulatory water-holding periods following herbicide applications have reduced herbicide discharges into public waters by more than 98% (Fig. 8), to acceptable levels or even below those levels. Adoption of modified irrigation management strategies in low-hectarage, high-rainfall, tropical Asian rice environments would be more difficult, but not impossible.

Herbicide resistance

Using propanil to control grass weeds in southern U.S. rice began in 1962 and, until recently, as much as 70% of Arkansas rice hectarage was treated twice a year with 3.4 kg ha^{-1}. But in 1990, after 30 yr of continuous treatment. barnyardgrass was found to be resistant to propanil (Walton and Holmdal 1992). Weed populations were not controlled by application rates three times higher than normal (Smith and Baltazar 1992, Carey et al 1992). In a 1991 survey, barnyardgrass samples from 60 Arkansas rice farms in 11 counties were found to be highly tolerant of propanil (Smith and Baltazar 1992). Propanil resistance occurred more often in continuous rice than in rice rotated with soybean. Rotation to soybean using alternative herbicides or, in continuous drill-seeded rice, to herbicides with different mechanisms of action than propanil, can control resistant barnyardgrass in rice (Baltazar and Smith 1994).

Bensulfuron, which can control nearly all annual aquatic broadleaf and sedge weeds (Hill et al 1990), was introduced in California in 1989. Regulatory restrictions on other herbicides and the effectiveness of bensulfuron resulted in immediate adoption on more than 90% of California rice hectarage (Hill et al 1994). Within 4 yr of its introduction, however, several weed species were confirmed to be resistant to bensulfuron applied at levels seven to ten times the normal rate (Pappas-Fader et al 1993, 1994). Only the phenoxy herbicides MCPA and 2,4-D remain available as alternatives, although thiobencarb may be used to control one resistant species, smallflower umbrella sedge *Cyperus difformis.* Alternative cultural practices and herbicides with different mechanisms of action are needed to control resistant weeds. In southern U.S. rice, alternative herbicides to control grass weeds are available to substitute for propanil. Alternative herbicides for bensulfuron are more limited; management strategies to break weed cycles, such as dry seeding, may provide a partial solution to use of that herbicide.

THE FUTURE OF HERBICIDES IN U.S. RICE PRODUCTION

For more than 50 yr, herbicides for selective weed control were readily adopted by U.S. rice farmers, contributing substantially to yield increases. High rates of adoption and extensive use of herbicides in the rice areas, however, led to agricultural and environmental problems from drift injury to other crops, water pollution, and the development of resistant weeds. Now, rice herbicides in the United States are highly regulated and, in some areas, routinely monitored. In California, rice herbicides with a potential for drift injury or water pollution are restricted. Before being allowed to use them, farmers must undergo training and obtain a permit from local agricultural officers. In addition, farmers or their agents must provide a 3-day notice of intent to apply the herbicide, a notice of the actual application date, and a use report. Use of nonrestricted rice herbicides requires less paperwork. but must be reported.

Initially, California rice farmers objected to this seemingly cumbersome regulatory process. Coupled with monitoring, however, it has proven to be useful in developing programs that curtail negative environmental impacts, as well as in documenting improvements in water quality. These benefits support good stewardship in the use of herbicides.

Regulation of rice herbicides also has increased in the southern United States, although it is still less extensive than in California. Herbicides that cause environmental degradation in any rice area of the United States, or with the potential to impair human health, have been deregistered.

The high cost of herbicide development and the risk of subsequent cancellation of registration or of obsolescence from weed resistance have discouraged private sector development of new herbicides for U.S. rice. Rice hectarage in the United States is less than 2% of the world's total, making it a minor, and high-risk, market for agricultural chemicals. Understandably, multinational companies are focusing on the discovery and registration of herbicides for Asian rice. In a 1994 survey, only four experimental herbicides were under investigation in public programs in the United States (J.E. Hill, University of California at Davis, unpubl.). Such programs are usually good indicators of pending commercial development, but registration and actual use of the herbicides being investigated is still at least 3 yr away.

Currently, five herbicides—bensulfuron, molinate, thiobencarb, propanil, and the phenoxys-are available in California, and two of them have severe hectarage restrictions. Rice farmers in the southern United States have a wider choice of herbicides, primarily because of better crop safety when they are applied on drill-seeded rice. But in the absence of new herbicides, even fewer herbicides are likely to be available for U.S. rice in the foreseeable future. Maintaining current rice herbicides will require better understanding of how best to use them for weed control and how to minimize or eliminate their negative impacts on the environment.

Continuing experiments on the influence of water management, crop rotation, and other cultural practices indicate that without herbicides, yields cannot be maintained at the high levels now possible. Commercial, nonchemical (organic) rice that has been produced for more than 20 yr by some California farmers provides some indication of expectations for rice grown without herbicides. First-year yields are somewhat lower than those of conventionally grown rice. Summer fallow rotation becomes necessary in 1 out of every 2 or 3 yr, to reduce weed seed banks and prevent severe weed populations in subsequent rice crops (National Research Council 1989). On soils suited only for rice production, fallow rotations essentially reduce yields by one-third to one-half compared with continuous rice.

Of all the cultural practices used by U.S. rice farmers to control or suppress weeds, water management has been the most important. Precision field leveling with laser-directed equipment has greatly improved a farmer's ability to manage water. In recent studies on water depth, 20 cm deep water suppressed barnyardgrass, but could not entirely replace herbicides for grass weed control. Yields in deep (20 cm) water treatments without herbicides dropped in successive years to 80, 73, and 60% of yields with herbicides, as infestations of the aquatic sedge ricefield bulrush *Scirpus* *mucronatus* increased (Williams et al 1990). Such shifts in weed populations are not uncommon. Even hand weeding in Asia is thought to have selected for *Echinochloa* spp. rice mimics. Use of herbicides or changes in cultural practices may make necessary continual changes in strategies for controlling shifting weed populations. A continuous flow of new, environmentally benign herbicides (biological or synthetic) and weed management technologies will be needed to maintain the yield gains of the last 4 decades.

Increasing labor costs in Asia are favoring a change from transplanted to direct-seeded rice. As this occurs, weed problems can be expected to increase. Asian rice farmers will need cultural practices and herbicides with more selectivity than those that were effective in transplanted rice. Private sector interest in the development of herbicides for Asian rice, driven by both market size and fewer regulatory restrictions, is considerably higher than for U.S. rice. In the United States, where food supplies are plentiful and incomes relatively high, a regulated agriculture has less impact on food availability than it does in countries where food may be scarce. Herbicide regulation in Asian countries can be expected to continue to be less than in the United States, given the focus of Asian governments on securing adequate food supplies for their people. The expected increase in herbicide use, however, should be coupled with appropriate regulation, perhaps standardized across countries so that costs of registration may be shared, to protect human health and environmental quality on a regional basis. Training and monitoring will be needed to ensure this safeguard.

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Impacts of herbicides

HERBICIDES AND RICE FARMER HEALTH: A PHILIPPINE STUDY

P.L. Pingali and C.B. Marquez

The use of herbicides in Asian rice production has been increasing during the last 10 yr, especially in countries where rural wages are rising rapidly. Higher herbicide use is closely associated with shifts from labor-intensive transplanted rice systems to labor-conserving direct-seeded rice systems. Even though direct-seeded rice is ostensibly more profitable than transplanted rice, the type of production inputs needed could mean that farm households where rice is direct seeded will incur significant health externalities. Adverse health effects due to prolonged exposure to insecticides and herbicides impose significant costs and reduce labor productivity.

Detailed studies of the impact of pesticides, in particular insecticides, on the health and productivity of Philippine rice farmers (Pingali et al 1994, Antle and Pingali 1994, Rola and Pingali 1993) were reanalyzed to quantify herbicide-related health impairment and to assess the trade-off between gains in profitability and increased risk of health impairment with greater use of herbicides in rice farming.

METHODOLOGY

Two communities of Philippine farmers who had long-term exposure to pesticide use in rice production were compared with a community of farmers with no history of pesticide exposure. All the farmers who participated in the study underwent a medical assessment that included an interview, a physical examination, and a battery of laboratory tests. Their pesticide exposure history was documented. A set of medical indices was defined and related econometrically (using logit regressions) to a set of pesticide use indicators obtained from farm monitoring. Probabilities of health risk were assessed relative to differential levels of pesticide use, differences in types of chemicals used, and farmer characteristics. The strength of this design lies in its ability to detect chronic and subacute effects. Its weakness lies in its inherent bias toward survivors.

Pesticide users

The pesticide user group (the exposed sample) included 31 farmers and 25 pesticide applicators in Laguna Province and 42 farmers and 15 pesticide applicators in Nueva Ecija Province. Laguna farmers were moderate users. Nueva Ecija farmers heavy users of both insecticides and herbicides. Both groups had documented exposure to pesticides (in particular to organophosphorous compounds and herbicides) for from 15 to 25 yr. The farmers and members of their households were interviewed intensively about rice production inputs and technologies, with special emphasis on pest management practices and methods of handling pesticides.

Pesticide nonusers

The pesticide nonuser group was made up of 39 farmers in Lucban, Quezon Province, a rainfed rice production area where pesticides are not commonly used. They were the nonexposed or control sample. These pesticide nonuse farm households had lower incomes than the pesticide use farm households. Rice production intensity in Lucban, Quezon Province, is lower than it is in Laguna and Nueva Ecija; farmers use less fertilizer and other inputs and usually grow only one crop a year. Pest pressure in the rice crop is lower, and the rice area in general is pesticide-free. Otherwise, the farmers use similar agricultural practices and live in similar socioeconomic conditions.

Data collection

All study participants were brought to the medical clinic at the International Rice Research Institute (IRRI) for a baseline medical assessment. That involved a detailed physical and laboratory examination plus documentation of personal health history and habits (especially drinking and smoking). The Laguna and Nueva Ecija farmers were monitored medically during the course of the study to identify any changes in their health, especially in relation to pesticide use.

PESTICIDE USE PRACTICES

The wide variety of pesticides used by Philippine rice farmers include insecticides, herbicides, and molluscicides (Rola and Pingali 1993, Warburton et a1 1994). Insecticides include organochlorine endosulfan; organophosphates such as methyl parathion, monocrotophos, and chlorpyrifos; carbamates such as BPMC, carbaryl, and carbofuran; and pyrethroids such as cypermethrin and deltamethrin. The principal herbicides are 2,4-D and butachlor (Table 1).

The insecticides used are classified by the World Health Organization as category I and II chemicals; the herbicides are classified as category II and IV chemicals. In terms of toxicity, category I chemicals are the most hazardous and category IV the least hazardous. Many of the herbicides used in the Philippines are not registered for use and cannot be sold in the United States or the United Kingdom (Table 2).

Table 1. Types of herbicides applied, by season, in Laguna (1966-90) and Nueva Ecija (1979-91), Philippines.

Chemical	Category[a]	Farmers reporting (%)						
		1966 WS[b]	1978 WS	1988 DS	1988 WS	1990 DS	1990 WS	
Laguna								
Phenoxy								
2, 4-D	II	88.2	32.4	5.9	15.1	7.1	17.2	
Acetamide								
Butachlor	IV	0	58.8	55.9	84.8	82.1	89.7	
		1979 DS[b]	1979 WS WS	1985 DS	1985 WS	1988 DS	1989 DS	1991 WS
Nueva Ecija								
Phenoxy								
2,4-D	II	4.5	6.0	2.9	0.7	0.7	1.7	0
2,4-D + butachlor	II	0	0	2.2	1.4	0.7	0	0
2,4-D + piperophos	II	0	0	15.9	19.6	10.3	6.7	5.3
2,4-D + thiobencarb	II	0	0	1.5	2.1	3.7	8.3	7.0
Acetamide								
Butachlor	IV	88.3	65.0	72.5	72.7	39.0	18.3	22.8
Pretilachlor	IV	0	0	0.7	0.7	43.4	85.0	70.2
Thiocarbamate								
Thiobencarb	II	1.8	0.8	5.1	2.8	5.9	11.6	17.5

[a] WHO classification: la = extremely hazardous; 1b = highly hazardous; II = moderately hazardous: III = slightly hazardous, IV = product unlikely to present acute hazard on normal use. [b] WS = wet season: DS = dry season.

Table 2. Registration status in the United States and the United Kingdom of herbicides commonly used in the Philippines.

Common name	Family[a]	Chemical ai hazard[b] category	Formulation hazard[c] category	Bans and restrictions[d]
2,4-D	PH	II	2	US: registered general use
+ Thiobencarb			2	US: registered general use
+ Butachlor			3	US, UK: not registered
+ Piperophos			3	US, UK: not registered
Thiobencarb	TC	II	3	UK: not registered
Butachlor	A	IV	4	US, UK: not registered
Pretilachlor	A	IV	4	UK: not registered

[a] A = acetamides: c = carbamates: OC = organochlorines; OP = organophosphates: P = pyrethroid; PH = phenoxy: T = organotins: TC = thiocarbamates. [b] Hazard category of active ingredient as defined by WHO: la extremely hazardous: Ib = highly hazardous: II = moderately hazardous: III = slightly hazardous: IV = product unlikely to present acute hazard on normal use. [c] Formulation hazard category of the most commonly sold products in the Philippines, as defined by the Philippine Fertilizer and Pesticide Authority (FPA), based on WHO guidelines. [d] Not registered = cannot be sold; restricted use = can only be used for specific registered uses; professional use = applicators must be trained and licensed. Sources: EPA (1992). ADB (1987), MAFF (1991).

Table 3. Frequency of pesticide application in Laguna (1966-90) and Nueva Ecija (1979-91), Philippines.

Applications (no.)	Laguna					
	Wet season				Dry season	
	1966	1978	1988	1990	1988	1990
Insecticides						
0	50.0	2.9	6.1	6.9	17.2	20.0
1	38.9	52.9	24.2	37.9	20.7	24.0
2	2.8	32.4	27.3	31.0	27.6	24.0
3	2.8	8.8	12.1	6.9	17.2	4.0
4	0.0	2.9	15.2	10.3	10.3	12.0
5	0.0	0.0	3.0	3.4	0.0	8.0
6 and more	0.0	0.0	12.1	3.4	6.9	8.0
Herbicides						
0	16.7	17.6	9.1	0.0	27.6	4.0
1	83.3	76.5	69.7	72.4	58.6	60.0
2 and more	0.0	14.7	21.2	27.6	13.8	36.0
Molluscicides						
0	100.0	100.0	84.8	75.9	86.2	56.0
1	0.0	0.0	15.2	17.2	13.8	28.0
2	0.0	0.0	0.0	6.9	0.0	16.0
Total respondents	36	34	33	29	29	25

Applications (no.)	Nueva Ecija					
	Wet season			Dry season		
	1979	1985	1991	1975	1985	1991
Insecticides						
0	19.3	0.0	7.5	22.4	0.0	10.5
1	20.0	4.2	35.5	22.4	8.7	15.8
2	26.2	20.3	30.1	16.8	23.2	43.2
3	17.2	16.8	15.1	18.2	27.5	20.0
4	9.0	25.2	5.4	10.5	21.0	7.4
5	2.8	11.2	6.5	4.9	6.5	2.1
6 and more	5.5	22.4	0.0	4.9	13.0	1.1
Herbicides						
0	44.1	6.3	10.8	29.4	6.5	4.2
1	46.2	69.2	81.7	58.7	76.1	77.9
2 and more	9.7	24.5	7.5	13.3	17.4	18.9
Molluscicides						
0	23.4	0.0	71.0	17.5	0.0	68.4
1	0.0	0.0	25.8	2.8	0.0	29.5
2 and more	0.0	0.0	3.2	0.0	0.0	2.1
Total respondents	145	143	93	143	138	95

Most of the pesticide-user farmers applied a herbicide once per crop, although the number of farmers who make a second application is increasing (Table 3). The users exposed themselves to pesticide hazards during handling, mixing, and spraying operations (Rola and Pingali 1993, Warburton et al 1993). They did not use any protective clothing, gloves, mask, or rubber boots when spraying.

PESTICIDE EXPOSURE AND HEALTH

Pesticide exposure can vary from the extreme case of intentional poisoning (ingesting one large dose) to occasional, low level ingestion of pesticide residues in food or water. Of particular concern in agricultural production is unintentional, occupational exposure to pesticides over a long time. Those who frequently mix and spray pesticides over many years are most at risk. People working in newly sprayed fields and family members in close proximity to spray equipment, contaminated clothing, and pesticide containers also are subject to risk of some exposure.

The medical literature provides a set of indicators for assessing long-term health effects due to pesticide exposure (Hock 1987, Morgan 1987, Nemery 1987). Of these, the impact of chemicals on the eyes, the respiratory system, the neurological system, the skin, and the gastrointestinal system are most discernible in a cross-section analysis.

The number of applications of insecticides and herbicides during a cropping season was used as a proxy for pesticide exposure. Logit regressions were used to relate the incidence of ailments to pesticide exposure.

Eye effects

The eyes are extremely vulnerable to the physical and chemical hazards that confront those involved in agriculture. Some herbicides, such as 2,4-D and the acetamides, are known eye irritants (Morgan 1977). The user group farmers had been using acetamides and 2,4-D for at least 5 yr.

A chronically irritated eye can form a pterygium, a vascular membrane over the cornea. The condition usually affects older people and people exposed to dust and wind. As severity increases, the vascular membrane may encroach on the pupil and diminish visual acuity. Surgery is required to improve eyesight. Initially, a pterygium could impact a farmer's productivity because of bothersome symptoms. Later, diminished vision would reduce productivity.

Logit regression estimates indicate that the incidence of eye abnormalities in the user group increased significantly with age and with exposure to insecticides (Table 4). Exposure to herbicides also had the expected positive sign, although the regression estimate was not significant. General health status, as measured by the ratio of weight to height, had the expected negative sign on eye abnormalities, although also not significant. The probability of eye abnormalities among the sample households was 0.36, determined from the logit function at the mean levels of all variables.

Table 4. Logit regressions on health impairments found among Philippine rice farmers.

	Eye	Pulmonary	Poly-neuropathy	Skin	Gastrointestinal	Multiple impairments
Intercept						
alpha 1	-3.2373**	-2.8914**	-5.8633*	-6.7327***	4.3077	0.0493
	(1.391)[a]	(1.464)	(3.4546)	(1.6778)	(1.95)	(1.2267)
alpha 2						-1.0807
						(1.2287)
alpha 3						-2.5382**
						(1.2462)
alpha 4						-4.8817***
						(1.3183)
Age	0.0455***	0.0501***	0.0508	0.0218	-0.0443***	0.0237*
	(0.0144)	(0.015)	(0.0323)	(0.0162)	(0.0159)	(0.0125)
Weight/height	-0.00174	-0.0263	-0.0708	0.151***	-0.1851**	-0.0354
	(0.049)	(0.0488)	(0.1186)	(0.057)	(0.0780)	(0.0419)
Smoking	-	0.6350*	-	-	-	0.6116*
		(0.3972)				(0.3533)
Drinking	-		1.9852*	-	-	-0.7123
			(1.1394)			(0.3575)
Total dosage of insecticides	0.3497**	0.259*	-0.1025	0.2180	0.0919	0.3551***
	(0.1714)	(0.1566)	(0.2967)	(0.1546)	(0.1695)	(0.1363)
Total dosage of herbicides	0.4986	0.0291	1.3815*	1.0414**	0.9849**	0.9616***
	(0.3942)	(0.3918)	(0.7131)	(0.4267)	(0.4348)	(0.3421)
Cloth cover over mouth	-	0.3833	-	-	-	0.6309*
		(0.4106)				(0.3487)
n	148	145	148	148	149	145
Chi-square	19.849	15.7	8.885	22.516	24.157	36.293

[a] Figures in parentheses are standard errors of estimate.

An increase in insecticide exposure, from an average of one application per season to two, increased the probability of eye problems by 22%. Farmers who followed the recommended three applications faced a probability of 0.53 of having chronic eye problems.

Skin effects

Pesticides primarily enter the body through the skin, not (contrary to common belief) through the respiratory tract. Mixing and transferring pesticide concentrates pose a greater health hazard to farm workers than does pesticide application. For spray operators, dermal exposure levels are higher than inhalation levels. The degree of contamination is proportional to the concentration of the chemical and the proximity to the source of emission (Hamilton 1982). Spraying or dusting pesticides leaves residues on exposed skin that are about 20-1700 times the amount that reaches the respiratory tract. The quantity varies with working conditions, application techniques, protective equipment, and duration of exposure (Bainova 1982). Dermal contamination is greater when a knapsack sprayer is used than when a spinning disc applicator or an electrodyne sprayer is used (Durand et al 1984). The hands and forearms are most exposed and have the highest potential for pesticide contamination (Zweig et al 1985, Castañeda et al 1990).

Of the pesticides used in rice, herbicides such as 2,4-D and acetamides, and the organochlorine insecticides are mild to moderate skin irritants and potential sensitizers (Morgan 1977). Eczema, a chronic allergic dermatitis characterized by lichenification and fissuring, is a health indicator of pesticide exposure. The skin appears thickened and has accentuated markings. Other health indicators are destruction of the distal portions of the toenails, which gives them an “eaten-up” appearance.

The incidence of skin problems among pesticide users was related positively to the use of both insecticides and herbicides, although only herbicide use was significant. Farmers at the respondent average for age and nutritional status who did not apply any herbicides had a probability of 0.12 of having skin problems. The probability of skin problems rose to 0.30 for farmers who made one herbicide application per season, and to 0.50 for farmers who made two applications.

Respiratory tract effects

Long-term exposure to chemical irritants can cause such respiratory symptoms as cough, cold, sputum formation, wheezing, rales, tenderness, and decreased chest expansion (Morgan 1982, Hock 1987, Nemery 1987). Incipient lung disorders can be detected by a thorough physical examination and medical history. Bronchial asthma and other abnormal lung findings are two respiratory tract indicators of pesticide exposure.

The incidence of respiratory abnormalities among the farmers studied was significantly related to age, smoking, and exposure to insecticides. Herbicides had the expected positive sign, although the regression was not significant. Nutritional status (weight/height) had the expected negative sign but was not significant. At the sample mean, the probability of abnormal respiratory findings for farmers who did not smoke was 0.30. These farmers applied one recommended treatment each of insecticides and herbicides. At this level of pesticide use, farmers who smoke had a 50% higher probability of abnormal respiratory findings. The probability of respiratory problems increased by 16% for farmers who applied two insecticide treatments, and by 30% for farmers who applied three treatments, regardless of their smoking habits.

Gastrointestinal tract effects

Pesticides usually enter the gastrointestinal tract accidentally. A farmer who is applying pesticides and who smokes or wipes off sweat near the mouth may unknowingly ingest pesticide particles. Carbamate insecticides formulated in methyl alcohol that are ingested can cause severe gastroenteritis irritation (Morgan 1977). When given in large doses to experimental animals, 2,4-D and organochlorines are moderately initating to the gastrointestinal lining, causing vomiting, diarrhea, and mouth ulcers (Morgan 1977). Organophosphates and copper salts also irritate the gastrointestinal tract, causing intense nausea, vomiting, and diarrhea. The health indicator chronic gastritis is clinically characterized by epigastric tenderness and pain associated with nausea and vomiting.

The incidence of gastrointestinal problems among the farmers studied was positively related to pesticide exposure, with exposure to herbicides a significant regression. Gastrointestinal problems had a significant negative relationship with nutritional status. A significant negative effect of age was unexpected. Farmers at the sample mean who applied one recommended dose of herbicides had a probability of 0.27 for an abnormal gastrointestinal evaluation. Two recommended applications of the same chemicals increased the probability by 85%, three applications increased the probability by 167%.

Neurological effects

Organophosphorous compounds and 2,4-D are neurotoxicants (Morgan 1977). They have been implicated as causative agents for polyneuropathy, a neurological disorder typically manifested as motor weakness in the distal muscles and sensory deficit with what has been called a “glove-and-stocking” distribution (Braunwald 1987). In the early stages, absence of deep tendon reflexes may be the only sign of a problem. The neuropathy may be purely motor or purely sensory.

Diabetes is highly prevalent in the Philippines, and must be considered in the differential diagnosis of polyneuropathy. Isolated hyporeflexia, another neurological index, is a known sensitive indicator of chronic exposure to organophosphorous pesticides (WHO 1990).

The incidence of polyneuropathy among the farmers studied was significantly associated with drinking alcohol and with pesticide use. Herbicides had a significant positive effect; the effect of insecticides was positive but not significant. Age had the expected positive sign and nutritional status had the expected negative sign on incidence of polyneuropathy, although both coefficients were not significantly different from zero.

Farmers who did not drink alcohol, when evaluated at the sample mean with respect to age, nutritional status, and use of pesticides, were found to have a probability of 0.02 for positive findings of polyneuropathy. The probability of positive findings rose to 0.11 for farmers who regularly consumed alcohol. Nondrinking farmers who applied herbicides at the recommended rate of three applications per season had a 0.24 probability of polyneuropathy findings. For farmers who drink, that probability was 0.70.

Multiple health effects

Farmers exposed to pesticides over a long time can face several illnesses at the same time. Pesticides also may cause other, nonspecific illnesses. Of the nonusers, 79% had two or fewer pesticide-related health impairments; of the users, 78.5% of Laguna farmers and 82.5% of Nueva Ecija farmers had three or more impairments. The maximum number of health impairments among nonusers was four; among users in Laguna, five; among users in Nueva Ecija, seven.

Multinomial logit regressions indicate the incidence of multiple health impairments was significantly and positively related to age, smoking habits, and the use of pesticides. Nutritional status had the expected negative sign, although the regression was not significant. The negative sign on drinking habits was contrary to expectations, but the regression was not significant. Using a cloth cover over the mouth and nose, a common practice during spraying, had an unexpected positive and significant regression. This probably indicates that, while farmers believe a cloth face mask provides protection, its use actually creates more problems. The cloth absorbs and concentrates a film of chemicals, which the wearer then inhales.

For nonsmoking farmers who applied one recommended dose each of insecticides and herbicides, the probability of being affected by three or more illnesses at the same time was 0.42. Farmers who applied only insecticides faced a probability of 0.22 of being affected by three or more illnesses. Farmers who smoked faced an additional 63% increase in the probability of being affected by three or more health impairments.

HEALTH COSTS ASSOCIATED WITH HERBICIDES

Logit regressions can be used to assess the health costs associated with herbicide use (Table 4). A standard treatment cost was estimated for each illness studied. It includes the cost of hospitalization, medication, doctor fees, etc. (Table 5). Opportunity costs associated with time lost from work are specified in addition to treatment costs. The expected costs faced by the average farmer being treated for the illnesses studied can be derived by multiplying the probability of incidence of each illness by the sum of treatment and opportunity costs (Table 5).

Table 5. Anticipated health costs of herbicide-related illnesses among Philippine rice farmers.

Illness	Treatment costs[a]	Days work lost[b] (no.)	Probability of incidence[c]	Expected health cost
Eye	900	10	0.36	594
Pulmonary	440	7	0.30[d]	290
Polyneuropathy	1285	30	0.02	70
Skin	300	14	0.20	405
Gastrointestinal	200	7	0.27	196

[a] Costs are given in Philippine peso. [b]Opportunity cost of labor quantified at 75 Philippine pesos d^{-1}. [c]Assessed at mean level of all variables including one recommended dose of insecticide and herbicide. [d]Incidence of pulmonary problems evaluated for nonsmoking farmers.

Expected health costs for each illness were derived at the sample mean values of age and nutritional status, assuming one recommended application each of insecticides and herbicides. For the average farmer studied, eye and skin problems were likely to be the most expensive, followed by respiratory and gastrointestinal problems. Although in absolute terms the health costs associated with polyneuropathy are the highest, the probability of incidence was very low, hence the low expected cost.

Health costs across illnesses were aggregated by assuming the average farmer in the study faced three or more illnesses at the same time. From the multinomial logit regression, the probability of three or more illnesses was found to be 0.42 for farmers using one recommended application each of insecticides and herbicides. Farmers applying only insecticide had a probability of 0.22 of incurring three or more illnesses.

Health-productivity trade-off

The health costs associated with insecticide exposure overwhelm any productivity gains; the value of the yield saved with insecticide use is lower than the costs of associated health impairments (Rola and Pingali 1993, Pingali et a1 1994). The health-productivity trade-off is not as clear with herbicides, especially given the trend toward rising wages and the movement toward direct-seeded rice culture.

The productivity benefits of herbicide use were estimated by the impact of herbicides on rice yield per hectare (Table 6). Nitrogen and herbicide use had significant positive effects on the yield function. The trade-off between labor and herbicides was measured by the interaction variable. Input productivities were adjusted for distance from the irrigation canal, a measure of the reliability of water supply. The marginal productivities of each input also were calculated.

The yield functions were evaluated in relation to three scenarios: transplanted rice without herbicide use, transplanted rice with herbicide use, and direct-seeded rice with herbicide use and without hand weeding (Table 7). Yield differences between the three strategies are small, but the difference in net benefits is substantial. The large positive shift in profitability with the switch to direct seeding can be attributed primarily to savings in labor with the use of chemical weed control.

Table 6. Yield regression for irrigated rice production in Nueva Ecija, Philippines.

Independent variable	Yield (kg ha^{-1})
Constant	6.7853***
Nitrogen (log N)	0.3224**
	(0.1475)
Insecticide dose (I)	-0.0439
	(0.0304)
Herbicide dose (H)	0.6606**
	(0.2649)
Preharvest labor (log lab)	0.0777
	(0.0525)
Distance to main canal	0.4544
(log dist)	(0.7652)
Log N * log dist	-0.0898
	(0.1587)
I * log dist	0.0661*
	(0.0383)
H * log dist	-0.0177
	(0.1318)
Log lab * log dist	-0.0149
	(0.0680)
H * log lab	-0.1764*
	(0.0920)
R-square	99.98
Degrees of freedom	113

***, **, * = Logarithm significant at the 1. 5, and 10% level, respectively. Figures in parentheses are standard errors of estimate.

Table 7. Mean yield and net benefit of alternative weed control strategies, with and without herbicide-related health costs.

Weed control strategy	Yield (kg ha^{-1})	Net benefits[a] Without health costs	With health costs
Transplanting + hand weeding	5043	16179	16179
Transplanting + hand weeding + herbicide	4927	16231	16108
Direct seeding + herbicide	5131	19880	19757

[a]Yields were estimated on the regression estimates presented in Table 6.

When no consideration is given to health externalities, herbicides are overwhelmingly more economical than hand weeding to control weeds in Philippine ricefields. Both complete substitution of herbicides for weeding labor, as in direct-seeding systems, and partial substitution, as in transplanted systems, are profitable. But these results may not hold when health externalities are explicitly taken into account.

The health costs of one recommended application each of insecticides and herbicides per hectare at the time of the study were approximately 650 Philippine pesos (about US$30). Farmers using one recommended application of insecticide per hectare, without any herbicide, faced health costs of 340 pesos (about US$15). These health costs were used to adjust the net benefits of herbicide use. Complete replacement of hand weeding by herbicides, as happens in direct-seeded rice, was economical even when health costs were explicitly subtracted (Table 7). With partial replacement of hand weeding by herbicides, as is occurring in transplanted rice, the labor savings were more than offset by increased health costs.

The social profitability of herbicide use, even in direct-seeded systems, would be substantially reduced when environmental externalities are taken into account. For example, herbicide contamination of groundwater could have negative health effects on water consumers beyond the farm household that is applying the chemical.

CONCLUSIONS

Careful documentation of the consequences to human health of pesticide use is rare in evaluations of developing country agricultural practices. This study that measured the health impact of long-term exposure to insecticides and herbicides in rice should be seen as only the first of the in-depth studies that are needed. The health effects and costs of pesticide use in the Philippines, even at the low levels prevailing in the areas studied, were substantial. Eye, skin, pulmonary, and neurological problems were associated significantly with long-term pesticide exposure. Most of the pesticides which might be linked to these impairments, the highly hazardous category I and II chemicals, are commonly available in the Philippines, although they are banned or severely restricted in industrialized countries. Herbicides in particular were implicated in high incidence of skin diseases, polyneuropathy, and gastrointestinal problems.

The net benefits of insecticide use are negative when health effects are explicitly accounted for (Rola and Pingali 1993). When insecticide use is reduced, the value of the positive health benefit of reduced exposure is invariably greater than the value of the crop lost to pests. In the case of herbicides, the health-productivity trade-off is less clear. The positive productivity benefits of a switch from transplanting and manual weeding to direct seeding with herbicide use are substantially greater than the cost of the adverse health effects. The productivity benefits of a switch from manual weeding to herbicides in transplanted rice are smaller and may not outweigh the health costs associated with herbicide exposure.

The challenge for researchers is to discover ways to make herbicide use in rice both judicious and safe. The movement away from prophylactic herbicide applications to integrated weed management systems should reduce pesticide requirements, even in intensively cultivated systems. Integrated weed control, however, is knowledge-intensive and location-specific; substantial allocations of technical and administrative resources will be needed for extension programs and farmer training. Farmer training should include procedures for safe handling, storage, and disposal of chemicals.

Evidence from industrialized countries indicates that productivity is affected when category III and IV chemicals replace category I and II chemicals. For example, switching from the category II herbicide, 2,4-D, to a category IV herbicide, butachlor, does not result in lower productivity. In fact, when the health gain associated with reduced exposure to highly hazardous chemicals is accounted for, there could actually be a net productivity gain.

Whenever the regulatory agency of a country registers or re-registers pesticides for use in rice production, risks of their use as well as productivity benefits should be taken into account. Risk-benefit assessment is the appropriate analytical tool for making such decisions. While country-specific measurements of impacts would give the most accurate technical coefficients for risk assessment, the value of similar information collected elsewhere should not be discounted, at least when predicting probabilities. Greater understanding of the trade-offs would allow a regulatory agency to be more discriminatory in its choice of chemicals to import and/or register. Farmers with increased knowledge of the consequences of pesticide use could be equally discriminating in their choice of pest control strategies.

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EFFECT OF HERBICIDE USE ON SOIL MICROBIOLOGY

P.A. Roger and I. Simpson

Modern rice-growing technologies-increasing cropping intensity, using optimum crop management practices, planting improved varieties, applying fertilizers, protecting the crop with pesticides-have increased yields markedly. These same technologies also have changed traditional rice-growing environments markedly. One change is less diversity of vertebrates and invertebrates in ricefields (Roger et al 1991). Other environmental impacts, whether short- or long-term, are far from being fully assessed.

The most intense pressure being exerted on the microbial, faunal, and floral communities of ricefields comes from the increasing use of fertilizers and pesticides. These agrochemicals significantly impact the composition and population dynamics of microorganism and invertebrate communities. Greater understanding is needed of how agrochemicals, especially pesticides, may affect soil fertility through their effects on the populations of microorganisms and invertebrates that recycle and translocate nutrients, and make them available to a crop. The issue is whether, as use of pesticides increases, the efficacy of soil microorganisms will be reduced by population shifts toward species more efficient in pesticide degradation.

In recent years, pesticide use in less developed countries has tended to increase faster than it has in the industrialized countries, and that trend is causing concern (Moody 1990). In most rice-growing countries, insecticides have been the dominant class of pesticides used (Van der Valk and Koeman 1988). In the Philippines, for example, 55-60% of the pesticides used before 1980 were insecticides, 20-25% were fungicides, and 5-16% herbicides. While that relative pattern still exists, herbicide use is increasing rapidly as labor availability in many agricultural areas is depleted by rapid urbanization (Moody 1990).

We undertook a bibliographic survey to identify studies that measured the impact of pesticides on nontarget microorganisms and soil and water invertebrates in ricefields (Roger et al 1994). A computerized data base was established and quantitative data on the fate of pesticides and their effects on microorganisms in rice soils were tabulated and analyzed. We used this data base to assess the relationships between herbicides and nontarget soil microorganisms and aquatic invertebrates in rice environments.

PESTICIDE FATE AND IMPACT

The bibliographic data base on pesticide fate and impact on microorganisms and invertebrates in rice environments contains about 600 references. Quantitative data collected from 63 articles on pesticide fate, 71 articles on impact on nonphotosynthetic microorganisms, and 149 articles on impact on photosynthetic microorganisms were tabulated and general trends analyzed (Roger et al 1994). Quantitative data on pesticide impact on soil and water invertebrates were only available in some dozen articles, not enough to be tabulated.

The general characteristics and limitations of this data base, and specific aspects that pertain to herbicide studies, include the following:

- Most pesticide studies conducted in ricefields, with ricefield soil, or with organisms isolated from ricefields, were published during the 1980s. More recent studies are scarce, which implies that current knowledge is somewhat outdated. Part of the information deals with superseded formulations, and little is known about recently released compounds and formulations. Table 1 lists the number of papers in the data base that deals with the impacts on microflora of the herbicides applied on California rice in 1990 (Crosby 1996). No information is available for two of the herbicides; for the others, most studies deal with cultures of microalgae and cyanobacteria tested in the laboratory.
- Most of the available information on the fate of different pesticides in ricefield soil is based on experiments with 20- 100 g of unplanted soil. Such experiments underestimate chemical degradation because of the absence of rhizospheric effect and because of variations of environmental conditions (light, wind, temperature, redox potential). Only about 70 of 200 references presented data on herbicides.
- Quantitative estimates of the effects of pesticides on microorganisms in ricefields are given in 240 references. Those studies assessed impacts using the classical methodology of soil microbiology, including enumeration and measurement of activity (Greaves et al 1978). Such quantitative analyses and interpretation should be accepted with caution, for the following reasons:
  - The organisms and pesticides studied do not constitute a representative sample of the numerous combinations occurring in ricefields. Data for photosynthetic microorganisms (149 references) are mostly on herbicides and cyanobacteria, and are more abundant than those on nonphotosynthetic microorganisms (71 references), which deal mostly with insecticides (Roger et al 1994). The impact of herbicides on photosynthetic microorganisms is found in 64 studies testing 54 formulations; only 16 studies, testing 22 formulations, deal with nonphotosynthetic microorganisms.

Table 1. Number of papers dealing with the impact of herbicides[a] on microorganisms in California ricefields, 1990.

Herbicide	Algae and cyanobacteria			Bacteria		
	Lab[b]	Pot	Field	Lab	Pot	Field
Bensulfuron methyl						
Copper sulfate	2		6			
2,4-D	21		2		1	
Glyphosate	2					
MCPA	5		1	1		
Mollnate	3	1	1	1	1	
Pendimethalin						
Propanil	7	1	3	2		
Thiobencarb	5	1	1	1		
Total	45	2	14	5		20

[a] Listed by Crosby (1996). [b] Lab = laboratory.

— Most studies are laboratory experiments with cultures of microorganisms or with only a few grams of soil. Less than 8% of the quantitative studies were conducted in ricefields. Experiments with microbial cultures give an index of a strain's sensitivity to pesticides, but the results cannot be extrapolated to field conditions where the initial concentrations of pesticides are likely to decrease rapidly, as their degradation is hastened by soil microflora, nonbiological decomposition, leaching, volatilization, and soil adsorption. Concentrations of pesticides that affect microorganism growth depend on the initial microbial population, its nutrient status, the method of pesticide application, and the degradation products. These factors markedly differ in vitro and in situ. For example, little agreement was found between the responses of microbial species to glyphosate in incubated soil samples and in pure culture (Wardle and Parkinson 1990).

— Many studies used pesticide concentrations higher than those resulting from the recommended level for field application. Such experiments may overestimate pesticide persistence because degradation is slowed at high concentrations, as has been shown with trifluralin (Parr and Smith 1973) and molinate (Deul et al 1978). The recommended levels of traditional pesticides range from a few hundred grams to a few kilograms of active ingredient per hectare. The median recommendation for herbicides (2.5 kg ai ha^{-1}) is higher than it is for fungicides (1.7 kg ai ha^{-1}) and insecticides (1.1 kg ai ha^{-1}) (Roger 1990). Experimental results should be interpreted in the context of the range of pesticide concentrations that can be expected in farmers' fields after application. If a herbicide applied on a nonflooded field stays within the surface 2 cm of soil, 2.5 kg ai ha^{-1} would correspond to 15 mg kg^{-1} dry weight of soil, for a bulk density of 1 mg m^{-3}. If a water-soluble herbicide is distributed in 10 cm water and 10 cm puddled soil, 1 kg ai ha^{-1} would correspond to 1 mg kg^{-1} of soil. The field situation is probably closer to the lower value. Our data base lists 1,045 articles that report quantitative data on the effects of pesticides on photosynthetic microorganisms. In 638 of the studies, effects were measured at concentrations higher than twice the recommended level for field application. This is probably because the studies were designed to establish the lethal concentration for strains rather than to measure possible effects in the field. Such data are of little value in drawing conclusions, except when no effect was recorded.

MICROBIAL DEGRADATION OF HERBICIDES

Pesticide degradation in ricefields is accelerated by the reducing conditions caused by submersion and by the temperature and pH ranges that favor microbial activity (Ponnamperuma 1972). As a result, pesticides often persist longer in nonflooded soils than they do in flooded soils (Sethunathan and Siddaramapa 1978). In a data base on the half-life of pesticides in rice soils, only 8 of 45 tests reported shorter half-lives in nonflooded than in flooded soils (Roger et al 1994). Herbicides with faster degradation in flooded soils include trifluralin (half-life >4 d in flooded soil and >20 d in nonflooded soil [Parr and Smith 1973, Willis et al 1974]), pyrazoxyfen (half-life <10 d in flooded soil and 3-34 d in nonflooded soil [Arita and Kuwatsuka 1991]), and MCPB-ethyl (half-life 2 d in flooded soil and 3 d in nonflooded soil [Asaka and Izawa 19821). Some herbicides degrade faster in nonflooded, upland soils than they do in flooded, lowland soils. These include molinate (half-life 4-160 d in flooded soil, 8-25 d in nonflooded soil [Deuel et al 1978, Thomas and Holt 1980, Imai and Kuwatsuka 1982]), thiobencarb (half-life 45 d in nonflooded soil, 100 d in flooded soil [Ishikawa et al 1976, Nakamura et al 1977, Duah-Yentumi and Kuwatsuka 1980]), and MCPA (4-chloro-2-methylphenoxyacetic acid [Duah-Yentumi and Kuwatsuka 19801). The persistence of MCPA, 2,4-D, and 2,4,5-T about half as long under moist as under flooded conditions was explained by the need of an aerobic microflora to rapidly degrade phenoxy acid herbicides (Sattar and Paasivirta 1980).

Herbicide-degrading microflora in ricefields

In dryland soils, bacteria and fungi are considered to be the organisms primarily responsible for pesticide degradation. In wetland soils, bacteria are the major agent (although fungi are involved in wetland soils [Rao and Sethunathan 19741, they probably are less important than bacteria). Microalgae may play a significant role in wetland soils, either directly by favoring photooxidation through the oxygen they release in floodwater or indirectly when their photosynthetic activity causes water pH to vary 1-2 units during the day, to favor chemical decomposition of pesticides. So far, the contribution of microalgae to pesticide decomposition in ricefields has been demonstrated mostly for insecticides. Photolysis of the insecticide methyl parathion was much faster in water containing algae than in distilled water (Zepp and Schlotzhauer 1983). The importance for pesticide degradation of the increase of water pH caused by algae is obvious for the insecticide carbofuran, whose hydrolysis was more than 700 times faster at pH 10 than at pH 7 (Seiber et al 1978). The cyanobacterium *Anacystis nidulans* can convert the phenylcarbamate herbicides propham and chlorpropham to their corresponding anilines (Wright and Maule 1982). A significant role of rice rhizospheric bacteria in pesticide degradation was also demonstrated for the insecticide parathion. After 2 wk in an unplanted, flooded soil, less than 5.5% of ^{14}C-labeled parathion was evolved as $^{14}CO_2$; in a planted, flooded soil, 22.6% was evolved (Rajasekhar Reddy and Sethunathan 1983a). Similar data are not available for herbicides.

Pesticide-decomposing microorganisms isolated from ricefield soils belong to the genera *Arthrobacter, Bacillus, Clostridium, Flavobacterium, Micrococcus, Mycobacterium, Pseudomonas,* and *Streptomyces* (Roger et al 1994). They can degrade pesticides by using them as their sole carbon sources, through cometabolism, or by synergy. Most of the species that have been isolated degrade insecticides; two species have been isolated that degrade pentachlorophenol (PCP), *Mycobacterium* sp. (Suzuki 1983a,b) and *Pseudomonas* sp. (Watanabe 1973). Several species have been characterized that degrade MCPA. *Flavobacterium peregrenum* and *Arthrobacter* spp. produced 4-chloro-2-methylphenol as the major metabolite, and Aspergillus niger produced 4-chloro-5-hydroxy-2-methylphenoxyacetic acid (Soderquist and Crosby 1975).

Relative importance of microbial degradation

The usually faster degradation of pesticides in nonsterilized than in sterilized (autoclaved) soils and, in some cases, faster degradation in soil on second exposure to a given pesticide demonstrate the importance of microbial degradation of pesticides (Roger et al 1994). Several pathways of degradation/dissipation may be involved for a single pesticide—adsorption, transport (volatilization, percolation, runoff), and transformation processes (photolysis, chemical hydrolysis, biodegradation). If a chemical is very volatile, it may not have a long enough residence time for significant degradation to occur, even though the rate of degradation could be relatively rapid if the chemical is maintained in contact with the soil. The relative importance of microbial decomposition will vary, depending on the nature of the herbicide, the environmental conditions, and the method of application.

For a number of herbicides, soil sterilization markedly reduced degradation, indicating that under the experimental conditions, degradation was mostly a microbial process. Those herbicides include thiobencarb (Nakamura et al 1977), butachlor (Chen 1980), MCPB-ethyl (Asaka and Izawa 1982), 2,4-D and 2,4,5-T (Yoshida and Castro 1975), and molinate (Imai and Kuwatsuka 1982). Studies of the dissipation of MCPA indicated that microbial decomposition was greater than photodecomposition, and that volatilization was of little importance (Soderquist and Crosby 1975). Dissipation of the rice herbicides thiobencarb and molinate was attributed primarily to volatilization, although some microbial decomposition was demonstrated (Crosby 1983). In a mass balance for molinate dissipation, 75-85% was attributed to volatilization and less than 1% to aqueous microbial metabolism (Soderquist et al 1977).

An interesting example is trifluralin, for which the relative importance of microbial degradation may vary markedly. In the presence of ultraviolet radiation, trifluralin is rapidly photodecomposed. It can also be extensively lost by volatilization, depending on its concentration and mode of application and on the moisture content of the soil (Bardsley et al 1968). Volatilization is reduced under flooded conditions (Parr and Smith 1973). In soil and water, trifluralin is decomposed by physicochemical and microbiological processes. Under aerobic conditions, it degrades by a pathway involving sequential dealkylation of propyl groups, and under anaerobic conditions, by a pathway involving initial reduction of the nitro groups (Parr and Smith 1973). Decomposition is usually faster under anaerobic conditions. A study of the relationship between Eh and the rate of trifluralin degradation used a system for controlling redox potential in soil suspensions. Oxygen exclusion by soil flooding initiated rapid trifluralin degradation only when the Eh decreased below a critical range between + 150 and +50 mV (Willis et al 1974). Depending on experimental conditions, physical and chemical processes (Probst and Tepe 1969) or microbiological processes (Parr and Smith 1973) predominate. Trifluralin was not significantly decomposed after 20 d in a sterilized soil, but had almost completely disappeared in the same, unsterilized soil enriched with alfalfa meal (Parr and Smith 1973).

The pesticide concentrations among replicated samples in field trials of pesticide persistence often are extremely variable. For example, the propanil remaining in four soil samples from the same field 40 d after its application ranged from 0.2 to <0.01 ppm (Kearney et al 1970). This may have been caused by several factors, including heterogeneity in soil properties and degradation by heterogeneously (log normally) distributed microflora (Roger et al 1991).

Effect of repeated pesticide application

Repeated application of the same pesticide on the same field has been reported to increase the growth of related, specific decomposing microorganisms and cause its rapid inactivation. Several bacteria that have the ability to degrade a given pesticide were isolated from the soil and water of ricefields previously treated with the pesticide. This has been reported for a number of insecticides, including gamma-BHC, diazinon, and aldicarb (Roger et al 1994). The available data for herbicides deal with PCP and thiobencarb. Watanabe (1973, 1977) isolated PCP-decomposing and PCP-tolerant bacteria from soils. He observed a 1000-fold difference in the number of PCP-decomposing microorganisms between treated and untreated soils (Watanabe 1978). Data for thiobencarb are somewhat contradictory. Nakamura et al (1977) reported that repetitive application of thiobencarb did not lead to an increase in thiobencarb-degrading microflora. However, Moon and Kuwatsuka (1985) reported that when thiobencarb was repeatedly applied to a soil, the lag time for dechlorination decreased from 20 d to 10 d to 2 d due to the multiplication of specific facultative anaerobes that degrade thiobencarb. Those anaerobes rapidly decreased or disappeared when thiobencarb was absent.

Effect of pesticide combinations

When two pesticides are applied simultaneously, one can inhibit the microorganisms responsible for the degradation of the other or modify the physicochemical conditions in a way that reduces the degradation of both. In a model ecosystem, the combination of the insecticide methyl parathion with atrazine substantially increased the persistence of both pesticides in the water and soil phases of the system (Au 1979). On the other hand, soil incorporation of thiobencarb with simetryn or propanil had no significant effect on the degradation rate of any of the pesticides (Nakamura et al 1977).

IMPACT ON MICROALGAE AND CYANOBACTERIA

Microalgae and cyanobacteria are major components of the photosynthetic aquatic biomass that develops in ricefield floodwater. Other components include macrophytic algae and vascular macrophytes. The average primary production reported in ricefield floodwater over a crop cycle ranged from 0.5 to 1 g C m^{-1} d^{-1} (Roger and Kurihara 1991). Cyanobacteria and microalgae trap both atmospheric C and N and C and N evolved from the soil, and, when reincorporated, help to reduce nutrient losses into the soil. They affect N fertility of ricefields through the following ways:

- Photodependent biological N_2 fixation (BNF) by cyanobacteria, which contributes 5-20 kg N ha^{-1} per crop from free-living forms and 30-60 kg N ha^{-1} per crop from symbiotic forms associated with azolla used as green manure (Roger et al 1993).
- N immobilization and recycling through death or grazing, followed by decomposition, N accumulation at the soil surface, and translocation to deeper soil by soil fauna (Roger and Kurihara 1991).
- Replenishment of the soil microbial biomass and available N, as shown by positive correlation with chlorophyll-type compounds (Watanabe and Inubushi 1986).
- Provision to the rice plant of an average 30% of the total N contained in cyanobacteria, algae, and aquatic plants incorporated into soil and 20% of those decomposing at the soil surface (Roger and Kurihara 1991).
- Induction of N losses by NH_3 volatilization (2-60% of the N applied), partly due to microalgae which deplete CO_2 in floodwater, which increases its pH and the concentration of volatile NH_3 (Fillery et al 1986).

In transplanted rice, cyanobacteria and microalgae are not considered weeds of major economic importance. In direct-seeded rice, however, they are detrimental at germination because they compete for light, form a membranaceous mat restricting penetration of the rice roots into the soil and the gaseous exchange between soil and water, and have detrimental mechanical effects on rice when their epiphytic growth either pulls seedlings down or lifts and uproots them when the water level varies (Smith et al 1977, Noble and Happey-Wood 1987).

Pesticides have three major effects on ricefield microalgae and cyanobacteria. Some preferentially affect green algae and promote cyanobacteria growth, as has been observed with the algicides simetryn (Yamagishi and Hashizume 1974) and algaedyn (Almazan and Robles 1956). Insecticides over the short term increase microalgae by temporarily decreasing populations of invertebrates that graze on algae. Insecticides also have a selective effect on cyanobacteria by causing the recruitment of algal grazers, which results in the dominance of strains that form mucilaginous macrocolonies resistant to grazing.

General trends

As photosynthetic organisms, cyanobacteria and algae can be expected to be more sensitive than other microorganisms to herbicides, especially the photosynthetic inhibitors. Several unicellular eukaryotic algae most common in ricefields (*Chlorella, Chlamydomonas, Euglena*) have been shown to be sensitive to photosynthetic inhibitor herbicides (Arvik et al 1973). Quantitative data obtained at concentrations corresponding to the recommended level of field application are mostly estimates of the inhibitory effect of herbicides on cyanobacteria cultures; experiments with soil in vitro and in situ make up less than 10% of the data (Table 2). Results confirm, however, that among pesticides not aimed at controlling algae, herbicides are most detrimental to cyanobacteria and algae, causing partial or total inhibition in 67% of the in vitro tests and in 42% of the in situ or soil tests at recommended levels of field appli-

Table 2. Effects of pesticides on photosynthetic ricefield microorganisms (cyanobacteria and microalgae) at concentrations corresponding to recommended field application.

Nature of data	Data (no.)	Data (%) corresponding to different levels of inhibition				
		None	<50	50	>50	100
All data	407	39	19	26	2	14
All data in situ or with soil	39	62	8	3	3	26
Algicides (3 tested)	33	3	0	67	0	30
Fungicides (22 tested) [a]	30	40	10	7	0	43
Herbicides (57 tested)	252	33	25	28	2	12
Herbicides in situ or with soil	24	59	8	4	4	25
Insecticides (28 tested)	97	67	11	14	3	4
Insecticides in situ or with soil	10	90	10	0	0	0

[a] Several fungicides are used as algicides.

cation. These values also confirm that pesticide effects are more marked in vitro than in situ.

Effects on photodependent BNF and biofertilizers

In the wake of interest in biofertilizers which developed in the 1980s, a number of studies dealt with the impact of herbicides on free-living and symbiotic N_2-fixing cyanobacteria indigenous to or inoculated in ricefields.

Indigenous cyanobacteria. Herbicides can inhibit cyanobacteria and photodependent BNF. Laboratory experiments showed that PCP—a pesticide used both as an insecticide and a herbicide—was inhibitory to cyanobacteria and diatoms when applied on the surface, but not when incorporated into the soil (Ishizawa and Matsuguchi 1966). In field studies, CNP (2,4,6-trichloropheny1 4-nitrophenyl ether) inhibited photodependent BNF (Matsuguchi 1979) and several formulations used in ricefields reduced algal growth (Srinivasan and Ponnuswami 1978). Some herbicides seem to affect the N_2-fixing ability of cyanobacteria specifically; the inhibitory effect of butachlor on N_2-fixing strains growing in an N-free medium was markedly decreased or reversed by inorganic N sources (Kashyap and Pandey 1982). Whereas many herbicides seem to be most detrimental for photodependent BNF, several species of cyanobacteria tolerated 100-500 ppm of 2,4-D, a level much higher than that recommended for field application. This suggests that this herbicide might be compatible with cultural practices aimed at promoting cyanobacteria growth as biofertilizer (Venkataraman and Rajyalakshmi 1971, 1972).

Algal inoculation. Although numerous experiments have dealt with inoculating ricefields with N_2-fixing strains of cyanobacteria (Roger 1990), almost no field trials have tested the interaction between pesticides and algal inoculation. Kerni et al (1983, 1984) reported that butachlor applied at 5-30 kg ha^{-1} in inoculated plots had no effect. El-Sawy et al (1984) tested the interaction between cyanobacteria inoculation and four herbicides in a pot experiment. When algal inoculation was effective, herbicide application mostly had no effect or a positive effect on plant characteristics and soil N at 40 d after transplanting. Negative effects were observed with propanil in only 2 out of 16 cases. Srinivasan and Ponnuswami (1978) reported that recommended levels of field application of Saturn (thiobencarb), Basalin, and TOK had no effect on the production of blue-green algae in cyanobacteria inoculum multiplication plots; Sirmate, Fernoxone, Stam F 30 (propanil), and Weedone (2,4-D) decreased growth by 15-40%.

Azolla involves a symbiosis between a N_2-fixing cyanobacterium and an aquatic fern traditionally used as green manure for rice (Roger et al 1993). Information on the effects of pesticides on BNF by azolla is limited. Insecticides decrease pest incidence, which usually favors azolla growth (Satapathy and Singh 1987). Herbicides more often have a detrimental effect. Holst et al (1982) tested the effect in vitro of 15 herbicides on growth and N_2 fixation of *Azolla mexicana.* Bipyridinlium and phenolic herbicides were the most detrimental; at 0.1 ppm, they caused up to a 75% reduction in N_2 fixation and nitrate reduction. Chloramben and the fungicide benomyl at 10 ppm caused 84-99% reduction in N_2 fixation without affecting nitrate reduction or growth. Simazine at 10 ppm stimulated nitrate reduction 20-fold, causing a 99% reduction in N_2 fixation. Growth and N_2 fixation were reduced by other benzoic, triazine, dinitroaniline, and urea herbicides tested at concentrations between 0.1 and 10 ppm. Naptalam was the only herbicide tested that had no effect on growth or N_2 fixation at 10 ppm. In a field test, preemergence herbicide applied about 1 wk before azolla inoculation had only limited effects on azolla; postemergence herbicides were more detrimental (Singh and Singh 1988).

Nevertheless, simultaneous application of herbicides and biofertilizer might not be a sound practice because both free-living cyanobacteria and azolla form a mat that covers the surface of the floodwater and reduces the growth of weeds (Roger et al 1993).

Field experiments

Little impact of herbicides on algae and cyanobacteria has been reported from field experiments in the tropics. Arvik et al (1971) found no change in the composition of algal flora within 18 mo after the application of a 1:4 commercial mixture of 4-amino-3,5,6-trichloropicolinic acid (picloram) and 2,4-D at the recommended field level. Srinivasan and Ponnuswami (1978) found no significant effect or only moderate inhibition of cyanobacteria by seven herbicides applied at recommended field levels. Singh et al (1986) studied the effect of butachlor, thiobencarb, and 2,4-D on N_2-fixing cyanobacteria and found that the recommended rates did not result in major changes in composition of the algal population. All herbicides increased the proportion of *Nostoc;* propanil reduced the proportion of *Anabaena* in the algal population.

In temperate climates, some inhibitory effect of herbicides has been reported. Benthic algae decreased with most applications of herbicides (oxadiazon, bentazon, thiobencarb, simetryn) in Japan (Takamura and Yasuno 1986). Heterocystous and nonheterocystous cyanobacteria and microalgae were affected differently by repeated use of simazine (4 kg ha^{-1}) in Italy, with heterocystous affected more severely. Simazine also reduced species diversity, which was very evident in the case of heterocystous cyanobacteria (Tomaselli et al 1987).

Resistance of algae and cyanobacteria

Resistance to pesticides is common among microalgae and cyanobacteria, and that resistance can adapt to increased concentrations of pesticides (Sharma and Gaur 1981). When several strains are tested for sensitivity to pesticides, some that are resistant to recommended field levels usually are identified (Gadkari 1987). Spontaneous mutants resistant to monuron and blitox have been isolated (Vaishampayan 1984 and 1985, Vaishampayan and Prasad 1982). A study of various classes of herbicides showed that s-triazines and substituted ureas could alter phytoplankton composition by selective inhibition of certain species (Hawxby et al 1977). Because sensitivity to any particular herbicide may vary considerably among algal strains, herbicide application might cause shifts in dominant strains within the algal/cyanobacterial community rather than a decrease of the entire algal biomass.

Bioconcentration in algae and cyanobacteria

Although bioconcentration of pesticides in food chains has been demonstrated in many ecosystems, the issue has received little attention in ricefield studies. Available data only refer to possible pesticide accumulation in vitro by the cyanobacteria common in ricefields (Das and Singh 1977, Kar and Singh 1979). The ability of microalgae to accumulate herbicides in freshwater environments has been demonstrated (Wright 1978). Algae and cyanobacteria also are known to accumulate heavy metals, which has implications in terms of copper- or tin-based pesticides. Invertebrate grazers that feed on phytoplankton that contains high concentrations of pesticide or metal could suffer. Bioconcentration of pesticides in phytoplankton and zooplankton is important when the ricefield ecosystem is considered as a possible environment for aquaculture (rice-fish, rice-shrimp).

IMPACTS OF HERBICIDES ON CHEMOTROPHIC MICROORGANISMS

Chemoautotrophic and chemoheterotrophic microorganisms are the agents of nutrient recycling and maintenance of soil fertility. The N fertility of rice soils results in part from the balance among activities of populations that perform the following tasks (Roger et al 1993):

- Transform organic N into forms available to rice (mineralizing microflora, ammonifiers, and nitrifiers),
- Provide inputs of N through BNF (heterotrophic N, fixers in the bulk of soil and the rhizosphere), and
- Cause gaseous losses of N (denitrifiers).

At the levels of inorganic fertilizer usually applied in ricefields, most of the N absorbed by the plant originates from the soil, where it is released by the turnover of a microbial biomass; it represents only a small proportion of the total soil N (Watanabe et al 1988).

General trends

In contrast to experiments with microalgae and cyanobacteria which were conducted primarily with laboratory cultures, tests of pesticide effects on nonphotosynthetic microflora and their activities were performed primarily in small-scale experiments with soil or in situ at concentrations corresponding to the recommended level of field application. The data base contains 606 records obtained at those concentrations, although most of the studies deal with insecticides. Studies with herbicides (a mere 102 records) only allow us to identify very general trends (Table 3). Insecticides affected the microflora or its activities less often (no effect in 68% of the studies) than fungi-

Table 3. Effects of pesticides on nonphotosynthetic ricefield microorganisms at concentrations corresponding to recommended field application.

Group	Data for each effect (%)*					
	Data (no.)	All negative	Negative trend	No effect	Positive trend	All positive
All data	606	8	12	60	11	9
Fungicides	58	5	0	50	24	21
Herbicides	102	13	23	30	21	14
Insecticides	440	6	11	68	7	8
Biological N_2 fixation	176	2	23	31	26	19
Fungicides	25	0	0	20	52	28
Herbicides	26	0	23	23	35	19
Insecticides	125	2	27	35	18	17

*Most experiments are bacterial counts and activity measurements performed several times after application. Each experiment was as follows: no effect–no significant difference between treatment and control; all negative/positive—for all measurements the treatment was statistically lower/higher than the control; negative trend—various effects; positive trend—various effects. Adapted from Roger et al (1994).

cides (no effect in 50% of the studies) and herbicides (no effect in 30% of the studies). Data from field experiments (Sato 1987, Mandal et al 1987, Roger et al 1994) are not numerous enough to be tabulated.

Changes in microbial populations

Reports of experiments where microbial populations were counted after herbicide was applied usually do not present a statistical analysis of the data. Microbial enumerations in soil are highly variable, making it difficult to assess the significance of data not supported by statistical evaluation. In many cases, the differences between microbial enumerations in treated and control soils were less than threefold, which indicates a need for caution in interpreting the results (Roger et al 1993). For example, among 14 microbial groups (aerobic bacteria, actinomycetes, fungi, ammonifiers, ammonium oxidizers, denitrifiers, aerobic and anaerobic N_2 fixers, aerobic and anaerobic P solubilizers, sulfate reducers, cellulose decomposers, and iron precipitators) counted 3 wk after the application of linuron to a flooded soil, only ammonium oxidizers and sulfate reducers exhibited changes in densities more than three times that of the control (Sivasithamparam 1970).

When changes in populations were considered significant, they were usually not long lasting. In one field experiment, counts at 4, 11, 18, and 25 d after application of preemergence herbicides (Goal, TOK E-25, Saturn, and Machete) indicated only a slight initial depression of total microflora, bacteria, actinomycetes, and fungi populations; recovery occurred within a few days. No prolonged effect of herbicides on microflora was observed (Mandal et al 1987). Immediately after thiobencarb was applied to a rice soil, total viable bacteria and populations of Gram-negative, ammonifying, nitrate-reducing, and denitrifying bacteria increased and populations of ammonium-oxidizing and nitrite-oxidizing bacteria decreased. The changes did not persist and the general dynamics of microbial populations during the crop cycle was not affected (Sato 1987). At 30 ºC and pH 6.8, 6 ppm butachlor had no significant effect on populations of fungi and actinomycetes, but possibly increased total populations of bacteria for about 2 wk (Chen 1980).

Effects on soil nutrients and enzymes

In a pot experiment using unplanted flooded soil, Ordram (molinate) reduced NH_4 availability and the decomposition of organic matter, and increased P and K availability for the 80-d duration of the experiment (Russo 1970). However, algal development in the pots may have interfered with the process. It was suggested that the effects observed on NH_4 and K availability were possibly correlated with stimulation/ inhibition of soil microorganisms, while P availability may have been affected by the capacities of the active chemical groups of the pesticides to substitute for P ions freed from stable combinations of the soil constituents.

Measurements of enzymatic activities in pot and flask experiments showed either an absence of effect or a slight and nonlasting inhibition of amylase, dehydrogenase, invertase, and urease by 2,4-D, atrazine, basalin 48-EC, butachlor, and oxyfluorfen (Chendrayan and Sethunathan 1980, Palaniappan and Balasubramanian 1985, Baruah and Mishra 1986). In a West Bengal ricefield soil, 10 kg MCPA ha^{-1} was needed to decrease cellulolytic populations (De and Mukhopadhyay 1971); the recommended field application is only 0.28-2.25 kg ha^{-1}.

Effects on nitrogen cycle

Ammonification. Thiobencarb (Sato 1987) and butachlor or mixtures of butachlor and diphenylether-type herbicides (nitrofen, chlornitrofen, and chlomethoxynil) (Chen 1980) had no significant effect on ammonification when applied at recommended field levels. Ten times the recommended rate of thiobencarb was needed to significantly affect ammonification (Sato 1987).

Nitrification. Various in vitro experiments with unplanted soil report either no or negative effects of herbicides on nitrification. At 30 °C and pH 6.8, butachlor or mixtures of butachlor and three diphenylether-type herbicides applied at recommended field level and at 10 times the recommended level had no significant effect on nitrification (Chen 1980). Propanil at 3.14 and 5.3 kg ha^{-1} decreased populations of nitrifiers (De and Mukhopadhyay 1971). Three weeks after linuron application, growth of nitrifiers was reduced, but population density recovered within 3 mo (Sivasithamparam 1970). Propanil and bifenox applied at the recommended field level inhibited nitrification during the first 10 d of incubation (Turner 1979). Their effectiveness varied with soil type. After 60 d of incubation, only bifenox still retarded nitrification. That both herbicides have the potential to retard nitrification should be recognized when N transformations in soils are studied, or their effect on plants grown in soil is evaluated, but it is unlikely that they significantly affect N transformation at recommended levels of field application.

Negative effects of herbicides on nitrification cannot necessarily be considered detrimental because reducing nitrification also reduces N losses by denitrification. Identifying efficient and economically feasible nitrification inhibitors has been an objective of the research on microbial management in ricefields (Roger et al 1993).

Denitrification. Denitrification is little affected by pesticides, probably because the complex and versatile denitrifying microflora can metabolize or resist a wide range of substrates. High levels of pesticide are needed to inhibit denitrification (Roger et al 1994). This probably explains why current research aiming at decreasing N fertilizer losses focuses on urease and nitrification inhibitors rather than on denitrification inhibitors (Roger et al 1993). Pesticides tested for their effects on denitrification are mostly fungicides and insecticides. Data for herbicides indicate no significant effect of PCP on denitrification of nitrate applied to flooded soil (Mitsui et al 1962, Mitsui et al 1964). On the other hand, a significant decrease in denitrifier population and denitrification was observed after 10.5 kg ha^{-1} of propanil and 2.25 kg ha^{-1} of MCPA were applied to a West Bengal ricefield soil (De and Mukhopadhyay 1971).

N_2 fixation. N_2-fixing microorganisms and BNF are more affected by pesticides than are other populations and activities (Table 3). With 25% of the negative effects and 45% of the positive effects, BNF seems quite versatile in its response to pesticides. Even the same pesticide could exhibit a negative or positive effect, depending on the soil type; the insecticide gamma-BHC stimulated BNF in alluvial and acid sulfate soils but inhibited it in other soils (Nayak and Rajaramamohan Rao 1980). These results were attributed to the differential responses of specific groups of N_2-fixing organisms to the pesticides, depending on soil type. When significant, the effects of pesticides on nonphotodependent BNF were more often positive than negative.

Reports of experiments on herbicide effects on heterotrophic BNF are scarce, most were conducted as laboratory incubations with a few grams of soil (Sivasithamparam 1970, Nayak and Rajaramamohan Rao 1982, Jena and Rajaramamohan Rao 1987). Jena and Rajaramamohan Rao studied the effect of herbicides thiobencarb and oxadiazon and insecticide carbofuran on three flooded soils. Carbofuran alone or in combination with herbicides had a clear stimulatory effect, up to 150%, on BNF (estimated from acetylene-reducing activity measurements after 30 d of incubation). Herbicides applied alone mostly had only a moderate effect, an average of 15% over 18 values. Similar results were obtained for nitrofen, at concentrations close to the recommended field level (5 $\mu g\ g^{-1}$). It stimulated N_2 fixation in a submerged rice soil under laboratory conditions and synergistic stimulatory effects were evident when it was applied in combination with the insecticide carbofuran (Nayak and Rajaramamohan Rao 1982).

Field experiments

Field experiments on the impacts of herbicides on microorganisms in ricefields have consisted of enumerations of soil microflora after application of thiobencarb (Sato 1987) or preemergence herbicides (Mandal et al 1987). Both experiments indicated either an absence of effect or a transitory change of population densities, followed by recovery within 2 or 3 wk.

Soil microbial biomass is regarded as a major channel through which nutrients are transferred to rice (Watanabe et al 1988). Field surveys on 32 rice farms in the Philippines showed no correlation between the intensity of pesticide use in farmers' fields, including the specific use of herbicide (as estimated from surveys of use over several previous cropping seasons) and the soil microbial biomass estimated at the beginning and end of the crop cycle (Roger et al 1994).

IMPACT ON INVERTEBRATES

The dominant soil and water invertebrates in ricefields are ostracods, copepods, cladocerans, rotifers, insect larvae, aquatic insects, mollusks, oligochaetes, and nematodes (Roger and Kurihara 1991). They have agricultural significance as nutrient recyclers, rice pests, and rice pest predators, and medical significance as vectors of human and animal diseases.

Microcrustaceans and larvae of mosquitoes and chironomids are ubiquitous primary consumers which recycle nutrients from the photosynthetic aquatic biomass. They usually proliferate about 2 wk after the peak of phytoplankton abundance (Kurasawa 1956) and may cause the disappearance of microalgae blooms within 1-2 wk. Ostracods have the potential to recycle 20 kg N ha^{-1} per crop. Primary consumers that feed on cyanobacteria may inhibit photodependent BNF or cause the dominance of mucilaginous colonial forms that are less susceptible to grazing than are noncolonial forms, but are less active N_2 fixers (Roger and Kurihara 1991).

Oligochaetes, especially tubificidae, are a major component of the zoobenthos that ensure nutrient exchange between soil and floodwater and increase soil N uptake by rice plants. Populations in ricefields range up to 40,000 m^{-2} (0-700 kg fresh weight ha^{-1}) (Simpson et al 1993a,b).

Aquatic invertebrates also have detrimental effects in rice-based ecosystems. Mosquitoes are vectors of diseases, including malaria and Japanese encephalitis (Roger and Bhuiyan 1990). Chironomids and ostracods feed on rice seedling roots, but this effect is limited in time and space (Clement et al 1977, Barrion and Litsinger 1984). Species of large snails that graze on rice seedlings have been recognized as an important rice pest in tropical countries and Japan. Other species (*Bilinus* spp., *Biomphalaria* spp., *Limnea* spp.) are detrimental as vectors of bilharziosis (Roger and Bhuiyan 1990).

Most information on the impacts of pesticides on nontarget invertebrates deal with insecticides applied alone or in combination with herbicides. Thiobencarb is the herbicide most often tested.

Floodwater invertebrates

Application of thiobencarb to experimental ricefields in Japan drastically reduced populations of cladocerans, odonatans, midges, and mosquito larvae. Resurgence of midges, cladocerans, and mosquito larvae occurred rapidly, to densities higher than those of the controls (Ishibashi and Itoh 1981). Simpson et al (1994a,b) studied the impact of carbofuran and butachlor applications on the population dynamics of floodwater invertebrates in Philippine ricefields. While significant effects were observed on ostracod, copepod, cladoceran, chironomid, and mosquito larvae populations, the impacts were relatively small, transient, and inconsistent. They concluded that, at realistic application rates, carbofuran and butachlor did not affect floodwater invertebrates in the context of crop cycle population dynamics.

Snails are not usually affected directly by conventional rice pesticides, but their populations may increase because of reduced competition. Ishibashi and Itoh (1981) observed larger snail populations after harvest in fields treated with thiobencarb than in untreated fields. Simpson et al (1994c) found little evidence that indigenous snail populations were affected by butachlor applications.

Soil invertebrates

Aquatic oligochaetes and nematodes dominate the soil fauna in wetland ricefields. The effects of pesticides on nontarget nematodes, however, have received little attention. Ishibashi and Itoh (1981) found no effect of thiobencarb on average populations of saprophytic and parasitic nematodes in a Japanese ricefield. Of 16 insecticides and 3 herbicides (2-4-D, butachlor, and pretilachlor) applied to ricefields in the Philippines, only the insecticides monocrotophos and ethofenprox had limited impact on parasitic nematodes (Prot and Mathias 1990). Information about herbicide impacts on populations of aquatic oligochaetes in ricefields also is scarce. The recent disappearance of aquatic oligochaetes from some Japanese ricefields is thought to be associated with the use of some herbicides. This would explain the reappearance of oligochaetes soon after PCP was replaced by NIP (2,4-dichlorophenyl p-nitrophenyl ether), CNP (4-nitrophenyl 2,4,6-trichlorophenyl ether), and thiobencarb. This conclusion has been supported by laboratory tests (Kurihara and Kikuchi 1988). A survey of aquatic oligochaetes in farmers' fields in the Philippines did not find differences among populations associated with differential pesticide use (Simpson et al 1993b).

Biodiversity

It is generally accepted that crop intensification and use of agrochemicals decrease biodiversity and provoke "blooms" of certain organisms. However, quantitative data on aquatic invertebrate diversity in ricefields are rare, and the limited amount of data that are available were obtained by different methods of sampling, over different time frames, from different locations. The studies do not specifically refer to herbicides but to pesticide use in general.

The only reference on the diversity of aquatic invertebrates in traditional ricefields is a 1975 study in Thailand, where 183 species (protozoans excluded) were recorded in one field within 1 yr (Heckman 1979). In a 2-yr study in Selangor, Malaysia, 39 invertebrate taxa were recorded in ricefields where pesticides were applied (Lim 1980). A single sampling in four Californian ricefields recorded 10-21 taxa (Takahashi et al 1982). Surveys of 18 sites in the Philippines (IRRI 1985) and India (Roger et al 1987) found population dominance inversely proportional to diversity. Ostracods, chironomids, and mollusks dominated the invertebrate community at most sites, and a few species attained exceptionally high densities at some sites. The highest number of taxa recorded at a site was 26; the lowest, 2. The marked decrease in number of taxa recorded since 1975 might be taken as a rough indication of a decrease in species richness. This agrees with, but does not demonstrate, the generally accepted concept that crop intensification has reduced biodiversity in ricefields (Roger et al 1991). A decrease of biodiversity also could be attributed to the disappearance of permanent reservoirs of organisms in the vicinity of the fields (Fernando et al 1980).

LONG-TERM EFFECTS

Available information indicates the possibility of detrimental impacts of herbicides on soil fertility and the microbial metabolism of herbicides over the long term.

Change in herbicide metabolism

Repeated application of a single pesticide has been reported to cause changes in the pattern of its metabolic decomposition. This has been observed for the insecticide parathion (Sudhakar-Barik et al 1979) and the herbicide thiobencarb (Moon and Kuwatsuka 1984). Such changes in degradation pathways could lead to agricultural problems. Thiobencarb usually is detoxified by hydrolysis, but its repeated application to flooded soil favors the multiplication of anaerobic bacteria that decompose thiobencarb by reductive dechlorination. That reaction results in the formation of a phytotoxic compound (S-benzyl N, N-diethylthiocarbamate) that causes dwarfing in rice (Moon and Kuwatsuka 1985).

Impacts on soil microbial biomass

Several long-term experiments evaluating continuous pesticide applications have resulted in declining rice yields over time (Cassman and Pingali 1995). The reasons are not fully understood, but one factor might be intensive hand weeding and herbicide use combined with a dense rice canopy that could restrict the growth of the photosynthetic aquatic biomass. That, in turn, would restrict the replenishment of soil microbial biomass and N fertility. Pesticides, including herbicides, also might be involved in decreasing populations of aquatic oligochaetes (Simpson et al 1993a) and the translocation of the nutrients accumulating at the soil surface to a deeper soil layer. Little data are available to substantiate this hypothesis, but in experiments at IRRI that totally prevented photosynthetic activity in the floodwater of planted fields by covering them with black cloth, soil microbial biomass was reduced 22% after 2 yr (IRRI 1989).

CONCLUSION

Most of the literature on pesticide fate and its impacts in wetland rice was published between 1970 and 1985. Since then, the number of studies has decreased precipitously. Most studies have dealt with the effects of insecticides on heterotrophic microorganisms and invertebrates, and of herbicides on cyanobacteria. In studies on the side effects of herbicides (and pesticides in general), data were generated primarily in the laboratory with microbial cultures or small samples of unplanted soil, using relatively high concentrations of pesticides. This makes extrapolation to field conditions questionable. Pure culture studies may not have much relevance, since the net effect on the microbial community is more important than the effect on an individual microorganism. This is particularly true for activities such as denitrification and N_2 fixation that are carried out by a broad range of taxonomically different microorganisms (Ray and Sethunathan 1988). Several researchers have developed small-scale models (microcosms) of ricefields or aquatic ecosystems to study and/or predict the bioaccumulation and dissipation of various pesticides applied to flooded ricefields (Higashi 1987). Such methods offer an interesting tool for detailed pesticide studies under controlled conditions, but they have not yet involved the study of the microbial component of the ecosystem. No field experiments have studied the impact of herbicide application on microorganisms and invertebrates over several crop cycles in a flooded soil. Studies of the microbial degradation of herbicides and their influence on microflora and nontarget invertebrates in flooded ricefields, hitherto mostly restricted to short-term laboratory experiments, should be performed under more realistic field conditions and cultural practices, over a long term.

The information on relationships between herbicides and nontarget microorganisms and invertebrates in wetland ricefields is not only biased by experimental designs that constrain extrapolation to field conditions, but also is too fragmentary to draw any conclusions other than general trends.

Microbial degradation is one of the main factors that affect herbicide persistence in flooded soils. Its importance varies quite broadly, depending upon the herbicide formulation, the mode of application, and the environmental conditions. While pesticides in general persist longer in nonflooded than in flooded soils, there is no obvious trend for herbicides. Trifluralin, pyrazoxyfen, and MCPB-ethyl persisted longer under nonflooded conditions; molinate, thiobencarb, and MCPA persisted longer under flooded conditions. Findings on the buildup of the degrading microflora after repeated application of herbicides in flooded soils are poorly documented, and this area needs further investigation.

In laboratory experiments, herbicides affected soil microflora and its activities more often than did fungicides or insecticides. However, when applied on soil at recommended levels, herbicides rarely had a detrimental effect on microbial populations or on their activities. When significant changes were observed, populations or activities usually recovered within 1-3 wk. This seems to partially confirm the common belief that pesticides applied at recommended levels and intervals are seldom deleterious to the beneficial microorganisms and their activities (Wainright 1978). While herbicides might have only temporary effects, when applied repeatedly they could lead to the promotion, depression, or disappearance of components of the microbial community, and promote a new equilibrium. This could bring about changes in the rate or pattern of microbial decomposition of the herbicides that might be detrimental. This aspect needs further investigation.

Invertebrates seem to be more sensitive to pesticides than are microorganisms. Combined use of insecticides and herbicides can lead to floodwater blooms of individual species (especially primary consumers) that might be detrimental. Aquatic oligochaetes in soil are at least partly inhibited by some herbicides, which might affect nutrient translocation and soil fertility. Greater understanding of floodwater ecology is needed as a basis for developing agricultural practices that maintain a biological equilibrium in the ricefield ecosystem. In particular, practices are needed that will decrease pesticide use and conserve the natural predators of rice pests and disease vectors. In order to develop cultural practices that favor the conservation of invertebrate predators—a major component of integrated pest and vector management—more knowledge on the long-term impact of herbicides on ricefield invertebrate populations is needed.

It is important to remember that impacts of pesticides on the soil-floodwater ecosystem can be significant without being detrimental. For example, a shift in algal community structure may not affect soil fertility, provided that aquatic primary production is unchanged. We should be cautious in identifying the nature of impacts, which should be considered in the context of ecosystem equilibrium, not in isolation. It would be as unwise to underestimate as to overestimate the significance of pesticide impacts in soils. Underestimation could cause avoidable ecological damage. Overestimation could restrict the judicious use of pesticide when appropriate. However, current knowledge on the long-term impacts of herbicide use in ricefields is fragmentary. Investigation is needed to establish how herbicide application over the long term may affect primary production in floodwater, soil microbial biomass and microbial populations, populations of invertebrates responsible for nutrient recycling and translocation, and populations of invertebrate predators of rice pests and vectors of human diseases.

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NOTES

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IMPACT OF HERBICIDE USE ON THE ENVIRONMENT

D.G. Crosby

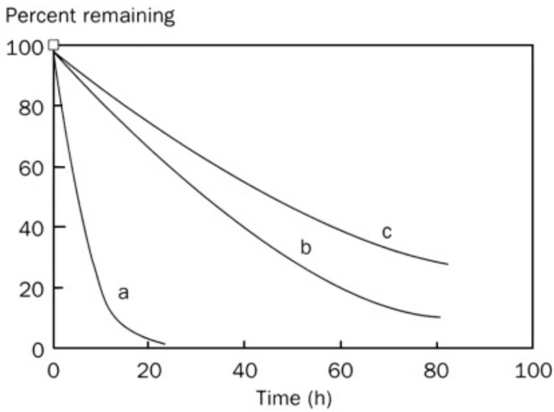
In agricultural production, herbicides are used to reduce the undesirable effects of noncrop plants (weeds) growing interspersed with crop plants. The ability of a herbicide to selectively affect unwanted plants while leaving desirable plants undamaged is based primarily on differences in physical and biochemical characteristics that are peculiar to plants, such as photosynthesis. Only a few chemicals are effective (Table 1).

A basic precept of toxicology is that some level of any chemical will damage life. Even though herbicides are chemicals designed to act only on plants, we can expect that they also will be toxic to some extent on animals and microorganisms. A second precept of toxicology is that effects will be in proportion to dosage, with the probability of an adverse effect related directly to the concentration of chemical available to an organism.

Table 1. Herbicides applied on California ricefields, 1990.

Common name	Trade name	Total kg ai	Applications (no.)
Bensulfuron methyl	Londax	19,032	3,613
Copper sulfate [a]	Bluestone	682,520	1,266
2,4-D [b]	Weedar	3,244	347
Glyphosate [c]	Roundup	1,110	69
MCPA [d]	MCPA	9,030	569
Molinate	Ordram	521,721	3,749
Pendimethalin	Prowl	127	5
Propanil	Stam	4,714	165
Thiobencarb	Bolero	33,266	214
Total		1,274,764	9,997

[a] CEPA (1993). [b] Includes salts and esters. [c] Isopropyl amine salt. [d] Salts.



1. Relative persistence of (a) fenoxaprop ethyl, (b) MCPA, and (c) molinate in ricefield water (Toole and Crosby [1989]; Crosby and Mabury, University of California, unpubl.; Soderquist et al [1977]).

Concentrations of herbicides in ricefields will vary widely, depending on the formulation and rate of application of the chemical, on climate and temperature, and on the time that has elapsed since the chemical was applied. Most herbicides dissipate over time, in response to physical, chemical, and biochemical forces. The effective life of a herbicide is defined as its persistence. Figure 1 illustrates the persistence of three herbicides in ricefield floodwater. Although it appears that dissipation slows as concentrations decline, in reality as much time is needed for a concentration of 2 parts per trillion to be reduced to 1 part per trillion as is needed for 2 parts per million to be reduced to 1 part per million. Theoretically, a concentration will never be reduced to zero.

Toxic impacts also are not instantaneous. The more persistent a chemical (the longer its concentration remains high), the greater the risk of an adverse environmental impact. Conversely, no matter how persistent a chemical, eventually there will be a concentration so low that no effect can be observed. This means that detection of a herbicide in an environment does not necessarily infer that it will have a toxic effect on nontarget organisms. Herbicide concentrations in ricefield floodwater normally are in a low parts-per-million range, declining rapidly to nontoxic levels.

FACTORS THAT INFLUENCE IMPACT

Some physical and chemical/biochemical factors lower the environmental impact of herbicides, others tend to increase the impact. Potential environmental effects can be anticipated and ways devised to reduce or avoid their impact.

Factors that reduce toxic risk

Physical factors. A significant physical factor that reduces the impact of a herbicide is dissolution, the ability of a chemical to dissolve in water and then undergo further dilution. To some degree, all pesticides are soluble in water, even those that may be labeled "insoluble." Over time, herbicides applied to flooded ricefields leach out of their formulation carrier and dissolve. The addition of more water to a herbicide-treated field, through rainfall or irrigation, dilutes the solution, which reduces toxic risk. The dissolved herbicide is absorbed into plants, adsorbed or bound to sediment, carried away by runoff, or volatilized into the atmosphere.

Volatilization is the most important route for the dissipation of many herbicides. The chemicals evaporate from fieldwater and, to a lesser extent, from damp soil. The rate of volatilization is governed primarily by Henry's Law: $H = P/S$, where H is the Henry's Law constant, P the vapor pressure of the chemical, and S the aqueous solubility of the chemical (Lyman et al 1990). Water depth, temperature, and windspeed also affect volatilization. Volatilization can be quite rapid (Table 2). The half-life (time required for an initial concentration to decrease by half) of the herbicide molinate is 2 d, close to that predicted by Henry's Law. This short half-life indicates that the dissipation of molinate is due primarily to its volatility. An estimated 75-85% of molinate applied as a granular formulation to a flooded ricefield volatilizes into the atmosphere (Crosby 1983). The odor of volatilizing molinate can be detected kilometers away from recently treated ricefields.

Applying herbicides to ricefield soil before the field is flooded inhibits dissolution and volatilization, and guarantees increased persistence of the chemicals. Although this is not necessarily detrimental—preflood application will tend to decrease the amount of herbicide needed for a given level of weed control—it does emphasize the fact that a large part of any herbicide treatment is dissipated.

Chemical/biochemical factors. Herbicides are chemicals that can combine with the environmental reactants oxygen, water, and natural organic matter. For example,

Table 2. Environmental properties of rice herbicides.[a]

Herbicide	Half-life[b] (h)	Relative volatility [c]	Solubility (ppm)	Soil binding [d]	BCF[e]
Fenoxaprop ethyl	3	0.003	1	6800	1056
Bensulfuron methyl	12	<0.001	120	57	2
Butachlor	20	0.03	23	1075	1355
MCPA	29	<0.001	825	20	<1
Molinate	50	1.2	800	190	25
Thiobencarb	60	0.11	30	1400	230

[a] Crosby and Mabury (1992); R. Marrese, Hoeschst-Roussel Agri-Vet Co., Somerville NJ, USA, pers. commun. (1993): W.P. Ridley, Environmental Science Department, Agricultural Group, Monsanto Company, St. Louis, MO, USA. pers. commun. (1994); Toole and Crosby (1989). [b] In field water. [c] H compared with that of water. [d] K_{OC}. [e] Calculated from K_{OW}.

common ester formulations of the herbicide 2,4-D will react with slightly alkaline ricefield water, for a half-life of 37 h for the 2-octyl ester and a half-life of 0.6 h for the widely used butoxyethyl ester (Zepp et al 1975). Those two reactions occur both during the day and at night, and are sometimes called “dark reactions.”

Other degradation reactions occur only in sunlight, or are accelerated by sunlight. For example, 2,4-D in an aqueous solution exposed to sunlight loses its chlorine atoms and its acidic side chain over a period of several days, eventually degrading photochemically to nontoxic products (Crosby and Tutass 1966).

Most herbicides undergo similar breakdown, and often are largely deactivated within a few hours or days (Crosby 1983). The herbicidal effects of fenoxaprop ethyl, which is dissipated primarily by photodegradation, must be initiated quickly after application, because essentially none of the chemical persists beyond a day or two. Herbicides such as pentachlorophenol (PCP) and many others also are photolyzed rapidly to small, nontoxic fragments (carbon dioxide, chloride ions, simple organic acids) (Wong and Crosby 1981).

Sunlit ricefield water also generates a powerful hydroxyl radical which eventually oxidizes any organic pesticide that is present (Mabury and Crosby 1993). But because sunlight does not penetrate the soil, herbicides applied directly to the soil before a field is flooded are not subject to appreciable photodegradation. Also, any factor that reduces the intensity of sunlight-cloudy weather, short days, heavy algal cover on the floodwater-will slow the rate of photodegradation. While sunlight is a major factor in herbicide dissipation when chemicals are applied during the long, cloudless days of a hot season, such as in California (Crosby 1983), it may not be as important in different climates and in regions with different growing seasons.

Breakdown of herbicides in the soil is especially important because soils and sediments often are the final repositories of chemical residues (Sethunathan and Siddaramappa 1978, Kuwatsuka 1983). Biodegradation of herbicides by microorganisms in the soil and water is largely independent of sunlight, except in the case of algae. The degradation will take place under either nonflooded (aerobic) or flooded (anaerobic) conditions, or both, depending on the chemical structure of the herbicide. Nitrofen or trifluralin, which contains easily reduced nitro groups, have especially short half-lives under anaerobic conditions, while readily oxidized compounds such as 2,4-D tend to be less persistent under aerobic conditions (Table 3). A herbicide such as propanil, which reacts rapidly with water, may have little persistence under either condition (Matsunaka 1968).

As with photodegradation in water, aerobic biodegradation usually leads to mineralization, or at least to simple organic fragments. Anaerobic degradation typically leads, after all reducible groups have reacted, to more stable intermediates which may be very slow to degrade further. The amines resulting from biodegradation of nitro-containing and anilide herbicides, such as nitrofen and propanil, are tightly bound to soil and may become irreversibly incorporated into the natural organic matter (Chisaka and Kearney 1970). If the flooded soil eventually is drained, residues can then be aerobically mineralized.

Table 3. Persistence in soil of rice herbicides.

Herbicide	Initial concentrate (mg kg^{-1})	Half-life (d)	
		Flooded	Nonflooded
Propanil	1	1	1
Trifluralin	10	3-10	150
Nitrofen	10	11	50
2,4-D	20	28	9
PCP	100	30	50
Thiobencarb	20	30-60	10-26

Source: Sethunathan and Siddaramappa (1978).

Higher plants and animals also are a degradative force in the environmental fate of rice herbicides, although they perhaps are not as important as microorganisms. Unlike many insecticides, most herbicides are absorbed by the plant roots and translocated upward, where they are metabolized. For example, propanil is readily absorbed from water into rice plants and weeds. The rice enzymatically hydrolyzes the chemical, while weeds, which are less effective at hydrolysis, are damaged (Matsunaka 1971). In fact, the entire range of different types of major metabolic reaction can be found among plants—oxidation, reduction, hydrolysis, and conjugation (Hatzios and Penner 1982). Molinate is absorbed by rice plants, translocated, partially oxidized, and conjugated with glutathione (Lamoureaux and Rusness 1983, Imai and Kuwatsuka 1984). Some proportion of the herbicide, however, may be translocated to plant leaves and volatilized unchanged into the atmosphere (Ferreira and Seiber 1981). Many herbicides become inextricably bound into plant tissue (Hatzios and Penner 1982). For example, Yih et al (1968) found 38% of absorbed propanil to be permanently incorporated into the lignin of treated rice plants.

The role of animals in the fate of herbicides has not been determined. The relative biomass of such terrestrial and aquatic animals such as mice and fish is too small to make much difference (although most of them seem fully capable of metabolizing the chemicals that are applied to agricultural fields). The effect of the large biomass of minute soil invertebrates (nematodes, insect larvae, earthworms) on herbicide degradation is largely unexplored. These animals, however, are found only in the uppermost sediment of flooded ricefields.

From the moment they are released into the environment, herbicides dissipate in all directions—diluted by volatilization and dissolution, broken apart chemically, biodegraded into nontoxic fragments, irreversibly bound into plant tissues.

Factors that increase toxic risk

Although the environmental risk associated with herbicides abates over time, several natural factors can temporarily increase concentrations, and therefore toxicity. Bioconcentration (and other solvent partitioning) and adsorption onto solid surfaces, such as soil particles, are some of these processes.

Table 4. Toxicity to aquatic animals of rice herbicides.

Herbicide	Bluegill sunfish[a] (96 h IC_{50}, ppm)	Daphnia magna (48 h IC_{50}, ppm)	Maximum water[b] concentration (ppm)
Butachlor	0.4	2.4	3
MCPA	1.5	>100	1
Thiobencarb	2.5	0.8	3
Fenoxaprop ethyl	0.3	3.2	0.5
Molinate	0.4	0.7[c]	2
Bensulfuron methyl	>150	2.4	0.3
Methyl parathion	4.4	0.00014	1

Sources: Crosby and Tucker (1996); WSSA (1989); R. Marrese, Hoeschst-Roussel Agri-Vet Company, Somervllle NJ. USA, pers. commun. 1993. [a]*Lepomis rnacrochirus.* [b]At normal application rates. [c]24 h.

Most chemicals are, to some degree, bioconcentrated—the levels in animal tissues will become higher than the levels in the surrounding environment. The ratio, called the bioconcentration factor (BCF), is directly related to the fat solubility of the chemical. Most herbicides have limited fat solubility and biodegrade easily, which translates into relatively low BCF. For example, the BCF of molinate, a herbicide, is 25; that of DDT, a powerful insecticide, is about 100,000. An average 100 parts per billion concentration of molinate in water would lead to about 2.5 parts per million concentration in whole fish tissues (Table 4). But as long as the accumulation of herbicide takes place slowly, no ill effects are observed in the fish. The tissue residues eventually disappear.

The level of herbicide concentration in fish tissues is related more to herbicide concentration in the water than to concentration in fish food. Any magnification of herbicides in the food chain of fish would be unusual, given that herbicides dissipate from water and are readily biodegradable (Mullison 1970).

Uptake and adsorption (binding) of herbicides into soil also increase and maintain local concentrations. Like bioconcentration, adsorption is inversely related to aqueous solubility and directly related to concentrations of the chemical in surrounding water and to the level of soil organic matter. In typical ricefield soils, most herbicides are taken up moderately and reversibly. For example, phenoxy herbicides such as MCPA scarcely concentrate at all (Table 2). A few herbicides, such as the triazines, are taken up more extensively and held more tightly (Crosby and Mabury 1992). Paraquat is so tightly bound it is almost impossible to remove from soil, but that also means it is not biologically available to other organisms.

The most dangerous factors involved in environmental risk from herbicides are unnatural events—pesticide spills and improper disposal of waste chemicals and pesticide containers. Spills can occur during the loading and transport of pesticides and application equipment, and while mixing and diluting chemicals for spray formulations. Dozens of spills occur in California each year, but most incidents are not widely publicized and small spills are seldom reported.

One infamous herbicide spill occurred in 1991. A railroad tank car carrying a 40% aqueous solution of metam-sodium fell into the Sacramento River near Dunsmuir, California. At least 50,000 liters of the chemical entered the water of the narrow river. Soon all life — plants, animals, microorganisms—for a number of kilometers downstream died. The vapor of metam-sodium's degradation product, methyl isothiocyanate, made many Dunsmuir inhabitants ill. But within a year, the herbicide had dissipated and some fish and plant life had started to reappear.

Problems with the disposal of waste pesticides usually involve two sources — unused spray and incompletely emptied containers. For example, until recently pesticide applicators in California dumped unused spray mix and the residue from washing their sprayer tanks directly on the ground or into shallow pools near rural air strips, many of them adjacent to ricefields. Each aerial application of a rice herbicide (even though the herbicides are applied at low concentrations) is estimated to generate about 20 liters of waste spray, for a seasonal total in excess of 2×10^5 liters containing 2,000 kg of active ingredients. Part of this pesticide residue volatilizes or degrades, but the rest remains in place or migrates into adjacent fields or drains, and in high concentrations (Sieber 1987).

Problems with the disposal of outdated pesticide concentrates and of the wastes from pesticide manufacture and formulation are more isolated.

ENVIRONMENTAL IMPACTS

Herbicides are intended to impact the environment, to weaken or kill undesirable plants. Incidental effects on other organisms, however, are possible and even probable, depending on a complex array of direct and indirect factors.

Direct impacts

Most people imagine direct toxic impacts of herbicides. But in general, adult fish and other large aquatic animals are not at acute risk because of their detoxification ability. Also, herbicides dissipate rapidly and concentrations rarely attain a lethal level.

There are exceptions. For example, severe anemia may occur in carp after extended exposure to molinate. Other species usually are not affected, and the problem can be managed. Small aquatic organisms, such as larval fish and microcrustaceans, are at greater risk, although insecticides are far more dangerous than herbicides. Table 4 shows typical lethal concentrations of some common rice pesticides. Even though the median toxic dose can be lower than the maximum concentrations expected in ricefield water, the toxicity data do not reflect any dissipation. Also, formulated herbicides are less toxic than the pure chemicals used in tests.

However, any environmental impact could damage a fishery and disrupt aquatic food chains, resulting in loss of food for larger organisms. Such disruption could include toxic effects on the countless small creatures that live in the upper layer of bottom sediments (the meiofauna). Little is known about their place in a ricefield ecosystem, or about the effects of herbicides on the fauna of anaerobic soils. (The effects of herbicides on the fauna of aerated soils were reviewed by Eijsackers and Van der Drift [1976].)

The role of the thin organic microlayer that coats the surface of ricefields also is unknown. The corresponding marine microlayer, however, provides a site for the hatching and early development of many fish and invertebrate species. Concentrations of herbicides in the surface microlayer have been measured at as much as 100,000 times the concentration in the underlying water (Gever 1993). This surely poses a direct threat to some aquatic species.

Concern also has been expressed about the possible toxic effects of herbicides on soil microflora, with subsequent reduction in soil fertility. Given the numerous species of bacteria and fungi in and on soil, the variety of soils and habitats, and the environmental interactions, this is obviously an extremely complex issue. Herbicides have been shown to both stimulate and inhibit some microbial populations, at least temporarily (Grossbard 1976). But the common mechanisms of herbicidal action in higher plants, such as photosynthesis inhibition and cellulose cell elongation, in general, do not apply to soil microorganisms. Any effects observed so far may be indirect, caused by older, more persistent pesticides that are no longer being used or by unusually high rates of application. Even so, preferential adsorption of herbicides to soil organic matter could expose microorganisms to unexpectedly high levels. Ecological change must be considered.

Most modern herbicides used in rice (with the possible exceptions of bensulfuron-methyl and thiobencarb) are considered to have low environmental persistence. Pesticides, however, are industrial chemicals and are not entirely pure. Some byproducts can be unusually toxic and persistent. At one time, chlorthal dimethyl contained up to 10% hexachlorobenzene—a very persistent and toxic chlorinated hydrocarbon. In other examples, 2,4,5-T and silvex at one time contained traces of 2,3,7,8-TCDD, an extremely toxic manmade substance; pentachlorophenol contained even larger amounts of other dioxins. These byproducts were applied to the fields along with the pesticide.

Now most manufacturers are aware of the significance of impurities, and remove most of them before marketing their product. However, information about the nature and level of impurities is not generally available, and the potential environmental impacts are unknown.

Another possible problem is synergism, a more-than-additive effect when two or more chemicals are combined. Normally, this involves herbicides that exhibit the same mechanism of toxic action. For example, the toxic effects of molinate and thiobencarb are at least additive, and they may be synergistic in their effect on fish (Cornacchia et al 1984).

Synergism also occurs when one pesticide blocks the detoxification of another. An example is the herbicide propanil, which becomes phytotoxic when a plant's detoxification enzymes (acylamidases) are inhibited by carbamate or organophosphate insecticides (Matsunaka 1968, Smith and Tugwell 1976). Synergism has not been widely investigated because of the large, complex effort needed to test all possible combinations of pesticides and their degradation products.

In general, environmental exposure to herbicide degradation products has not been considered harmful, although little investigation has been undertaken. Acylanilides such as propanil can be converted to carcinogenic azobenzenes by soil microorganisms (Chisaka and Kearney 1970), but there is no evidence that this presents an actual environmental problem. While some degradation products, such as thiolcarbamate sulfones and the chlorophenols formed by photolysis of phenoxy compounds, are acutely more toxic than their parents, they are so unstable and so dilute they are unlikely to produce lasting effects. In addition, degradation products ordinarily are short-lived.

For sheer destructive potential, the threat is massive mechanical spills. Ricefields often are crisscrossed by roads and railroads, and spills from crashed applicator aircraft are not unknown. Small spills of concentrates or spray formulations are an almost daily occurrence wherever pesticides are used.

Indirect impacts

To be successful, application of herbicides must result in ecological impact. Weed populations, vigor, and biomass are expected to be reduced. The effect on other species appears to be negligible (Mahn and Helmecke 1979). Herbicides may, however, cause a number of indirect environmental changes—some subtle, some obvious; some reversible, some not.

Loss of habitat for a number of organisms is a major impact (Way and Chancellor 1976). Removal of weeds alters water flow, changes water temperature, affects sunlight intensity, and takes away hiding places. While these changes may benefit some organisms, such as fish and algae, substantially, small invertebrates may suffer increased predation, migration, and destruction (May et al 1973, Walter 1964). If weed or algal infestation has been great, herbicide treatment may result in a large volume of decaying vegetation that will lower dissolved oxygen levels. Some fish deaths that have been attributed to pesticides may be due instead to oxygen starvation (Way et al 1971). The nutrients released by decaying vegetation also can result in massive algal blooms (Fish 1966).

Currently, herbicides are approved for use partly on the basis of demonstrated low persistence. But inorganic chemicals historically used as herbicides may dissipate very little. For example, copper sulfate (bluestone) is applied heavily worldwide as a herbicide and algaecide. While analysis shows that copper sulfate remains in field water only a few hours, current research indicates the chemical actually is precipitated onto bottom sediment as an insoluble and very persistent cupric hydroxycarbonate. With repeated applications, that sediment would build up until the soil would be too toxic to support rice seedling growth.

The impact of the migration of herbicides out of a ricefield is difficult to document. The chemicals volatilize and are carried away by wind, move off in surface tailwater, or remain in postharvest residues. Ordinarily, at this point they are highly dilute and produce no noticeable effect. The principal impact may be the cost of maintaining extensive and expensive monitoring systems, such as are required in some places (i.e., California).

The potential for impact, however, exists. Aerial drift during application of the rice herbicides MPCA and propanil has caused extensive damage in orchards adjacent to the treated ricefields. Thiobencarb has been associated with an off-taste in chlorinated drinking water from rivers receiving ricefield runoff. Molinate has killed carp in drainage ditches. Movement of bensulfuron methyl adsorbed to waterborne sediment has been implicated in downstream crop damage.

The beneficial effects of inadvertent herbicide movement do not appear to have been addressed. Yet low concentrations of herbicides and some other chemicals have been shown to alter plant composition (Ries 1976). Application of dilute herbicide sprays to mature rice increased grain protein content by up to 18%, as well as improved vigor and germination (Miller and Mikkelson 1970, De Datta et a1 1972). Application of 2,4-D or MCPA increased protein in other crops dramatically, although sometimes nitrate levels also increased.

CONCLUSIONS

The most obvious toxic impact of herbicides on flooded rice is to change plant, and perhaps animal, ecology. However, in many places establishment of a rice monoculture already has erased the native ecosystem. Does it make a difference, then, if unwanted plants are thinned by hand or by the application of chemicals? If the ricefield also is to culture fish, either for human food or to control insects, then the toxicity of herbicides to fish and to aquatic invertebrates must be considered. Current evidence, however, indicates that modern organic weed killers do no lasting harm and may even be ecologically beneficial, if the recommended rates and frequency of application are followed and modern herbicides are selected. This is not true of insecticides and other types of chemicals.

Obviously, over-application, spills, and indiscriminate disposal of herbicide waste—any circumstance that elevates concentrations beyond a field's natural assimilative capacity to dissipate and biodegrade a chemical—will produce toxicity. While most modern herbicides have low persistence, use of a slowly dissipating chemical, such as a copper compound, should be avoided. Because off-site movement in air or water, or on soil, can produce temporary toxic effects in susceptible plants, basic management of water release and pesticide drift is important.

More and more rice-growing nations are regulating pesticide use, through government policy, education, and research. Governments can regulate and supervise pesticide importation, storage, and use. Given comparatively few serious weed species, and with effective chemical controls identified for those (Baltazar and De Datta 1992), regulation of this aspect of agricultural chemicals might not be difficult. A high priority is control of spills and waste.

Given the current state of knowledge about rice, relatively little additional research may be needed to substantially reduce the toxic risk of herbicide use. In the past, herbicide research often concentrated on efficacy trials under local conditions. While this applied work needs to continue, additional attention should be given to safety and environmental protection. Although local persistence of each formulation should be assessed, a simple immunoassay or similar test should suffice.

Increased effort is needed to more effectively deliver existing information to potential users, through local education and agricultural extension programs that provide demonstrations, recommendations, and advice to growers (B. L. Brennan, University of Hawaii, Honolulu, HI, USA, pers. commun., 1994). Unsafe storage, mixing, and container disposal may be the most difficult area, and corporate efforts are needed to address these problems.

Use of defoliants during the war in Southeast Asia and several spectacular accidental spills have fostered a negative public image of herbicide use in the industrialized nations. However, in any part of the world, the toxic risk from insecticide application, from sewage and industrial waste, and from urbanization is much greater than the risk from herbicide use. Government policy in regard to rice herbicides can legitimately be based on land use, water, health, social, demographic, and cultural issues. The environmental impact of herbicides on nontarget organisms is negligible.

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EFFECT OF HERBICIDE USE ON AQUACULTURE

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In China, crop losses due to weeds have been estimated at 20-25 million tons a year. Of more than 3,000 species of weeds found in China, 395 species grow in Jiangsu Province, 189 of them in Shanghai District. In Shanghai District, 115 of the species are spring and summer weeds, 74 are autumn and winter weeds. No weeds grow during the intense summer heat of July and August nor during the severe winter cold from December to February (Tang et a1 1980).

China began developing its domestic pesticide industry in 1950. Production continually increased and by 1981, more than 500,000 t of raw materials were being used annually to produce more than 100 types of pesticides. Of those, 10 were herbicides. In the early 1980s, 18 agricultural chemical companies from France, Germany, Great Britain, Japan, Switzerland, and the United States field-tested 67 chemicals in China.

Briskly developing township enterprises, decreasing availability and increasing costs of labor, and growing agricultural mechanization continue to promote herbicide use. Nationwide, the area treated with herbicides reached 2.7 million ha by 1974, 4 million ha by 1997, 4.7 million ha by 1978, and is expected to cover 6.7 million ha by 2000.

China's traditional freshwater aquaculture is being impacted by growing water pollution from increasing use of agricultural chemicals and from increasing waste discharge by cities and towns.

HERBICIDE USE IN CHINA

China is 10-20 yr behind the more industrialized countries in use of pesticides. Of the more than 100 types of agricultural chemicals produced, nitrofen is the main herbicide. It has been broadly used to control annual grasses such as barnyardgrass *Echinochloa crus-galli, Scirpus vagara,* and some algae, with an effective rate above 95%. In the early 1980s, annual nitrofen production was about 5,000 t (25% wettable powder)—one-third the total amount of herbicides produced. Nitrofen was used in rice, maize, soybean, and cotton, alone or mixed with other herbicides (Qian et a1 1982). Production of chlorinated hydrocarbons ceased during 1983-85, and in 1993 five types of chemicals—BYC, DDT, N,N'-methylenebis, fumazone, and chlordimeform—were formally banned. While in the past, pesticides were sold through state-owned production material companies, in the market economy now being established, chemicals may be sold by private enterprises.

Controlling weeds contributes largely to yield. If a hill of rice is invaded by one barnyardgrass plant, grain production can be reduced by 35%; invasion by two barnyardgrass plants can reduce production by 62%; three barnyardgrass plants can reduce production by 88% (Zhou 1984). Using herbicides greatly reduces the labor needed for manual weed control-harrowing, hoeing, and hand weeding. With herbicides, a single crop of rice only needs 2 wk of labor. Using herbicides also solves the problem of weed infestations that follow changing land management patterns and agricultural mechanization.

RICE-FISH FARMING IN THE WUXI SPECIAL DEVELOPMENT DISTRICT

The special development district of Wuxi in southern Jiangsu Province is located adjacent to Lake Taihu on the delta of the Changjiang River. In 1987,226,900 ha were under cultivation, with rice the main crop and wheat or rapeseed the second crop. Integrated fish farming, with pond fish culture its major component, is a type of agricultural diversification in the Wuxi District. The surface area used for aquaculture totaled 64,466 ha in 1987 (Li 1991).

Small-scale farming in Wuxi District is declining and moderate-scale farming (more than 1 ha per household laborer) is increasing. In 1990, nearly 3,500 medium-sized farms in the district accounted for about 8,000 ha (Jiang 1992). Village ownership is another form of moderate-scale farming. In 1993, 585 village-owned farms covered 4,000 ha—64% of the hectarage under moderate-scale land management.

Use of herbicides in crops

During 1970-75, nitrofen was used on 13,333 ha of rice nursery beds. Its use spread to the main ricefields during 1975-80, and became common during 1981-88. During 1988-91, delachlor was used; after 1991, londax was used.

In 1993, the total area of land used for rice production was 140,533 ha, with 136,420 ha treated with herbicides. Nitrofen was applied to 14,766 ha, delachlor to 3,800 ha, londax to 49,600 ha, bensulfuron + metsulfuron to 31,666 ha, butachlor + simetryn to 9,800 ha, lolops to 6.466 ha, and other chemicals to 20,333 ha. Swiss-made sofit was used in rice nurseries. The area planted to wheat totaled 100,600 ha; 98.7% of it treated with the herbicides chlorsulfuron, chlorotoluron, and super puma. The area planted to rape totaled 20,400 ha, more than 90% of it treated with the herbicides fluazifop, gallant, and chlorotoluron.

Use of agricultural chemicals in fisheries

Agricultural chemicals are often used in diked fishpond systems (mulberry, sugarcane, fruit and vegetables) and rice-fish systems to clear ponds of unwanted fishes and pathogens; to control parasites, bacteria, and viruses; and to suppress water blooms and aquatic weeds. Herbicides used include quick lime, copper sulfate, ferrous sulfate, borax, and pentachlorophenol; insecticides include dipterex and DDV; bactericides include malachite green (copper carbonate). Some antibiotics also are used. Some pesticides act as herbicides, bactericides, and molluscicides all at the same time.

To protect public health, pentachlorophenol and copper chloride have been used in infested areas to eradicate the pond snail *Lymnaea,* an intermediate host of the blood fluke schistosome.

IMPACT OF HERBICIDES ON AQUACULTURE

The Lake Taihu watershed is an intensive commercial aquaculture area. In recent years, waste discharge from urban areas and agriculture has resulted in pollution of rivers, streams, ponds, and lakes. Fish in the rivers and streams were affected, fish farmers faced the threat of no clean water for their ponds, and Lake Taihu deteriorated.

Effect of herbicides on fish

The type and degree of toxicity seen in fish as a result of pesticides depend on the types of chemicals applied. It is not possible to separate herbicide impact from insecticide impact because the same chemicals might be used both as herbicides and as germicides or as insecticides and molluscicides. Insecticides are the most toxic to fish, molluscicides the next most toxic, and herbicides the least toxic (Cagauan and Arce 1992).

The persistence of herbicides in soil and water is rather short. In submerged ricefields, nitrofen has a half-life of 206 d (Quan et al 1982). If the irrigation water is slightly basic, the half-life of molinate is only about 1 d (Feng et al 1988).

In 1987, nitrofen was sprayed on ricefields in Yanshan Village, Yucheng Town, Jiangying City, Jiangsu Province. The drainage water from the ricefields flowed into nearby fish ponds, causing massive fish kill. The quick lime or pentachlorophenol often used in fish ponds to eradicate unwanted fish and shrimp also can kill nontargeted fish. Studies have been under way since the 1980s on the toxicity of agricultural chemicals to aquatic organisms. The herbicides studied include 2,4-D, pentachlorophenol, copper sulfate, and ferrous sulfate, among others.

Fish and shellfish have keen senses of taste and smell. Fish will take avoidance action and clams will close their shells when they encounter water containing only a small amount of pollutants. This means that fish have avoidance thresholds to different pollutants that will be lower than the lethal toxic thresholds. With some pollutants, however—such as cyanide and phenol—fish may not avoid or escape even lethal concentrations, which makes mass mortality possible (Li et al 1985).

Jiang (1986) studied the reactions of sensitive fish species silver carp *Hypophthalmichthys molitrix* and grass carp *Ctenopharyngodon idella* and strongly tolerant species crucian carp *Carassius auratus* and tilapia *Oreochromis niloticus* to 25 pollutants. The pollutants included heavy metal ions separated from chemical compounds, insecticides, herbicides, germicides, and some drugs used to cure fish diseases (Table 1).

Different fish species showed different avoidance reactions to different pollutants. Silver carp, grass carp, and tilapia were sensitive to pentachlorophenol, but much less sensitive to benzene phenol. These findings are consistent with those reported by Li et al (1985).

Fish confined over a relatively long time in water containing nonlethal levels of pollutants may exhibit irregular behavior or abnormal movement. Organic phosphates can inhibit the activity of cholinesterase. Copper sulfate mercuric compounds, and arsenide herbicides can damage sensory systems, destroy respiratory function, and affect feeding, spawning, and hatching rates (Table 2).

Acute fish toxicity values for commonly used herbicides, expressed as LC_{50}, are given in Table 3 (Mao et al 1985).

Effect on water quality

There are indirect effects on water quality, which involves oxygen content, pH, ammonia content, sediment, and taste and odor.

Reduced oxygen. During summer and autumn, blue-green algae blooms often

Table 1. Avoidance by fish of different herbicides.

Herbicide type	Concentration (mg L^{-1})	Avoidance index[a]			
		Silver carp	Grass carp	Crucian carp	Tilapia
Ferrous sulfate	20.00			74.17	
	16.00			55.55	
	7.50			-10.50	
Copper sulfate	0.50	85.74			
	0.30	50.20			
	0.05	-3.65			
Pentachlorophenol	1.00	100.00	100.00		100.00
	0.80	53.30	60.00		50.00
	0.50	-100.00	-40.00		-60.00
Benzene	25.00	-100.00	37.00		36.80
	10.00	-60.00	0.00		0.00
	5.00	14.20	13.00		18.90

[a]When fish enter clean water, avoidance index is 100; when fish swim into trial fluid, it is -100; when fish enter neither clean water nor trial fluid, avoidance index is 0.
Source: Adapted from Jiang (1986).

Table 2. Effect of pentachlorophenol on hatching rates of fish embryos.

Chemical	Concentration ($mg\ L^{-1}$)	Hatching rate of fish embryos	
		Silver carp	Grass carp
Pentachloro-phenol	0.45	0	0
	0.018	70	85
	0.009	80	90
Control	0	90	90

Source: Jiang, pers. commun.

Table 3. Toxicity to fish of commonly used herbicides.

Herbicide	Test fish	48 h LC_{50}	Toxicity grade[a]
2,4-D	Common carp	40.00	L
MCPA	Common carp	14.00	L
Propanil	Common carp	0.42	H
Nitrofen	Common carp	2.10	M
Benthiocarb	Common carp	3.60	M
Dimethachlor	Common carp	3.72	M
Delachlor	Common carp	0.86	H
Hedazhuang	Common carp	34.00	L
Oxadiazon	Common carp	3.20	M
Prornetryne	Common carp	23.50	L
	Rainbow trout	6.20	M
Glyphosate	Common carp	119.00	L
Penta	Common carp	0.35	H
Triazine group	Crucian carp	56	L
	Shrimp	1	H
Quick lime	Common carp	140	L
Puma super	Common carp	4.3	M
K-223	Common carp	300	L

[a] L = low toxicity above 10: M = medium toxicity from 1 to 10; H = high toxicity less than 1. Source: Mao et al (1985).

occur on the surface of water bodies used for aquaculture. The primary method used currently to control those blooms is the application of 0.7 ppm copper sulfate. Copper sulfate is a herbicide, an algicide, and a bactericide.

The decaying of dead algae consumes large amounts of dissolved oxygen in fish-pond water, depriving aquatic life. National fishery water quality criteria recommend that dissolved oxygen levels be greater than 5 mg liter^{-1} for 16 h out of 24, and not less than 3 mg liter^{-1} for the remaining 8 h. For salmon habitat, the recommendation is not less than 4 mg liter^{-1}.

Tang and Chen (1983) reported that waste water from a Jiangduan agricultural chemical factory had only 0.2 mg liter^{-1} dissolved oxygen. The fry of grass carp and common carp *Cyprinus carpio* placed in that water died within half an hour.

In both 1987 and 1988, 42 t of copper sulfate were used in the Wuxi District. If mixtures of copper sulfate and ferrous sulfate were included, the amount would be even higher.

Extreme pH values. Caustic lime is often used to clear fish ponds. It forms calcium hydroxide, which increases the pH of pond water to greater than 11, which kills unwanted aquatic organisms. In laboratory tests, pH values between 9 and 10 have been harmful to a few species of fish; higher pH values have been lethal to most species. If high pH is accompanied with high temperature, some fish inevitably die.

In the example cited earlier, the pH value of waste effluent from a Jiangduan agricultural chemical factory was in the range of 1.7-2.6. Below a pH of 5.0, fish mortality can be expected.

The life cycle of certain fish parasites is also affected by the pH value. For example, if *Odinium acidophilum* is prevalent in a fish pond, the water in the pond is likely to be acidic. Applying copper sulfate increases the acidity, encouraging the parasite (Tang 1990). Examples include *Costria necatrix* and *Chilodonella,* both of which require an acid environment for reproduction. If copper sulfate is sprayed, disease increases.

Ammonia production. Urea group herbicides (methylurea, dimethylurea, phenylurea) produce ammonia after hydrolysis (Guenzi 1974). Un-ionized ammonia is poisonous to fish. The un-ionized fraction increases with higher pH and rising temperature. Low levels of oxygen also increase its toxicity. Vamos (1963) found that the concentration of un-ionized ammonia required to kill common carp was 0.5 mg liter^{-1} within only a few hours. In other experiments, 1.0 mg ammonia liter^{-1} decreased the ability of hemoglobin to combine with oxygen. In this environment, fish can die due to lack of oxygen (Li et al 1985). National fishery water quality criteria recommend an un-ionized ammonia level of less than or equal to 0.04 mg liter^{-1}.

Sediment contamination. Smith and Isom (1967) treated *Myrionphyllum spicatum* with 112 kg 2,4-D ha^{-1}. The concentration of 2,4-D in the water decreased to below 1 ppb after 8 h, the concentration of 2,4-D in the sediment reached 950-5,600 ppb 4 d later. This indicates that fish in the bottom layers of a pond could be exposed to higher concentrations of chemicals and for a longer time than fish in the surface layers. Zhuang (1982) reported that bottom layer snakehead *Ophiocephalus argus,* soft-shelled turtle *Triony sinensis,* and shrimp *Macrobrachium* spp. died first when Lake Yanjiahu, Hecheng County, Hubei Province, was contaminated by wastes from an agricultural chemical factory. Aquatic organisms in the bottom layers had almost disappeared by 1976.

Taste and odor. For most chemicals, a concentration of 10 mg liter^{-1} produces only a slight taint (Albersmeyer and Erichsen 1959). Xylenols and some other constituents of phenolic wastes, including naphthols and quinols, however, affected bream and common carp at concentrations between 0.5 and 5.0 mg liter^{-1} (Baudt 1955). *p*-chlorophenol and *o*-chlorophenol produced an undesirable response in common carp at concentrations of 10.06 and 0.015 mg liter^{-1}, respectively. The taste and odor of phenolic wastes (2, 4-dichlorophenol in the manufacture of 2,4-D and 2,4,5-T) can persist for several years. Phenolic wastes at concentrations of 200-060 µg liter^{-1} can produce the typical chlorophenol taste and odor in bodies of water (Faust and Aly 1964). If the water is contaminated by phenols, it cannot be used for aquaculture for a long time.

Effect on the food chain

Herbicides can also have an indirect effect on the food chain. Fish depend on the natural foods present in natural bodies of water. That food supply can be affected by feed and manure applied to ponds. Filter-feeding fish primarily eat phytoplankton: herbivorous fish feed mainly on aquatic plants; omnivorous fish mainly eat benthos. In their juvenile stages, all fry and fingerlings feed on zooplankton. When herbicides are sprayed, these chemicals can have direct or indirect effects on the links in the food chain, which in turn may indirectly affect fish. When algicides are sprayed, all phytoplankton will be killed, affecting growth of filter-feeding fish.

Chlorazine and atrazine sprayed to kill pond weed *Potamogeton, Naiad najas,* and coontail *Ceratophyllum* caused a temporary decrease in phytoplankton. As the aquatic plants decayed, however, phytoplankton once again formed the water blooms which can cause fish mortality (Walker 1964).

When herbicides are used to kill aquatic plants, aquatic animals that feed on those plants can be affected. After diquat at 102 ppm was sprayed on a pond to control water weed *Elodea,* the biomass of mollusks (snails and gastropods) that fed on *Elodea* sharply decreased (Hilsenhoff 1986). When monuron was sprayed to eradicate aquatic weeds, nymphs of dragonfly and damselfly, larvae of stonefly, and nymphs of Ephemeropteran disappeared because their food source was eradicated (Walker 1965). In contrast. when fenoprop was sprayed on fish ponds, densities of oligochaete worms and chronomus increased up to 10-fold (Harp and Campbell 1964).

Control of water weeds has changed the composition of the aquatic flora population. Within 1 mo after dichlobenil was sprayed, *Chara* recovered and entered a flourishing growth stage. filling the niche of the pond weeds that were eradicated (Walsh et al 1971). Eradication of *Elodea* by the application of diquat promoted an increase in *Nitella* (Guenzi 1974). Herbivorous fish that have a selective feeding habit, preferring some aquatic weeds but not others, could be affected.

The heavy metals in chemical compounds can accumulate in fish that feed on aquatic plants. Alligator weed *Alternanthera phylloxeroides* can accumulate copper ion to a concentration 30,000 times greater than the concentration in the water in which it grows. Watermeal *Wolffia* can accumulate lead and cadmium ions to concentrations 2,000 times and 4,8000 times greater, respectively, than that in the water (Cao 1990).

Interrelationships of herbicide and other chemicals

Arsenic compounds continue to be used as insecticides and herbicides (for weeds, as sodium arsenate). When used to kill aquatic weeds in lakes and reservoirs, they make the water unsuitable for drinking or even swimming (Carson 1962). When arsenic compounds such as the germicide Asomate are used, copper sulfate must not be applied because the interaction releases arsenic. Arsenic is extremely toxic to fish (Tang 1990).

INTEGRATED WEED MANAGEMENT STRATEGIES FOR CROP - FISH SYSTEMS

The goal of integrated weed management is to achieve a dynamic equilibrium in the ecosystem. When pests are within acceptable limits, applying chemicals is unnecessary. Integrated weed control strategies should be preferred.

Biological control

Weed control in rice-fish fields. Fish can control weeds in ricefields. Surveys in Jiangsu Province in 1985-87 identified four types of weeds in ricefields. Arrowhead *Sagittaria pygmaea* dominated. Weeds averaged 58 m^{-2}. Twenty days after stocking fish, the number of weeds dropped sharply, to an average 15 m^{-2}, and weed reduction reached 75%. Wet weight of weeds in control fields without fish was 0.23 kg m^{-2}, 5.5 times higher than in rice-fish fields. Weed species diversified as well.

At the panicle initiation stage of rice, the number of weeds in rice-fish fields averaged 1 m^{-2}, while weeds in rice-only fields averaged 28 m^{-2}.

In consecutive experiments at the same fields, the average number of weeds in control fields increased from 45 m^{-2} in 1985 to 56 m^{-2} in 1987, while the number of weeds in rice-fish fields decreased from 58 m^{-2} in 1985 to 20 m^{-2} in 1987 (Table 4) (Li et al 1990). This indicates that rice-fish culture not only can eradicate wild weeds within the same year but also can control weeds across years.

Weed control in rice-azolla systems. Watervelvet azolla forms a flat mat to cover the surface of shallow water, and that inhibits weed growth. Azolla inoculated after rice transplanting reduced the wet weight of pond weed *Potumogeton natans* by 80%; the wet weight of *Scirpus pygmaea* by 96%; and the wet weight of *Eleochuris acicularis* by 90% (Table 5).

Natural enemies. Natural enemies can be used to control weed infestations. Alligator weed *A. phylloxeroides* was introduced into China early in the 1960s. With deep roots, strong adaptation, and asexual reproduction, it quickly became a major weed pest. With the release in 1964 of the insect *Agasicles* sp. from Argentina, that feeds

Table 4. Eradication of weeds by fish in rice-fish multiple cropping.

	Before stocking [a]		20 d after stocking				Panicle formation stage		
	Density (plants m^{-2})	Type	Density (plants m^{-2})	Type	Weight (kg m^{-2})	Reduction (%)	Density (plants m^{-2})	Weight (kg m^{-2})	Reduction (%)
Rice	45.40	4	32.2	10	0.227		27.6	0.367	
Rice-fish	57.67	4	14.6	3	0.041	74.7	1.0	0.022	98.3

[a] Common carp, grass carp, and tilapia were stocked. Source: Adapted according to Li Xueping et al (1990).

Table 5. Reduction of aquatic weeds in ricefields inoculated with azolla.

Weed type	Without azolla (wet wt g m^2)	With azolla (wet wt g m^2)	Reduction rate (%)
Scirpus vagara	590	21	96
Juncus L.	10	2	80
Sagittana pygmaea	40	15	62
Monochoria korsakowii	20	10	50
Potamogeton natans	100	20	80
Eleocharis acicularis	50	5	90
Total	810	73	90

Azolla was Inoculated at 200 g m^{-2} on 20 Jun.

specifically on alligator weed, the perennial alligator weed eventually was brought under control without damage to other crops.

In Jiangsu Province, *Lixus acutipennis,* a natural enemy of yellow-flower wormwood Artemisia, was released. It controlled more than 80% of that weed. *Gastrophsa atrocyanea,* a natural enemy of the weed family Polygonum, and *Lemascute uaris.* a natural enemy of Chinese dodder *Cuscuta chinensis,* also were released (Lin 1984). Dodder also was controlled by *Colletotrichum gleosporoides* (Gao and Can 1992). *Eupatorium adenophorum* in southwestern China can be controlled at a 50-60% level through the synergism of three natural enemies, *Procecidochares utilis, Dihammus argentatus,* and *Cercospovu eupatorii* (Liu et al 1985).

Effects of allelopathy

The concept of allelopathy was proposed by H. Molish in 1937. He realized that the allelopathy responses between different plants involved biochemistry and included microorganisms. The concept originally included both beneficial and harmful aspects. Today, the term usually means the toxic effect of one kind of plant on the germination, growth, and development of other plants (Song 1990).

Water hyacinth *Eichhornia crassipes* was introducted to control blue-green algae in the water source protection zone of Lake Taihu. Water hyacinth has several benefits, one of which is its allelopathic effects on other plants (Zhao et al 1993). Water hyacinth secretes an exudate from its roots that can inhibit the growth of algae (Yu et al 1992).

Coronella varia planted on highway verges and along ditches can inhibit the growth of other weeds for up to 10 yr (Lin 1984).

Rotation farming and intercropping

Alopecurus aequalis and *Capsella bursa pastoris* are the primary weeds in winter wheat fields. If a spring crop follows wheat, they will be eradicated before the next wheat crop is sowed. Chinese dodder is a weed destructive to soybean. If soybean, wheat, and maize are cultivated in rotation, Chinese dodder can be eradicated. The rotation of one wet season, one dry season crop has had excellent weed control effects in the Changjiang River drainage. Weeds were reduced by 50-75% in a rice - cotton rotation compared with continuous cotton, and by 65% compared with continuous rice (Zhou 1984).

In 1985, Shouyang County extended the intercropping approach by planting garlic, sweet potato, cotton, melon, and radish in close sequence. The back-to-back production, intended to utilize space, also reduced weed infestations.

Other measures

Quarantine and selection of seeds are important aspects of weed control. Construction of cement revetments on the banks of fish ponds and irrigation ditches can reduce weed infestations. Colored plastic sheet mulching is being tried to control weeds in tomato and maize fields.

CONCLUSION

Herbicide use impacts aquaculture by directly harming fish, by indirectly reducing the quality of the aquatic environment, and by changing linkages in the fish food chain. Integrated weed control strategies that can alleviate these impacts include, among others, biological control, exploiting allelopathic interactions among plants, and rotation cropping.

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ECOLOGICAL FORCES INFLUENCING CROP-WEED COMPETITION

S.E. Weaver

In a crop-weed ecosystem, mixtures of plant species compete for light, water, and nutrients. Associations among the species change as crop management practices and environmental conditions change. In most farm fields, the plant community includes the crop, 4-6 major weed species, and 1-20 minor weed species (Aldrich 1984, Moody 1991). Farmers select their crop management practices in relation to environmental constraints and to the number and types of weeds present. A dramatic change in practices, such as a switch from manual to chemical weed control, or from conventional tillage to no tillage, or from transplanted to direct-seeded rice, can lead to shifts in weed species. Intense, repeated selection pressure leads to adaptation. Examples include the morphological mimicry of *Echinochloa oryzoides* in response to hand weeding, and the evolution of herbicide-resistant weed biotypes (Moody 1991, Warwick 1991).

Competition is a complex phenomenon. Many factors determine the outcome of the process, even in a simple situation where two species compete only for light. Competitive intensity will vary with the number and type of weed species present, and with the extent to which their demands for resources conflict with those of the crop.

Traditionally, weed scientists have focused on the relationship between weed density and crop yield as a way to estimate the magnitude of yield losses. Although the relationship between weed biomass (usually expressed as dry weight per unit area) and yield usually is closer than that between weed density (number of plants per unit area) and yield, density is measured more quickly and easily than biomass for evaluation in practical weed management programs. Both weed biomass and weed density are an indirect reflection of the resources—the amounts of light, water, and nutrients—not available to the crop because of weed competition.

Parameters of regression models that describe the relationship between crop yield and weed density vary with crop and weed species, the relative time of emergence of the crop and the weed, crop density, fertility, and other environmental conditions (Kropff et al 1992). Clearly, the degree to which weeds can reduce crop yield varies with the level of resources and with the ability of the species to compete for those resources. The competition is a dynamic process which changes with resource supply and demand across the growing season.

RESOURCE LEVELS

Light is the factor for which plants compete most often. Competition for light is different from competition for water or nutrients. Light cannot be stored, it is direct and instantaneous. A plant's efficiency of resource capture, its ability to compete, is related to its interception and use of light.

Light-capturing capacity within the plant canopy varies at each point in time, as well as over the course of the season. In a mixed canopy, light interception by an individual plant is determined by its relative height, the amount and distribution of its leaf area, and the light absorption characteristics of its individual leaves (such as leaf angle orientation and leaf thickness).

Plants respond both to the amount of light and to the quality and duration of light. Although competition for light quanta (the amount of incident radiation) is instantaneous, the spectral quality and duration of light at a given point in time can affect a plant's subsequent response. In many species, shaded leaves adapt to low light levels and to altered red to far-red light ratios. Those effects may persist even after competitors have been removed. Recent evidence suggests that a plant can detect the presence of neighboring plants by the reflection of far-red or blue light from adjacent leaves even before shading has occurred. The competitive response is stem elongation to avoid shading (Ballare et al 1990). Duration of light, or photoperiod, controls the rate of development of many species, and may indirectly affect competition for light by triggering changes in the allocation of biomass to leaf and stem tissue.

Competition for water and nutrients has both direct and indirect components, because these resources can be stored. Direct competition occurs when water or nutrients are limiting. Indirect competition occurs when weeds remove water or nutrients early in the season which will be needed by the crop later in the season, possibly after the weeds have been removed. The availability of water and nutrients to a plant depends on their initial levels, their mobility within the soil matrix, the amount and frequency of inputs (e.g., irrigation or fertilization), and the rates of mineralization and depletion through uptake, evaporation, or leaching.

Plants frequently compete for water and nitrogen (usually in the form of the nitrate ion) which are highly mobile in the soil and often in limited supply. Competition for phosphorus or potassium is less common among annual crops and weeds, except late in the season when roots overlap extensively, because these nutrients are relatively immobile in the soil. Competitive ability for water or nutrients is often correlated with the relative volume of soil occupied by the roots of each species, but may also vary with the resource use efficiency of the species (Tilman 1988). Many grass and broadleaf weed species have higher rates of nutrient uptake and greater water use efficiency than crop species (Aldrich 1984, Ampong-Nyarko and De Datta 1993).

In empirical studies, it is difficult to identify the relative importance of competition for light, nutrients, and water because they are interrelated resources. Decreased availability of one resource reduces plant growth, lowering demand for other resources. Because the nitrate ion is highly soluble in water, the availability of nitrogen to a plant is severely limited under drought conditions. As a result, even though nitrogen is the most important nutrient for rice growth, shaded or water-stressed rice plants show little response to added nitrogen (Ampong-Nyarko and De Datta 1993).

Simulation models of crop-weed competition which are based on physiological processes provide a tool for exploring the mechanisms of competition and for separating the effects of different factors, insofar as these processes are understood. Graf et al (1990) showed that for irrigated but unfertilized transplanted rice and a mixed natural weed community, 65% of the simulated reduction in crop biomass could be attributed to competition for light and 35% to competition for nitrogen, with nitrogen deficiency occurring relatively late in the season. He cautioned that different soil types and initial conditions of nitrogen availability would produce different results. Kropff et al (1993) suggested that when direct-seeded rice was irrigated and fertilized according to standard practice, competition for nitrogen from barnyardgrass was relatively unimportant. They based these conclusions on observations of similar concentrations of nitrogen in the leaves of weed-free and weed-infested rice in the field, and on the ability of their model to simulate crop yield losses assuming only competition for light.

Kropff et al (1993) also used sensitivity analysis to examine the relative importance of Competition for light and water between sugar beets and lamb's-quarter. Varying only the height of the weeds, they showed that when the weed was considerably taller than the crop, water shortage had little effect on yield loss. But when the weed was shorter than the crop, water shortage strongly increased the competitive effect of the weeds. Similar conclusions were drawn from a field study of competition between cotton and velvetleaf (Salisbury and Chandler 1993). It is interesting to note that simulation models of competition between a wide range of crop and weed species have adequately described yield losses in terms of availability of light, water, and nutrients, without postulating allelopathic effects.

ABILITY TO COMPETE FOR RESOURCES

Many attempts have been made to identify key mechanisms in the process of competition, and the plant traits or attributes which are most important for competitive ability. Kropff et al (1993) suggested that, for rice, the most important determinants of yield loss due to competition from a given weed species are crop and weed densities and their relative times of emergence. Similar conclusions have been drawn for a variety of crop and weed interactions (Cousens et al 1987, Kropff et al 1992, Weaver et al 1992).

In crops which may be either direct-seeded or transplanted, such as rice, the relative time of emergence of the weeds in relation to the crop is largely determined by the method of crop establishment. In direct-seeded rice, weeds usually emerge at the same time as the crop and cause greater yield losses than weeds in transplanted rice which emerge later than the crop. An exception is weeds which are transplanted with the rice seedlings. These can cause yield losses equal to those in direct-seeded rice.

In general, plants which emerge earlier or develop a canopy more quickly have a competitive advantage that increases over time in proportion to their rate of growth. Time of emergence is related to the preemption of resources, particularly of light. Increased seeding rates of a crop also can suppress weed growth and seed production (Pantone and Baker 1991), but that is most effective in combination with delayed weed emergence.

Many studies of annual weeds and crops have identified early emergence, rapid leaf area development, and rapid height growth as the plant traits most highly correlated with competitive ability (Spitters and Aerts 1983, Seibert and Pearce 1993). Other studies have suggested that competitive ability is related to such physiological traits as photosynthetic rate or water or nutrient use efficiency, especially in communities of perennial species (Tilman 1988).

Unless genetic isolines are used, it is difficult to differentiate cause and effect in such empirical studies because the entire genetic background differs among species being compared. Using model sensitivity analysis in which only one parameter was changed at a time, Kropff et al (1993) concluded that morphological characteristics which lead to early ground cover and height development are more important for competitive ability than physiological traits, such as those related to photosynthesis. In a modeling study of wild oat competition in winter wheat, Weaver et al (1994) showed that wheat growth was extremely sensitive not only to the maximum canopy height of wild oat, but also to the relative timing of canopy height growth. A delay of only 30 degree days in stem extension by winter wheat resulted in a 65% reduction in yield in a wheat-wild oat mixture, but not in wheat alone.

Attributes that determine resource capture are more important in mixtures of species than in monocultures because they regulate the distribution of the limiting resources among the competing species. Crop breeding programs usually are carried out under weed-free conditions, but different crops and even different varieties are known to vary in their competitiveness with weeds. Incorporating traits which increase competitive ability into crop varieties is not simple, because the competitive ability traits may be associated with undesirable agronomic traits, such as a tendency to lodge or a lower harvest index.

In rice, competitive ability may be negatively correlated with yield potential (Jennings and Aquino 1967, Moody 1991). Kropff et al (1993) have suggested that panicle position within the rice canopy varies among cultivars. The trait of panicle position could be modified by breeders to improve productivity and competitive ability. Panicles positioned above the canopy reduce overall photosynthesis because, while the panicle intercepts light, its efficiency of light use is lower than that of leaves.

Another strategy might be to manipulate weed traits to reduce their competitive ability. For example, weeds which escape soil-applied herbicides often are less competitive than untreated weeds. Application of sublethal rates of postemergence herbicides can alter weed morphology and reduce seed production (Adcock and Banks 1991). Plant growth regulators have the ability to decrease stem elongation, and therefore the height of some weed species (Netherland and Lembi 1992). Delaying the emergence of weeds which have a photoperiodic flowering response may reduce their competitive ability by triggering an earlier switch from vegetative growth to the reproductive phase (Oliver 1979).

IMPLICATIONS FOR WEED MANAGEMENT

Taking the key mechanisms involved in competition and the traits which confer competitive ability into consideration may help in designing more effective weed management programs. Altering one factor, however, probably will not be enough. A systems approach is needed, in which many factors are combined to shift the competitive balance in favor of the crop.

Exploration is just beginning into the ways in which crop density, date of planting, cultivar selection, manipulation of inputs such as fertilizers, and reduced rates of herbicides can be combined to manage weed populations. Perhaps the focus should be on managing the crucial resources of light, nutrients, and water, rather than on managing weeds. Ultimately, adoption of integrated weed management systems will depend on the net benefit to the farmer.

It is important to remember that the range of genetic variation and phenotypic plasticity within and among weed species suggests that weed response to any management practice will vary. Adhering to a management system uncritically and pursuing it without change will result in weed evolution and adaptation, as has been strikingly demonstrated by the proliferation of herbicide-resistant weed populations.

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ECOLOGICAL FORCES INFLUENCING WEED COMPETITION AND HERBICIDE RESISTANCE

K.U. Kim

Weed communities, like other plant communities on arable land, are affected by the environment, by climatic and physiographic factors, and by human activity. The frequent disturbances of plant habitat by agricultural activities make it difficult to identify the distinct wild plant communities that exist in less disturbed, more stable habitats (Streibig et al 1993). Many species, however, are able to flourish under a wide range of conditions; the adaptability of these weeds is an important factor in their successful competition with crop species.

Herbicides are an essential component of commercial rice production. In temperate East Asia and tropical Southeast Asia, increased use of herbicides and a trend toward a major change in rice cultivation, from transplanting to direct seeding, have changed the weed communities in ricefields. Continual use of herbicides moves an agroecosystem toward low species diversity; at the same time, new problem weeds appear (Moody 1992). An ecological approach to weed control is needed.

The most important weeds in rice in East Asia (China, Japan, Korea) are listed in Table 1. Although species dominance in the weed flora has been changed by planting methods and herbicide use, it seems evident that the weeds listed will be problems for years to come (Kim 1993b).

ECOLOGICAL FORCES AND WEED FLORA

Until the advent of herbicides, mechanical practices (tillage, mowing, burning, flooding, hand weeding) and cultural practices (crop selection, rotation, variety selection, planting date and methods, plant population and spacing, inorganic fertilizers, irrigation) were the only weed control methods available to farmers. Changes in cultural practices (shifting planting dates, different planting methods, new crop selections, crop rotation, rice monoculture, improved water management) and the availability of herbicides have influenced rice-weed competition. Differences in the emergence abilities of weeds also influence rice-weed competition.

Table 1. Important rice weeds in temperate East Asia.

Class	Species	Family
Grass, annual	*Echinochloa oryzicola*	Poaceae
	Echinochloa crus-galli	Poaceae
	Leptochloa chinenss	Poaceae
Grass, perennial	*Leersia japonica*	Poaceae
	Paspalum distichum	Poaceae
Sedge, annual	*Cyperus difformis*	Cyperaceae
	Cyperus iria	Cyperaceae
Sedge, perennial	*Cyperus serotinus*	Cyperaceae
	Eleocharis acicularis	Cyperaceae
	Eleocharis kuroguwai	Cyperaceae
	Scirpus juncoides	Cyperaceae
	Scirpus planiculmis	Cyperaceae
Broadleaf, annual	*Monochoria vaginalis*	Pontederiaceae
	Rotala indica	Lythraceae
	Ammannia spp.	Lythraceae
	Eclipta prostrata	Compositae
	Lindernia procumbens	Scrophulariaceae
Broadleaf, perennial	*Alisma canaliculatum*	Alismataceae
	Potamogeton distinctus	Potamogetonaceae
	Sagittaria pygmaea	Alismataceae
	Sagittaria trifolia	Alismataceae
	Oenanthe javanica	Umbellifera

Source: Kim (1993b).

Emergence times of ricefield weeds

The cumulative temperature needed for emergence differs by weed species (Table 2). *Echinochloa crus-galli* needs a cumulative temperature of 119 °C to emerge in 7.8 d. Perennial weeds like *Eleocharis kuroguwai* need a cumulative temperature of 417 °C to emerge in 26 d.

These differences in cumulative temperature needed for emergence may be related to the adaptation of weed survival strategies to changes in rice production systems. Annual weeds show an emergence flush within a relatively short time; perennials show a more evenly distributed emergence pattern (Fig. 1). These differences may explain some of the difficulty in controlling weeds in rice using only one method or with a single application of herbicide (Shibayama 1990).

Changes in cultural practices

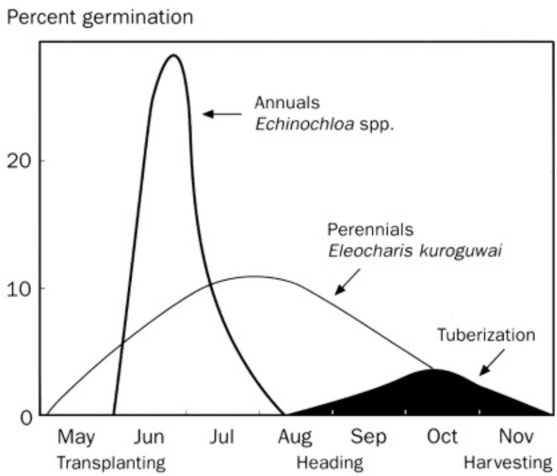
Planting methods. Until recently, the rice cultivation target was maximum yield; today, the target is economic yield that minimizes inputs. The emphasis is on optimum tillage, heavy fertilization, effective water management. and weed control. All these cultural practices significantly affect weed occurrence and growth.

In Korea, it costs US$0.864 to produce 1 kg of milled rice and US$1.329 to produce 1 kg of soybean; in the United States, it costs only US$0.238 to produce 1 kg

Table 2. Cumulative temperature required for germination of rice weeds.

Species	Cumulative temperature (°C)	Days needed for germination			Range of occurrence[a] (d)
		First	Maximum	Last	
Echinochloa crus-galli	119	7.8	16.7	32.7	24.9
Monochloria vaginalis	263	16.9	29.0	39.9	23.0
Cyperus serotinus	103	7.5	20.0	37.0	29.5
Eleocharis acicularis	149	0.5	22.7	34.3	24.8
Scirpus juncoides	181	12.1	23.9	34.7	22.6
Sagittaria pygmaea	262	17.3	26.0	37.0	19.7
Sagittaria trifolia	297	18.7	22.7	27.3	8.6
Neocharis kuroguwai	417	26.0	34.3	51.5	26.5

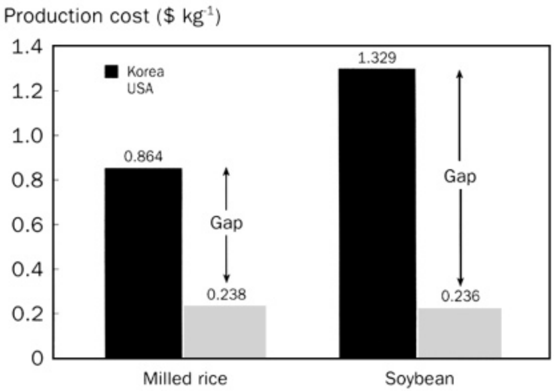
[a]Days = first to last. Source: Obuchi (1991).



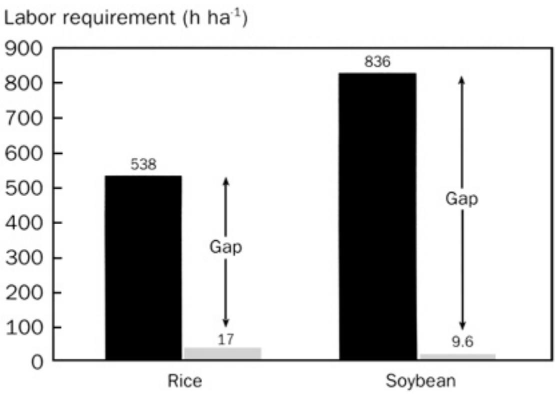
1. Difference in time of emergence of annuals, such as *Echinochloa* spp., and perennials, such as *Eleocharis kuroguwai* (Shibayama 1990).

of rice and US$0.236 to produce 1 kg of soybean. The labor requirement in Korea is about 536 h ha^{-1} for rice and 836 h ha^{-1} for soybean, but only 17 h ha^{-1} for rice and 9.6 h ha^{-1} for soybean in the United States (Kim and Shin 1993). These gaps in production costs and labor requirements pressure the development of more resource-efficient technology in Korea, reinforcing changes in cultural practices (Figs. 2 and 3).

Until 1977, hand transplanting was the most common rice planting method. Labor shortages and increasing farm wages encouraged the adoption of machine transplanting, which by 1993 was being used on 95% of the rice hectarage (Table 3). Management of rice nursery beds for either hand or machine transplanting, however,



2. Costs of production of rice and soybean in Korea and in the United States.



3. Labor requirements for rice and soybean production in Korea and in the United States.

is labor-intensive. Current practices use 45-d-old seedlings at the 5-6 leaf stage or 35-d-old seedlings at the 3-4 leaf stage for machine transplanting. Infant seedling culture (8- to 10-d-old seedlings at the 1.5-2.0 leaf stage) is being recommended to economize on the labor required to rear rice seedlings. Using infant seedlings can reduce the cost of nursery bed management by 54%. In 1993, nearly half the machine-transplanted areas used infant seedlings, and infant seedlings are expected to replace 35-d-old seedlings in the near future.

Direct seeding is the most promising alternative to transplanting. In recent years, growth in irrigated area, availability of short-duration modern rices and cost-efficient herbicides, and high labor costs have motivated Southeast Asia farmers to shift from transplanting to wet-seeded rice (De Datta 1989). Although direct seeding in Korea

Table 3. Rice planting methods in Korea, 1977-93.

	1977	1982	1984	1986	1988	1992	1993
Paddy rice (ha)	1,208,335	1,175,964	1,226,475	1,232,679	1,257,158	1,193,354	1,168,648
Planted with (ha)	218	133,716	229.933	365,000	679,395	1,105,046	1,111,127
machinery (%)	0.2	11.4	21.9	29.6	54.0	92.6	95.1
Planted with (ha)	–	–		–	–	395,000	572,756
infant seedling (%)	–	–		–	–	33.1	49.0
Direct seeded (ha)	–	–		–	–	4,000	7,589

Source: Kwon et al (1993).

covered only about 7,500 ha in 1993 (Table 3), about 70,000 ha of ricefields were expected to be direct seeded in 1994. Considering the cost savings, a further dramatic increase in direct-seeded hectarage is inevitable.

Changes in planting method may be one of the most important ecological forces influencing changes in weed dominance and competition in ricefields. In particular, the switch from transplanting to direct seeding has caused a shift in the dominant weed species, to grass weeds which require new control measures (De Datta 1989, Moody 1992, Kim 1993a). Table 4 shows the effect of planting method on weed occurrence. Weed occurrence in dry-seeded rice was 3 times, and in infant seedling machine-transplanted rice 2.3 times, greater than in older seedling hand-transplanted rice. *Echinochloa crus-galli* and *Cyperus difformis* became the dominant species in dry-seeded rice; *E. crus-galli* and *Scirpus juncoides* in wet-seeded rice. The young, weak rice seedlings with shallow water management and earlier transplanting used in infant seedling transplanted rice encouraged weed growth more than using older seedlings in both machine- and hand-transplanted rice, although perennial weeds such as *E. kuroguwai* dominate in all three cultures.

Crop variety. In most rice improvement programs, new varieties are developed under minimal weed, insect, and disease pressure. Little information on the competitive ability of new cultivars against weeds is available. However, more vigorous, faster growing, taller crop varieties are likely to be better competitors.

Introduction of higher yielding, tongil-type cultivars (indica × japonica types) which were faster growing and more fertilizer-responsive than traditional cultivars helped Korea attain self-sufficiency in rice production in 1977. But those characteristics favored weed infestation. Now the tongil types are being phased out and conventional japonica cultivars have been reintroduced (in part, because Koreans prefer the eating quality of japonica rice).

Table 4. Effect of planting method on weed biomass.

Species	Direct seeding		Machine transplanting		Hand transplanting
	Dry	Wet	Infant	Conventional	
Echinochloa crus-galli	254	200	49	32	29
Scirpus juncoides	44	206	217	81	144
Monochoria vaginalis	–	6	22	6	6
Cyperus difformis	240	144	6	6	0
Eleocharis kuroguwai	89	94	290	140	72
Others	463	201	41	30	18
Total	1090	851	625	295	269
Simpson's diversity index	0.865	0.793	0.657	0.687	0.631

Crop rotation. Rotation of different crops on the same land has been an important method of weed control. The chances of any one weed species becoming dominant are minimized by the variation in cultural practices and competitive abilities of crops; some weed species are encouraged, others discouraged. The result has been a highly diverse weed flora. With a rice monoculture, the proportions of life forms of weed flora and the distribution of weeds within similar life forms change. Planting soybean in rice - upland crop rotations has significantly reduced weed growth, and the rotation itself has helped control weeds. Perennial weeds are discouraged in direct-seeded rice after soybean (Kim and Shin 1993). Annual crop rotation or double cropping rice and winter cereals also are considered promising supplementary means of controlling weeds in rice.

Water management. Irrigation water is a major way weed seeds and vegetative propagules of weeds are spread. Flowing water carries millions of seeds from one place to another. The amount and type of seeds moved depend on their size and weight. It is advisable to clean irrigation canals to remove sources of weed seed production. Controlling weeds before flowering is particularly important. Keeping ricefields flooded at transplanting controls some weeds and slows the growth of others. *Monochoria vaginalis* can grow well in flooded conditions, but *E. crus-galli* and *C. difformis* prosper only at shallow or zero water depth. The dominance of *E. crus-galli* and *C. difformis* in direct-seeded rice may be partly related to shallow water management.

Herbicide use

Today, herbicides are the main method of weed control in Korean ricefields, and there seems to be no suitable alternative. Herbicides are used on 140% of the rice hectarage (some farmers treat a rice crop more than once, probably to control *E. kuroguwai,* the most difficult ricefield weed in Korea). Until the mid-1960s, only a negligible amount of herbicide was used, mainly 2,4-D, with PCP coming into use in the late 1960s. Nitrofen became popular in the early 1970s. Acid amide-type herbicides such as butachlor and alachlor shared more than 60% of the herbicide market for more than 15 yr, until 1989 (Kim 1990). The markedly reduced occurrence of *E. crus-galli* and *Rotala indica* in the late 1970s may be related to the intensive use of acid amide and carbamate types, which until the middle 1980s had a more than 80% market share. However *M. vaginalis,* which has been dominant since the late 1970s, is poorly controlled by these herbicides.

Use of butachlor has declined significantly, from 82.8% of all ricefield hectarage in 1981 and 80% in 1986 to 35.6% of the hectarage in 1991 (Kwon et al 1993). Reduced use of this herbicide has increased dominance of *E. crus-galli* and *M. vaginalis.*

An important development has been a dramatic increase in the use of herbicide mixtures, from 3.5% coverage in 1981 to 79% in 1991 (Table 5). This reflects farmer

Table 5. Herbicide-treated area in Korea, 1981-91.

1981		1986		1991	
Herbicide	% applied area	Herbicide	% applied area	Herbicide	% applied area
Single					
Butachlor	82.8	Butachlor	80.0	Butachlor	35.6
Thiobencarb	10.9	Thiobencarb	4.5	Thiobencarb	2.0
Pretilachlor	2.5	Pretilachlor	5.2	Pretilachlor	6.9
Oxadiazon E.C.	1.9	Oxadiazon E.C.	4.9	Oxadiazon E.C.	4.9
Nitrofen	5.2	Chlomethoxyfen	2.0	Others	0.4
Others	0.5	Bifenox	1.2		
		CNP	1.1		
		Others	2.8		
Subtotal	103.8		101.7		50.3
Mixtures					
Piperophos + dimethametryn	3.2	Butachlor + chlomethoxyfen	4.7	Butachlor + chlomethoxyfen	5.8
Molinate + simetryn	0.3	Butachlor + pyrazolate	8.1	Butachlor + pyrazolate	12.4
Others	–	Piperophos + dimethametryn	2.7	Butachlor + bensulfuron	23.2
		Molinate + simetryn	2.3	Quinclorac + bensulfuron	2.8
		Thiobencarb + naproanilide	1.3	Mefenacet + bensulfuron	5.5
		Pretilachlor + naproanilide	1.2	Pretilachlor + bensulfuron	4.7
		Others	3.3	Molinate + pyrazosulfuron	3.3
				Thiobencarb + pyrazosulfuron	3.2
				Butachlor + pyrazosulfuron	5.1
				Quinclorac + pyrazosulfuron	1.0
				Thiobencarb + bensulfuron	2.4
				Dithiopyr + bensulfuron	0.3
				Mefenacet + bensulfuron + dymron	2.6
				Others	4.1
Subtotal	3.5		23.6		76.4
Spray type					
Bentazon E.C.	0.7	Bentazon E.C.	0.4	Bentazon E.C.	7.8
Others	6.8	Others	4.3	Bentazon + quinclorac W.P.	2.6
				Others	4.8
Subtotal	7.5		4.6		15.2
Total	114.8		130.0		141.9
Total area planted with rice					
(ha)	1,212,258		1,232,679		1,206,613
(%)	(100)		(100)		(100)

Source: Kwon et al (1993).

demand for herbicide combinations capable of controlling annual as well as perennial weeds with one application. Most of these mixtures are based on sulfonyl urea types, such as bensulfuron and pyrazosulfuron. A single application of a herbicide mixture seems to be effective and economical, but relatively early application, within 10 d after transplanting, does not give satisfactory control of *E. kuroguwai* and *Sagittaria triforia,* which need a long period for emergence and often escape the residual effect of the herbicides. These species have become the most troublesome weeds in transplanted rice in Korea (Kim 1993a).

Changes in weed flora caused by cultural practices

About 92 weed species belonging to 27 families are found in Korean ricefields; 30 species are considered to be common weeds (Kim 1981). Changes in weed flora over the last 3 decades may be useful in predicting weed flora changes in other countries as their rice culture changes (Kim 1993a).

About 10 species, including both annuals and perennials, were the major weeds in transplanted rice for half a century. The relative importance of different species has been affected by recent changes in rice cultural practices and weed control measures used by farmers, in particular by the type and amount of herbicide applied. The heavy applications of herbicides in rice since 1980 have stabilized weed populations, with perennial weeds dominating.

In 1965, before herbicide use had become prevalent, 17 species were identified as common (Table 6). *Echinochloa crus-galli* was the most troublesome, followed by *M. vaginalis,* which was also a serious weed in rice seedbeds. Other species were minor weeds. In 1971, *Rotala indica* was recognized as the dominant species, followed by *Eleocharis acicularis, M. vaginalis, C. difformis, E. crus-gulli, Lindernia procurnbens, Potarnogeton distinctus, Aneilema japonica, E. kuroguwai, S. juncoides,* and *Persicaria hydropiper.* These species constituted 86% of all ricefield weeds; 81% are annuals. In 1981, the most important weed was again *M. vaginalis,* followed by *Sagittaria pygrnaea, S. trifolia, P distinctus, Cyperus serotinus, R. indica, A. japonica, L. procumbens, E. kuroguwai,* and *Ludwigia prostrata.* These species constituted 87% of all ricefield weeds; 54% are perennials. In 1990, *S. trifolia* had become the dominant weed species, followed by *S. pygmaea, E. crus-galli, P. distinctus, C. serotinus,* and M. vaginalis. About 60% of these species are perennials.

Similarity coefficients of change in the level of dominance of different weed species over time were 37-39 from 1971 to 1981, but 62 from 1981 to 1991 (Table 7). This confirms a major change in weed flora between 1971 and 1981, but indicates little change between 1981 and 1991, except that *E. kuroguwai* and *E. crus-galli* became the dominant species.

Eleocharis kuroguwai and *S. trifolia* are regarded as the most difficult weeds to control. They require a relatively higher cumulative temperature (417 °C for *E. kuroguwai* and 297 °C for *S. trifolia)* and can easily escape the effects of herbicide applied early, within 5-10 d after transplanting.

Table 6. Dominant weed species in Korean ricefields, 1965-90.

Weed	Dominance of weed [a]				Life cycle
	1965	1971	1981	1990	
Echinochloa crus-galli	+++++	++	+	+++	Annual
Monochoria vaginalis	+++++	+++	++++	+++	Annual
Rotala indica	++	+++++	++	++	Annual
Persicaria hydropiper	–	–	–	–	Annual
Ludwigia prostrata	–	+	+	+	Annual
Lindernia procumbens	–	+	–	–	Annual
Dopatrium junceum	–	–	–	–	Annual
Aneilema japonica	–	+	+	+	Annual
Cyperus difformis	–	++	–	+	Annual
Cyperus iria	–	–	–	–	Annual
Sagittaria pygmaea	–	–	+++	+++	Perennial
Sagittaria trifolia	–	+	++	+++	Perennial
Potamogeton distinctus	–	+	++	++	Perennial
Neocharis kuroguwai	–	+	+	+++	Perennial
Cyperus serotinus	–	+	++	++	Perennial
Neocharis acicularis	–	++++	–	–	Perennial
Scirpus juncoides	+	+	+	+	Perennial

[a] — = present, but of minor importance, + = below 5%, ++ = 5-10%, +++ = 11-20%, ++++ = 21-30%, +++++ = more than 30%.

Table 7. Similarity coefficient in terms of changes in dominant species over time (15).

Year	1971	1981	1991
1971	(0.208)[a]	39.3	36.5
1981		(0.111)	62.0
			(0.117)

[a] Parentheses indicate index of diversity. Source: Kim (1993a).

The currently dominant weed species can be expected to continue as major weeds in Korean ricefields, with varying degrees of dominance, for at least the next 10-20 yr, if current control methods continue to be used.

WEED RESISTANCE TO HERBICIDE

Herbicide resistance is the inherited ability of a weed io escape control by a herbicide (Gressel 1993). Resistance is relative; one important modifier is the rate of herbicide applied. Resistance to normal agricultural levels of herbicide application is assumed here. Resistance evolves in one of the following ways:

- Through the selection of a naturally occurring biotype. A rare resistant individual is successful in competing within the species, creating a resistant population.
- Through genetic mutation. Mutations always occur, whether or not a herbicide is used. Virtually all nonlethal mutants are at a disadvantage in a herbicide-free environment, and are found much less often than natural mutation frequency would suggest because of their inability to compete with more fit genotypes.

The frequency of mutation caused by sulfonylurea herbicides has been shown to be one in a million plants with a semidominant nuclear mutation in the target site, acetolactate synthase (ALS), that is resistant. Sulfonylurea resistance appeared within 3-5 yr of limited use. The frequency of resistance to some herbicides is unknown. Carbamates, chloroacetamides, and auxin types are thought to be multisite inhibitors, primarily because no specific sites have been found.

Evolution of weed resistance to herbicides

The repeated use of a herbicide can cause a shift in the weed spectrum present in a given field. Other species and biotypes within a species will fill in the vacancies left by the disappearance of susceptible weeds. Over time, these resistant weeds will spread and become the majority.

A shift to resistant weeds can evolve slowly or rapidly, depending on both cultural and ecological conditions. The key factors that favor the rapid development of a herbicide-resistant weed population are the following:

- Use of a highly effective herbicide which controls most of the susceptible biotypes (selection pressure), causing a rapid population shift in favor of the resistant biotypes. Effective kills may be the most important factor affecting the rate of enrichment of a population with herbicide resistance.
- The number of naturally occurring resistant biotypes within the native weed population, which increases under selection pressure.
- Monoculture cropping with repeated use of the same herbicide on the same crop. This creates an ideal environment for herbicide resistance to spread.

Two other factors are probably the major reasons why resistant species have not evolved in the temperate climate ricefields of Japan and Korea, even though herbicides have been used intensively since the 1970s. First, herbicides like butachlor or thiobencarb, which probably have no specific target site, were the ones used most intensively (on more than 80% of Korean ricefields until 1986). Second, the use of herbicide mixtures increased rapidly between 1981 and 1991.

Herbicide mixtures have been discussed as a means of preventing or delaying the evolution of resistance in weeds. It has been suggested that the use of combinations of herbicides with different modes of action will substantially delay or preclude the evolution of resistance to the more vulnerable or at-risk herbicide. This is because individuals resistant to the vulnerable herbicides will be destroyed by the partner herbicides in the mix. Most mixtures, whether they are heterologous mixtures or synergistic mixtures, have been formulated with a reduced use rate of each chemical, compared with a single product. However, lowering the use rate lowers the selective pressure for resistance to each herbicide, lowering the rate of evolution of resistance to each one (Gressel 1993).

Sulfonylurea-type herbicides recently were introduced in Asia. Intensive use of these types of herbicides may produce herbicide-resistant biotypes because they are inhibitors of the ALS-specific target site. In 1991, 54.6% of the herbicide-treated areas received a mixture of sulfonylurea types, either bensulfuron or pyrazosulfuron with butachlor, thiobencarb, and molinate. At present, it is not clear whether or not any resistant biotypes against this type of herbicide have evolved in Asia.

However, Du Pont Agricultural Products (1992) has confirmed the existence in California of two ALS inhibitor-resistant biotypes of *C. difformis* and *Sagittaria montervensis.* It has been suggested that a naturally occurring resistant biotype has become a resistant population because of the intense selection pressure created by the lack of crop rotation and by the use of the same mode-of-action herbicide (bensulfuron) on the same fields over a number of years.

Selection pressure is the relative ability of a herbicide to decimate the weed population and leave resistant individuals. Some herbicides exert greater selection pressure than others (Gressel 1993). Selection pressure is greatly influenced by herbicide persistence. The longer a herbicide remains active, the greater its selection pressure where weeds germinate throughout the cropping season. The rice herbicide bensulfuron has exerted extremely strong selection pressure because of its persistence at levels that can control many susceptible weed species up to a year after application.

Another example is propanil-resistant biotypes. Resistance to propanil has been found in jungle rice *Echinochloa colona* and barnyardgrass *E. crus-galli* (Fisher et al 1993), and in Greece (Giannopolitis andvissilou 1989), the United States (Smith and Baltazar 1992), and Japan (LeBaron and McFarland 1988). Herbicide-resistant biotypes have lower ecological fitness than susceptible biotypes. This differential fitness would allow a susceptible population to replace resistant biotypes in the absence of herbicide (Gressel and Segel 1978). Propanil-resistant jungle rice showed a trend toward lower reproductive fitness, which may reduce its ecological success when growing with propanil-susceptible plants in the absence of the herbicide (Fisher et al 1993). So far, propanil has been used in limited areas of transplanted rice in Korea, but it will be an important herbicide in direct-seeded rice because of the predominance of barnyardgrass. No propanil resistance has been reported in Korea, yet.

More reports are available on the development of weed resistance against rice herbicides, such as butachlor-resistant *E. crus-galli* in China (Huang and Lin 1993), 2,4-D-resistant *Sphenoclea zeylanica* in the Philippines (Sy and Mercado 1993), and 2,CD-resistant *Fimbristylis miliacea* in Malaysia (Ho 1992). Further studies of these types of herbicides, which are multisite inhibitors, should increase our understanding of the development of weed resistance.

Preventing or managing herbicide resistance

Effective ways to prevent the evolution of herbicide resistance include the following:

- Crop rotation, which usually means following a diversified herbicide program that makes it difficult for resistant biotypes to increase.
- Herbicide rotation in parallel to crop rotation, which provides different modes of action on the same spectrum of weeds.
- Use of herbicide mixtures (including tank mixes) that have different modes of action on the same spectrum of weeds.
- Alternating low and medium herbicide application rates, to delay evolution of weed resistance.
- Alternating planting method, from direct seeding to transplanting every other year.
- Using other cultural practices, such as tillage and water management, that complement herbicide applications.

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Integrated weed management

INTEGRATED WEED MANAGEMENT IN RICE IN ASIA

S.K. De Datta and A.M. Baltazar

In Asia, irrigated and rainfed rice may be transplanted, wet-seeded (pregerminated seed broadcast in puddled soil), or dry-seeded (sown in dry soil). All three cultures are grown in flooded soil for most of the crop's life cycle (De Datta 198 1). The type of crop culture will affect the nature of weed competition and, in turn, weed control.

Transplanted rice is currently the most common rice culture, established either by hand transplanting (South and Southeast Asia) or by machine transplanting (East Asia). When older seedlings (30- to 35-d-old seedlings have a head start over weeds), appropriate water management, and other indirect weed control methods are used, hand or rotary weeding and/or application of preemergence herbicides usually will provide adequate weed control in flooded ricefields.

Time and economic constraints, however, are accelerating trends toward using younger (8- to 10-d-old) rice seedlings for transplanting and toward the adoption of direct seeding. These crop establishment methods shorten the head start older rice seedlings enjoy. Rice and weeds germinate, emerge, and grow at the same time. As a result, grasses, with their similar morphophysiological traits and growth requirements to rice, become the dominant weed species in ricefields (Ho and Zuki 1988). The similarity of rice and grass weeds creates a double impact: stiffer competition during growth and problems with selectivity when grass herbicides are used. Among the grasses, barnyardgrass (*Echinochloa* spp.) is considered the most aggressive competitor with rice. It is found in practically all rice-growing areas of the world.

Broadleaf weeds and sedges also pose control problems during the course of a rice-growing season. Soil moisture conditions early in the season encourage growth of semiaquatic grasses. Longer submergence toward mid-season favors aquatic broadleaf weeds and sedges. A series of agronomic and ecological approaches involving direct and indirect control measures from seeding or transplanting to harvest is needed to control dominant weed species at different growth stages of the rice crop (i.e., grass control early, broadleaf or sedge control later).

Direct control methods involve cultural, chemical, and some biological inputs applied across the cropping season, from seeding to harvest, for the sole purpose of removing or controlling weeds. Indirect control methods include cultural and ecological practices followed to optimize rice production before, during, and after a cropping season; they may also suppress weeds or help rice compete better with weeds.

DIRECT METHODS OF WEED CONTROL

Cultural (hand weeding, hoeing, interrow cultivation)

Hand weeding and use of hand tools or hand-pushed interrow cultivators are the principal direct weed control methods used in most of Asia, either alone or to supplement chemical control. Depending on weed pressure, it takes from 200 to 500 h of labor in two to three operations to weed 1 ha of rice by hand (Chang 1967, De Datta 1974). Under optimum conditions, one properly timed hand weeding in transplanted rice, two weedings in wet-seeded rice, and three weedings in dry-seeded rice will provide adequate weed control in a crop. The critical periods, beyond which more weeding hours are needed and reduced grain yields occur, range from 21 to 42 d after planting for transplanted rice (De Datta 1979) and from 15 to 40 d after seeding for direct-seeded rice (Moody and De Datta 1982).

Lack of available labor during critical crop growth periods, increasing costs of labor compared with herbicide prices, and the tediousness and impracticality of using hand labor in broadcast-seeded rice are reasons why many farmers now only use hand weeding to supplement herbicides or other control methods. Unless labor is free (i.e., family labor on small farms) or cheaper than herbicides, hand weeding typically is used only to remove weeds not controlled by herbicides or interrow cultivation. Only 30-40 h of hand weeding are needed to remove weed escapes after herbicide application (Chiang 1981).

Interrow cultivation using hand-pushed or engine-powered rotary weeders is the preferred weed control method in most of Asia. It is twice as efficient as hand weeding, with only 50-60 h needed to weed 1 ha of rice (Parthasarati and Negi 1977). This method, however, is practical only in row-seeded rice, and does not remove the weeds within the rows or close to the hills that can still significantly reduce yields (De Datta 1981). Rotary weeders do not work well if the soil is too dry, if weeds are too tall, or if the floodwater is too deep (Moody 1991). In Japan, engine-powered rotary weeders are used to control perennial weeds that become dominant once the annuals are controlled with herbicides. Fields are tilled in the fall or winter, between cropping seasons, to expose underground propagules of perennials to freezing temperatures (Shibayama 1992).

Chemical (herbicides)

In general, the herbicides used to control weeds in rice are classified for preemergence or postemergence application. Preemergence treatments (from 2 d before to 8 d after crop establishment) mostly control the annual grass weeds which are dominant at the start of rice growth. Early postemergence treatments (8-20 d after crop establishment) control annual grasses and/or broadleaf weeds or sedges. Late postemergence treatments (20-30 d after crop establishment) mostly control annual broadleaf weeds or sedges which are dominant at later stages of rice growth. The preemergence herbicides are chloroacetamides, thiocarbamates, a few triazines, and dinitroanilines; the postemergence herbicides are phenoxys, diphenylethers, and sulfonylureas.

In the late 1980s, new herbicides were developed for use any time from preemergence to early postemergence (i.e., quinclorac) or from early postemergence to late postemergence (i.e., sulfonylureas), to control annual or perennial grasses, broadleaf weeds, and sedges. In 1991, 33 herbicides and 68 formulated mixtures, for a total of 700 herbicide products, were listed in the ARSAP/CIRAD Regional Agro-Pesticide Index (Table 1). The new chemicals and formulated mixtures have much lower application rates, wider application windows, and broader weed control spectra than the older compounds, and some are probably safer.

The kind of herbicide used, application rate, and time of application vary among countries, depending on the rice culture system; dominant weeds; agronomic practices; and environmental, climatic, social, and economic conditions. Application rates specified on product labels range from 0.8 to 3.0 kg ha^{-1} for herbicides developed from 1950 to 1980 and from 0.03 to 0.5 kg ha^{-1} for herbicides developed after 1980. The most effective time of application is from germination to no later than the one-leaf stage of weeds for preemergence treatments and from the one-leaf to no later than the four-leaf stage of weeds for postemergence treatments.

Because preemergence treatments do not last through the cropping season and because they mainly control grass species, most herbicide treatments are mixtures (tank-mixed or formulated) of a preemergence herbicide (e.g., butachlor for grasses) and a postemergence herbicide (e.g., 2,4-D for broadleaf weeds and sedges), or are sequential applications of a preemergence herbicide followed by a postemergence herbicide. Phenoxys, chloroacetamides, and thiocarbamates are widely used in Thailand; Malaysia; Taiwan, China; Indonesia; and the Philippines (Table 2), while the new compounds (sulfonylureas, etc.) and their mixtures are widely used in Korea and Japan (Tables 3 and 4).

An accelerating trend is to use two or three active ingredients combined in a tank mix or commercially formulated mixture. The mixtures, applied once during the cropping season to control the whole spectrum of annual and perennial grasses, broadleaf weeds, and sedges, are becoming popular where difficult-to-control perennials are increasing in dominance. In 1990, 68% of the ricefields in Korea received one-time treatments (Kim 1992); in 1991, 84% of the ricefields in Japan received one-time treatments (Shibayama 1992). This trend is a result of two developments: First, the need for labor-saving technology; one application instead of two or three in a cropping season reduces the cost of production. Second, the increase in dominance of difficult-to-control perennials (such as *Eleacharis kuroguwai* in Japan and *Sagittaria*

Table 1. Herbicides used for weed control in rice in Asia.[a]

Class[b]	Common name	Mixtures[c] (no.)	Countries[d] (no.)	Products[e] (no.)
Phenoxys	2,4-D	8	14	351
(1950)	MCPA	3	9	2
Diphenylethers	Acifluorfen	1	1	3
(1960)	Bifenox	1	1	3
	Chlornltrofen (CW	0	2	4
	Nitrofen	0	2	6
	Oxyfluorfen	0	8	9
	Chlomethoxyfen	1	3	5
Chloroacetamides	Butachlor	8	10	54
(1970)	Pretilachlor	1	8	11
	Propanil	4	13	71
	Naproanilide	3	1	3
Thiocarbamates	Thiobencarb	5	8	23
(1970)	Molinate	3	5	14
	Pyridate	0	1	2
	Dimepiperate	0	1	1
Dinitroanilines (1970)	Pendimethalin	1	7	12
Triazines	Dimethametryn	1	4	4
(1970)	Simetryn	3	1	7
Sulfonylureas	Bensulfuron	3	6	12
(1980)	Pyrazosulfuron	3	1	3
	Metsulfuron	2	3	5
	Cinosulfuron	0	1	1
Others (1970)	Piperophos	3	1	11
	Anilofos	0	1	1
	Bentazon	3	6	13
	Oxadiazon	3	9	16
	Pyrazolate	2	1	4
Others (1980)	Cinmethylin	0	1	1
	Quinclorac	2	3	3
	Mefenacet	2	2	3
	Pyrazoxyfen	1	1	1
	Triclopyr	0	6	9

[a] Source: ARSAP/CIRAD Regional Agro-pesticide Index for Asia, 1991. Does not include glyphosate, glufosinate, and paraquat which are used in no-till rice, or in conventional tillage before land preparation, or between cropping seasons. [b] year in parenthesis Indicates start of use in Asia. [c] Used in commercially formulated mixtures with other rice herbicides. [d] includes the following countries: Bangladesh, India. Malaysia, Pakistan, Singapore, Brunei Darussalam. Indonesia. Myanmar, Philippines, Sri Lanka, China. Lao PDR, Nepal, Republic of Korea, Thailand. [e] Refers to different trade names.

Table 2. **Most common rice herbicides and herbicide mixtures used in selected Asian countries.**

Herbicide/mixture	Country	Trade names (no.)
2,4-D	Thailand	120
	Malaysia	98
	Philippines	23
	Indonesia	12
	Sri Lanka	7
	Bangladesh	6
	Korea	5
2,4-D + butachlor	Thailand	28
2,4-D + propanil	Thailand	10
Butachlor	Philippines	11
	China	8
	Korea	8
MCPA	Sri Lanka	21
	Malaysia	6
Molinate + propanil	Thailand	6
Propanil	Thailand	35
	Sri Lanka	12
	Malaysia	7
Thiobencarb	Pakistan	5

[a] Source: 1991 ARSAP/CIRAD Regional Agro-pesticide Index for Asia (same countries as Table 1). [b]Includes only those countries where five or more trade names are found.

spp. in Korea) following the decreased incidence of annuals that has resulted from continuous use of herbicides that control annuals (i.e., phenoxys since 1950 and chloroacetamides and thiocarbamates since late 1960 [Kim 1992, Park 19931).

New herbicides currently in advanced stages of development are expected to be available soon: sulfamoylureas for postemergence broadleaf/sedgecontrol (Quakenbush et al 1993, Murai et al 1993) and aryloxyphenoxypropionates or APPs (fenoxaprop, cyhalofop) for postemergence grass control (Matsumoto et al 1993, Ray et al 1993). Fenoxaprop, currently used for postemergence grass control in rice in the United States (Khodayari et al 1989), is now used in some countries in Asia.

In general, the rice herbicides currently being used have adequate selectivity to rice. However, rice is most susceptible to herbicide treatments at the same growth stages as are weeds (i.e., from germination to the four-leaf stage). Herbicides for broadleaf weeds and sedges have adequate physiological and morphological selectivity to rice. Certain selectivity problems may occur with grass herbicides which do not have adequate physiological selectivity to rice.

Table 3. New rice herbicides and herbicide mixtures used in different Asian countries.[a]

Herbicide/herbicide mixture	User country
2,4-D + metsulfuron	Malaysia
Bensulfuron	China, India. Malaysia, Korea Thailand, Philippines
Bensulfuron + butachlor	Korea
Bensulfuron + mefenacet	Korea
Bensulfuron + metsulfuron	Indonesia, Thailand
Bentazon + quinclorac	Korea
Butachlor + chlomethoxyfen	Korea
Butachlor + naproanilide	Korea
Butachlor + pyrazolate	Korea
Butachlor + pyrazosulfuron	Korea
Chlomethoxyfen	Indonesia, Malaysia, Korea
Cinmethylin	China
Cinosulfuron	Thailand
Dimepiperate	China
Mefenacet	Korea, Sri Lanka
Mefenacet + pyrazolate	Korea
Metsulfuron	Indonesia, Malaysia, Thailand
Naproanilide + pretilachlor	Korea
Naproanilide + thiobencarb	Korea
Piperophos + pyrazoxyfen	Korea
Pyrazolate	Korea
Pyrazosulfuron + quinclorac	Korea
Pyrazosulfuron + thiobencarb	Korea
Pyridate	China
Quinclorac	China, Malaysia

[a] Source: 1991 ARSAP/CIRAD Regional Agro-pesticide Index for Asia.

With preemergence, soil-applied grass herbicides, adequate selectivity can be obtained by timing application to crop stages when the absorbing tissues of rice, known as the mesocotyl/coleoptile region, have emerged above the soil surface or are away from the herbicide-treated soil layer (Arceo and Mercado 1981, Chun and Moody 1985,). Other herbicides, such as butachlor and pretilachlor, have formulations that are safer for rice.

With postemergence grass herbicides, treatments are fine-tuned to rates and times most selective to rice while still providing adequate control of grass weeds (Baltazar et al 1987). Rice may suffer no more than 30% injury of chlorosis and stunting, which will disappear within 2-4 wk. The rice recovers fully and yields are not reduced. Marginal selectivity and rice injury greater than 30% can occur with grass herbicides applied when moisture levels are excessive, i.e., if heavy rainfall occurs just before or after herbicide application (Bernasor and De Datta 1983). Transplanted and wet-seeded rice usually incur greater injury than dry-seeded rice (Baltazar et al 1990), suggesting that the role of moisture in herbicide selectivity, particularly with grass herbicides, is critical.

Table 4. Examples of rice herbicide mixtures used in selected Asian countries.

Country	Herbicide mixture	Source
Malaysia	Pretilachlor + bensulfuron Molinate + bensulfuron Quinclorac + bensulfuron	Baki and Azmi (1992)
Japan[a]	Mefenacet + bensulfuron Mefenacet + thiobencarb + bensulfuron Molinate + simetryn + MCPB Mefenacet + pyrazosulfuron Dimepiperate + bensulfuron Butachlor + pyrazolate	Shibayama (1992)
Taiwan	Butachlor + chlomethoxynil Butachlor + bensulfuron Butachlor + oxadiazon	Chiang (1992)
Thailand	Propanil + 2,4-D Butachlor + 2,4-D Propanil + thiobencarb Propanil + molinate	Vongsaroj (1992)

[a]All combinations listed are one-time applications at preemergence or at early post-emergence.

Biological (insects, plant pathogens, herbivores, allelochemicals)

A classical (using insects or natural enemies) or inundative (using plant pathogen inoculum or mycoherbicides) biological method to control weeds in rice and suitable for widespread use in Asia has not yet been developed. In the United States, northern jointvetch (*Aeschynomene virginica* (L.) BSP) has been controlled by the mycoherbicide Collego, an inoculum from an endogenous fungal pathogen *Colletotrichum gloeosporioides* (Penz.) Sacc. f. sp. *aeschynomene,* since 1982 (Smith 1986).

Inundative biocontrol approaches are in the research and development phase, with ongoing research in different laboratories in Japan, Korea, the Philippines, and China. Promising organisms that have been identified include a leaf blight pathogen against *Sphenoclea zeylanica* (Bayot et al 1992), *Epicoccosorus nematosporus,* and *Nimbya scirpicola* for *Eleocharis kuroguwai* (Gohbara and Yamaguchi 1992, Tanaka et al 1992); *Drechslera monoceras* against *Echinochloa* spp. (Gohbara and Yamaguchi 1992); *Alternaria* sp. for *Scirpus planiculmis* (Hong et al 1991,Gohbara and Yamaguchi 1992); and *Colletotrichum* sp. and *Sphacelothea* sp. for *Rottboellia cochinchinensis* (Watson 1992). Greenhouse and field screenings have shown excellent efficacy of these organisms against these weeds, with good selectivity to transplanted rice. Their selectivity to direct-seeded rice has yet to be determined.

The greatest constraints to widespread use of mycoherbicides are low virulence, unfavorable environmental conditions, selectivity to rice in all types of culture (and selectivity to other crops), and development of efficient formulation and application techniques (Watson 1992). The feasibility of using mycoherbicides on small farms with few resources, as well as on large commercial farms with adequate resources, should be considered in developing application techniques.

Except for *Salvinia molesta* and *Pistia stratiotes,* which have been reported as rice weeds in a few countries, no known rice weed in Asia is being controlled by classical biological methods. Waterhouse (1992) cites two reasons why rice weeds are not likely targets for classical biological control: 1) more than half (17 of 32) of the worst weeds in rice are grasses, and 2) most of the weeds are native to Asia. Because of the close similarity between rice and grass weeds, there is widespread belief that the natural enemies that attack grasses will also feed on other cereal crops, if not on rice itself. In addition, classical biological control works best, if not exclusively, on introduced (exotic) species. Of 61 species listed as major weeds in rice, only six were identified by Waterhouse (1992) as likely targets for classical biological control; these are *Monochoria vaginalis, Fimbristylis miliacea, Echinochloa crus-galli, Ageratum conyzoides, Sphenoclea zeylanica,* and *Rottboellia cochinchinensis.* A stem borer, *Emmalocera* sp., was identified in Japan and Malaysia as a potential biocontrol agent against *Echinochloa oryzicola* (Itoh 1991, Goto 1992).

Herbivores that control particular rice weeds are used on a small scale in some areas in Asia. Fish (grass carp, red tilapia) in Malaysia and Japan (Itoh 1991); tadpole shrimp, shellfish, and ducks in Japan (Takahashi 1992, Shibayama 1992), and apple snail in Taiwan (Chiang 1992) are being evaluated for their potential on a larger scale. A major problem with herbivores is that while they are selective to transplanted rice because the seedlings are older, they are not selective to the young, succulent seedlings of direct seeded rice. This has been particularly noted in the Philippines with the apple snail *Pomacea canaliculata* (Lamarck) (Basilio and Litsinger 1988).

Rice cultivars that have allelopathic activity against certain aquatic weeds have been identified in the United States and Japan (Fujii 1992, Smith 1992), but no widespread breeding program for this characteristic has been undertaken. In Korea, allelochemicals against *Potamogeton distinctus,* a major rice weed in that area, have been isolated and identified (Kim 1992), but research is still in the initial stages.

INDIRECT METHODS OF WEED CONTROL

Indirect methods of weed control do not remove or kill weeds. They help suppress weed growth, make weeds more vulnerable to direct control methods, or enhance the ability of rice to compete with weeds. In long-term weed management strategies, indirect methods complement direct methods, which reduce direct control inputs, in particular the application of herbicides. Using indirect methods is probably most important where direct method options are limited by environmental or economic constraints.

Tillage/land preparation

Tillage (plowing, harrowing, puddling) is done primarily to provide relatively weed-free soil at planting. Studies have shown a direct correlation between weed weight and the number of plowing or harrowing operations (Barker 1970), deeper plowing (Kusanagi 1977), and puddling (Moody and De Datta 1982). In most areas, one to two plowings and two to three harrowings will reduce weeds below an economic threshold. Time between the last tillage operation and seeding or transplanting should be as short as possible. In areas where inadequate irrigation facilities delay seeding by as much as 10 d after land preparation, germinating weeds get a head start over rice (Baki and Azmi 1992).

Tillage not only helps suppress weed growth, it also helps level the field (Baki and Azmi 1992). All or most of the rice crop life cycle requires flooded conditions, and level land is important for good drainage. Weed problems are aggravated in uneven fields; rice stands are poor in low spots and weed growth enhanced in high spots. In industrialized countries, precise land leveling is highly mechanized and laser-controlled; in Asia, small farmers use animal-drawn or small engine-powered rototillers, judge leveling by eye, and dig shallow ditches to drain excess water (Takashima 1984).

Tillage will effectively suppress growth of *Puspalum distichum* L., a perennial grass that has increased in dominance over the years due to poor land preparation or zero tillage (De Datta 1977). *Puspalum distichum* stands decreased significantly as tillage was increased, from zero to one plowing plus two harrowings or from one to three harrowings (Bernasor and De Datta 1988). The weed is not a serious problem with adequate tillage and good water management (De Datta 1981).

Seeding rate/plant spacing

Seeding rate or plant spacing should provide a rice plant density adequate enough to prevent weeds from occupying open spaces, but not so dense as to result in intraspecific competition. Weed weight decreased as seeding rate increased from 50 to 250 kg ha^{-1} (Moody 1977). When cost-benefit ratios and other factors are taken into account, the optimum seeding rate in direct-seeded rice is about 100 kg ha^{-1} (De Datta 1989) and the optimum plant spacing in irrigated rice is from 20 × 20 to 25 × 25 cm (Kim and Moody 1980). In wet-seeded rice, where weed pressure is not as intense as it is in dry-seeded rice, even higher seeding rates (up to 400 kg ha^{-1}) will help control weeds (Moody 1977). In dry-seeded rice, where weed pressure is intense, increased seeding rates (160 kg ha^{-1}) will not work, especially with semidwarf cultivars (Moody 1982).

Optimum seeding rate or plant spacing is critical in areas where weed control inputs are inadequate. Where weeds are adequately controlled by other means, it is not necessary to use high seeding rates to suppress weed growth (Castin and Moody 1989).

Nitrogen fertilizer management

In Asia, the recommended N fertilizer rates for rice range from 60 to 150 kg ha^{-1}, depending on the cropping season; 75-100 kg N ha^{-1} results in optimal dry matter (Ampong-Nyarko and De Datta 1989). In the absence of weeds, this amount can be applied anytime between seeding and onset of the reproductive stage of rice. Assuming that weeds are adequately controlled, the recommended practice is a two- or three-split application, with the first and second applications 0-30 d after seeding or transplanting and the third, 5-7 d before panicle initiation (Nantasomsaran and De Datta 1988, Bernasor and De Datta 1993).

When weeds are not adequately controlled, it is best to not apply N, apply at low levels, or delay application until the rate of N uptake by weeds has slowed, usually after the weeds have flowered (Matsunaka 1970) or shortly before panicle initiation in the rice crop (Bernasor and De Datta 1993). Delayed application should be easy to practice because most rice weeds flower in 30-40 d, much earlier than medium-duration rice cultivars which flower 70-80 d after seeding (Bernasor and De Datta 1993).

Weeds compete better than rice for available N, and applying N, especially at high rates, not only will not compensate for inadequate weed control but will also enhance weed growth, resulting in greater competition and lower yields than when no fertilizer is applied. Without applied N, rice and weeds showed similar rates of N uptake, but at 150 kg N ha^{-1}, weeds absorbed more N than rice (Ampong-Nyarko and De Datta 1989).

Water management

In addition to being a requirement for optimum rice growth, maintaining standing water in the ricefield is believed to be one of the first weed control practices (Matsunaka 1983). Most weed species respond to an optimal flooding depth, below or above which weed growth is suppressed. Manipulating the time, duration, and depth of flooding suppresses weed growth. Weed populations decrease with an increase in water depth, and water levels as low as 2.5 cm can suppress weed growth markedly (Mabbayad 1967). Growth of aquatic broadleaf weeds (i.e., *Monochoria vaginalis*) is suppressed by saturation or shallow flooding; growth of terrestrial or semiaquatic grasses (i.e., *Echinochlou crus-galli*) is suppressed by deep flooding of 20 cm or more (Moody 1991). Some weed species are killed in continuous flood, others thrive in continuous flood (i.e., *Pistia stratiotes*) but are killed by intermittent flooding (De Datta and Jereza 1977). While draining will expose aquatic weeds to dry conditions, killing them in the process, draining in the middle of the growing season may injure rice or give semiaquatic weeds such as grasses a chance to grow (Moody 1991). In addition, in areas with golden snail problems (such as in the Philippines), draining to control snails enhances weed growth and prevents the use of granular herbicides which require moisture for maximum efficacy. How to manage water for both snail and weed control is challenging rice researchers in the Philippines.

Soil moisture also affects other factors related to weed control. The efficacy of both cultural and chemical control methods is reduced when ricefield soil is too dry or too wet. Optimum moisture is needed for optimal herbicide efficacy; too little or too much moisture can result in either weed control failure or in severe crop injury. Wet-seeded, flooded rice is more susceptible to herbicide injury than dry-seeded or dryland rice, although low moisture or drought reduces herbicide activity and weed control (Jikihara and Kimura 1977, Janiya and Moody 1984). It is also difficult to hand weed or rototill too dry or too wet soil.

Using competitive cultivars

Rice cultivars that can compete for resources as well as or better than weeds would require less weed control inputs. Tall, droopy leaves and fast-growing, high tillering capacity are characteristics believed to contribute to the weed-competing ability of rice. Unfortunately, these traits are in sharp contrast to those that favor high yields: short, erect leaves; lodging resistance; and responsiveness to applied N. Rice breeding programs usually are designed to capture high-yielding traits, with the assumption that adequate weed control inputs will be used when the resulting varieties are cropped.

Most of the existing high-yielding cultivars are short- or intermediate-statured, easily outgrown by tall, fast-growing grass weeds such as *Echinochloa* spp. in flooded rice and *Rottboellia cochinchinensis* in dryland rice. With the trend toward adoption of direct-seeded rice, which does not have the head start over weeds that transplanted rice does, use of cultivars that grow rapidly, especially within the first 30 d of the life cycle, is highly desirable. Some cultivars have been identified that compete well with weeds under particular growing conditions. Tall traditional cultivars are more competitive than short modern cultivars (Moody and De Datta 1982). Among the modern cultivars, those with intermediate stature are more competitive than the semidwarfs (De Datta 1974).

Weeds are sensitive to interspecific competition, a vulnerability that can be exploited to the advantage of a rice crop (Ampong-Nyarko and De Datta 1989). Models are needed that will predict the competitive value of morphophysiological traits, to explore genetic diversity for those traits, and to include them in formulating long-term weed management strategies (Pamplona et al 1990). Recent studies at IRRI have attempted to identify morphophysiological traits that can contribute to the competitive ability of rice (Janiya and Moody 1993).

Factors that help weeds outcompete rice include the following:

- The presence of chlorophyll in the first leaf of barnyardgrass, in contrast to a nonchlorophyllous first leaf in rice; this gives barnyardgrass a 4-d head start over direct-seeded rice (Kim and Moody 1989).
- The higher photosynthetic ability, greater N and water use efficiency, and larger potential to acclimatize to change of most grass weeds, which are C4 plants, than rice, a C3 plant (Ampong-Nyarko and De Datta 1989, Pamplona et al 1990).

The higher water use efficiency of weeds suggests that efforts should be focused on breeding rice cultivars with a greater potential to access water rather than breeding for drought tolerance (Pamplona et al 1990). Dryland rice has a higher acclimation potential to shade than *Rottboellia cochinchinensis.*

Another indirect control option being explored is the use of allelopathic cultivars. Studies in Japan have identified some native japonica cultivars that possess allelopathic activity against certain rice weeds (Fujii 1992). In small-plot field trials in the United States, some rice lines have been shown to possess weed suppression bands against certain aquatic broadleaf weeds (Smith 1992). An offshoot of the development of allelopathic cultivars could be the transfer of allelopathic traits from rice or other plants to existing rice cultivars, if these traits are found to be genetically determined. An initial step in this direction is the identification of allelochemicals; work is under way in some laboratories in Korea and Japan (Kim 1992). Allelochemicals also may be developed as botanical herbicides.

Crop rotation

Particular crops are associated with particular weeds. Monocropping on the same land using the same cultural and chemical weed control practices can lead to the buildup of dominant weed species or to the development of weed tolerance or resistance to control measures. To break the weed cycle, flooded rice is rotated with dryland crops having different growth or cultural requirements, such as maize, soybean, peanut, mungbean, vegetables, wheat, barley, or pasture. In rainfed areas in the Philippines, where a rice-based cropping system is common practice, farmers plant vegetables and legumes for a food and/or cash crop in the dry season and wait for the next rainy season to plant rice. In Korea and Japan, the choice of rotation crops with rice depends on the potential market value of the crop (Kim 1992).

Rotating flooded rice with a dryland crop is an effective way to dry out and kill aquatic weeds. *Scirpus maritimus* populations, which increased with continuous cropping of transplanted irrigated rice, decreased when rice was rotated with a dryland crop (De Datta and Jereza 1977, Bernasor and De Datta 1986). In the United States, rotating rice with soybean, sorghum, or cotton every 2 yr reduced the red rice population (Smith 1976).

Rotating rice with a broadleaf crop also enables using herbicides that otherwise could not be used in rice due to selectivity problems. For example, postemergence grass herbicides can be used to control grass weeds in soybean without fear of injury to rice.

Preventive measures

Preventive measures include practices to avoid or minimize weed and weed seed dispersal and buildup of a field's weed seed bank. They include using weed-free seeds or weed seedling-free transplants; using clean, weed-free farm equipment to prevent transfer of weed-contaminated soil from one farm to another, and maintaining clean fields, field borders, levees, and irrigation canals during the cropping season and during fallow periods.

For direct-seeded rice, the availability of clean, certified seed can be difficult in some parts of tropical Asia where seed saved from previous harvests is used to lower production costs. For transplanted rice, grass seedlings can be transplanted with rice seedlings because they are difficult to distinguish from the rice seedlings (Rao and Moody 1987). While great efforts to control weeds are exerted during the cropping season, equal attention should be given to maintaining clean fields during fallow periods. Weeds allowed to grow and set seeds between cropping seasons contribute to the buildup of seed reserves in the soil. In Japan and Korea, farmers use nonselective herbicides (glyphosate, glufosinate, paraquat) or rotary weeders to control winter weeds before land preparation and to control weeds that grow during the autumn after rice harvest (Kim 1992, Shibayama 1992). In Taiwan, China, farmers burn rice straw after harvest to control existing weeds and prevent a buildup of weed seed reserves (Chiang 1992).

INTEGRATED WEED MANAGEMENT

Integration of chemical and manual weed control methods, complemented by rice production practices best suited to local cultural and ecological conditions, is standard practice in Asia. These farmers, even though relatively unaware of the concept, already are practicing integrated weed management (IWM). The degree to which each control method is used is determined not only by crop, weed, and environmental factors, but also by socioeconomic factors. For example, because labor for manual weeding is expensive, herbicides are a major component of weed management in Japan, Korea, and Taiwan, supplemented by manual or rotary weeding and indirect practices. In South and Southeast Asia, hand or rotary weeding accounts for more than half of the weed management practices, supplemented by indirect practices, with low use of herbicides.

Applying the best herbicide treatments, however, is sometimes not adequate to control the whole spectrum of weeds that grow with rice throughout the cropping season. Even in countries with almost 100% herbicide use, spot manual weeding supplements herbicide application.

In Taiwan, China, IWM has five components-weed control in levees; application of soil-applied (preemergence) herbicides just before, during, or just after transplanting, before weed emergence; manual weeding 2-4 wk after transplanting to control escapes from the preemergence treatment; application of postemergence herbicides; and late stage manual weeding to control barnyardgrass escapes (Chiang 1992). Late-stage manual weeding has been discontinued in recent years because of the decreased incidence of barnyardgrass. In addition, rice straw is burned or nonselective herbicides are applied during fallow periods (Chiang 1992).

In Japan and Korea, IWM practices in transplanted rice are similar-manual weeding/cultivation (engine-powered rotary weeder) in late autumn or winter after rice harvest to decompose rice straw and to decrease perennial weeds by exposing buried propagules to freezing temperatures; nonselective herbicide applied after harvest or before planting to control winter and spring weeds; two or three herbicide applications (one application if one-shot treatment) during rice cropping, applied either preemergence, early postemergence, or late postemergence; and manual or rotary weeding to control perennial weeds or barnyardgrass escapes (Shibayama 1992).

The IWM practices in dry-seeded rice also are similar in Korea and Japan: herbicide applications, twice before flood and once after flood, supplemented by manual or rotary weeding (Shibayama 1992, Kim 1993). Some examples of herbicide treatments are pendimethalin or molinate + pyrazosulfuron-ethyl at 0-5 d after seeding (preemergence), propanil + butachlor or pendimethalin 12-15 d after seeding (early postemergence), and quinclorac or bentazon 30-35 d after seeding (late postemergence). These are supplemented with hand or rotary weeding to control escapes.

In Thailand, Malaysia, Indonesia, and the Philippines, IWM consists of one of the following: preemergence herbicide followed by postemergence herbicide; preemergence herbicide followed by hand or rotary weeding; preemergence herbicide tank-mixed or commercially formulated with a postemergence herbicide, followed by hand or rotary weeding; or rotary weeding supplemented by hand weeding and indirect methods.

USE OF HERBICIDE-RESISTANT RICE

With the trend toward adopting novel approaches to pest management, herbicide-resistant rice offers great potential as an additional weed control option. Use of herbicide-resistant rice would eliminate problems of herbicide selectivity, allow herbicide application at the most vulnerable stages of weed growth under a wide range of climatic conditions, and reduce the number of herbicide applications within a cropping season. There are risks; the most important are the possibility of transferring resistance traits to weeds, either by selection pressure or by cross-pollination (given the close similarity between rice and grass weeds, especially red rice), and the temptation to increase the use of herbicides.

If the issues involved in the risks are resolved, the process would involve selecting appropriate herbicides for the efficacy needed (i.e., for broad-spectrum or grass weed control only), for protecting the environment, and for the safety of nontarget organisms. Traits conferring resistance to the selected herbicides should have a high chance of successful transfer in rice breeding programs. Cao et al (1992) used transgenic techniques to develop glufosinate-resistant rice. Of course, any resistant cultivar developed should have agronomic traits comparable with existing commercial cultivars.

PERSPECTIVES ON CURRENT PRACTICES AND KNOWLEDGE

Direct weed control methods, such as hand or rotary weeding and herbicide application, are widely used in rice production in Asia because they have immediate and visible effects. These methods are supplemented by cultural and ecological practices suitable to conditions in a particular area that indirectly suppress weed growth. The effects of indirect methods are not immediate and sometimes are considered not necessary if direct methods are adequate. Over time, however, indirect methods help reduce the need for direct control inputs. This impact on weed control systems should be considered in long-range weed management strategies.

By combining methods, many rice growers knowingly or unknowingly practice a type of IWM. More widespread, deliberate adoption of IWM by Asian farmers is constrained by a lack of basic knowledge and understanding of IWM principles and how to integrate IWM into crop protection and crop production systems.

Among the direct weed control methods used, the proportion that is cultural or chemical is dictated primarily by economic factors, from 100% hand or rotary weeding in areas with relatively inexpensive labor, such as in South and Southeast Asia, to 90% or higher use of herbicides where labor is expensive, as is practiced in the industrialized countries of East Asia. In highly industrialized countries where labor costs are very high, many farmers prefer one-time herbicide applications to save costs.

Herbicides are used to control rice weeds in virtually all of Asia. The first group of herbicides (the phenoxys), used since 1950 for postemergence broadleaf and sedge control, are still popular. The second group (chloroacetamides, thiocarbamates), introduced in 1960 for preemergence grass control, continue to be widely used. Their specificity with regard to time of application (pre- or postemergence) and to type of weed controlled (annual grass or annual broadleaf/sedge) resulted in two significant developments, an increase in perennial weed populations and the need to apply the herbicides two to three times within a season to control all three types of weeds.

Recent development of new herbicides or mixtures of old and new herbicides that provide wider application windows and efficacy against broader weed spectra are helping to control all types of weeds in a one-time application, saving on both herbicide and labor costs. These new compounds also have new chemistries, new modes of action, and much lower application rates than older compounds. How these new compounds and related practices will impact weed species shifts and the various components of rice weed control systems is unknown.

Biological control agents that have been identified as having potential for possible widespread use need to be studied for their selectivity in all types of rice culture, in particular in direct-seeded rice. Deeper understanding is needed of both the biology of the control agent and that of the host weed, and of the relationship between the two. Although initial results indicate the potential of biocontrol methods as another direct control option, only a few weed species are involved, making biocontrol not an alternative, but a supplement to other methods. There is also a need to identify formulation and application techniques that are efficient and practical for small farms as well as commercial farms.

Among indirect weed control methods, water management remains a critical factor, particularly in tropical Asia because of poor water control and highly unpredictable rainfall, with the resulting extreme moisture fluctuations, from drought to flood within a single cropping season. Soil moisture has been identified in most studies as the single most critical factor affecting weed control, even surpassing the effects of fertilizer. In rainfed areas, which make up a large part of the rice areas of Asia, rainfall dictates when to plant rice and affects not only rice and weed growth but also factors related to weed control, notably herbicide efficacy. Because herbicides require optimum moisture for optimum efficacy, too little moisture during a drought will result in poor weed control, and too much moisture during a flood will injure rice (De Datta 1980, Bernasor and De Datta 1983). This is significant in the growing trend toward adoption of wet-seeded rice, where crop stand and herbicide injury are major problems, in particular when grass herbicides are used (Moody 1992). Studying the relationship of moisture and herbicide activity may help provide answers on how to improve weed control during drought and how to avoid rice injury during floods.

The use of weed-competitive rice cultivars has possibilities as an indirect control alternative, should there be an opportunity to breed for this trait. A major issue that needs to be resolved is how to combine contrasting traits, those that confer high yielding ability with those that confer competitiveness, or whether this is even possible. Some morphophysiological traits of weeds that make them more aggressive competitors than rice have been identified that could serve as bases for considering traits to be incorporated into a competitive, high-yielding cultivar.

Related to the development of competitive cultivars is the development of allelopathic cultivars. Allelopathic cultivars are being identified and factors related to their potential use in Asia are being studied. Identification of allelochemicals, either for use in developing botanical herbicides or for transfer of allelopathic traits into commercially acceptable cultivars (if allelopathy is genetically determined), is another option being explored.

Development of transgenic, herbicide-resistant rice cultivars is another indirect control option. Two important questions need to be considered: 1) will herbicide-resistant cultivars encourage increased herbicide use, and 2) will herbicide-resistant cultivars result in the development of resistant weeds? This new technology should be carefully studied in terms of both its feasibility and its short- and long-term impact on socioeconomic, environmental, and health-related issues in Asian rice production systems.

Integrated weed management elements should take into consideration all other practices in rice and rice-based production systems, if adoption of new technology is to be successful. While basic and strategic research are important, research that builds on farmer knowledge and practices is equally important. It is the partnership of science and rice farming that will facilitate the development of relevant integrated pest management (IPM) practices that include weed management strategies.

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NOTES

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INTRODUCING INTEGRATED WEED MANAGEMENT IN MALAYSIA

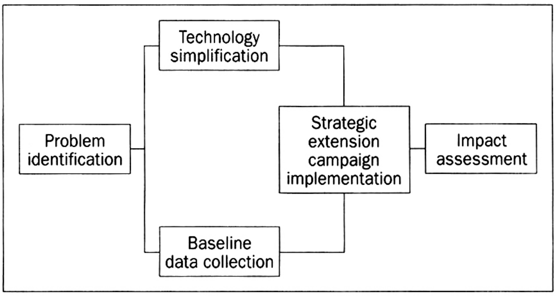
N.K. Ho

In Malaysia in the 1980s, seasonal labor shortages and high labor costs caused many irrigated rice farmers to shift from transplanting to direct seeding (Ho 1982). Widespread adoption of direct seeding contributed significantly to earlier crop establishment (Yeoh 1972), higher yields (Ramli and Khor 1993), and lower labor inputs and production costs (Wong 1993). In Malaysia's Muda Irrigation Scheme, direct seeding was being practiced on 65-99% of the planted area in 1987 and 1988 (Ho and Zuki 1988).

Weed competition, however, is greater in direct-seeded rice than in transplanted rice (Moody 1983). When farmers shifted from transplanting to direct seeding, weed dominance shifted from the less competitive broadleaf weeds and sedges to the more competitive grasses (Ho and Zuki 1988). Weed infestations in direct-seeded fields have caused 30-100% yield losses (Ho 1994). Poor land preparation and uncontrolled moisture were important contributors to increased weed problems. The resemblance of grass weed seedlings and rice seedlings also misled farmers into postponing weed control (De Datta and Bernasor 1973).

A 1984 weed survey indicated 92% of Muda farmers practiced weeding. However, a more thorough field investigation revealed that rigorous weeding was not a standard cultivation practice. Manual weeding was only undertaken when family labor was available. As far as chemical weeding was concerned, the majority of the farmers applied 2,4-D for grass weed control, despite the fact that the herbicide was ineffective and expenditure for its application wasteful (Ho 1984).

To help farmers address grass weed problems in their direct seeded rice, the Muda Agricultural Development Authority (MADA)—the principal public administrative and management organization responsible for agricultural development in the Muda area-adopted an integrated weed management (IWM) approach in its extension program. The central principle of IWM is that no single weed control method is effective in all circumstances. The best weed control is achieved through the integration of



1. Framework for planning and implementing an extension program on integrated weed management.

several methods applied simultaneously (Moody and De Datta 1982). The framework adopted for planning and implementing a comprehensive extension program for IWM involved five steps: problem identification, baseline data collection, technology simplification, strategic extension campaign implementation, and impact assessment (Fig. 1).

IDENTIFYING WEED COMMUNITY SHIFTS

Weed problems in direct-seeded rice are influenced by a number of biological, technological, ecological, socioeconomic, and political factors. Systematic analysis of shifts in the composition of the weed community is important in exploring the problem. MADA management used seasonal and historical profiles to identify weed dominance and associated ecological factors. A historical perspective on weed population dynamics helps extension workers explain current weed problems to farmers. A historical profile that highlights changes in key factors that affect weed infestation is useful in anticipating changes in weed status and in planning weed management.

Historical profiles revealed that after the introduction of rice double cropping in 1970, the weed flora in transplanted fields in the Muda area were dominated by broadleaf weeds (*Monochoria vaginalis, Sagittaria guyanensis, Limnocharis flava, Marsilea minuta*) and sedges (*Fimbristylis miliacea, Scirpus grossus, Cyperus difformis*). While grasses (*Echinochloa crus-galli, E. colona, Leersia hexandra, Isachne globosa*) were found growing sporadically along the edges of ricefield levees and on river banks, their occurrence was considered minor (Table 1).

The adoption of direct seeding during the 1980s caused drastic changes in rice cultivation. The exponential increase in direct-seeded hectarage led to aerobic conditions conducive to grass weeds (Moody and De Datta 1982). Direct-seeded fields are not flooded during initial crop growth stages, allowing rice and grass weeds to germinate simultaneously. Extensive use of tractors and combine harvesters, coupled with indiscriminate broadcasting of weed-contaminated rice seeds, further contributed to weed infestations (Ho 1991). In 1982, after three consecutive seasons of direct seed-

Table 1. Changes in weed flora with shift from transplanting to direct seeding in the Muda area, 1979-89.

Item	Season					
	2/79	1/82	1/84	2/84	1/87	1/89
Species (no.)	21	34	42	45	50	57
Genera (no.)	18	18	30	30	38	44
Families (no.)	13	14	19	17	22	28
Direct-seeded area (%)	0.2	20.7	53.0	24.0	98.9	81.7
Dominant weed species[a]	Mv	MV	Fm	Ecr	Ecr	Ecr
	Lhy	Lhy	Mv	Sg	Eco	Lc
	Fm	Fm	Ecr	Lhy	Lc	Fm
	Cd	Lhe	Sg	Pa	Sg	Mc
	Lf	Sg	Mc	Lc	Fm	Mv

[a]Mv = *Monochoria vaginalis,* Fm = *Fimbristylis miliacea.* Ecr = *Echinochloa crus-galli.* Lhy = *Ludwigia hyssopifolia,* Sg = *Scirpus grossus,* Eco = *Echinochloa colona,* Lc = *Leptochloa chinensis,* Cd = *Cyperus difformis,* Lhe = *Leersia hexandra,* Pa = *Panicum amplexicaule,* Mc = *Marsilea crenata,* and Lf = *Limnochans flava.* Source: Ho and Itoh (1991).

ing in the southern part of the Muda area, serious infestations of *E. crus-galli* were observed (Ho 1984).

When direct seeding became the dominant crop establishment practice, covering 53% of the Muda area rice hectarage, grasses dominated the weed community. *Echinochloa crus-galli* was widespread, infesting all direct-seeded fields. *Leptochloa chinensis* had become conspicuous in the southern area where direct seeding had been practiced for 10 consecutive seasons (Ho 1986). In 1987, the grass *Ischaemum rugosum* was detected for the first time; it caused severe yield losses in direct-seeded fields in the southern part of the Muda area. In 1990, a weedy form of rice (*Oryza sativa*) was found to be occurring sporadically in the southern tip of the area (Ho and Zainuddin 1995). By 1994, the area affected by weedy rice had reached 300 ha. The undesirable early shattering characteristic of this weedy rice has caused yield losses of 45-90%.

Historical profiles show that, as direct seeding progressed from the south to the north of the Muda area, grass weeds invaded the ricefields. The sequential order was *E. crus-galli, L. chinensis, I. rugosum,* and *O. sativa* (weedy form).

PLANNING RESEARCH AND EXTENSION

Identification of the weed shift provided a basis for prioritizing research and extension activities, helped MADA management predict the effects of future changes in cultural practices on weed population dynamics, and indicated areas where more efficient control practices might already exist.

Baseline data

The problems associated with the interactions of weeds and the agroecosystem are complex. During the last decade, substantial efforts were made to develop different weed management techniques to address the problems. Typically, a comprehensive package of technology was developed and delivered to farmers through traditional training programs and field demonstrations. The success rate, however, was unsatisfactory. Further analysis indicated that a key problem was the lack of an adequate data base before an extension program was planned and implemented. Without weed assessments and problem identification, it is not possible to develop an extension program that will persuade farmers to adopt IWM.

MADA decided to conduct two studies before developing communication strategies for informing farmers about weed control. The first systematically surveyed farmers to assess their knowledge, attitudes, and practices toward identifying weed problems and undertaking weed control. The structured interview covered four major topics related to weed management: water management, current cultural practices, social limitations, and economic constraints.

That study identified the following problems and misconceptions about weed management among farmers in the Muda area (Khor 1989):

Problems: inability of farmers to identify different grass weed species at early growth stages; incorrect usage of herbicides to control grasses; unawareness of the importance of good cultural practices to enable herbicides to exert their full potential.

Misconceptions: that rodents caused more losses than grass weeds; that weed control is tedious and a waste of time; that herbicides are expensive.

The second study used focus group interviews to explore the reasons and motives that various categories of farmers held toward different practices related to weed management, and on farmers' perceptions of the availability and effectiveness of various weed control measures. Focus group participants were selected to represent small farmers, large farmers, female farmers, farm leaders, and religious leaders.

Large farmers were the most knowledgeable and innovative of the five groups interviewed, religious leaders and female farmers were the least knowledgeable. The study identified the need to change farmers' attitudes toward cultural weed control activities (Khor and Ramli 1988). Greater emphasis was needed on the following aspects:

- Manual weeding using a sickle to cut the panicles of grass weeds.
- Seed selection to avoid mixing rice varieties and to eliminate sowing of noxious weed seeds.
- Land leveling to ensure that there are no elevated spots in ricefields that might not be submerged by water, which would encourage the growth of grass weeds.
- Encouraging farmers to coordinate their farming activities.

MADA's extension program

The following areas are emphasized in MADA's extension program on weed management:

1. Farmers are encouraged to organize group farming projects based on self-help, mutual assistance, and obedience to group decision. Group farming can help reduce squabbling among farmers and promote better cooperation in water management.
2. Farmers are encouraged to adopt recommended cultural practices such as the use of certified seeds and manual weeding.
3. Farmers are trained to identify weeds at early growth stages to enable timing herbicide applications to gain the most effect.
4. Farmers are advised to familiarize themselves with herbicide application procedures and related safety precautions.

Developing weed control technology

From the farmers' perspective, sophisticated technology which is beyond their comprehension seldom merits investment of scarce resources. The availability of an arsenal of simplified technology on weed control is fundamental to improving the likelihood of farmer adoption (Ho et al 1990).

In simplifying technology, it is important to avoid the pitfall of formulating rigid 'package deals.' A variety of options should be made available, from which farmers can choose those most suitable to their farm conditions and managerial skills, as well as resource capacities (Tamin et al l980). The transfer of simplified technology should include teaching the principles which illustrate cause-and-effect relationships, as well as helping farmers learn to learn, so that they may continue to acquire new knowledge and skills (FAO-IPM 1993). At the same time, it is important to avoid theories and principles which are too abstract for the target farmers' understanding.

Pilot IWM extension projects

Recognizing that the rice agroecosystem is changing rapidly, MADA management initiated a series of pilot IWM extension projects in the mid-1980s. These pilot projects were much larger in both concept and scope than the conventional demonstration plots which had been used by extension workers. Each project covered 10-15 ha and involved 5-10 farmers, and projects were located to represent a wide range of soil and environmental characteristics. Farmers and extension workers worked together as participatory research teams. Those teams were the central components of the entire research and extension network of MADA.

Simplified technology was developed through dialogue and jointly conducted field testing. Emphasis was on farmer mastery of the IWM package involving the following components:

1. Using two cycles of cultivation and land leveling.
2. Using clean, weed-free seeds.

3. Filling vacant areas in the fields with healthy seedlings as soon as possible after emergence.
4. Applying direct weed control measures, using herbicides judiciously, and carrying out hand weeding rigorously.
5. Adhering closely to irrigation schedules.

In addition to acquiring such field management skills as selection of herbicides, simple dosage calculation, proper spray nozzle selection, and appropriate timing of herbicide application, farmers also were trained to handle herbicides safely, in ways that would minimize overapplication, spillage, and indiscriminate disposal of herbicide waste.

Farmers were advised to use the simplified technology as a guide in dealing with their particular ricefield situations. They were encouraged to explore their individual experiences, to use their own fields as laboratories in analyzing particular situations, and to choose from the options available the ones that would optimize the use of their own resources for resolving their weed problems. The objective was to adopt the most appropriate technology for local situations.

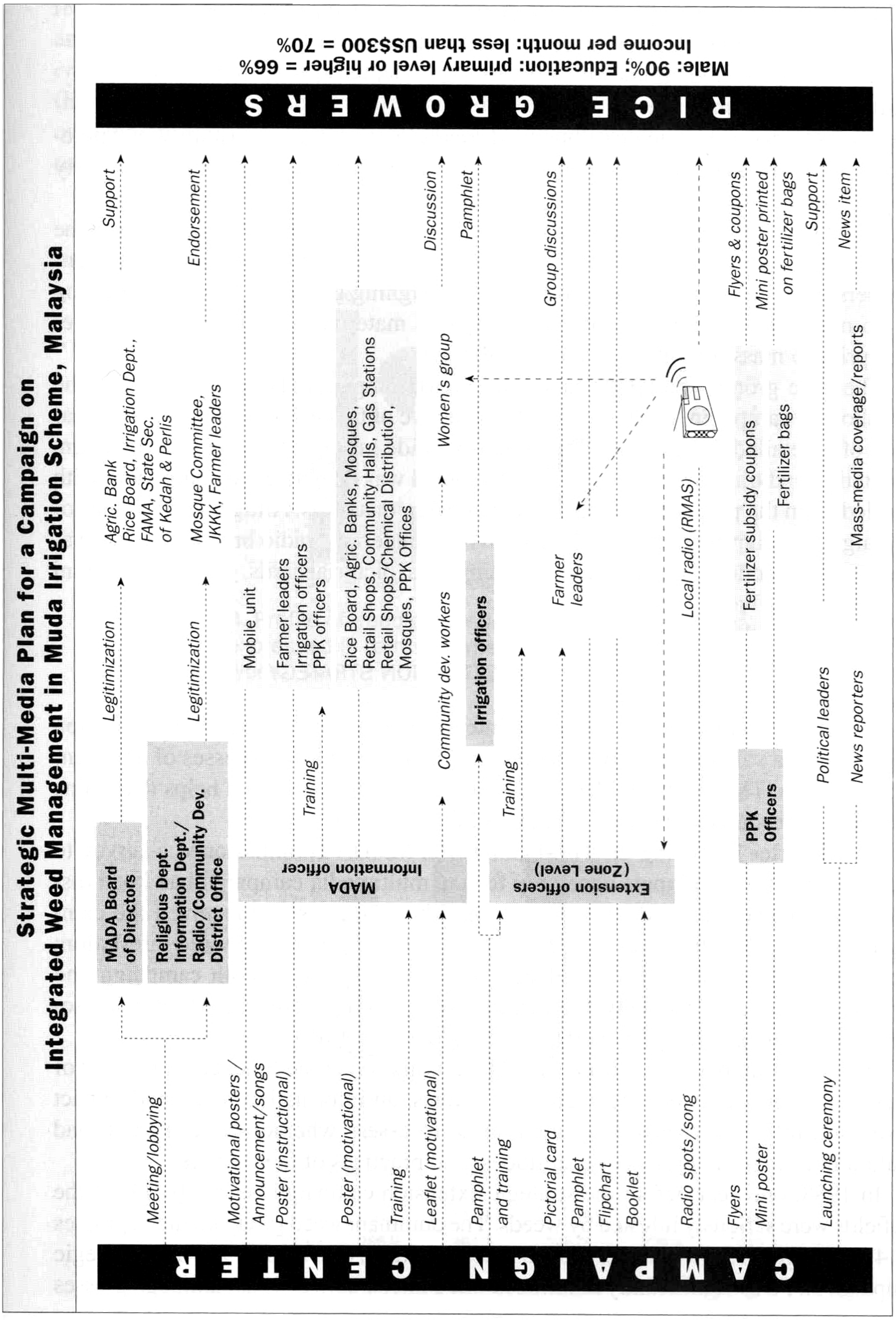
Through their new awareness of the fundamental principles of weed ecology and their mastery of basic technical concepts regarding the critical period of rice-weed competition, the farmers realized that it is more cost-effective to control weeds before fertilizer application, rather than to follow rigidly the recommended schedule of applying the first topdressing of NPK fertilizer at 15-20 d after seeding, regardless of the weed situation.

PLANNING AND IMPLEMENTING THE STRATEGIC CAMPAIGN

After formulating appropriate simplified technology and acquiring adequate information about the response of the target group to the technology, MADA launched a strategic extension campaign in 1989 to introduce the IWM concept (Fig. 2). The campaign methodology, developed by FAO, emphasizes farmer participation in strategic planning, systematic management, and field implementation of agricultural extension and training programs (Adhikarya and Posamentier 1987). It is need-based and demand-driven, orientated toward problem-solving, starts with what the farmers already know, and builds upon what they already have. Farmers are consulted during the planning process to narrow the gap between knowledge, attitudes, and practices of the farmers and the technology recommendations. Strategic extension campaigns employ a cost-effective, multimedia approach to minimize problems which can cause nonadoption of recommended technology by farmers (Adhikarya 1994).

Objectives of the Muda campaign

Objectives identified for the strategic extension campaign initiated in the Muda area were based on the problems identified through the baseline surveys, in relation to the recommended technology:



2. Strategic media plan for a campaign on integrated weed management in the Muda Irrigation Scheme (adapted from Adhikarya 1994).

1. To reduce grass weed infestations in direct-seeded ricefields by 70%.
2. To reduce rice crop losses due to weeds by 25%.

Designing the campaign

The effectiveness of a strategic campaign depends on the relevance, validity, and practicality of the messages communicated to the farmers. The messages must be clearly understood and accurately perceived.

To facilitate effective packaging and positioning of the campaign messages in the farmers' minds, several workshops were organized to train the core group of extension personnel on planning the campaign, on designing messages, and on pretesting and formative evaluation of prototype campaign materials. The materials were revised prior to mass reproduction and distribution.

The core group who spearheaded the IWM campaign also participated in the workshop on campaign management. The objective of that workshop included preparation of a detailed framework to be used as a guide in implementing the campaign. Orientation and training of all extension personnel was conducted to equip them with knowledge on the proper handling of the campaign materials. Altogether, 12 types of campaign materials were prepared—audiovisual materials, radio broadcasts, motivational and instructional posters, leaflets, pamphlets, pictorial cards, guide books, mini flip charts, and flyers.

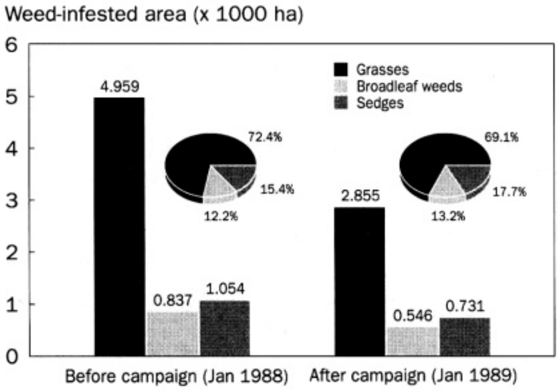
IMPACT OF THE IWM EXTENSION STRATEGY

Systematic summative evaluation is an integral component of the IWM extension program. It is a valuable tool for assessing the strengths and weaknesses of an extension campaign. The feedback identifies areas needing followup and helps determine allocation of resources for future action (Adhikarya 1994).

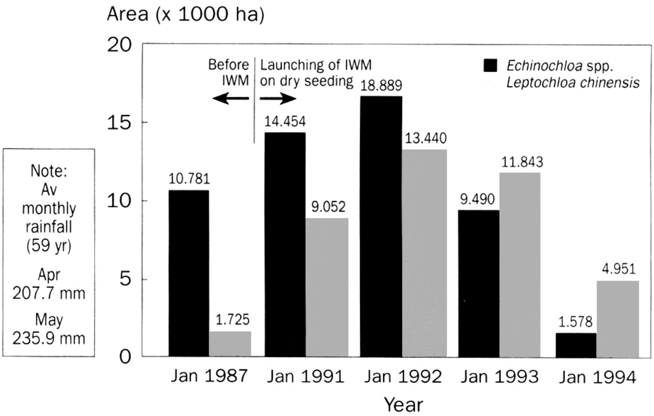
Shortly after launching the IWM campaign, MADA commissioned a survey to determine whether the inputs necessary for the multimedia campaign had been distributed as planned, and whether the intended beneficiaries had received the campaign materials. Another evaluation study assessed crop loss due to weed infestation; weed coverage and other pest incidences were investigated in both campaign and noncampaign areas. This study and a crop cutting survey were conducted in subsequent seasons to analyze yield performance (Ho et al 1990).

When the campaign was over, MADA commissioned the Science University of Malaysia to conduct two more evaluation studies, an information recall and impact survey and followup focus group interviews, to assess whether the campaign had resulted in changes in knowledge, attitudes, and practices of the farmers.

In 1988, one year before the strategic extension campaign began, 14.4% of the ricefields were seriously infested by weeds. The dominant weed group included grasses (72.4%), sedges (15.4%), and broadleaf weeds (12.2%) (Ho et al 1990). The strategic campaign on IWM significantly minimized weed infestation. In 1989, although grasses remained the dominant weed, their incidence had declined to 69.1%; sedges (17.7%) and broadleaf weeds (13.2%) had increased slightly (Fig. 3). Infestations of *E. crus-galli/E. colona,* the principal target weeds of the campaign, declined by 66.3% (Ho et al 1990). Despite an acute water shortage due to severe drought, the continuous implementation of IWM 1991-94 over the entire Muda area has led to further reduction of *Echinochloa* species and *L. chinensis* infestations (Fig. 4).



3. Profile of weed groups in the IWM campaign area, expressed in terms of weed-infested area and weed types.



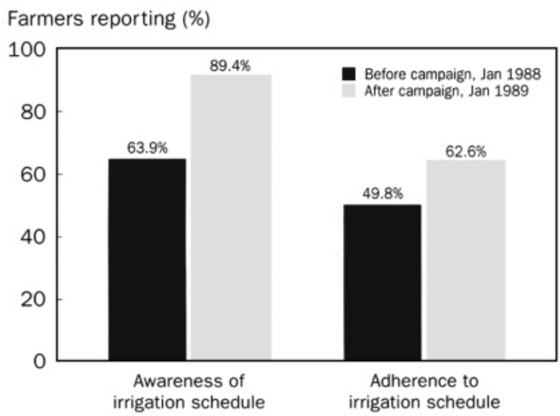
		Jan 1987	Jan 1991	Jan 1992	Jan 1993	Jan 1994
Crop establishment		Rainfed	Rainfed	Rainfed	Rainfed	Irrigation in late March
Supplementary irrigation supply		Late June	None	Mid-May	Late April	Early April
Rainfall (mm) during crop establishment	Apr	80.2	178.6	79.6	73.2	148.0
	May	286.9	364.3	245.2	229.9	182.7

4. Grass weed infestation before and after IWM campaign.

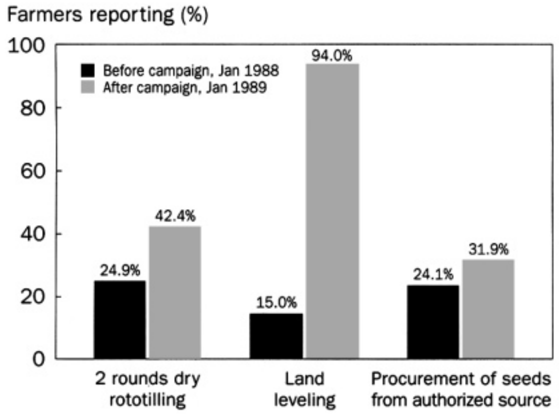
Surveys of information recall and impact indicate that the remarkable reduction of *Echinochloa* population was attributable to the following factors (Khor and Ramli 1990):

- General improvement in water management. More farmers (89.4%) were aware of the irrigation schedule issued by MADA, and approximately 62.6% were capable of adhering to the schedule. Before the campaign, only 63.9% of the farmers were aware of the schedule and 49.8% could adhere to it (Fig. 5).
- Appropriate adoption of cultural practices. Post-campaign evaluation indicated that more farmers (42.4%) dry-cultivated their land twice, as recommended, compared with only 24.9% prior to the campaign. The number of farmers who leveled their fields also increased remarkably, from 15 to 94%. The campaign also created an awareness among the farmers of the importance of using pure seeds. Approximately 31.9% of the farmers obtained their seeds from authorized sources after the campaign, compared with 24.1 % before (Fig. 6).
- Appropriate herbicide application. Post-campaign data indicated an increase in the use of propanil, from 4.8% of the farmers to 16.7%. Similar increased use was observed for the propanil + molinate mixture, from 5.3 to 19.3% (Fig. 7). Farmers' knowledge about correct timing of herbicide application increased from 11.1 to 40% for propanil, and from 30 to 63.6% for propanil + molinate mixture. Knowledge of correct herbicide dosage increased from 9 to 45.4% for propanil and from 9 to 54.1 % for propanil + molinate.

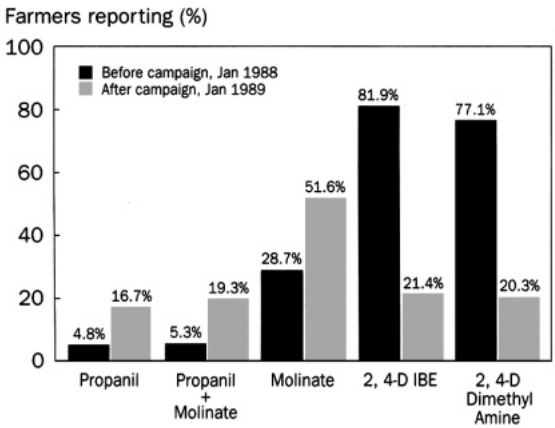
On the whole, the systematically planned, multimedia strategic campaign was successful in controlling *Echinochloa* species, the most serious weed problem in the Muda area. Average rice yields increased 27%, from 3.1 t ha^{-1} in the first 1988 season to 3.95 t ha^{-1} in the first 1989 season. Continuing implementation of the 1990-94 campaign has had remarkable results. Dry-seeded, first-season rice yields have in-



5. Water management in the Muda area before and after IWM campaign (Khor and Ramli 1990).



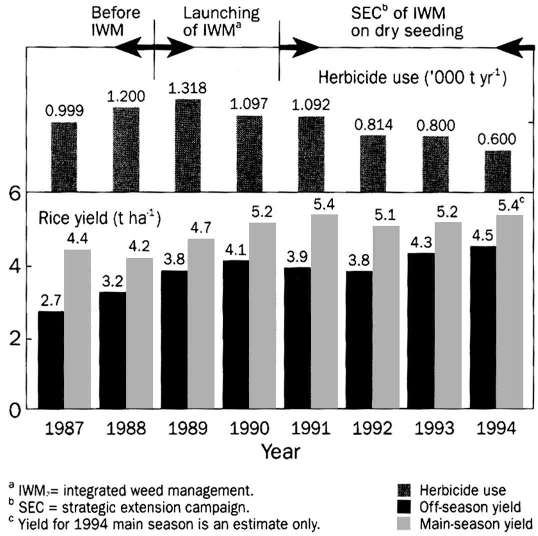
6. Cultural practices in the Muda area before and after IWM campaign (Khor and Ramli 1990).



7. Use of herbicides in the Muda area before and after IWM campaign (Khor and Ramli 1990).

creased steadily, to 4.5 t ha^{-1} in 1994. Wet-seeded, second-season rice yields have been consistently above 5 t ha^{-1} . It is noteworthy that over the same period, use of herbicides declined (Fig. 8). This is attributable to significant improvement in the standards of land preparation.

In addition, more farmers have become aware of the appropriate methods of herbicide application. Field observations have confirmed that farmers who adopted recommended cultural practices could manage their weed problems with only one round of herbicide application, while farmers with poor land preparation and improper water management had to apply herbicides 3-4 times per season to control weeds (Table 2).



8. Herbicide use and rice yield in the Muda area, 1987-94.

Table 2. Herbicide application under different land preparation practices in the Muda area, first season, 1993.

Frequency of herbicide application	2 rototilling + land leveling (n=20)		2 rototilling (n=20)		1 rototilling (n=20)	
	Farmers (no.)	Weed control (%)	Farmers (no.)	Weed control (%)	Farmers (no.)	Weed control (%)
1 round	15 (75)	90	10 (50)	75	3 (15)	20
2 rounds	5 (25)	95	5 (25)	80	7 (35)	50
3 rounds	–	–	5 (25)	90	5 (25)	70
4 rounds or more	–	–	–	–	5 (25)	70

[a] Figures in parentheses are percentages of farmers applying herbicides. Source: MADA (1994).

Studies on crop-weed interactions in the Muda area indicate that consistent removal of weeds has increased rice yields. Nevertheless, total weed eradication is not practical in the rice agroecosystem. Removal of the last 5% of weeds remaining in a ricefield is usually not cost-effective. The additional herbicide needed for total weed control also raises concerns about environmental side effects.

The weed-rice ecological relationship is dynamic. Continuous adoption of a single weed control method frequently leads to serious weed shift problems. In the Muda area, continuous application of molinate selectively suppressed *E. crus-galli* and *E. colona,* leaving other grass weeds uncontrolled (Ho et al 1990). Sharp escalation of *L. chinensis* and *I. rugosum* populations have been observed in ricefields treated consistently with molinate over several seasons. A switch to pretilachlor and fenoxaprop-p-ethyl kept *L. chinensis* and *I. rugosum* under control. The application levels of pretilachlor (0.5 kg ai ha^{-1}) and fenoxaprop-p-ethyl (0.06 kg ai ha^{-1}) are much lower than that of molinate (3.0 kg ai ha^{-1}). Adoption of pretilachlor and fenoxaprop has helped reduce herbicide usage and decrease fish toxicity problems.

It should be noted that the average cost for weed control has increased. This is because farmers are switching from the relatively cheaper 2,4-D to more expensive herbicides for grass weed control (Table 3).

Experiences gained from the extension program also indicate that farmers who have gone through the sensitization process are more likely to adopt the technological innovations best suited to location-specific farming environments. Farmers in the group farming projects are more willing to abide by the group's consensus decision in water management. Land preparation and crop establishment are usually more uniform. Only 2.6% of the ricefields in the group farming projects surveyed had more than

Table 3. Herbicide use under different crop establishment practices in the Muda area, first season 1988 and 1994.

Item	1988		1994	
	Transplanting	Direct seeding	Transplanting	Direct seeding
Average herbicide cost (US$ ha^{-1})	4.8	24.8	6.0	48.0
Farmers using herbicide (%)	82	98	86	100
Frequency of herbicide application (rounds season^{-1})[a]	1.2 (1-2)	2.9 (2-4)	1.0 (1)	2 (1-3)

[a] Figures in parentheses denote range of herbicide application frequency. Source: MADA (1994).

25% weed coverage of *Echinochloa,* while 8.4% of the fields outside the group farming projects had more than 50% infestation (Ho et al 1990).

Access to farm equipment is another important factor for successful weed management. Jirstrom (1995) indicates a strong relationship between satisfactory land preparation and water management. Farmers who own walking tractors and water pumps are, on average, experiencing less weed problems.

The effectiveness of an extension program depends largely on the abilities of the program planners and the local extension agents. A comprehensive training curriculum, instruction manual, multimedia communication and teaching aids, as well as other well-tested training materials, contribute significantly to the overall success of IWM. A specific extension program with clearly defined responsibilities for the local agents, and a unified extension service with a single line of command from the implementing agency to the field level, are important prerequisites to the successful implementation of IWM.

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BIOHERBICIDES AND WEED MANAGEMENT IN ASIAN RICEFIELDS

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Historically, weeds in rice were removed physically. With the advent of chemical herbicides, that approach changed drastically and the success of weed control increased greatly. Over time, however, heavy use of chemical herbicides could change the characteristics of ricefields and their environs. As our understanding of the importance of ecosystem balance increases and becomes more sophisticated, our concern about the impact on the environment of a weed control strategy based solely on chemicals increases.

If the level of rice production needed to meet the ever increasing demands in countries where rice is a staple food were to be achieved, improvements are needed in a range of crop inputs, including improvements in weed management. The improvements that will make possible dramatic increases in production at the national level cannot be achieved solely through conventional research (David 1991). While much is expected from applying biotechnology to modify the rice plant itself (Khush and Toenniessen 1991), new approaches involving research on the biological environment in which improved rices will grow also have great potential to contribute to production increases.

Biological weed control using plant pathogens is emerging as a viable component of the different interrelated and interdependent weed control strategies now available. Classical biological control involved introducing exotic insect predators to control populations of a once exotic, but now naturalized, pest (Waterhouse 1992). While the same approach has been applied to weeds, native weeds (as distinct from introduced weeds) are not promising targets for classical biological control. Any strategy that depends on long-term population dynamics and natural dispersal of a plant pathogen, which can be relatively successful in noncropping situations, is not useful in intensive production systems with annual cropping cycles. An inundative approach—introducing a new pathogen or augmenting natural background populations of pathogens—is more appropriate (Marois 1992).

Using mycoherbicides involves applying large quantities of infective propagules of a fungus (usually, but not necessarily, by spraying) at a stage of plant growth and under environmental conditions conducive to maximum infection and disease progression. This should kill or severely restrict the growth of a susceptible weed. The discussion here is confined to biological herbicides involving living organisms. The more focused area of pathogen phytotoxins as potential herbicides has many properties in common with synthetic chemical herbicides, as reviewed by Strobe1 et al (1991).

USING BIOHERBICIDES

Mycoherbicides have become an established branch of plant pathology, and a number of wide-ranging reviews are available (Charudattan 1988, Templeton and Heiny 1989, Templeton et al 1990, TeBeest 1991, Trujillo 1992). ("Mycoherbicide" is not as precise a term as would be desirable, in that while it implies weed mortality, at the same time it evokes a fear of herbicide residues [Winder and Shamoun 1991]. A more explanatory term to describe this control tactic would be useful.)

Theoretically, an inundative approach using a mycoherbicide could control almost any weed, if a sufficiently destructive, naturally occurring organism were available (Charudattan and DeLoach 1988). The inoculi also should be relatively inexpensive to produce. Each plant host-pathogen relationship, however, is unique (Templeton 1986). Most plant pathogens will not cause rapid or complete death of the plants they infect, unless environmental conditions either stress the plant or substantially encourage increased frequency of infection and greater disease severity. Using complete weed kill as a criterion for selecting a bioherbicide will drastically reduce the number of pathogens that would be candidates for development.

INTEGRATING BIOHERBICIDES INTO WEED MANAGEMENT

Biological agents have long been regarded as an alternative to other methods of weed control. But thinking in terms of alternatives is restrictive, evoking a dichotomy of either/or (Watson 1992b). Integrated weed management involves a holistic approach to reducing and maintaining weeds below the level of significant economic competition with a crop (Kim 1992, Kon 1993). Integrated weed management concepts have been discussed by Moody (1991) and Marois (1992). The long-term objective is to optimize farm productivity.

Managing rather than eliminating weeds relies on yield loss assessment and on exploiting the interactions between rice and weeds in a ricefield ecosystem. This involves evaluating the impact of disease and other biotic factors on the dynamics of a weed population within a rice crop. It is likely that the crop yield-weed density relationship changes significantly when a weed disease is present (Hasan and Ayers 1990). Integrated weed management utilizes a combination of control tactics; biological and chemical control are integrated with other methods, such as water management and hand or machine weeding (Kim 1992, Moody 1992, Smith 1992).

Many integrated pest management (IPM) programs are already in place in Southeast Asia; most emphasize insect pests (Adalla and Rola 1987, Adalla et al 1987, Galvan and Kenmore 1991). These can be useful background as farmers and farming communities are informed and trained on using integrated weed management systems, and on including biocontrol agents in those systems.

Farmers who implement a wide range of weed control measures already practice biological control, even if unwittingly, as they make weed control choices within their individual perspectives of productivity (which often are much broader than merely maximizing yield per unit area.) Although Baki and Azmi (1992) believe that it is not possible for a rice farmer to carry out two roles, both as a business manager and as a protector of the environment, the inherent philosophy of IPM programs should contribute to resolving any role conflict a farmer might feel. Community involvement in IPM programs that emphasize education (Galvan and Kenmore 1991) can help reconcile the differences between short-term economic gain for the farmer and long-term environmental stability for the community.

IPM developed during a period when pest management focused on eliminating or controlling an individual pest in a cropping system, without taking into account the interactions of multiple pests that might be attacking a crop. Now, with increased scientific ability to collect and analyze larger data bases, it is possible to undertake an ecological approach to pest management research (Marois 1992).

Norris (1992) claimed that the studies on weed biology and ecology carried out during the last 50 yr have contributed little to improved weed management, probably because little attention was given to applying the knowledge gained to the design of weed control strategies (Cullen 1992). Knowledge of the biology of a target weed, however, is essential in formulating an effective weed management strategy (Piggin 1993).

The preoccupation of weed scientists with the efficacy of chemical herbicides also detracted from initiation of biological studies that focused on site-specific considerations of agriculture in the less developed areas of the world (Alstrom 1990). Biological control constituted only 0.4% of all weed research reports published in the Philippines in 1978-88 (Paller 1989). Malaysian weed science also has been a herbicide-based discipline (Baki and Azmi 1992). Although this lopsided research attention may be changing, biological control is still a neglected area of weed science.

The optimism displayed by IPM practitioners is not universally shared, and opinions about the future of IPM depend on the background of the observer. Woodburn (1990) argues that because the components of IPM are not transferable from region to region, it is of less significance than continued use of agrochemicals. Norton and Way (1990) see the site specificity of IPM components as a strength. Even though IPM is being applied in only about 3% of irrigated rice in Asia, results are encouraging and programs are expanding rapidly. Changes that are needed in the posture of agrochemical companies toward IPM principles have been identified (Vorley 1990) that would make it possible to meet the needs of farmers through a collaboration of industry and governmental authority.

Community education also is important in creating a realistic perception of what can be achieved by a biological control agent. Charudattan (1990) believes that the number of pathogens that might be suitable for bioherbicide development will be severely limited if the demand for efficacy is similar to that achieved with chemical control. High efficacy, a demand which may originate in the private sector, is unnecessarily rigid when biological weed management is considered within the broader framework of IPM.

Concerns that weeds may act as reservoirs of disease and insect pests have not been substantiated. The question should be, is weed suppression instead of elimination an environmental luxury or an economic benefit?

The presence of a diversity of weed vegetation near or within a crop that will sustain populations of beneficial predators of harmful insects is an advantage of IPM that has been recognized for some time (Altieri and Whitcomb 1979). Moody (1990) listed numerous records of weed/insect and weed/disease associations, while acknowledging that the listing was uncritical. Whether weed populations pose a risk as reservoirs of crop diseases should be quantified.

In determining risk, the following questions arise: How many weed-crop disease associations have been studied in the field? How many of the associations reported were based on greenhouse studies where no alternative food supply was available to the potential insect vector or pest? Was pathogenicity proved by realistic methods? Did the pathogen (particularly fungi) sporulate on the infected plant? Was the virus or mycoplasma able to be acquired from infected weeds by an appropriate vector?

Merely recording the occurrence of a disease (especially of a virus) or of known disease vectors on a weed species in proximity to rice provides only circumstantial evidence that the weed may be acting as an inoculum or pest source. Speculations (Karim and Saxena 1989) must be viewed with caution: each association should be examined in detail. For example, Borromeo et al (1993) have shown that populations of *Pyricularia oryzae*-infected weeds did not provide inoculum to infect rice crops in the Philippines.

Similarly, the presence of an insect pest on both rice and an adjacent weed does not automatically mean that the weed population is the source of the pest. Heinrichs and Medrano (1984) found that different populations of the brown leafhopper *Nilaparvata lugens* on the weed *Leersia hexandra* and on rice did not trade hosts. The insect complex on weeds, however, is important in managing leafhoppers on rice; the leafhoppers on the weeds are attacked by the same predators, parasites, and pathogens as the leafhoppers on the rice. The number of leafhopper predators on weeds can be several times greater than the leafhopper population, and can migrate to attack leafhoppers on a rice crop (Xiaonan and Wenxi 1987).

RESEARCH ON BIOHERBICIDES FOR RICE

Most research on studying inundative bioherbicide weed control has been directed at controlling weeds important in capital-intensive agriculture (Charudattan 1991). The success of Collego® against *Aeschynomene virginica* in rice in the United States is well known. Several promising research projects, however, have focused on inundative control of rice weeds in Southeast Asia. Studies on growth suppression and death of water chestnut *Eleocharis kuroguwai* following inoculation with an unknown fungus was reported by Suzuki (1991). Kim (1992) reported that the fungus *Epicoccosorus nematosporus* controlled water chestnut with an efficacy similar to that of the herbicide bentazon. Two other fungal pathogens, *Nimbya scirpicola* and a *Dendrophiella* sp., are under investigation for control of water chestnut (Tanaka et al 1992); *N. scirpicola* appears to be more effective if it is applied after a chemical herbicide (Shibayama 1993). Kim (1992) achieved 85% mortality of the perennial sedge *Scirpus planiculmis* following inoculation with an *Alternaria* sp., with negligible pathogenicity to the other hosts tested.

Grass weeds pose the biggest challenge to bioherbicide control in rice because the biological constraints are real and immediate. Pathogens of grass weeds tend to have very broad host ranges, reducing or negating their usefulness for grass weed control in rice. However, progress is being made. Recently Gohbara and Yamaguchi (1992) reported possible control of barnyardgrass *Echinochloa crus-galli* using *Drechslera monoceras* in conjunction with a herbicide.

Several other weed host-pathogen relationships in rice crops warrant further study (Smith 1992). A noticeable increase of interest in pathogens of rice weeds has followed the initiation of a research program at IRRI that is focusing on nine major weeds of rice (Watson 1994); early results with a pathogen of gooseweed *Sphenoclea zeylanica* are promising.

In Australia, the non-native aquatic plant *Alisma lanceolatum* emerged as a problem in rice following the introduction of the herbicide bensulfuron-methyl (Londax®). The native plant *Damasonium minus,* which grows profusely in the ricefield environment, is being controlled currently by Londax, but resistance to ALS-inhibiting chemicals is occurring. The naturally occurring fungus *Rhynchosporium alismatis* is being studied as a potential mycoherbicide for control of these two weeds (Cother et al 1994, Cother and Gilbert 1994). The weeds are suppressed but not killed by the fungus. The potential host range of *R. alismatis* extends to other genera in the family *Alismataceae,* and pathogenicity has been demonstrated to *A. canaliculatum, A. plantago-aquatica, Sagittaria guyanensis,* and *S. pygmaea.* In limited studies in a quarantine glasshouse, spray-inoculation of seedlings caused significant reductions in biomass production in these species, with dry mass production of *S. guyanensis* reduced 62-87% (Cother 1994).

Selecting potential bioherbicides

A protocol for assessing the potential efficacy of mycoherbicide candidates developed by Charudattan (1990) could guide the study of host-pathogen associations. It is essential that weed scientists and agronomists reach a consensus on what constitutes a satisfactory level of control for a given weed problem. The usual procedure begins with a survey of disease occurrence within the weed community in the country and the crop of interest. This should include noncultivated areas where the pathogen-host cycle has existed undisturbed for many years (Templeton 1983).

Biotic and abiotic factors influence populations of both host and pathogens, so that even though diseases eventually become endemic, epidemics occur naturally only on a microscale. Endemic disease is a result of homeostasis between host and pathogen (Charudattan 1988). The classical biocontrol tactic is to search the area of a weed's origin for diseases normally absent in areas where the weed has become a problem. The inundative biocontrol tactic using fungal plant pathogens has been based on using indigenous pathogens that are exempt from quarantine regulations. Because they have coevolved with native plants and weed hosts, selection for host specificity and adaptation to regional ecoclimatic conditions has occurred already (Charudattan 1988). An endemic pathogen may be assisted to initiate epidemic disease by inundative application of inoculum.

The high host specificity of fungal plant pathogens is a strong argument for using them as mycoherbicides (Hasan and Ayers 1990). Any particular fungus, however, has its own history of evolution. If it has been abundant over a wide range of the target species for a long time, then the possibility of coevolution of some form of defense in the host is greater. Dennill and Hokkanen (1990) argued that specialized agents and their hosts may develop a degree of homeostasis which could hamper their successful use in biological control, and that new associations between biocontrol agent and target plant have more likelihood of success. Although these arguments are derived from insect associations, they also are valid for evaluating plant-pathogen associations (Hokkanen 1985) and provide a different perspective for bioherbicide research.

If the majority of important aquatic rice weeds in Southeast Asia are in their natural habitat (albeit more frequent and disturbed), and if there are few endemic diseases, then the idea of Hokkanen (1985) about exploiter species is a potentially fertile area of research. Effective biocontrol agents are seldom found among the usual exploiters of a target weed. More destructive agents are more likely to be found among exploiter species from outside the native area of the weed (Hokkanen 1985). *R. alismatis* in southern Australia is an example (Cother et al 1994). The pathogen has coevolved with *Alisma lanceolatum* and *A. plantago-aquatica* for decades. Leaf necrosis is only observed on maturing plants of both species, presumably because there is insufficient natural inoculum early in the season. However, inoculation of seedlings with *R. alismatis* causes stunting in *A. lanceolatum* and, to a lesser extent, in *A. plantago-aquatica. A. plantago-aquatica* is an old world host of this fungus (the first record is almost 120 yr old). Inoculating seedlings of *Sagittaria guyanensis,* a species which does not occur in Australia and which has not been reported as a host of this pathogen, with *R. alismatis* resulted in a severe effect (Cother 1994). It appears that *R. alismatis* and *S. guyanensis* represent a new exploiter-target association.

Potential bioherbicide agents could be identified by following the pattern suggested by Hokkanen and Pimentel (1984):

1. Identify pathogens from herbarium surveys of disease occurrence on plants in the same genera or family elsewhere in the world. A fungus with a wide host

range need not be excluded as it may have a selective niche for weed control where other potential nontarget hosts are absent.

2. Obtain pathogens from a climatic region similar to that in which the target weed is growing. The importance of secondary infection consequent to the primary application of the biocontrol agent should not be overlooked; understanding the epidemiology of the pathogen may contribute to increased disease severity (Yang and TeBeest 1993).

Such an approach to acquiring potentially inundative agents need not be as risky as may first appear. National and regional centers such as ASEAN PLANTI already take a unified approach to the introduction of biological control agents, dissemination of information, and training of personnel (Sastroutomo 1992). Such centers could facilitate involving the countries of Southeast Asia in an expanded approach to biocontrol based on sound quarantine practices.

Assessing bioherbicide efficacy

Evaluation of a bioherbicide's efficacy on a target weed should include studying its effect at different growth stages of the plant. Measurements should include not only weed mortality but also plant growth rates, biomass production, and reproductive potential. Testing should include isolates from different hosts and/or geographic locations, in order to compare variation within the pathogen; that would increase the chances of selecting the most virulent isolate. Host range studies conducted with potential pathogens should be as realistic as possible (Cother 1975) for the plant, the pathogen, and the environment (Watson 1985), and should challenge taxa that represent the full range of plant genetic diversity within the area of intended use (Weidemann and TeBeest 1990). Performance under appropriate conditions in the field should be the final determinant of efficacy (Charudattan 1988). If an inundatively applied inoculum is packaged in any adjuvant (i.e., nutrient sources, wetting agents, ultraviolet protectants, etc.), host range assessments should take into consideration that natural dispersal of inoculum from diseased plants to beyond the ricefield may not pose a threat to other plant species because of the absence of specific enhanced requirements for infection.

Herbicide industry involvement

For bioherbicides to become a practical reality, the herbicide industry must become involved in small niche markets (Watson 1992a). These markets, however, are not economically attractive to many agrochemical companies (Hess 1992). Even while recognizing the usefulness of bioherbicides in small niche markets, the chemical industry has narrow, fixed perceptions of the future value of commercial bioherbicides (Wilson 1990) and, in some cases, unrealistic expectations (Powell 1993). Commercialization is influenced primarily by the views of the larger chemical pesticide companies. That relatively few marketable biocontrol agents are available appears to be due to the absence of a broad industry perspective (Watson and Wymore 1990).

Charudattan (1988) and Watson and Wymore (1990) discussed perceived limitations to the development of biocontrol agents. Those limitations can be classified as basically biological, technological, environmental, legislative, or economic. Apart from the biological aspects, none are peculiar to the development of bioherbicides, but apply equally to the development of chemical herbicides. The validity of the limitations that are perceived also can be questioned.

Dew period requirement. The requirement for a long dew period (plant surface wetness conducive to spore germination) is often cited as a weakness of bioherbicides which will limit their usefulness (Yang and TeBeest 1993). However, the registration and marketing of BioMal® (Makowski and Mortensen 1992) was not hindered by environmental requirements which at first appeared to be very restrictive (12-15 h dew period following application or precipitation >6 mm within 48 h of application, coupled with temperatures <20 °C and overcast skies). This illustrates that the constraints seen by many to the development of bioherbicides can be weakened or removed if there is sufficient interest. Moreover, the moist microenvironment immediately above a water-soaked ricefield will be more favorable to pathogenesis than the highly variable environments of many other cropping situations.

Specificity. The ambivalence of the outlook for mycoherbicides is exemplified by the fact that high specificity in a biocontrol agent is simultaneously seen as a prerequisite for (Hasan and Ayers 1990) and an economic hindrance to (Templeton and Heiny 1989, Greaves and MacQueen 1990) their development. Ironically, high target specificity is seen by the agrochemical industry as a significant achievement for chemical herbicides (McMinn and Thomas 1991). A general impression gained from reviewing the literature on mycoherbicides is the widely held belief that biocontrol agents will only succeed if they mimic conventional chemical herbicides. Otherwise, there is no need to develop an additional agent, despite any potential environmental benefit (Charudattan 1988). Optimistically, however, perceived limitations to bioherbicide development appear to be surmountable by research and by the application of recent advances in biotechnology (Templeton and Heiny 1989).

Economic. Economic limitations, particularly market size, are valid from the perspective of industry involvement and profitability. Given a very favorable development cost advantage (Watson and Wymore 1990) and public sector involvement in discovery/early development phases, bioherbicides should become more attractive to commercial enterprise than they are at present. But should there be many failures on the research path to success, the possibility of significantly reduced costs has been questioned (Powell 1990). This is ironical, given that only one of several thousand candidate synthetic chemicals ever enters the marketplace. We are aware of the failures from publicly funded biological herbicide research, but we are not privileged to see similar information on chemical herbicides developed within the proprietary confines of industry.

Commercial development of bioherbicides is only impeded when we demand techniques that are beyond current biological and physical knowledge and ability. Applying known technology or pursuing research on formulations are not constraints. Weed scientists and pathologists are not required to develop needed technology by themselves; a good deal of the research in nonrelated fields (e.g. pharmaceuticals, food technology, industrial microbiology, polymer chemistry) can supply methods adaptable to the development of bioherbicides. The discussion on perceived constraints by Greaves and MacQueen (1990) concludes with the declaration that these issues can be overcome, that they are not real constraints. Constraints that do exist should be viewed as opportunities for achievement (Dorschner 1983). Yet 13 yr after this advice was published, the issues raised are still seen as shackles, not challenges. The impetus for bioherbicide development will not be assisted by perpetuating a belief in constraints (Auld and Morin 1995).

Overcoming limitations

Despite the optimism I hold, it cannot be denied that there are biological limitations to some host-pathogen associations which, without considerably more research, will impede further development (Cartwright and Templeton 1988). These limitations should be seen within the context of likelihood of success. For example, lack of sporulation by a pathogen in culture may not prevent its further development as a mycoherbicide if mycelia fragments are infective and could be produced locally. Tanaka et al (1992) found that mycelia suspensions of *N. scirpicola* supplemented with nutrients produced the same disease incidence and severity on *E. kuroguwai* as did spore inoculum. Bayot et al (1992) reported that an unnamed pathogen of *S. zeylanica* did not sporulate in culture, and that the disease was only observed in older plants. Sporulation studies with this fungus are clearly a fertile area of research; mycelia inoculum should be tested in conjunction with chemical adjuvants to increase susceptibility of young plants. The same fungus was pathogenic to, but did not kill, the important ricefield weed *Monochovia vaginalis,* and therefore was not considered a bioherbicide prospect. No mention was made by Bayot et al (1992) of measurements of competitive ability, biomass accumulation, or reproductive capacity of infected weeds in a mixed species situation. It would be premature to discard a pathogen if such studies are incomplete. The composition and type of medium on which growth and/or sporulation is induced can impact directly on spore viability, yield, and virulence. In each instance, research is needed to determine the optimum conditions for production of the most stable and durable propagules (Morin 1992).

Improving performance

Efficacy or field performance of a potential bioherbicide may be improved in the following ways:

- Normal strain selection, which offers excellent opportunities to enhance desirable traits (Watson 1992a).
- Genetic manipulation, which may be simple, e.g., fungicide-tolerant strains developed by induced mutations (Smith 1991) or more complex, e.g., host range modification (Sands et al 1990). The prospects of development and release of genetically modified biocontrol agents are bright, in particular be-

cause they are likely to be applied in habitats in which genotypically and phenotypically similar organisms already exist (Wilson and Lindow 1993).

- New application technology. The areas of invert emulsions or similar means of enhancing virulence (Boyette et a1 1991, Egley et a1 1993) and adjuvants to prolong spore longevity before or after application (Templeton and Heiny 1989) are promising.
- Combining a chemical herbicide and a bioherbicide or, if the two are not directly compatible, applying a chemical herbicide shortly before or after the bioherbicide. This allows incorporating application into other management activities and, equally important, allows the chemical to compromise host physiology, aiding infection and/or disease progression (Sorsa et a1 1988, Altman et a1 1990). In many instances, the rate of chemical herbicide applied can be considerably less than recommended when it is the sole control measure (Smith 1991).
- Using microbial facilitators, such as bacteria (Schisler et a1 1991) or fungi (Cother 1992). These may act as synergistic or early subsidiary colonizers to augment disease.

ADVANTAGES OF BIOHERBICIDES

Cost of development

Much of the expense of chemical herbicide development is associated with toxicology, metabolism, and residue research required by government regulation. These studies prolong the time between discovery and market introduction. The United States Department of Agriculture/Environmental Protection Agency protocols categorize bioherbicides as biorational pesticides because of their nontoxic mode of action (Trujillo 1992). Such an approach followed by other countries would contribute to lowering the registration costs of biocontrol agents.

In spite of the high development costs of conventional herbicides, the agrochemical industry still views with optimism the discovery and development of new synthetic chemicals while simultaneously viewing with pessimism the perceived problems associated with the discovery and development of biologicals (Williams 1992, Whitton and Oakeshott 1992). This optimism exists even though these innovative crop protection chemicals may not yet have been invented (Evans 1992, Whitton and Oakeshott 1992), and the properties desired may mirror the already extant advantages of biological agents (Scheurer 1987, quoted in Pfalzer 1993). Overall, the problems associated with biological control agents are no greater than those associated with synthetic molecules, although there are understandable reasons why the private sector should favor synthetics.

Although the concept of return on investment was paramount in the development of the mycoherbicide DeVine®, it is clear that constraints to its development (Kenney 1986) were overcome only because of the will to do so. From a commercial point of view, laboratory-produced inoculum was unacceptable for both Devine® and College® (Bowers 1986). The successful inoculi were produced, however, when appropriate research was carried out.

Alternative means of production

Much of the discovery and early development of biocontrol agents is carried out and funded by public institutions, while later development and registration is seen as the domain of the private sector (Templeton 1990, Marois 1992, Turner et al 1992). Where commercialization is not likely to occur because of market size or industry perspective, there may be a role for national and international agencies to undertake further research and, if appropriate, adopt orphaned mycoherbicides (Templeton 1992). In particular, this extended role will be needed where analysis of wider social and environmental costs necessitates alternative weed management tactics within which biological control could play an integral part. Consistent with this approach, but not the sole outcome, is the potential for inoculum production on a local scale, at the village level (Watson 1992a). The mass production of the entomophagous fungus *Beauveria bassiana* in Chinese villages, using simple substrates in bamboo trays, illustrates this approach (Hussey 1990). Contamination problems are overcome by high inoculation rates. Community or village level production of biological control inoculum has the obvious advantages of proximity to the end user (obviating the need for long shelf life) (Auld 1993), low raw material and labor costs, and replacement of imports. It also avoids the criticism that the desire to relieve the drudgery of hand pulling of weeds is based more on the interests of powerful commercial forces to penetrate a market than on concern for labor hardships (Alstrom 1990).

Safety

Bioherbicides may have some limitations in common with agrochemicals. For example, control of one weed may lead to its replacement by another. However, many of the problems associated with pesticide use are less relevant when bioherbicides are used. Increased application resulting in decreased efficacy; greater complexity of pest problems; nontarget damage; poisoning during production, distribution, and application; faulty sprayers; nonexistent or poor first aid provisions; and unequal sharing of benefits and environmental risks among community groups (Soerjani 1988, Forget 1991) are problems of chemical herbicides not shared by biological agents.

Appropriate techniques for applying pesticides are critically important to the safety of the pesticide applicator (Mohan 1987, Alstrom 1990, Matthews and Bateman 1990). Chemical herbicides increasingly are being implicated in poisoning cases in less developed countries, often due to careless attitudes and dangerous practices (Forget 1991). Although it is folly to consider any concentrated substance as completely harmless, plant pathogens in general have very low or no mammalian toxicity. This means there is considerably less risk to an inadequately or inappropriately protected operator who may also have low literacy from a biocontrol agent than from some currently available chemical herbicides (Alstrom 1990).

Similarly, the risks of bioherbicides to nontarget species are low due to host specificity and to emphasis on indigenous species. Even exotic exploiter species have limited risk associated with their use if host range studies are performed adequately. The often cited advantage of the environmental safety of biological control agents should ease the passage of bioherbicides through legislative procedures, which are much more of a minefield for conventional agrochemicals and likely to remain so (McMinn and Thomas 1991, Pfalzer 1993).

CONCLUSIONS

The approach to using bioherbicides in less developed areas of the world should be more broadly based and more interdisciplinary than the narrow conceptual approach imposed on bioherbicide research for capital-intensive western agriculture. My assertions here conflict with those of Charudattan (1990) and others who contend that only those pathogens capable of killing, not merely stressing, target weeds should be considered for development. There is evidence that this restrictive attitude is changing (USDA-ARS 1994), and that weed management can be as effective as total elimination.

The development of a number of successful mycoherbicides is testimony to the viability of the concept. Each host-pathogen relationship is unique. Individual relationships may have inherent problems that will limit their development as bioherbicides (e.g., poor sporulation, very long dew requirement) but these are individual constraints peculiar to a single association. The overarching constraints to the development of bioherbicides for rice production are, in the long run, largely attitudinal. Perpetuating the idea that constraints exist to the development of bioherbicides on the premise that a problem may be identified further along the research track is myopic. Such thinking continues the bias against biological agents.

As market forces and legislative requirements cause contractions in the agrochemical industry and increase the emphasis on major crops (Ellis 1992), two options lie ahead. If attitudes toward biocontrol do not improve, with research funding proportional to investments in synthetic chemical research, the present “them” and “us” attitude toward weed control will continue. If bioherbicides cannot shake off the stepchild image given them by agrobusiness, the importance of the involvement of national or international agencies will increase. An international bioherbicide institute (Templeton 1992), with satellite stations at IRRI, MARDI, ASEAN PLANTI, and other appropriate regional locations, could focus on bioherbicide research, training, and technology transfer. Small specialist biotechnology companies which do not require a global approach to justify project involvement could provide venture capital for development and marketing into the more industrialized economies of Japan, Korea, and Taiwan, China.

The prospects for discovery and development of bioherbicides for major rice weeds in Southeast Asia are excellent (Watson 1991, 1992); there will never be a better chance for their acceptance (Powell 1990). The challenge is to adopt a more pragmatic research philosophy, one designed to create new approaches appropriate to the social environment of the less developed regions of the world.

Recommendations

- The validity of comparing bioherbicides with chemical herbicides should be rigorously challenged. The comparison is inappropriate and diverts attention from the specific characteristics of each product that are useful in integrated weed management.
- The search for candidate bioherbicide agents should not be confined solely to indigenous pathogens but should also consider the use of new exploiter-target associations.
- The effects of disease on weed biomass production and weed competitiveness should be the principal assessment criteria, not the degree of weed mortality.
- Variance of any one candidate pathogen from the profile of the ideal bioherbicide should not be regarded as an insurmountable barrier to further progress.
- A regional arrangement of cooperative research should be established to examine orphaned bioherbicides, with research directed at improving properties of a candidate pathogen that are considered impediments to its adoption.

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GENETIC IMPROVEMENT OF RICE FOR WEED MANAGEMENT

G.S. Khush

As the cost of agricultural labor continues to increase, many farmers in a number of Asian countries are switching from transplanting to direct seeding their rice crops, and are using more herbicides rather than depending on hand weeding for weed control. If the trend of increasing dependence on heavy use of chemicals for pest control is to be reversed, alternatives to herbicides are needed for weed control.

One weed management strategy that has not been exploited to any great extent is varietal improvement. The possibility of incorporating traits into improved rice cultivars that would reduce the need for applying herbicides to the crop is worth exploring. Plant traits of interest include competitiveness with weeds, seedling emergence under anaerobic conditions, allelopathy, tolerance for parasitic weeds, and resistance to herbicide.

PLANT TRAITS FOR WEED COMPETITIVENESS

Longer growth duration and morphological characteristics such as early seedling emergence, seedling vigor, faster growth rates that produce a dense canopy, greater plant height, and greater root volume are known to increase the ability of rice cultivars to compete with weeds (Minotti and Sweet 1981, Berkowitz 1988).

Growth duration

Yield losses due to weed infestations are greater in short- duration than in long-duration cultivars (Smith 1974, Murakami et a1 1978, Kim et a1 1984). Smith reported that long-duration Starbonnet was less affected by competition from *Echinochloa crus-galli* than short-duration Bluebelle, even though the two cultivars had the same height. Murakami's group also observed that *E. crus-galli* caused greater yield reduction in a short-duration cultivar than in a long-duration cultivar. Smith and Shaw (1966) reported that *E. crus-galli* was not nearly as competitive with medium-duration cultivars as it was with very short-duration cultivars. Belle Patna and Vegold, which mature approximately 100 d after seeding, did not have an opportunity to recover from competition from *E. crus-galli,* which appeared to mature only shortly before the rice. Ahmad et al (1977) and Kim et al (1984) also reported that a longer duration rice cultivar was more competitive against weeds than a short-duration cultivar.

Moody (1979) noted that when weeds mature rapidly, the shorter duration rice cultivars suffer competition from weeds for a relatively longer part of their crop life than longer duration cultivars. The longer growth period appears to provide time for rice to compensate for competition from weeds.

Morphology

Characters which give a plant an advantage in competing for aboveground resources include early emergence, large initial photosynthetic surface, higher net assimilation rate, higher rate of leaf production, and superior leaf arrangement (Sagar 1968). Plant height, tiller number, leaf number and length, and root volume also contribute to competitiveness.

Plant height. Plant height is highly correlated with competitive ability—the taller the rice plant, the lower the yield reduction due to weeds (Jennings and Aquino 1968, Jennings and de Jesus 1968, Jennings and Herrera 1968, Ahmad et al 1977, Moody and De Datta 1982).

Tiller number. Tillering capacity has been found in some studies to be correlated with competitive ability (Jennings and Aquino 1968); other studies concluded that tillering was not related to competitive ability (Kawano et al 1974). My own observations agree with those of Jennings and Aquino: high-tillering cultivars develop their leaf canopy faster and crowd out weeds.

Leaf number and length. Strong competitors have more leaves than weak competitors. Cultivars with long, droopy leaves are more competitive than those with short, erect leaves (Jennings and Aquino 1968). Traditional cultivars are usually tall and low-tillering, with long, droopy leaves that form a wide angle with the stem– advantages in competing with weeds.

Roots. Roots are the foundation of plants, yet they have been studied relatively less often than aboveground plant organs. A strong root system will withstand competition with other cultivars, intercropped species, and weeds (Janssen et al 1990). Cultivars differ as much in the plant parts below the soil surface as in parts above the ground. For example, cultivars differ in root elongation, degree of root branching, overall length of roots for a given soil volume, and diameter of roots. For competition for substrate resources, the characters needed are a more rapidly produced root system, a more extensive and strategically placed root system, more rapid uptake of nutrients, and greater drought tolerance (Sagar 1968).

TOLERANCE FOR ANAEROBIC CONDITIONS

Sowing pregerminated seeds into standing water is practiced in some areas (such as in California) and some U.S. cultivars have been bred for their ability to emerge through standing water. This characteristic is effective for weed control because most weed seedlings cannot emerge through standing water.

Now some farmers in the tropics are beginning to seed into standing water. But current tropical rice cultivars do not have a strong ability to emerge through standing water. In temperate areas, low water temperatures and sufficient dissolved oxygen in the water sustain seedling growth and emergence; this makes it possible for many rice cultivars bred for those areas to emerge through the standing water. In the tropics and subtropics, however, water temperatures are high and the amount of dissolved oxygen is negligible; most current tropical rice cultivars emerge poorly.

Recently, researchers at IRRI (Yamauchi and others, unpubl.) screened tropical rice cultivars for their ability to emerge after seeding in standing water. Two traditional cultivars, ASDl and CO 25, and two improved cultivars, IR41996-50-2-1-3 and BR 1870-89-1-1-1, showed much better emergence than other standard cultivars. Stand establishment was excellent. Weeds were suppressed by plant populations and standing water. Adoption of water seeding using cultivars tolerant of a low oxygen floodwater environment should help reduce herbicide use for weed control.

ALLELOPATHY

Plant allelochemicals or allelopathic chemicals are secondary plant metabolites that play an important role, sometimes beneficial, sometimes detrimental, in plant-plant, plant-microorganism, and plant-insect interactions. These interactions are important ecological factors that influence plant dominance, succession, and crop productivity. Allelopathic substances may be released into the environment from plants by means of volatilization, leaching, root exudation, and decomposition of plant residues in the soil. Some allelochemicals serve as weed control agents and, if present in rice, might reduce the need for herbicides.

Some rice cultivars have been reported to produce weed-suppressing allelochemicals (Smith 1988, Chou 1989, Dilday et al 1989, Dilday et al 1996). Dilday et al (1996) found rice accessions from 27 countries that demonstrated allelopathic activity. Smith (1988) observed suppression of several weed species by rice cultivars in Arkansas ricefields. Fujii (1992) used lettuce as the assay crop to screen 189 rice cultivars for allelopathic activity; he found distinct differences among cultivars. Improved japonica cultivars showed little allelopathic activity but traditional tropical japonica rice cultivars and red rice strains showed strong activity. These observations indicate the possibility of selecting donors and breeding allelopathic properties into new rice cultivars.

While it may not be possible to identify rice varieties that have allelopathic properties against all rice weeds, allelopathic compounds for some weeds may be produced by other plant species. The genes responsible for such allelochemicals could be cloned and introduced into rice through genetic transformation, leading to the development of rice cultivars with a broad spectrum of allelopathic properties against rice weeds.

It should be remembered, however, that over time, weeds may develop resistance to allelopathic chemicals. New weeds may become dominant in ricefields as the weed ecology changes with the introduction of rice cultivars with allelopathic abilities.

TOLERANCE FOR PARASITIC WEEDS

Several parasitic weeds cause yield losses in rice. *Striga* spp. parasitize dryland rice in Africa and Asia, although the problem is not serious in wetland rice (Parker 1980). Parkinson et al (1989) estimated 20-90% yield reduction in dryland rice with heavy striga infestations. Uttamen (1949) reported rice yield losses of 80-95% due to striga parasitism at the Agricultural Research Station in Pattambi, India. In some areas of Kerala, India, infestations were so severe that farmers were forced to abandon growing rice.

Preliminary work in Madagascar and the Comores identified some cultivar differences in susceptibility to *S. asiatica* (Parker 1980). Harahap et al (1992) evaluated 40 upland rice lines for striga resistance in Kenya. IR38547-B-B-B-7-2-2, IR47255-B-B-5-4, IR47697-4-3-1, and IR49255-B-B-5-2 were striga-free and were rated as highly resistant. B3913F- 16-5-St-4 and Ble Chai had only light infestation and were rated as resistant. These results support the possibility of developing rice cultivars with resistance to striga.

HERBICIDE RESISTANCE

All crops have some tolerance for one or more herbicides. This natural tolerance could be exploited in developing herbicide resistance. Modern biological tools have improved our ability to develop cultivars resistant to herbicides to which they normally would be sensitive. Such herbicide-resistant cultivars offer farmers more choices in choosing herbicides to protect their crops. If used properly, this technology could be directed toward production of crops resistant to herbicides that are toxicologically and environmentally less hazardous than those now used. This also would provide an opportunity to reduce the quantity of herbicides applied.

Today, many private sector chemical companies have their own breeding programs. There is a danger that a proprietary company might develop resistant varieties that favor their own herbicides, regardless of whether or not these herbicides are safe to human health and the environment.

The genes coded for herbicide resistance can be obtained from the crop gene pool or from organisms such as bacteria. Somaclonal variants for herbicide resistance also may be selected in tissue culture. Technology for introducing bacterial genes for herbicide resistance into rice has been developed and genes for resistance to bialaphos and glufosinate-ammonium have been introduced (Christou et a1 1991, Toki et al 1992, Cao et al 1992, Datta et a1 1992, Rathore et a1 1993). Christou showed that when progeny from transgenic plants carrying a gene for resistance to bialaphos were sprayed with herbicide, total resistance to the herbicide was expressed at levels of 500 ppm. Toki reported the development of transgenic rice plants resistant to bialaphos and phosphinothricin. Mendelian segregation of bialaphos resistance in the T_1 progeny of the primary transformants was confirmed.

Because some concerns have been expressed about the possibility of adverse effects of transgenic plants on the environment, selecting somaclonal variants for herbicide resistance in tissue culture may be more acceptable. Sulfonylurea-tolerant mutants in higher plants have been isolated (Chaleff and Mauvais 1984). Herbicide-tolerant cell lines of rice variety IR28 were selected by transferring callus into gradually higher concentrations of thiobencarb in the culture medium; plants were regenerated from the tolerant cell lines (Shin et a1 1990). It should be remembered, however, that it may be possible for genes for herbicide tolerance to be transferred to closely related wild species of rice by outcrossing in areas where wild and cultivated rice are sympatric.

PROSPECTS OF DIFFERENT PLANT TRAITS

Of the many plant traits that are competitive to weeds, it may be possible to select for some, such as rapid seedling emergence, early seedling vigor, faster growth rates, and higher root biomass. It may not be possible, however, to incorporate other traits, such as longer growth duration, greater plant height, and higher tillering, because these traits are in direct conflict with the traits (such as fewer tillers but more panicles) of new plant types now being developed for high yield potential. Development of cultivars capable of emergence in standing water under tropical conditions offers a real possibility for managing weeds in direct-seeded rice. Genetic differences for resistance to parasitic weeds appear strong enough to justify a breeding effort. Parasitic weeds, however, are a minor problem in commercial wetland rice.

Development of rice cultivars with herbicide tolerance using biotechnology tools may permit controlling weeds with lower levels of herbicides. Environmental protection concerns, however, may override the agronomic benefits of a herbicide-tolerant rice unless environmentally safer herbicides also are developed.

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USING BIOTECHNOLOGY IN GENETIC IMPROVEMENT OF RICE FOR WEED MANAGEMENT

G.H. Toenniessen

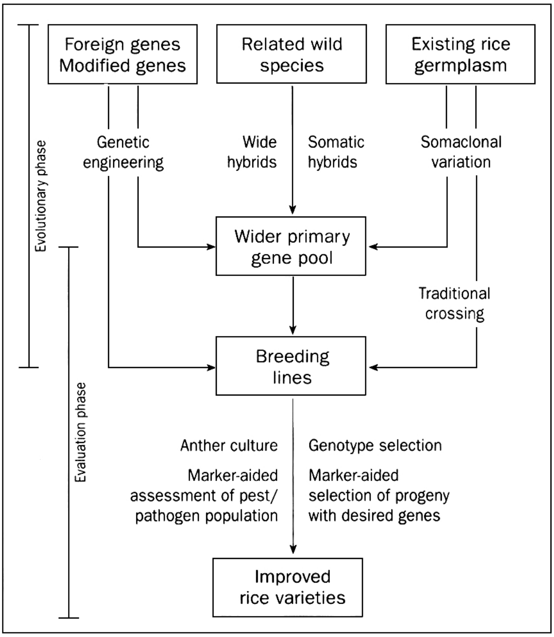
Biotechnology is on the verge of significantly impacting agriculture. Transgenic crops already are being grown commercially in the United States, Canada, and China, and soon will be grown in other countries. New biopesticides, some genetically engineered to increase their effectiveness, are being tested as alternatives to chemicals for controlling insect pests, pathogens, and weeds. The rapidly advancing science underlying the biotechnology that enabled these breakthroughs can be expected to generate a continuing stream of new and improved technology.

In work on improving cereal crops, research on rice has been at the forefront in developing relevant biotechnology. Many of the new techniques are being applied in rice breeding. Those applications have strong potential to contribute to the development of improved weed management in rice production.

APPLICATIONS OF BIOTECHNOLOGY IN RICE BREEDING

Rice breeding involves two phases (Fig. 1). During the evolutionary phase, variable populations are produced. During the evaluation phase, desirable genotypes are selected from the variable populations. Traditionally, variability has been created by hybridization and, to a lesser extent, by utilizing mutation. Embryo rescue or somatic hybridization, somaclonal variation, and genetic engineering are biotechnology tools that enable wide hybridization and significantly expand the range of variability available to breeders. Genetic engineering, which involves the precise transfer of well-characterized cloned genes into rice, should greatly increase the predictability of generating desirable variability and help breeders attain goals not feasible using conventional techniques.

A number of biotechnology tools can be applied in the evaluation phase. Anther culture is used to produce doubled haploids which help eliminate dominance variance. Molecular maps and markers of the rice genome are used to tag and follow the



1. Biotechnology tools for use in strengthening rice breeding.

inheritance of genes for important traits, in particular quantitative traits and those that are difficult to score. Molecular maps and markers of the genomes of pests and pathogens can be used to characterize and monitor the structure and dynamics of their populations, enabling more effective selection and deployment of resistant plants.

The use of both DNA-based genetic maps and markers and genetic engineering should contribute to the production of new varieties having characteristics which can be utilized in improved weed management.

Rice genome maps and markers

Rice is particularly well-suited to DNA-based genetic mapping. It is a true diploid, with one copy of most genes per haploid genome. It has a relatively high percentage (ca. 75%) of single copy DNA and a DNA content per cell smaller than that of any other grain species (Arumanagathan and Earle 1991). Two independently developed molecular genetic maps of rice are available. The one developed at Cornell University has more than 700 markers; they have been widely distributed throughout the world (Causse et a1 1994). The one developed by the Rice Genome Research Program in Tsukuba, Japan, has more than 1,500 markers; on request, they are available for research (Shomura et al 1994). The two maps have been correlated using reciprocal clone exchange. Together, they provide one of the best available resources for gene tagging and map-based gene cloning.

Molecular markers are being used routinely in germplasm management to study rice genetic diversity, classification, and phylogeny (Wang et al 1992). Researchers from more than a dozen countries are making rapid progress in finding markers tightly linked to rice genes of agronomic or economic interest and in using the markers to follow inheritance of the genes in breeding programs. Plant breeders are using the markers to pyramid multiple genes for resistance into elite breeding lines. In some cases, combinations of genes for resistance provide broader resistance than might be expected from simple additive gene action (Yoshimura et al 1994). The durability of the multiple gene-based resistance is being tested.

Markers that detect quantitative trait loci (QTLs) have been identified for a few quantitative traits of rice that are relatively easy to score, such as cooked grain elongation (Ahn et al 1993). For more complex traits, such as submergence tolerance, crosses which give significant genetic variation for component traits are being used for QTL analyses.

Research on developing rice molecular genetic mapping technology into a practical and inexpensive breeding tool continues. The ends of the most useful markers are being sequenced at the International Rice Research Institute (IRRI) to facilitate their distribution as data sets (sequence-tagged sites) rather than as bacterial clones. Microsatellite markers useful in the analysis of closely related germplasm (the type of crosses breeders usually make) are being developed. A simple, rapid method for determining the genotype of seeds before germination, without DNA isolation, has been developed at Cornell University (Chunwongse et al 1993). The analysis is conducted on supernatants from half seeds preincubated in aqueous solution. Remnant half-seeds that have the desired genotypes can be grown into plants.

The linkage maps may have applications beyond rice. Comparative mapping of cDNA clones with maize and rice and with wheat and rice demonstrate conservation of linkage relationships across substantial regions of chromosomes in these distantly related monocot genera (Ahn et al 1994). In some cases, the gene order and gene content of entire chromosomes or chromosome arms are nearly identical. This suggests that it may be possible to develop a common reservoir of markers and linkage information for several of the important Gramineae crop species, and to gain new insights by comparing them.

Rice genetic engineering

Transgenic cereal plants were first obtained in rice using protoplast-based transformation systems (Toriyama et al 1988, Zhang and Wu 1988, Yang et al 1988, Peng et al 1992). In these systems, uptake of DNA by protoplasts is usually mediated by treatments that increase the permeability of the cell membrane. Regeneration depends on delicate manipulations of both protoplasts and embryogenic cell suspension cultures. Although regeneration efficiencies are still low and many of the resulting transgenic plants are pollen sterile, these techniques have provided a basis for the first field tests of transgenic cereals and for the production of numerous transgenic rice plants containing potentially useful alien genes, including genes for herbicide tolerance (Datta et al 1992, Hayakawa et al 1992, Rathore et al 1993).

Biolistic techniques also are being used for rice transformation, with excellent results-especially as they appear to be genotype independent. Christou et al (1991) obtained transformants by subjecting 12- to 15-d-old immature embryos to electric discharge, particle-mediated transformation with a selectable marker gene. Cao et al (1992) used a helium gas particle gun to transform cells in an embryogenic suspension culture with a selectable marker gene. Transformed calli could be selected and regenerated into plants. The particle gun-based rice transformation system originally developed by Li et al (1993) has been refined into a highly efficient transformation protocol and transferred to laboratories in several countries.

Additional techniques for producing transgenic rice have been reported. Dekeyser et al (1990) developed a procedure to electroporate DNA into intact and organized rice tissues; they reported transient gene expression. The technique has been refined to give stable transformation of rice and other crops. Agroinfection was measured to show that *Agrobacterium* transferred its T-DNA into rice (Raineri et al 1990). Using a so-called “superbinary” vector, Hiei et al (1994) presented convincing evidence of stable rice transformation mediated by *Agrobacterium.*

Using these techniques, chimeric gene constructs can now be integrated into the nuclear DNA of rice plants and passed on to subsequent generations as part of the rice genome. The added gene may encode a new protein or it may alter the level or location of expression of existing proteins, or both. The site of integration appears to be random. Techniques for targeting genes to a particular site on the rice genome, or for replacing an existing gene with an engineered alternative, are in development.

The coding sequence of these chimeric genes can come from any source—rice, wild relatives of rice, other plants, microbes, animals, chemical synthesis. The regulatory sequences that will need to function in rice often will come from rice. Many of the more sophisticated and powerful uses of genetic engineering will involve highly regulated genes that are expressed at desired levels in particular cells, tissues, or organs at particular stages of development, or in response to particular environmental stimuli. Considerable research effort has been committed to understanding and utilizing these regulatory mechanisms in rice (Izawa et al 1994).

Transgenic rice plants with a variety of potentially useful genes (viral coat protein genes, herbicide resistance genes, *Bacillus thuringiensis* endotoxin genes, male sterility genes, modified storage protein genes) have been produced and are being evaluated. Within a few years, transgenic rice plants with useful new genes should be providing rice breeders with an ever expanding source of valuable genetic variability.

HERBICIDE TOLERANCE

In rice production, as with many other crops, even though much of the labor input is spent on controlling weeds, the total yield loss due to weeds is still significant. The use of herbicides as part of a rice farmer's weed management strategy is increasing in Asia, especially in association with direct-seeded rice.

Genetically engineering plants for herbicide tolerance has been an early and widely employed application of biotechnology. The first field tests of transgenic plants were approved in 1986, for herbicide-tolerant tobacco. As of May 1994,360 field trials of herbicide-tolerant transgenic plants had been approved in the United States (USDA-APHIS, 1994). Of all field trials of transgenic plants approved in OECD countries through August 1994, 36% were for herbicide tolerance, the highest proportion for any trait in the list categorized by Krattiger (1994). Of 114 field trials approved in developing countries, 28 were for herbicide tolerance. In 1995, USDA-APHIS announced that herbicide-tolerant transgenic soybeans (trade name Round-up Ready) will no longer be regulated and can now be commercialized.

At least three different strategies have been employed to engineer herbicide-tolerant plants. Perhaps the most straightforward is to identify an enzyme or other gene product that detoxifies or inactivates the herbicide. For example, the broad-spectrum herbicide glufosinate-ammonium (Basta) is a potent inhibitor of glutamine synthetase, the only enzyme in plants that can detoxify ammonia. Plants sprayed with the herbicide rapidly accumulate ammonia and die. Murakami et al (1986) cloned a gene termed *bar* from the bacterium *Streptomyces hygroscopicus,* which encodes an enzyme (phosphinothricin acetyl transferase) that deactivates glufosinate. Numerous crop plants, including rice, that have been transformed with the *bar* gene give complete resistance to the herbicide under normal field applications (DeGreef et al 1989). In fact, *bar* is so effective it is often used as a selectable marker gene in transformation experiments.

Another strategy involves identifying a gene that encodes a different form of the target enzyme, one which is less sensitive to the herbicide. The target of the herbicide glyphosate (Roundup) is 5-enol-pyruvylshikimate-3-phosphate synthase (EPSP), a key enzyme in the synthesis of aromatic amino acids. Della-Cioppa et al (1987) cloned an *epsp* gene from *Escherichia coli* encoding an EPSP enzyme less sensitive to glyphosate than the product of plant *epsp* genes. Transfer of *E. coli* genes to plants conferred glyphosate resistance.

A third strategy involves overproducing the target enzyme in transformed plants. Shah et al (1986) cloned an *epsp* gene from a glyphosate-tolerant petunia cell line. Transgenic plants containing this gene had EPSP activity about 20 times greater than that of normal plants and were tolerant of glyphosate.

Numerous transgenes for herbicide tolerance have been developed. Most have been patented in industrialized countries, but not in the less developed countries. Even where patents exist, special partnerships or licensing can usually be arranged, since the patent holder often is more interested in selling herbicide than in selling seeds. Using these transgenes, it is now possible to extend the use of a given herbicide to many additional crops. It also is possible to increase the number of herbicides that can be used on any given crop and to use completely different classes of herbicides. Rice farmers will be able to select safer and lower cost herbicides, and will have a greater number of options available for developing rotations and mixtures of herbicides which will allow multiple and mixed cropping, while reducing the risk of selecting for herbicide-tolerant weeds.

The effectiveness of such transgenes in rice was recently demonstrated under field conditions by Linscombe et al (1994). They used particle bombardment techniques to engineer commercial rice varieties Gulfmont and Koshihikari with the *bar* gene. The rice was dry seeded and flushed to a stand. Glufosinate (0, 1.12, and 2.24 kg ha^{-1}) was applied at the 4-leaf stage. All nontransgenic plants were killed within 7 d of treatment. Gulfmont-derived transgenic lines showed no visible injury. Koshihikari-derived lines displayed initial yellowing at both levels of glufosinate, but the syrnptoms disappeared within 7 d. Two of six Gulfmont-derived transgenic lines and eight of nine Koshihikari-derived transgenic lines were higher in grain yield than their checks.

OTHER OPTIONS

Although herbicide use in rice production will no doubt become more economical and more widespread as biotechnology is applied to improvements in rice varieties, increased use of herbicides could have environmental and, in some locations, social drawbacks. A better approach would be to develop integrated weed management systems within which herbicides would be used sparingly, if at all. Considerable research is needed to develop such systems; biotechnology can make important contributions.

Allelopathy is the release into the environment by a plant of substances which have an effect, often inhibitory, on other plants. Fujii (1992) and Dilday et al (1996), and others have shown that allelopathy exists in rice and related wild species. Using markers to tag genes controlling synthesis of allelopathic compounds, it should be possible to accumulate genes for the synthesis of a variety of such compounds in elite rice lines. Eventually, it should be possible to clone genes for enzymes in the biosynthetic pathway of allelopathic compounds from any plant and move them into rice via genetic engineering.

Enhanced submergence tolerance and seedling vigor also would contribute to weed management, especially in direct-seeded rice. The objective is to be able to use flooding to control weeds while still enabling the rice seedlings to get a good start. Research at IRRI has suggested that inheritance of submergence tolerance is governed by a few genes (Vanavichit et al 1994). These genes have been tagged with molecular markers through collaborative research with scientists in Thailand.

Efforts to engineer rice so that it can more readily and effectively shift its energy production pathway during submergence to the anaerobic mode are also progressing (Umeda and Uchimiya 1994, Hossain et al 1994). Similarly, it may be possible to accelerate rice seedling growth rates by increasing the expression of alpha-amylase and other enzymes which convert stored energy (starch) into useful energy for germination and early growth.

A final strategy would be to use biotechnology to develop more effective biocontrol of weeds. Numerous biocontrol agents, such as fungal pathogens, have the potential to control weeds (Julien 1992). A few such mycoherbicides have been approved for commercial use (Makowski and Mortensen 1992). Genetic engineering of pathogens to make them more effective, more specific, and safer biocontrol agents has occurred, particularly for agents designed to control insect pests (St. Leger et al 1992, Wood and Granados 1991). Similar research on pathogens of weeds should improve this technology and help make it available as a useful component of integrated weed management.

CONCLUSION

Biotechnology already is impacting rice production. New resistant rice varieties developed in part through anther culture and wide crosses have reached farmers' fields and are contributing to pest control. Improved seeds resulting from marker-aided selection are not far behind. Rice plants with potentially useful new traits incorporated through genetic engineering, including herbicide tolerance, are being evaluated and should contribute to the development of new varieties within 5 yr. Over the long term, genetically engineered biocontrol agents will become available that can be included in integrated weed management strategies for rice production. They should help reduce the use of chemical herbicides and allow food production in Asia to keep pace with population growth, until a stable population can be fed by sustainable agricultural systems.

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IDENTIFYING ALLELOPATHY IN RICE GERMPLASM

R.H. Dilday, W. Yan, and J. Lin

Effective weed management in rice involves prevention and cultural, mechanical, chemical, and biological control (Smith et al 1977, Smith and Moody 1979). Until recently, biological control was the least used. Now, exploiting allelopathy for weed control is receiving increased attention. In 1977, it was estimated that development of new technology from allelopathics would benefit U.S. agriculture by 2% of its total production (USDA 1977).

Molisch coined the term allelopathy in 1937 to describe biochemical interactions among plants, including microorganisms (Rice 1974). Molisch's definition includes both detrimental and beneficial interactions; more recently allelopathy has been defined as any direct or indirect harmful effect by one plant on another through the production of chemical compounds released into the environment (Rice 1974).

Allelopathy occurs widely in natural plant communities and is postulated to be one mechanism by which weeds affect crop growth (Bell and Koeppe 1972, Gressel and Holm 1964, Whittaker and Feeny 1971). The allelopathic potential of weeds through the release of toxic substances into the environment, either by root exudation or from decaying plant material, has been demonstrated in about 90 species (Putnam 1986). The weeds include quackgrass [*Agropyron repens* (L.)Beauv.] (Gabor and Veatch 1981, Kommedahl et al 1959), yellow and purple nutsedge [*Cyprus esculentus* L. and *C. rotundus* L.] (Friedman and Horowitz 1971), Johnson grass [*Sorghum halepense* (L.)Pers.] (Abdul-Wahab and Rice 1967), Canada thistle [*Cirsium arvense* (L.)Scop.] (Bendall I975), leafy spurge [*Euphorbia esula* L.] (LeTourneau et al 1956, LeTourneau and Heggeness 1957), giant foxtail [*Setaria faberri* Herrm.], yellow foxtail [*Setaria glauca* (L.) Beauv.], velvetleaf [*Abutilon theophrasti* Medic.] (Elmore 1980), and tall fescue [*Festuca arundinacea* Schreb.] (Peters 1968, Peters and Luu 1984). In addition to the existence of allelopathy in weeds, crops such as rye [*Selecale cereales* L.] and wheat [*Triricum aestivum* L.] (Shilling et al 1985), sunflower [*Helianthus annuus* L.] (Leather 1983), and oats [*Avena sativa* L.] (Fay and Duke 1977) have been found to possess allelopathic activity or have weed-suppressing properties.

Putnam and Duke (1974) postulated that wild species of existing crops may have possessed high allelopathic activity, but that this character was reduced or lost as plants were hybridized and selected for other characteristics. Fay and Duke (1977) evaluated 3,000 accessions of *Avena* spp. germplasm for production of scopoletin (6-methoxy-7-hydroxy coumarin), a chemical identified as the allelopathic agent in a wide range of wild plants. They found four accessions that exuded up to three times as much of the chemical as the standard oat cultivar Garry.

The USDA/ARS world rice collection of 16,476 rice accessions from 99 countries is the primary genetic base for germplasm used in rice breeding programs in the United States. An examination of cultivars that have been released in the southern rice belt (Arkansas, Louisiana, Mississippi, and Texas) shows that all of the genetic diversity in those cultivars can be traced to only 22 accessions (Dilday 1990). The genetic base of rices released in Arkansas can be traced to just 13 accessions.

SEARCHING FOR ALLELOPATHIC PROPERTIES

We screened the USDA/ARS rice collection to discover if any accessions possessed allelopathic properties to aquatic and dry-seeded weed species. Development and utilization of such germplasm could lessen herbicide use in rice production, which would improve water quality and reduce environmental contamination.

Field and laboratory experiments in 1988-93 at the Rice Research and Extension Center, Stuttgart, Arkansas, were undertaken to identify rice accessions possessing allelopathic properties to the aquatic weed ducksalad.

Field experiments

Test 1. Approximately 10,000 accessions, including checks, were screened, half in 1988 and half in 1989. Cultivars were seeded in April, on a 0.75- × 0.75-m grid, 5-7 seeds per hill, with two replications. The field was a Crowley silt loam (fine montmorillonitic, thermic Typic Albaqualfs). A natural and uniform infestation of ducksalad occurs at the research center, and seeding with ducksalad was not necessary.

Allelopathic activity to ducksalad was recorded in July, at panicle initiation for most accessions. Two measurements were taken: 1) affected area (the radius around the plant where no ducksalad growth appeared or where the stand was reduced), and 2) degree of weed control within the affected area (compared with ducksalad plants m^{-2} around a control plant that had no apparent allelopathic activity).

Test plots received 84 kg N ha^{-1} as urea in a 3-way split, 41 kg at the 4th leaf stage of development, 21.5 kg 23 d later, and 21.5 kg 12 d after the second application. Plots were irrigated twice in May to ensure uniform seedling emergence, and a permanent flood was established in June.

Plant height, days to maturity, plant type, panicle type, hull cover or pubescence, hull color, lemma color, awning, lodging, and grain type were recorded.

Test 2. The efficacy of 38 rice accessions or germplasm lines identified as allelopathic for aquatic weeds in dry-seeded and water-seeded culture was evaluated in the field, in 1990 and 1991 for dry-seeded rice and in 1992 and 1993 for water-seeded rice. Four cultivars (Gulfmont, Mercury, Palmyra, and Rexmont) that have no apparent allelopathic activity were the controls.

The dry-seeded cultivars were seeded in 2.1- × 1.1-m plots, in three rows spaced 53 cm apart, with three replications. Unwanted weeds were controlled with herbicides (propanil, fenoxaprop, and bentazon). Aquatic weeds, including ducksalad, purple ammannia (*Ammannia coccinea*), and disc waterhyssop (*Bacopa rotundifolia*) that germinated after the plots were flooded were not affected by the herbicides.

When the rice was ready for harvest, the 53-cm-wide space on each side of the center row was evaluated for weed suppression. Weeds between the outside rice rows were pulled, dried, and weighed. In 1990, a core soil sample (6.5 cm diameter by 2.5 cm deep) was taken on each side of the center row of eight test accessions and three checks to determine root biomass. Soil samples were washed through a 20-mesh screen, and the roots dried and weighed.

In the wet-seeded experiments, seeds of the same 38 accessions and four check cultivars were placed in cloth bags, soaked in water for 24 h, and drained. The soaked seeds were water-seeded in 2.1- × 1.1 -m plots in three 2-cm-deep furrows spaced 53 cm apart. Plots were surrounded with metal levees to prevent movement of the rice seedlings.

Aquatic weeds ducksalad, purple ammannia, and disc waterhyssop germinated when the rice germinated. Unwanted weeds were controlled by hand weeding. Visual ratings were made 7 wk after flooding. At rice maturity, weeds between the outside rice rows were harvested, dried, and weighed.

Test 3. In 1992-93, we compared the allelopathic activity of rice in dry- and water-seeded cultures, seeded in rows or broadcast. Five allelopathic rice lines — T65/2 × TN1, IR644-1-63-1-1, IR782- 131, IR643-75-1–1, and IR788-16-1-1-1 and Rexmont, a standard Arkansas cultivar without allelopathic activity, were evaluated in a split-split plot design with four replications. Dry- and water-seeded cultures were main plots, broadcast and row seeding were subplots, and rice lines were subsubplots (2 × 1 m). Rows were spaced 53 cm apart.

In the dry-seeded culture, rice seeds were broadcast on the soil surface or seeded in 2.5-cm-deep furrows and covered with soil. In the water-seeded culture, rice seed pregerminated for 36 h was broadcast or row-seeded onto soil flooded 5 cm deep. All water-seeded plots were surrounded by a metal levee to prevent movement of rice seedlings. A bird netting protected the plots from immediately after seeding until the rice plants were 15 cm tall.

In dry-seeded rice, aquatic weeds germinated 37 d after seeding (7 d after flooding); in water-seeded rice, 5-7 d after seeding. In dry-seeded rice, unwanted weeds were controlled by propanil, bentazon, and fenoxaprop; in water-seeded rice, by hand weeding. Aquatic weeds included ducksalad, purple ammannia, and disc waterhyssop.

Visual ratings were made 7 wk after flooding. Weeds were harvested from the entire plot at rice maturity, dried, and weighed.

Laboratory experiment

Test 4. In November 1989, rice straw was collected from 26 accessions, including checks, selected for their allelopathic activity in 1988 and 1989 field tests. The accessions were separated into three groups: high (radius of more than 15 cm), medium (radius of 10-15 cm), and low (radius of less than 10 cm) allelopathic activity.

The straw was dried at 60 °C for 24 h and ground. A 100-g dried sample was added to 1 liter of distilled water and homogenized in a blender for 10 min. The mixture was filtered for 100% concentrate. The supernatant was lyophilized. Extracts were diluted with distilled water to final concentrations of 25, 50, and 100%.

Twenty lettuce seeds, 1 ml extract, and 0.15 ml Vitavax 200 fungicide (3:400 v/v) were placed on filter paper (Whatman #1) in petri dishes. An untreated check (distilled water) was included. The petri dishes were incubated at 25 °C in a germinator for 5 d, and germination percentage and radical length were determined.

The experimental design was a complete randomized design with four replications; the test was repeated once.

Test 5. Rice root and leaf tissue extracts were tested for their effect on ducksalad germination. Seven rice germplasm accessions-Chiu Chiu Ku/Nan Toh Hao, AC 1423, 1R238, CH242, YHI, IR788-6-1-1-1, and GPNO 2151 — and control variety Rexmont were planted in 137-cm rows 53 cm apart. Leaves and roots were collected at maturity, dried, and ground. Plant tissue (100 g) was extracted with 200 ml of distilled water. Fifty ducksalad seeds were placed evenly on filter paper (Whatman #1) in a petri dish (100 × 15 mm), covered with a thin layer of ground soil, and 10 ml extract was added. Petri dishes were arranged randomly in a growth chamber at 25 °C with 12 h photoperiod.

Germination was measured 5, 6, 7, 8, and 11 d after seeding. Germination percentages for each petri dish during each interval were used to develop a germination index, as described by McKenzie et a1 (1980). The test was replicated three times.

RESULTS AND DISCUSSION

Field experiments

Test 1. About 4% of the accessions (357) had greater than 10 cm activity radius of allelopathic activity against ducksalad. Of those, 23 had 17-20 cm activity radius, with 70-90% weed control (Table 1); 18 had 10-15 cm activity radius, with 50-95% weed control (Table 2). The accessions exhibiting allelopathic activity originated in 30 countries and possessed genetic diversity for a number of plant characteristics. For example, days from emergence to anthesis ranged from less than 60 d to more than 140 d; plant height ranged from less than 79 cm to more than 160 cm; grain type included short (4.50 mm), medium (5.51-6.60 mm), and long (6.61-7.50 mm) ker-

Table 1. Origin and characteristics of rice germplasm exhibiting moderate allelopathic activity (radial mean 17-20 cm) to ducksalad.

Cultivar	Origin	Radial mean activity	Weed control (%)
Basmati PAK 134	Pakistan	20	85
Kingmen T. C.	China	18	90
P828	Pakistan	18	88
Gin Shun	China	18	85
IARI 10560-India	India	18	85
Recorded as *O. glaberrima*	Pakistan	18	80
B1293 B-PN-24	IRRI, Philippines	18	80
Mamoriaka	Brazil	18	80
Dou U Lan	China	18	80
Santhi Pak-209	Pakistan	18	80
San Chiao Tswen	China	18	80
Hwei Ju	China	18	80
Juma 10	Dominican Republic	18	85
Taichung Native 1	Taiwan, China	18	85
Shuang Chiang G-30-21	Taiwan, China	18	85
India AC 1423	India	18	85
Woo Co Chin Yu	Taiwan	18	80
CICA4	Brazil	18	70
Melanothrix	Japan	18	70
IR781-497-2-3	IRRI	17	90
NSSL10/28STP8	United States	17	85
Tono Brea 439	Dominican Republic	17	85
T65/2* TN1	IRRI, Philippines	17	85
Rexmont (control)	United States	0	0
LSD (0.05)		4	14

Table 2. Origin and characteristics of rice germplasm exhibiting relatively high allelopathic activity (radial mean 13-15 cm) to ducksalad.

Cultivar	Origin	Radial mean activity	Weed control (%)
Tsai Yuan Chon	Taiwan	15	90
IR644-163-11	IRRI, Philippines	15	85
Red Khosha Cerma	Afghanistan	15	85
IET60	India	15	80
Unknown	United States	15	75
Mutant 12/42	Pakistan	15	55
Basmati 140	Pakistan	15	50
Bul Do	Korea	14	85
IR782-131	IRRI	14	85
Shah I Mahin.	Afghanistan	14	65
CH242	IRRI, Philippines	13	80
Pak116	Pakistan	13	80
Yuan Hsing 1	Taiwan, China	13	80
Afghanistan No. 2	Afghanistan	11	85
YH1	Taiwan, China	10	95
IR643-75-1-1	IRRI, Philippines	10	90
IR788-16-1-1-1	IRRI, Philippines	10	90
SH 30-21	Taiwan	10	85
Rexmont (control)	United States	0	0
LSD (0.05)		3	21

nels; and most of the genotypes that were less than 110 cm tall exhibited little lodging. These agronomic characteristics are important in selecting parents for varietal development programs.

The data suggest that germplasm from two regions, East Asia (China, Korea, and Japan) and South Asia (Afghanistan, India, and Pakistan) constitute a promising genetic base for capturing allelopathic activity to ducksalad. For example, after excluding improved IR breeding lines, 69% of the accessions identified as having allelopathy to ducksalad came from Pakistan (7); China (5); Taiwan, China (5); India (3); and Afghanistan (3). The germplasm from China and Taiwan, China, are japonica rices with short and medium grain; the germplasm from Pakistan and Afghanistan are indica rices with long grain.

Test 2. Thirty-eight germplasm accessions were evaluated in dry - and water-seeded culture. Some germplasm reduced weeds equally in both dry - and water-seeded tests, some reduced weeds more when dry-seeded, and some reduced weeds more when water-seeded (Table 3). GPNO 11904, Tsai Yuan Chon, IR782-131, IET 60 (HR12/TNl), and Mon Z Wuan reduced weed dry weight 72-83% more than the control in both dry- and water-seeded tests. Red Khosha Cerma, T65/2 X TN1, and Sh 30-21 reduced weed dry weight 80-82% in the dry-seeded tests, but only 57-61% in the water-seeded tests. GPNO 6081 and Hukushima Kaisen Mochi Select reduced weed dry weight 44-56% in the water-seeded tests, but only 0- 10% in the dry-seeded tests.

Table 3. Reduction in dry weight of ducksalad by allelopathic activity of rice germplasm in dry- and water-seeded culture.

Cultivar	Dry wt (g 2.3 m-2) reduction (%)	
	Dry-seeded	Water-seeded
Equal reduction in dry- and water-seeded culture		
Afghanistan no. 2	72	82
Tsai Yuan Chon	83	78
IR782-131	74	72
IET60	74	76
Mon Z Wuan	81	82
Greater reduction in dry-seeded culture		
Redkhosha Cerma	82	57
T65/2*TN1	80	61
SH 30-21	81	60
Greater reduction in water-seeded culture		
GPNO 6081	10	56
Hukushima Kaisen Mochi Select	0	44
Control		
Rexmont	0	0
LSD (0.05)	16	33

Test 3. No significant differences in aquatic weed suppression occurred between dry- and water-seeded cultures of five allelopathic accessions (Table 3). However, there was a significant difference between row and broadcast seeding. Aquatic weed biomass was reduced 77-83% in broadcast-seeded plots and 62-70% in row-seeded culture. T65/2 X TN1, IR788-16-1-1-1, and IR782-131 controlled aquatic weeds sufficiently to prevent yield loss in water-seeded plots, while the check Rexmont had a 29% yield loss due to weeds.

Laboratory experiments

Test 4. Rexmont and Palmyra do not show allelopathic activity in the field; IR781-497-2-3 and T65/2 X-TN1, derivatives of Taichung Native 1, do demonstrate allelopathic activity in the field. In laboratory tests using lettuce as an indicator plant, however, all four cultivars significantly reduced seed germination and radical elongation at high concentrations.

Germination of lettuce seed in 25% rice straw filtrate concentrations from Rexmont, Palmyra, T65/2 X-TN1, and IR781-497-2-3 was 96, 94, 16, and 3%, respectively (Table 4). Germination in 100% filtrate concentrations was 76, 67, 0, and 0%, respectively. Growth and development of the radical of 20 lettuce seedlings in a 25% concentration totaled 26.8, 22.4,0.4, and 0.1 mm, respectively; in a 100% concentration, the total was 8.0,4.4,0.0, and 0.0 mm, respectively.

Table 4. Effect of filtrate extracts of rice germplasm on germination and radicle growth of lettuce.

Cultivar	Extract concentration (%)	Lettuce seed germination (%)	Lettuce radicle length (mm)
Rexmont	100	75.6	159
Palmyra		66.9	89
T65/2*TN1		0.0	0
IR781-497-2-3		0.0	0
LSD (0.05)		8.4	24
Rexmont	50	93.7	417
Palmyra		88.8	356
T65/2*TN1		7.5	4
IR781-497-2-3		4.4	1
LSD (0.05)		6.9	41
Rexmont	25	95.6	536
Palmyra		94.4	448
T65/2*TN1		16.3	9
IR781-497-2-3		3.1	1
LSD (0.05)		8.1	42
	0	99.0	485

Table 5. Effect of tissue extracts of rice germplasm on germination of ducksalad.

Cultivar	Ducksalad germination (%)										Germination index	
	Day 5		Day 6		Day 7		Day a		Day 11			
	Leaf	Root	Leaf	Root	Leaf	Root	Leaf	Root	Leaf	Root	Leaf	Root
Chiu Chiu ku/Nan Ton Hao	72	9	87	21	87	21	87	22	87	25	272	58
AC1423	62	8	83	17	86	17	88	21	89	21	258	49
IR238	48	10	71	15	75	16	77	16	80	16	218	46
CH242	34	7	58	7	61	9	62	11	63	15	172	27
Yhi	58	11	80	22	85	22	87	23	87	23	250	62
IR788-16-1-1-1	45	7	68	9	73	9	73	11	75	21	210	31
GPNO 2151	41	13	72	13	82	15	83	16	85	23	221	47
Rexmont	58	12	73	29	75	31	77	31	79	38	330	82
Mean	52	9	74	17	78	18	79	19	81	23	229	50
LSD (0.05)	3		4		4		4		6		12	

Table 6. Reduction in weed root dry weight and aquatic weed dry weight of six rice cultivars that demonstrated allelopathic activity to ducksalad, compared with check cultivar, Rexmont, which demonstrated no allelopathic activity in the field.

Cultivar	Root dry weight (g kg soil^{-1})	Reduction in aquatic weed dry weight (%)
IET60 (HR12X/TN-1)	8.0	81
Sh30-21	7.5	81
IR788-16-1-1-1	7.4	87
T65/2*TN1	7.4	81
IR643-75-1-1	5.2	76
Afghanistan no. 2	4.8	81
Rexmont	0.8	0
LSD (0.05)	4.0	39

These results tend to support the theory that wild ancestors of existing crops may have possessed high allelopathic activity, and that this character was reduced or lost as the wild ancestors were hybridized and selected for other characteristics (Putman and Duke 1974).

Test 5. Root extracts of allelopathic rice cultivars reduced ducksalad germination significantly more than leaf extracts (Table 5). This suggests that compounds present in both leaves and roots, but especially in the roots, of all the germplasm accessions, including the checks, can inhibit weed germination. Most of the cultivars with allelopathic activity to aquatic weeds in the field have as much as 10 times greater aboveground fibrous root biomass than check cultivars (Table 6).

SUMMARY AND CONCLUSIONS

Approximately 4% of the rice germplasm accessions that were evaluated for allelopathy to ducksalad demonstrated some activity. The 347 accessions that demonstrated allelopathic activity also exhibited genetic diversity for such plant characteristics as plant height, maturity, grain type, plant type, hull cover, hull color, and culm strength.

In laboratory tests, allelochemicals that inhibit seed germination and radicle length of lettuce, a common indicator plant, were present in rice straw of accessions that showed allelopathic activity to aquatic weeds in the field. Tests to isolate and identify the allelochemicals that are responsible for the allelopathic activity are being conducted.

Root extracts from some germplasm accessions also reduced weed germination. These differences are important in comparing laboratory results with field results. Filtrate extracted from the same root dry-weight biomass of both allelopathic accession and checks would not be representative of field conditions.

One hypothesis is that rice plants can be separated into four categories: 1) plants that do not produce allelochemicals and have poorly developed fibrous root systems; 2) plants that do not produce allelochemicals but have well-developed fibrous root systems; 3) plants that produce allelochemicals but have poorly developed fibrous root systems, with a small avenue of egress for the allelochemicals; and 4) plants that produce allelochemicals and have well-developed fibrous root systems which act as an enhanced release mechanism or an enlarged avenue of egress for allelochemicals into the environment. Experiments have been initiated to test this hypothesis.

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Use of herbicides in Asian rice

ECONOMIC AND TECHNOLOGICAL INFLUENCES ON HERBICIDE USE IN THE LESS DEVELOPED COUNTRIES OF ASIA

K. Moody

Production and consumption of rice are closely associated with the nations of South, Southeast, and East Asia. In 1991, 520 million tons of rice were produced on 148 million hectares (IRRI 1993). Current production, however, cannot be sustained, much less increased to the level needed within the next 25 yr, without greatly increasing the productivity of current cropland (Barbier 1989).

Improved weed control will be an essential component of the technology needed to achieve that objective (Williams 1992). Herbicides are currently the most widely used method to control weeds. This agrochemical can be expected to be a major growth area in the pesticide industry of less developed countries for at least the next decade. For example, the rice herbicide market in China and India could increase from a total of US\$67 million to more than \$550 million (Woodburn 1993). Over the next 6-8 yr, average global expenditure on rice herbicides could exceed US\$10 ha^{-1}, compared with the current US\$7.50 ha^{-1}.

In the Philippines, sales of pesticides during the 5 yr 1985-89 grew an average 19.8% for herbicides, 13.8% for insecticides, and 2.9% for fungicides. Most of the herbicide (85%) was applied to rice, with more than 1 million ha treated nationwide (Cruz 1990). Herbicide use on rice increased from 54% of all herbicide sales in 1981 to 82% in 1987 (Rola and Pingali 1993).

In India, herbicide use during the 1980s dramatically outstripped use of other pesticides. Herbicides were only 2% of total pesticide use in the 1970s; they now account for 12% of the herbicide market. About 2,000 t of herbicides are used annually on more than 4 million ha of rice (Mehta 1992). In the Punjab area alone, herbicide use in transplanted rice increased almost 600%, and 90% of the ricelands are now treated with herbicides (Brar and Randhawa 1992). Herbicide use also is increasing in less favorable rice-growing areas.

In Thailand, the rice herbicide market has increased dramatically. Products such as bensulfuron-methyl, pretilachlor, and fenoxaprop-ethyl have benefited; older herbicides such as 2,4-D and butachlor continue to be important as well (Woodburn 1993).

In Malaysia, herbicide use in rice in the Muda irrigated area increased 700% in 9 yr, from 166 t in 1980 to 1,318 t in 1989 (Ho et al 1990).

FORCES PRESSURING HERBICIDE USE

The increasing use of rice herbicides can be attributed to the substitution of chemical weed control for manual weeding in irrigated rice and to a growing preference of farmers for direct seeding their rice instead of transplanting.

Labor availability

Manual weeding of rice has a high labor requirement. A major factor affecting rice culture and weed control technology in many countries is the steady movement of labor from rural to urban areas, as industrialization creates more attractive employment opportunities.

Crop establishment practices

As transplanting costs increase, farmers increasingly are switching to labor-saving direct seeding of their rice crops. Weeds become a more serious problem, and farmers adopt herbicides (Tan et al 1992). Erguiza et al (1990) reported that farmers who wet-seeded their rice relied more heavily on herbicides to control weeds than did farmers who transplanted.

Shifts in weed flora

In Peninsular Malaysia, increased weed problems and the shift in weed flora that resulted from adoption of direct-seeded rice have boosted use of herbicides, and the type of herbicides used has changed. In transplanted rice, phenoxy herbicides were applied 10-14 d after transplanting to control broadleaf weeds and sedges. With direct seeding, grass weeds have become dominant, resulting in a shift to residual herbicides applied soon after sowing (Hamzah and Ramasamy 1993).

Herbicides were introduced in Sabah, Malaysia, along with wet seeding. Molinate is used to control increased grass problems in wet-seeded rice in Kota Marudu. In Cho Moi District, An Giang Province, Vietnam, weed species shifted as crop establishment changed from transplanting to wet seeding. Sedges dominate in transplanted rice due to standing water in the field; in wet-seeded rice, grasses dominate. This has changed the herbicide used, from 2,4-D to pyrazosulfuron-ethyl.

COST-BENEFIT OF HERBICIDE USE

Herbicides are a highly productive input, with the marginal return for every dollar invested strongly positive. As a general rule, the higher the wage rate or the more severe the weed infestation, the more likely herbicides will be more economical than hand weeding.

In Peninsular Malaysia, only 46% of transplanting farmers use herbicides, but 95% of direct seeding farmers do. The wide use of herbicides in direct-seeded fields is to be expected, given the weed problems that accompany the practice. Without herbicides, yields would be seriously reduced (Wong 1993). US\$4.25 ha^{-1} is spent on herbicides for the transplanted crop; US\$29.96 ha^{-1} for the direct-seeded crop.

In 1993, in Iloilo Province, Philippines, a wet-seeded rice farmer using pretilachlor + fenclorim, the most widely used herbicide in the province, at the recommended rate of 0.3 kg ai ha^{-1}, would spend US\$24.20 ha^{-1} to control weeds. With a farmgate price for rice of US\$0.20 kg^{-1}, a yield increase of only 121 kg ha^{-1} would cover the cost of the herbicide. Hand weeding once would cost US\$l28 ha^{-1} (40 people × 2 d × US\$1.60 d^{-1}), more than five times the cost of herbicide.

A similar situation occurs in wet-seeded rice in the Mekong Delta, Vietnam: hand weeding is at least five times more expensive than herbicides (Moody 1992). In West Java, Indonesia, hand weeding of transplanted rice costs about US\$33 ha^{-1}, equivalent to 280 kg of rough rice, or 16% of average yield. This is three to four times the cost of herbicides (Burhan 1993).

The cost advantage of wet seeding more than compensates for herbicide cost, and use of herbicides is increasing even with higher herbicide prices (the real price of butachlor increased 15% between 1979 and 1986) (Erguiza et al 1990). In the Philippines, rice herbicide prices increased an average of 48% within 10 yr, while labor costs for weeding increased 78%.

In Thailand, rice herbicide prices have not increased appreciably for the last 6 yr; the price of thiobencarb + 2,4-D has not increased since 1982. The cost of labor, however, has more than doubled (P. Vongsaroj, 1993, National Weed Science Research Institute, Department of Agriculture, Bangkok, Thailand, pers. commun.).

In Muñoz, Nueva Ecija Province, Philippines, in 1994, the cost of pretilachlor (US\$21.50 L^{-1}) was equal to 1.7% of the value of the crop (5 t ha^{-1} at US\$0.25 kg^{-1}). Butachlor cost only \$10.80 L^{-1} and piperophos + 2,4-D \$12.30 L^{-1}. Clearly, the cost of herbicides is a relatively small part of the total value of a rice crop.

IMPACTS OF INCREASED HERBICIDE USE

Weed shifts

Weed control does not simply remove one species from within a plant community, it alters the relationships among constituent species. Disturbing the environment, altering competitive interactions, and creating stress disrupt the natural pattern of development (Cook 1990). Weeds that were of secondary importance may emerge as primary problems.

In Japan and Korea, weed management in rice is herbicide-based (Kim 1993). Overreliance on herbicides has not only failed to give long-term control of weed problems, it has resulted in quantitative changes in the structure of the weed population, in just 5 yr.

Widespread adoption of molinate in the Muda area, Malaysia, to control *Echinochloa* species resulted in their displacement in favor of *Leptochloa chinensis* and *Ischaemum rugosum.*

In the Philippines, perennial weeds such as *Scirpus maritimus* and *Paspalum distichum* have become troublesome where herbicides have been used to control annual weeds such as *Echinochloa crus-galli* and *Monochoria vaginalis* (Vega et al 1971).

In Indonesia, *E. crus-galli* is increasing in transplanted rice because of the continued use of 24-D and metsulfuron-methyl to control broadleaf weeds (Moody 1991).

Development of herbicide resistance

An important result of continual application of the same herbicide is the evolution of weed species with resistance to herbicides. Giannopolitis and Vassiliou (1989) reported that *E. crus-galli* collected from ricefields in Greece where propanil had been applied for more than a decade was not killed by 8 kg ai ha^{-1}, but the weed collected from vegetable fields was killed by 2-4 kg ai ha^{-1}. Propanil-resistant *Echinochloa* species also have been found in Costa Rica (Garro et al 1991) and the United States (Carey et al 1992).

Butachlor-resistant *E. crus-galli* has been reported in China (Huang and Lin 1993). More resistance is observed where butachlor has been applied for 8-12 yr and where two rice crops are grown per year.

In Malaysia, a resistant form of *Fimbristylis miliacea* was found in ricefields where 2,4-D had been applied for 25 yr; the weed was not controlled by six times the recommended rate (Ho 1992).

As use of herbicides increases over the next 5-10 yr, resistance is expected to become a much more serious economic problem (LeBaron and McFarland 1990). The problem can be avoided or reduced by exploiting a wide range of crop protection measures rather than overreliance on chemical inputs (Tan et al 1992).

EXTERNALITIES OF HERBICIDE USE

Environmental fate

Despite increasing use of herbicides in the ricefields of South and Southeast Asia, especially when the crop is direct seeded, there is surprisingly little information on the environmental fate of the chemicals. For a long time, the economics of crop protection dealt with gross margin of the crop, with total farm income, not with the environment of the farm and surrounding area.

Pesticides, however, have effects beyond the farm gate, so-called externalities. Externalities have value because of some people who can afford to pay for health and happiness, for clean water, for fresh air, and for healthy food (Zadoks 1992).

One of the main difficulties associated with the use of farm chemicals is ensuring that there is no pollution of water, for any of its many uses. Caution must be used when applying herbicides in floodwater to avoid movement of the herbicide into groundwater and to keep treated water from contaminating other water as it drains from treated fields (Bayer 1991). It is highly dangerous to introduce any chemical into waterways without first determining whether it could have any ill effects on human and animal health. III effects may be direct, in that they affect the quality of domestic water supplies, be distasteful to livestock or wildlife, or create a hazard for irrigated crops. They may be indirect, in that decomposition of dead plant material causes a problem.

The need for effective protection against water pollution is acute and urgent for protecting the welfare of rural people living in remote villages and using water from irrigation canals for drinking, bathing, and other household purposes (Cheam 1974). In Malaysia, 51.3% of farmer respondents said that they had experienced symptoms associated with pesticide poisoning. The highest incidence (24.8%) was due to herbicides, primarily 2,4-D and paraquat. Headaches and dizziness were the most frequently mentioned symptoms. However, only 12.8% said they had sought medical treatment (Ho et al 1990).

Current concerns over the environmental impact of pesticides may lead to a reduction in the number of rice herbicides available to the farmer and to social and financial pressures to reduce herbicide use. Although there are many ways the safety and effectiveness of existing products can be improved, concerns such as persistence, leachability, and adverse toxicology can only be overcome through product replacement. Industrial research aimed at discovering new products will be an important key to meeting the challenges of crop protection (Mehta 1992).

Injudicious use of herbicides

A major concern about pesticide use in rice is injudicious and unsafe use (Rola and Pingali 1993). In Sabah and Sarawak, Malaysia, paraquat is applied either alone or in combination with 2,4-D to control weeds in transplanted rice. In upland rice in northern Thailand, paraquat is applied after seeding but before crop emergence to control emerging weeds. In Malaysia, paraquat is recommended as a preplanting treatment in both transplanted and direct-seeded rice (N.K. Ho, 1993, Muda Agricultural Development Authority, pers. commun.).

The recommended way to apply herbicides is with knapsack sprayers (the most widely used method) or as granules. Farmers, however, have been known to mix liquid herbicides with sand, fertilizer (usually urea), or a mixture of fertilizer and insecticide; to apply tank mixtures of herbicides and insecticides; to apply liquid herbicides with mist blowers; and to pour undiluted herbicides directly into floodwater. Although herbicides that control weeds effectively in all rice cultures are available, farmers need guidance on how to optimize their use. Application methods that save labor, reduce exposure hazards, and avoid environmental pollution are needed.

Reasons for herbicide selection

Farmers in Iloilo Province, Philippines, consider effectiveness, price, endorsement from government technicians and chemical company representatives, availability, and popularity in selecting the herbicides they use. In Vietnam, advertising and promotion by chemical companies are important influences on farmers' decision making; the official extension system has far less influence on farmers than the pesticide industry (Jansma et al 1993).

INTEGRATED WEED MANAGEMENT

In wet-seeded rice, reliance on herbicides for weed control is high. But no single weed control technique provides a final cure. Because the weed population constantly adapts to its physical environment, a multilateral approach is needed to ensure sustainability. Ways to reduce dependency on herbicides are needed.

In the short term, widespread availability of herbicides could result in a move away from integrated weed control. Longer term factors, such as the evolution of herbicide-resistant weeds, buildup of tolerant weed species, and environmental contamination, should eventually result in greater integration of weed control practices. Cultural practices, some of which have evolved specifically as weed management practices, and weed-competitive rice cultivars will form the basis for integrated weed management strategies. Better herbicide performance at lower rates is achieved when optimum cultural practices are used. Day (1972) noted that, however powerful and effective herbicides may be, they are virtually worthless in the absence of other sound management practices. Chemicals supplement traditional methods, they do not substitute for them. Weeds are most effectively controlled by the simultaneous application of a variety of practices, the total effect of which is usually greater than the effects of individual measures employed separately.

The integration of chemical weed control into rice husbandry systems is important in providing acceptable weed management at economic levels. To be successful, weed management in rice must include cultural, mechanical, and chemical methods (Turner 1983).

CONCLUSIONS

Within the next 50 yr, the world's population is projected to more than double to 11 billion people. This will drastically increase the pressure on the land available for food production. As agriculture intensifies, man's battle with crop pests will increase. Effective weed management technology will become even more important. Cultural, chemical, genetic, and biological control technology will all contribute to developing effective integrated weed management (Mehta 1992).

Within the coming decade, weed control methods in rice in South and Southeast Asia will not differ greatly from the methods used today. However, the area treated with herbicides will increase with expansion of the irrigated area planted to direct-seeded rice and with an increase in herbicide use in the less favorable environments. More effective herbicides, applied at lower rates, will be used, but the number of applications per field per crop is unlikely to change. (A shift to herbicides that require lower application rates for the same effect is already taking place.) The net result will be a reduction in total amount of active ingredient applied. More emphasis will be placed on using less persistent, postemergence herbicides that allow farmers to respond to the nature and extent of emerging weed problems.

Williams (1992) stated the herbicide decision succinctly: “An axiom that would apply to the use situation might be ‘as little as possible and as much as necessary’.” Applying that axiom will require clear information about the components of weed flora, the effects of infestation level on crop performance, and the efficacy and cost of control. The goal will be to reduce the rate and frequency of herbicide application by combining herbicides with other practices to achieve the weed control needed.

Farmers perceive that withdrawal of herbicides would result in increased weeding costs, reduced production, lower profit, greater debt, crop failure, and hunger (L.E. Estorninos, Jr. and K. Moody, IRRI, Los Baños, Philippines, unpubl.). Such impacts, however, depend on the time it will take to develop alternative weed control measures. Profitable and efficient chemical weed control discourages the development of other practices and this makes chemical methods seem more necessary (Anonymous 1975) The lack of profitable alternatives will seriously hinder any reduction of dependence on herbicides. An assessment of backup systems for control of future weed problems is needed to be certain that a rapid response could be made to insure adequate food production (Anonymous 1975).

The relative cheapness of chemical crop protection and its ease of use is a great achievement but it is also the major constraint to the introduction of alternative methods. National authorities have the important task of creating a climate in which alternative methods of crop protection become more cost-effective (Jansma et al 1993).

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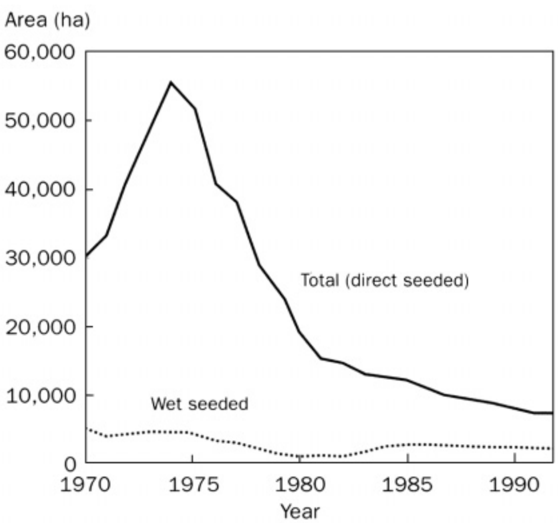
EXPERIENCE WITH RICE HERBICIDES IN JAPAN

H. Shibayama

Agricultural land in Japan totaled 5.12 million ha in 1993, with 2.13 million ha planted to irrigated rice. Other crops include wheat, barley, potato, soybean, vegetables, feed and forage crops, and fruits.

The prevailing method of irrigated rice cultivation is machine-transplanting (99% of the rice area) using young, 2-5-leaf seedlings cultivated in nursery boxes. Transplanting infant, 1-2-leaf seedlings and direct seeding have not been widely adopted (Fig. 1).



1. Area of direct-seeded rice, with proportion of wet-seeded, in Japan 1970-92.

Current methods

The primary method of weed management in irrigated rice is to apply herbicides. Small-scale rice farmers often hand-weed to eradicate barnyardgrass. Use of rotary weeders is not common because they are heavy to operate, but some farmers use them to control perennial weeds which are tolerant of preemergence or early postemergence herbicides.

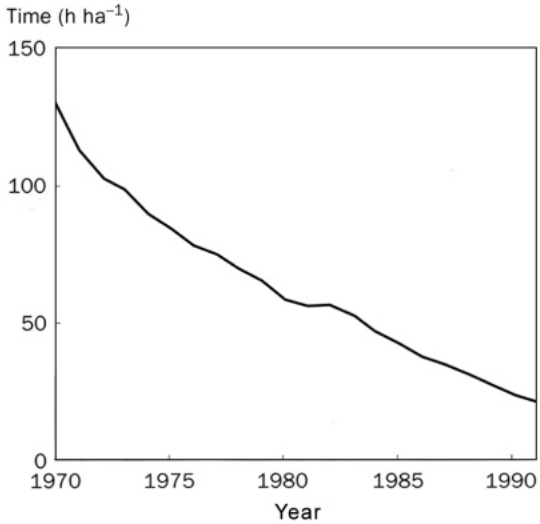
Farmers typically cultivate their ricefields in late autumn or winter to eradicate germinated winter weeds and to decompose rice straw. This cultivation also decreases perennial summer weeds by bringing their tubers or other propagules to the soil surface, where they are killed by cold, dry weather. Farmers also apply nonselective herbicides after harvest or before planting to control regrowth of weeds and to retard spring weeds (Table 1).

On transplanted fields, most rice farmers systematically apply herbicides an average of two times per season. On dry-seeded fields, herbicides are applied three times, just after seeding, before flooding at 20-30 d after seeding, and within 1 wk after flooding. Manual weeding of dry-seeded fields usually is done before flooding. On wet-seeded fields, herbicides are applied two times, for preemergence and early postemergence control.

Table 1. Area of Japanese cropped fields treated with herbicides in 1993.

Crop	Herbicide applied	Area (ha x 1000)	%
Irrigated rice	Area planted	2127	100
	Area treated	3772	177
	One-shot combination	1883	89
	Soil-incorporated application	266	13
	Soil application	697	33
	Foliar and soil application[a]	379	18
	Foliar application	266	13
	Others	282	13
Upland crops	Area planted	1796[b]	100
	Area treated	1993	111
	Soil application	1101	61
	Foliar application	892	50
Permanent crops and nonagricultural lands	Area treated	1412	
	Soil application	238	
	Foliar application	1063	
	Foliar and soil application[a]	111	

[a]Early postemergence application. [b]1990.



2. Time spent weeding Japanese ricefields, 1970-91 (includes spraying herbicide, hand weeding, mechanical weeding).

Weed control costs

Weeding costs are high. Changes in labor costs over the last 20 yr are shown in Figure 2. The average for 1991, 22 h ha^{-1}, is calculated to cost the equivalent of US$289. Herbicides cost US$347 ha^{-1}. Total cost for weeding was estimated at US$636 ha^{-1}, nearly 5% of the total cost of rice production.

HERBICIDE USE

Herbicides registered for rice

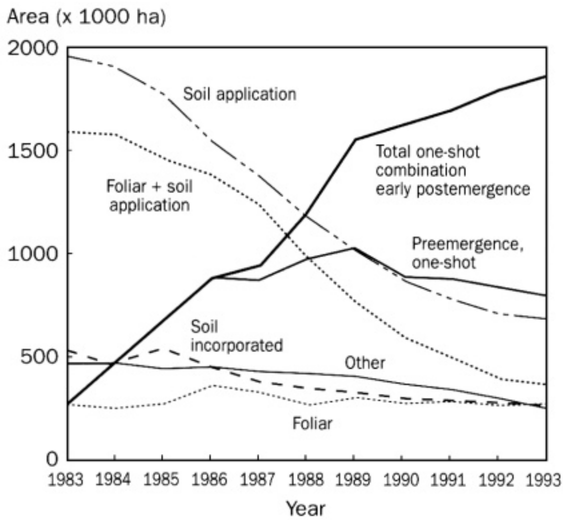
The main herbicides registered for rice, both those introduced into and those developed in Japan, are listed in Table 2 (a few of them have now been deregistered). Phenoxys as 2,4-D and MCPA were registered more than 40 yr ago. Many of the herbicides that followed are single chemicals or combination products, including sulfonylurea compounds such as bensulfuron-methyl (BSM). Most of the herbicides are for transplanted rice and are usually sold as mixtures of two or three active ingredients to control annual and perennial weeds simultaneously. Granules as combination products have been the most popular form of herbicide, widely applied at the early growth stage of rice.

Recommended herbicides

The chemicals popular among Japanese rice farmers change from year-to-year. Recently, so-called "one-shot herbicides," which are combinations of two or three chemi-

Table 2. **Main herbicides registered in Japan for use in rice.**

Year	For irrigated rice		For upland rice, dry-seeded rice, levees
	Single herbicides	Combination products	
1950	2,4-D		
	MCPA		
	Pentachlorophenol (PCP)		Simazine
1960	Propanil	PCP • MCPA	Diuron, dalapon
	Nitrofen, MCPA		Propanil
	2,4,5-T		Prometryn, diquat
1965	Chlornitrofen (CNP)		Paraquat
	Swep		Swep, trifluralin
	ACN	Swep • MCPA	
		Thiobencarb • simetryn	
1970	Thiobencarb	Thiobencarb • CNP, Molinate • simetryn	
	Oxadiazon	Simetryn • MCPA-thioethyl	
	Butachlor, Chlomethoxyfen		Thiobencarb • prometryn
	Daimuron		MCPA • propanil • dalapon
1975	Bentazon	Dimethametryn • piperophos • bentazon	Oxadiazon
		Bentazon • 2,4-D	
		Thiobencarb • simetryn • MCPB	
	Pyrazolate, Naproanilide		
1980		Oxadiazon • butachlor	Glyphosate
	Bifenox		Propanil • dalapon
		Pyrazolate • butachlor	
	Pretilachlor		
		Pyrazolate • pretilachlor	Bialaphos, glufosinate
1985	Pyrazoxyfen, Dimepiperate	Pyrazoxyfen • pretilachlor	Diquat • paraquat
	Mefenacet, Bromobutide		
	Benzofenap	Bensulfuronmethyl (BSM) • thiobencarb	
		BSM • mefenacet, BSM • dimepiperate	
		BSM • pretilachlor	
	Quinclorac	BSM • esprocarb	
1990	Pyrazosulfuronethyl (PSE)	PSE • mefenacet	
		PSE • pretilachlor	
		Pyributicarb • bromobutide • benzofenap	
		BSM • thiobencarb • mefenacet	
		BSM • mefenacet • daimuron	
		PSE • esprocarb	



3. Area of Japanese ricefields receiving herbicide applications, 1983-93.

cals to control both annual and perennial weeds with one application, have become popular; they were applied on 89% of the ricefields in 1993. The decrease in use of different herbicides for "soil" and for "foliar and soil" (the same as early postemergence) applications was striking (Fig. 3).

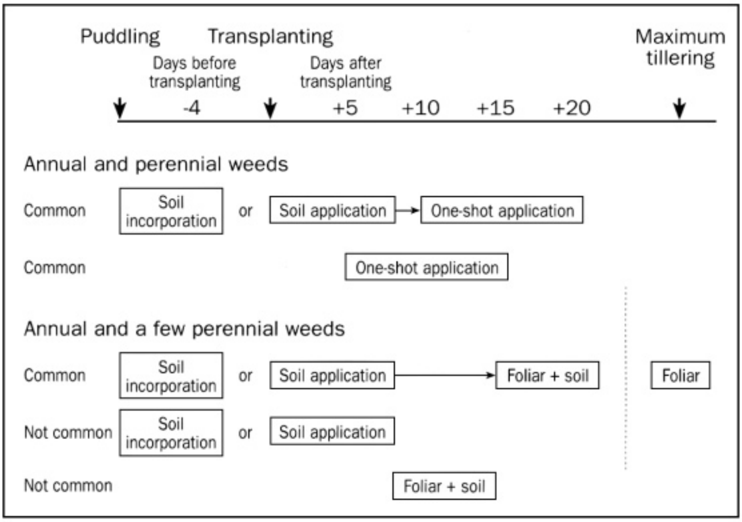
Currently recommended herbicides are listed in Table 3. The herbicide most used in 1993, applied on more than half of Japan's ricefields, was a combination of BSM and mefenacet; the second, a combination of BSM, thiobencarb, and mefenacet. Preemergence herbicides are widely used for supplemental treatments (Fig. 4).

Commercial herbicide products for transplanted rice are primarily granule formulations which can be easily applied by an individual farmer in small-scale fields. Granules are applied by knapsack engine sprayer in the northern region and by manual sprayer or by hand in the southwestern region. Although commercial granules applied at 30 kg h^{-1} have been used widely for the last 30 yr, newly developed, lighter products that can be applied at 10 kg ha^{-1} have come onto the market. These products use new chemicals, such as the sulfonylureas, which are adsorbed well into smaller amounts of the clay soil used in formulating them. They are likely to become popular because they require less labor for application. Flowable products applied in solution at 5-10 L ha^{-1} also are becoming popular (Table 4) because they can be easily applied on small-scale fields using handy 1/2-1-L bottles.

Table 3. Main herbicides used in Japanese ricefields in 1993.

Herbicide	Area (ha × 1000)
Soil incorporation (preemergence)	
Oxadiazon (EC)[a]	61
Oxadiazon + butachlor (EC)	194
Soil application (preemergence)	
Butachlor (G)	76
Chlomethoxyfen (G)	85
Chlornitrofen (G)	266
Chlornitrofen + daimuron (G)	101
Pretilachlor (G)	93
Thiobencarb + chlornitrofen (G)	33
Foliar and soil application [b]	
Bentazone (AS, G)	36
MCPA - thioethyl (phenothiol) + simetryn + dimethametryn (G)	16
Molinate + simetryn + MCPB (G)	153
Piperophos + dimethametryn (G)	19
Thiobencarb + simetryn (G)	36
Thiobencarb + simetryn + MCPB (G)	74
Foliar application (postemergence)	
ACN(G)	26
2,4-D (EC,G, SP, AS)	98
MCPA (EC, G, SP, AS)	112
Propanil (EC)	11
Bentazon + 2,4-D or MCPA (G, SP)	19
After harvesting rice or levee (postemergence)	
Diquat + paraquat (AS)	102
Glufosinate (AS)	65
Glyphosate (AS, SP)	107
Preemergence one-shot application	
Bensulfuron-methyl (BSM) + dimepiperate (G)	68
BSM + pretilachlor (G)	59
BSM + thiobencarb + mefenacet (G)	491
Pyrazolate + butachlor (G)	76
Pyrazolate + pretilachlor + dimetharnetryn (G)	27
Pyrazosulfuron-ethyl (PSE) + pretilachlor (G)	19
Pyrazoxyfen + pretilachlor (G)	23
Pyributicarb + bromobutide + benzofenap (FL)	43
Early postemergence one-shot application	
BSM + esprocarb (G)	229
BSM + mefenacet (+ daimuron) (G)	510
Naproanilide + bromobutide + mefenacet (G)	32
PSE + mefenacet (G)	219
PSE + esprocarb	59

[a]AS = aqueous solution, EC = emulslfiable concentrate, FL = flowable, G = granule, SP = water-soluble powder. [b]Same as early postemergence application.



4. Sequence of herbicide application in transplanted Japanese ricefields.

Table 4. One-shot herbicide combinations and recommended use in Japan.

Herbicide combination	Formulation and rates (kg ha^{-1})	Time of application [a]	Dose (kg ai ha^{-1})
Bensulfuronmethyl (BSM) • dimepiperate (Push)	G [b] 30	0 DAT to BG 2.0 leaf stage	0.051 + 3.0
BSM • pretilachlor (Gorbo)	G 10, 30	5 DAT to BG 2.0 leaf stage	0.051 + 0.6
BSM • thiobencarb • mefenacet (Wolf-Ace)	G 10, 30	5 DAT to BG 2.0 leaf stage	0.051 + 1.5 + 0.45
Pyrazolate • butachlor (Kusakarin)	G 30	3 DAT to BG 2.0 leaf stage	1.8 + 0.75
Pyrazolate • pretilachlor • dimethametryn (Kusahope-D)	G 30	3 DAT to BG 2.0 leaf stage	1.8 + 0.45 +0.06
Pyrazosulfuronethyl (PSE) • pretilachlor (Riser)	G 10, 30	3 DAT to BG 2.0 leaf stage	0.021 + 0.6
Pyrazoxyfen • pretilachlor (Oneall)	G 30	3 DAT to BG 2.0 leaf stage	1.8 + 0.45
Pyributicarb • brornobutide • benzofenap (C-Z)	FL [c] 10	0 DAT to BG 1.5 leaf stage	0.57 + 1.0 + 1.2
BSM • esprocarb (Fujigrass)	G 10, 30	5 DAT to BG 2.5 leaf stage	0.051 + 2.1
BSM • mefenacet (•daimuron) (Zark, Zark-D)	G 10, 30	5 DAT to BG 3.0 leaf stage	0.051 + 1.05 (+0.45)
Naproanilide • bromobutide • mefenacet (Shinzan)	G 10, 30	7 DAT to BG 2.5 leaf stage	2.1 + 1.2 + 1.05
PSE • mefenacet (Act)	G 30	5 DAT to BG 2.5 leaf stage	0.021 + 1.05
PSE • esprocarb (Contract)	G 10, 30	5 DAT to BG 2.5 leaf stage	0.021 + 2.1

[a] DAT = days after transplanting, BG = barnyardgrass. [b] G = granule. [c] FL = flowable.

CHANGES IN WEED COMMUNITIES

The serious weeds in Japanese ricefields have changed since the introduction of herbicides (Table 5). Before herbicides, a mixed weed community including barnyardgrass *(Echinochloa oryzicola),* annual broadleaf weeds such as *Monochoria vaginalis,* and other species was controlled by hand weeding and use of the rotary weeder.

After 2,4-D and MCPA were introduced for broadleaf weed control in the 1950s, barnyardgrass became the dominant weed. It was difficult to eradicate by hand weeding. Pentachlorophenol(PCP), nitrofen, and chlornitrofen (CNP) were introduced in the 1960s to control barnyardgrass and other annual weeds at germination. Spikerush *(Eleocharis acicularis)* became very serious, inhibiting rice through nutritional competition and allelopathic activity.

Thiobencarb became popular in the 1970s because it effectively controlled annual weeds and spikerush. But after a few years with no competition from annual weeds and spikerush, perennial weeds such as *sagittaria (Sagittaria pygmea)* and bulrush *(Scirpus juncoides)* became the dominant species. In the 1980s, one-shot herbicides were introduced as compounds which would control annuals and widely distributed perennials. With that competition removed, kuroguwai *(Eleocharis kuroguwai),* arrowhead *(S. trifolia),* and other species have become the new problem.

The dominant weeds in Japanese ricefields are shown in Table 6. While the perennials kuroguwai and arrowhead are the most serious, annual broadleaf weeds such as monochoria and several other species are reported to be increasing in a few regions because of their tolerance for single-application herbicide combinations.

Table 5. Changes in weed species seriously affecting Japanese ricefields before and after adoption of herbicides.

Decade	Primary herbicide	Weed species
Before 1950	Rotary and hand weeding	Annual and some perennial weeds
1950	Foliar application: 2.4-D, MCPA	*Echinochloa oryzicola*
1960	Soil application: pentachlorophenol, chlornitrofen, nitrofen	*Eleocharis acicularis*
1970	Foliar + soil application[a]: thiobencarb, simetryn, molinate	*Sagittaria pygmea* *Scirpus juncoides* *Cyperus serotinus*
1980	One-shot combination: pyrazolate, bensulfuron-methyl, pyrazosulfuron-ethyl, mefenacet	*Eleocharis kuroguwai* *Sagittaria trifolia*
1990	New labor-saving formulations	Annual broadleaf weeds

[a] Same as early postemergence application.

Table 6. Important weed species in Japanese ricefields.

Common name	Species	Family
Annual grasses		
Barnyardgrass	*Echinochloa oryzicola* Vasing.	Poaceae
Barnyardgrass	*E. crus-galli* (L.) Beauv. var. *crus-galli*	Poaceae
Sprangletop [a]	*Leptochloa chinensis* (L.) Nees	Poaceae
Annual sedges		
Small flower umbrella sedge	*Cyperus difformis* L.	Cyperaceae
Annual broadleaf weeds		
Mizuaoi [b]	*Monochoria korsakowii* Regel et Maack	Pontederiaceae
Monochoria	*M. vaginalis* (Burm. f.) Presl var. *plantaginea* (Roxb.) Solms-Laub.	Pontederiaceae
Toothcup	*Rotala indica* (Willd.) Koehne var. *uliginosa* (Miq.) Koehne	Lythraceae
Ammannia [a]	*Ammannia multiflora* Roxb.	Lythraceae
Purple ammannia [a]	*A. coccinea* Rottb.	Lythraceae
Falsepimpernel [a]	*Linderna procumbens* (Krock.) Borbas	Scrophulariaceae
Oabunome [b]	*Gratiola japonica* Miq.	Scrophulariaceae
Eclipta [a]	*Eclipta prostrata* (l.) L.	Compositae
Bidens	*Bidens frondosa* L.	Compositae
Bidens	*B. tripartita* L.	Compositae
Jointvetch [b]	*Aeschynomene indica* L.	Leguminosae
Perennial grasses		
Rice cutgrass [b]	*Leersia oryzoides* (L.) Sw.	Poaceae
Knotgrass [a]	*Paspalum distichum* L.	Poaceae
Perennial sedges		
Mizugayatsuri	*Cyperus serotinus* Rottb.	Cyperaceae
Spikerush	*Eleocharis acicularis* (L.) Roem. et Schult. var. *longiseta* Sven	Cyperaceae
Kuroguwai	*E. kuroguwai* Ohwi	Cyperaceae
Bulrush	*Scirpus juncoides* Roxb. var. *ohwianus T. Koyama*	Cyperaceae
Shizui [b]	*S. nipponicus* Makino	Cyperaceae
Koukiyagara	*S. planiculmis* Fr. Schm.	Cyperaceae
Perennial broadleaf weeds		
Waterplantain [b]	*Alisma canaliculatum* A. Br. et Bouche	Alismataceae
Saggitaria	*Sagittaria pygmaea* Miq.	Alismataceae
Arrowhead	*S. trifolia* L.	Alismataceae
Poamogeton	*Potamogeton distinctus* A. Benn.	Potamoge-tonaceae
Oenanthe	*Oenanthe javanica* (Blume) DC.	Umbelliferae
Algae		
Spirogyra [b]	*Spirogyra arcla* Kutz.	Zygnemataceae
Pithophora [a]	*Pithophora zelleri* (Martius) Wittrock	Cladophoraceae

[a]Serious mainly in southwestern Japan. [b]Serious mainly in northern Japan.

Prevention of weeds

Weeds in ricefields and irrigation ditches should be eradicated by hand weeding, cultivation practices, and chemical control before they mature and scatter. The compost applied to ricefields also should be clean of weed propagules.

Manual eradication. Hand weeding is still practiced by small-scale farmers. They pull barnyardgrass and other big weeds as they monitor their small fields every 2 or 3 d during the rice-growing season. Older, retired farmers also are available to do this kind of work.

Water management. Flooding ricefields at 10-15 cm was found to be effective in controlling barnyardgrass and some other hygrophytic weeds, but the levees of Japanese ricefields are only high enough to flood at 3-5 cm. Shallow flooding has long been the standard recommendation, to encourage rice tiller growth and increase yields.

Mechanical weeding. Man- and engine-powered rotary weeders are useful in controlling weeds, and some Japanese farmers still like to use them, especially to control perennial weeds which emerged from underground tubers after annual species have been controlled by herbicides. This method is not suitable for small-scale farmers, however, because of the heavy labor required.

Rice-weed competition. Transplanted rice seedlings, especially older, larger seedlings, are highly competitive with weeds. Closely planted seedlings are more competitive than those planted at the usual density, although yields are not necessarily higher. The plant types of Japanese rice varieties are not very tolerant of weed competition and have little allelopathic activity.

Cropping system. Late autumn cultivation of ricefields is recommended to decrease overwintering of perennial weeds. Japanese farmers usually use rotary tillers, but plowing has been found to be more effective in digging up the propagules of perennials. Double cropping or a rice - soybean rotation also is recommended. Rice weeds are decreased under upland crop conditions, and upland crop weeds are decreased under flooded rice conditions, in a 2- or 3-yr rotation. The economic returns, however, are not satisfactory.

Chemical control. With labor shortages and the need for lighter work by aging farmers, chemical methods of weed control are the most popular in Japan. Herbicides can be expected to be the key technology of weed management in future.

Biological control. Some organisms—insects, tadpole shrimp, fungi, shellfish, carp, and ducks—were studied for their usefulness in controlling ricefield weeds. Some were effective in farmers' fields under traditional rice cultivation practices and were favored by farmers interested in organic farming. The costs—labor and enclosures of fields—were high, and sometimes carp and ducks needed to be guarded from homeless dogs and other wild hunters. These methods were successful for only a few small-scale farmers. Weed scientists are working to develop fungal diseases as bioherbicides for rice.

CURRENT PROBLEMS IN WEED MANAGEMENT

Developing low-cost, labor-saving technology

Decreasing the labor hours for weed control will be the most effective measure to lessen the cost of weed management in Japan. The need is to improve the more labor-saving herbicide formulations and application methods. More effective single-application herbicide combinations may contribute to decreasing the number of herbicidal applications.

Farmers should choose the most suitable chemicals for each field. It is a waste of chemicals to use the same, expensive herbicides continuously, year after year, after target perennial weeds have been controlled. Rotating several herbicides on a field is recommended, to avoid infestation by new species resistant to a routine herbicide.

Developing efficient herbicides for direct-seeded rice

Under a new government policy for rice cultivation, large-scale cultivation of 15-20-ha ricefields is being encouraged. The farmers are expected to adopt direct seeding to save labor. The success of this recommendation is uncertain, however, because Japanese farmers on average own only about 1 ha of ricefields.

New herbicides are expected to be developed for dry- and wet-seeded rice which will not damage rice seedlings and will control barnyardgrass and broadleaf weeds from germination to beyond the 3-leaf stage of rice.

Changing efficacy of herbicides

Susceptible weeds are decreased by specific herbicides, but tolerant weeds increase. Even in one species, intraspecific variations in ecological characteristics or in herbicide susceptibility often appear in ricefields, decreasing the efficacy of weed management practices. Naturalized species which have been introduced into Japan within the last 40-50 yr by importation of cereals, hay, and other crops are causing new weed problems.

IMPROVING WEED MANAGEMENT

Japanese rice farmers depended on herbicides. They often spray between rice seasons to control reappearing perennials and germinating winter and spring weeds. Mechanical and cultural weed control methods are not popular because many are weekend farmers who derive their primary income from urban jobs. They look for ways to save labor in their fields.

Irrigated rice and upland crop rotation is recommended as an effective way to decrease rice weeds, especially perennial weeds. The farmers, however, usually do not like to cultivate upland crops because of low returns.

With looming environmental problems, farmers are expected to use herbicides more judiciously and safely and to develop integrated weed management strategies.

To prevent overapplication of chemicals, alternative weed control measures such as bioherbicides are needed to substitute for at least one chemical application.

NOTES

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DEVELOPING A WEED MANAGEMENT STRATEGY FOR ASIAN RICE PRODUCTION

R. Naylor, W. Falcon, and D. Kennedy

Weeds have been a major scourge to farming since the beginning of settled agriculture, cursed by farmers, studied by scientists, and vilified by authors from Shakespeare to Emerson. Yet, despite the general progress in agriculture during the 20th century, especially in the rice-based ecosystems of Asia, weeds remain a principal constraint to agricultural productivity (Herdt 1991). Even with significant new research using biotechnology techniques, allelopathy, biological controls, and plant breeding to increase the competitive ability of rice over weeds, weed problems cannot be expected to disappear. A general conclusion is that herbicides are here to stay.

The first theme discussed here is why weeds are likely to be a permanent problem in Asian rice production and why the central debate surrounding herbicides focuses on the proper use of herbicides in an integrated weed management system, not on the abolishment of herbicides.

A second theme discusses the dangers of pesticide use in agriculture, drawing conclusions by way of analogy. The productivity, health, and environmental problems associated with the use of insecticides have been much more severe and have aroused much more attention than those associated with herbicides. While many mistakes have been made with respect to insecticides during the last 50 years, within the last 15 years, considerable progress has been made in defining integrated pest management strategies that include nonchemical control approaches that suppress rather than eradicate pests. Progress is now being made to define the institutional changes required for effective integrated pest management. Lessons learned from the insecticide experience thus have important implications for the judicious use of herbicides.

The final theme summarizes the complexity of weed problems within Asian rice production systems; outlines the breeding, management, and chemical practices that are likely to be components of integrated weed management strategies; and discusses the roles of the public and private sectors in making those components operational. Within this context, some simple guidelines are suggested that farmers, governments, and research institutions might follow to mitigate herbicide-related risks to human health, ecosystems, and crop production.

Intelligent use of herbicides can have positive impacts on rice productivity and farm incomes, with only minimal negative impacts on human health and the environment. But misuse of herbicides or overuse of a single herbicide could result in disaster for the rice-based agroecosystems of Asia.

DETERMINANTS OF HERBICIDE USE IN ASIA

Use of herbicides in Asian rice production is growing rapidly. From near-zero use in 1945, rice herbicide sales now total upwards of US$1 billion (Naylor 1996). Many products are available, with few signs of a leveling off of their use. Indeed, three factors—rice technology, economic growth, and policy liberalization—are interacting in ways that are likely to increase the application of herbicides to Asian ricefields substantially.

One fascinating dimension of technical change is the extent to which one change may force or entrap subsequent innovations and promote complementary input use. These advances are often triggered by changes in prices or other economic variables, which in turn induce a new chemical, biological, or mechanical breakthrough (Hayami and Ruttan 1985). A classic example is found with tomatoes. Labor availability and costs triggered the invention of the mechanical tomato harvester, which in turn necessitated the development of tomato varieties that ripen evenly and have thick skins (Hightower 1973, Ruttan 1982).

The new rice plant types (the so-called "super rice") being developed by IRRI in anticipation of the exponential increase in demand for rice well into the next century promise to be such a forcing innovation (IRRI 1991). They are designed to increase maximum yields by some 20%; to reach that yield potential, they will need to be direct seeded rather than transplanted. Such a shift from transplanting to broadcast sowing has huge implications for increased herbicide use. Broadcast fields do not have rows of rice plants, making both hand weeding and mechanical weeding nearly impossible and far too expensive for farmers. Innovative use of irrigation and of shading and other forms of plant competition will still be important in weed control, but there is no doubt that direct-seeded varieties and herbicides will have a strong positive linkage. Full development and adoption of new, super rice varieties may not take place until the turn of the century, but both the direction and general magnitude of their effects on herbicide use are already clear.

The move toward direct seeding and increased use of herbicides is being fueled by the broadly based economic growth occurring throughout much of Asia. Farmers are finding themselves in a double bind: rising wages for unskilled agricultural labor as workers are pulled into more lucrative nonagricultural jobs, and falling real prices for rice as a consequence of rapid technological change on the supply side and the diminishing role of cereals in middle- and upper-income diets on the demand side

(Timmer et al 1983, World Bank 1993, Naylor 1996). The rise in real rural wages in such large and densely populated countries as China and Indonesia is especially noteworthy, since farmers in those countries traditionally have used 300 or more person days/ha per crop in rice production (Naylor 1992, Huang and Rozelle 1996). With the labor costs associated with hand transplanting and weeding rising rapidly, it is little wonder that farmers are turning to herbicides as a cost-containing alternative.

The economic liberalization and decontrol taking place in Asian agriculture already is impacting herbicide use, and will likely exert even greater influence in the years ahead. Widespread reduction in agricultural subsidies, privatization of input firms, and GATT-induced liberalization of trade in agricultural inputs and outputs can be expected to increase the availability of herbicides in Asian countries and enlarge the presence of private agrochemical companies in rice-growing areas. In contrast, additional environmental and health regulations in industrialized countries will dampen new product development and demand for herbicides in those areas, as is already evident in the United States (Hill and Hawkins 1996).

The net result of all of these factors will almost surely be increased herbicide sales in the less developed countries of Asia. The extent and speed of this process, and its implications for rice productivity, rural incomes, human health, and ecosystem functions, must be recognized early if the types of mistakes that resulted from widespread insecticide use are to be avoided. The linkage of labor costs and pesticide use is stronger with herbicides than it is with insecticides, and will likely lead to an irreversible pattern of chemical weed control in many Asian countries, even in very poor countries like Bangladesh and Cambodia, if low-cost herbicides become widely available. In poor countries where productive, nonagricultural jobs are limited, potentially the most adverse consequence of herbicide use will be labor displacement and increased rural unemployment, at least in the short run.

ANALOGIES WITH INSECTICIDE USE

A number of lessons that can be drawn from the experience with insecticide use in Asian rice systems are directly relevant to managing weeds and using herbicides. It is clear, for example, that an ecological approach, as opposed to a chemical component-based approach, is needed to deal with the difficult issues of resistance and yield loss from pests in intensive rice production systems. It is also clear that simple solutions for eliminating pests from ricefields do not exist. A broader, more information-intensive approach is needed, and that demands the involvement of a set of institutions, with participation from both private and public sectors. These institutions must develop a new set of principles for managing pest-predator relations that farmers can understand and apply in avoiding, or at least in mitigating, pest outbreaks.

The insecticide experience evokes four issues related to pest control: resistance, risk assessment, integration, and cooperation.

Development of resistance

The evolution of pest resistance is an old and well-studied problem with chemical insecticides, and has been one of the major factors in the movement of insect-control policies away from strict reliance on chemicals (NAS 1975). Indeed, the drive to understand the evolution of resistance under selective regimes of pesticide use has been focused so strongly on insect studies, the capacity of weeds to develop resistance in the same way has been underestimated.

Development of resistance on the part of weed species to the herbicides being applied is now recognized as a serious threat in some highly productive rice-growing regions (Kim 1996, Hill 1996). Moreover, the use of biotechnology to confer resistance to selective chemicals in rice (Toenniessen 1996) could have important implications for future genetic mutations in rice ecosystems. It will be essential that any resistance factors incorporated into rice cannot be transferred to weeds, especially to its grass relatives that pose special problems of selective elimination.

Risk assessment

Overuse or misuse of certain herbicides presents risks to human health and the environment in and surrounding rice ecosystems. This second issue emerging from the insecticide experience is linked to the complex and difficult topic of risk assessment. If, as seems overwhelmingly likely, there are to be strong incentives for the massive substitution of chemical for manual weed control, careful analysis of the risks entailed in such substitution will be needed. In that analysis, it is important to differentiate the different populations or systems that may be at risk. The risks to human health, for example, may be quite different for those who are occupationally exposed than for those who make use of the same or connected water supplies but are not themselves engaged in rice agriculture.

Moreover, in the case of insect control, threats to the health of farm workers have often been quite different from threats to the consumers of the agricultural commodity being protected. Health threats to farm workers have been largely a function of acute exposure to pesticides of high toxicity and short half-lives (Rola and Pingali 1993, Pingali and Roger 1995). Those risks have been managed by limiting reentry times and by preventing exposure with protective clothing and the use of careful storage, handling, and spraying techniques. Nonoccupational risks have been a function of chronic, low-level exposure to persistent compounds. They have been managed to a large extent by monitoring and regulation. Frequently the two types of risks are even deliberately confused, such as when, for political purposes, environmental groups and advocates for farm worker safety in California attempted to persuade consumers to boycott grapes by citing residue hazards (Kuhrt, 1992).

Less is known about the health effects of herbicide use in rice production than about insecticide use (Rola and Pingali 1993, Pingali and Marquez 1996). There is a simple explanation: insecticides are designed to intercept physiological systems in animals, and therefore are more likely to be active in humans. The physiological targets of plant growth regulators and other herbicides are much less likely to have human homologues. There have, however, been some disquieting experiences with herbicides, including the long and not yet fully resolved story of dioxin as an accompanying byproduct of herbicide manufacture and use (Moore et al 1993). The experience with insecticides cautions against comforting assumptions based on physiological dissimilarity. No one would have guessed in 1950 that the organochlorines would have turned out to present a chronic health threat based on their persistence and bioaccumulation.

Another category must be added to risk assessment: the potential damage to aquatic ecosystems caused by herbicide use. Considerable uncertainty operates in this case, an uncertainty derived in part from the fact that the flooded rice environment is so different from the nonflooded agricultural ecosystems in which most of the earlier research on pesticide risks to the environment has been conducted (NAS 1975). Under nonflooded conditions, pesticides may drift from one field to a neighboring one during application, and soil contamination may be a problem. But only occasionally and accidentally is there an invasion of water supplies. In the case of herbicides and insecticides applied to flooded rice systems, there is an immediate threat to water supplies because the chemicals are placed in the water intentionally. The interconnectedness of surface water and shallow aquifers is notoriously dynamic (Fetter 1994). The opportunity for an agricultural chemical to spread from the point of application to supplies in which fish are grown or that support valuable natural communities may be high.

Although herbicides have been shown to be less persistent than insecticides under flooded, anaerobic conditions (Roger and Kurihara 1988, Crosby 1996), the use of certain herbicides still poses a significant risk to aquatic ecosystems and aquaculture (Li and Li 1996). Those risks have not yet been evaluated thoroughly under the conditions of continuous herbicide use in densely settled regions that characterize Asian rice systems. What is thought to be a risk of acute contamination with insecticides may, with herbicides, be a long-term or chronic threat to an ecosystem.

Integration

One of the most important lessons from the long, often disappointing pursuit of insect control is that there is no magic bullet. The gradual development of integrated pest management that combines biological, chemical, and cultural control measures in ways that make all measures more effective has been a significant triumph of applied population biology (Flint and van den Bosch 1981, Holl et al 1990, Luna and House 1990, Altieri 1994). In view of the propensity of weeds to develop resistance to chemical herbicides, there is every reason to pursue the goal of integrated management as aggressively in this domain as in the case of insect pests. Well-planned crop rotations, selection of rice varieties that are effective weed competitors, and water management are all components of a strategy that has the potential to limit reliance on herbicides. The trick is how to bring these components together.

Cooperation

The development of new practices in rice production takes place in a complex environment, with multiple sectors participating at many different levels. Governmental and quasi-governmental bodies are engaged in research on and development of improved cultivars. Individual farmers have varied land holdings and capital resources. Proprietary companies are engaged in the development and sale of germplasm and agricultural chemicals, and sometimes both. Moreover. the proprietary sector is expanding beyond the multinational agrochemical companies based in the United States, Europe, and Japan. That sector now includes a rapidly growing and largely unregulated group of companies based in China and other less developed countries of Asia.

Farmers will make their weed control choices from a confusing, continuously expanding array of products. The future course of herbicide use in Asian rice systems will depend on how and where farmers obtain their information: from local examples of "best practice," from government or other public sector sources, from representatives of the proprietary sector. Much will also depend on how farmers blend information about the different elements of a production strategy, and on the degree to which upstream research and development are integrated with downstream application.

One example should suffice to illustrate what a complex challenge this is. Suppose, plausibly, that the ideal outcome for a particular locale is a careful mix of water management, cultivar selection, crop rotation, planting schedule, limited chemical treatment, and perhaps the introduction of some as-yet-unidentified biological control agent. Many questions loom. What process will determine the matching of genetic resistance in the rice plant with the health and environmental risks of the herbicide, in order to minimize costs? What will be done to optimize other properties of the resistant cultivar so that farm management practices have the maximum effect, reducing the need for chemical control? What systems of information and advice are available at the farm gate to help bring these technologies together in the best way?

Clearly, some guidelines are needed to direct future decisions on herbicide use and weed management in Asia. If the decision-making process cannot be simplified, it seems unlikely that herbicide use will be moderated sufficiently to avoid long-term ecological and health damage.

DEVELOPING A STRATEGY FOR WEED MANAGEMENT

Given the wide range of weed management choices that millions of small-scale rice farmers in Asia will face, blunt policy instruments will be needed, in conjunction with information-intensive programs, to encourage sensible use of herbicides. The increasing success of integrated pest management for insect control is the result of a combination of factors: some simple rules to change farm-level practices, government regulations to ban the import and use of the most harmful insecticides, and the development of a broader range of alternatives for insect control that includes host plant resistance (Fischer 1994). The combined efforts of agricultural extension agencies; governments, in their role of implementing agricultural input price and trade policies; and international and national agricultural research institutions have helped change the direction and magnitude of insecticide use in Asian rice systems.

A similar set of initiatives is needed to launch anintegrated weed management program. At the farm level, a prescriptive approach that relies on a few simple principles is more likely to succeed than a cafeteria approach that requires farmers to become knowledgeable about a wide array of weed management practices and technologies. In the case of insecticides, the general principles include "no prophylactic spraying" and "don't spray insecticides for the first 40 days of the crop season" (Teng 1989, IRRI 1994). In the case of herbicides, three general principles have emerged that can help guide farmers' decisions:

- It is not necessary to kill all of the weeds in a ricefield. Control only the weeds that compete directly with rice plants, limiting yields, and that contribute to the spread of harmful weed seeds in the field. Some weeds may actually act as hosts to beneficial insects and provide an alternative source of food for rice pests. Unless these weeds are severely limiting crop growth, they can be maintained as a component of a broader integrated pest management strategy. The challenges are to understand which weeds are good or bad, at what point in the crop cycle farmers can stop worrying about weeds in their fields, and how to manage selective weed control in direct-seeded rice. The overall principle is weed control, not weed elimination.
- Maintaining rice seed cleanliness will help dramatically to limit weed growth, reduce the spread of weeds, and slow weed resistance to herbicides. The principle is to prevent seed contamination through rigorous quality control in seed production. Such prevention can be achieved through careful seed inspection, seed certification programs, and development and use of hybrid seed (Delouche 1988). At the farm level, it is important that contaminated rice seeds not be circulated through the production process, especially in areas where red rice and other grass weeds are pervasive.
- Continuous use of a single herbicide or group of herbicides will lead over time to a buildup of resistance in weed populations, and potentially large losses in rice yields. To the extent that herbicides are used, the principle is that chemical formulations applied to rice must be altered on a regular basis, either through substitutions among herbicides or the use of different herbicide mixtures. Herbicides that are associated with the emergence of resistant weed biotypes, such as the sulfonylurea herbicides (Hill 1996, Kim 1996), should be used with great caution or avoided all together.

Application of these principles is straightforward enough at the farm level. Their adoption, however, will require support from governments and the proprietary sectors responsible for the development and sale of agricultural chemicals and seeds in Asia. For example, it is up to individual governments to establish seed certification programs that include inspection, testing, and quarantine procedures. Such programs require regulations and restrictions on the importation of seeds, which may or may not be part of existing phytosanitary and quarantine regulations. In addition, information on and monitoring of agricultural equipment and facilities, seed sources, and land use are needed (Delouche 1988). Governments can ensure seed cleanliness, for example, by making provisions for the development of a hybrid seed industry in the private sector (governments themselves have had a notoriously bad history in developing and operating seed industries). Here a government's primary role would be to help develop transportation and marketing infrastructure, make credit available for agricultural inputs (especially seeds and fertilizers), and create a suitable economic climate in which private companies can operate effectively.

Given the complicated array of herbicide products on the Asian market, joint efforts by governments and agrochemical companies also are needed to harmonize labeling, which includes consistent specification of chemical content. Harmonization is required so that farmers know exactly what chemicals they are using; without full knowledge, they will not be able to avoid problems of weed resistance to herbicides and ecological and health damages. Moreover, harmonization is needed so that extension agencies and regulatory bodies of governments will have adequate information on which chemicals are currently in use. Although the proprietary sectors may resist a harmonization strategy, it seems virtually impossible to monitor or control herbicide use in Asian rice systems without first knowing the full range and extent of the herbicides available in rural markets.

Developing a regulatory strategy for herbicides is a large challenge, both conceptually and politically. Some regulation is needed, in the form of import controls and bans on certain types of herbicides, especially for the more dangerous category 1 (hazardous) and category 2 (moderately hazardous) chemicals. Some widely used herbicides, such as 2,4-D, are in category 2. The preponderance of the herbicides being applied in Asian rice production systems has shifted, however, to chemicals in the less toxic category 4; these products that are unlikely to present acute hazards in normal use (Pingali and Roger 1995). As the experience with insect control has shown, farmers tend to adopt integrated pest management strategies more readily if the pesticides they had depended on in the past are banned (Dinham 1995).

Imposing quantitative controls on a select group of chemicals probably is preferable to implementing a tax on a broad set of herbicides because the magnitude of externalities and potential threshold effects of herbicides are not well understood. In principle, a tax on herbicides should be equivalent to the difference between the market price and the social price (Baumol and Oates 1988). If there is a significant probability that environmental or health damages might rise sharply in relation to the benefits of herbicide use, quantitative controls should be used in preference to taxation (Weitzman 1974). A tax would discourage but not forbid the use of a given herbicide, and the tax value would have to be set subjectively.

If regulatory measures are accepted in principle, the question for each country is which herbicides to ban and which to permit. A range of herbicides in the market is clearly needed if farmers are to avoid overuse of a single chemical and the buildup of herbicide resistance in weeds. This diversity, of course, should not include chemicals that carry a high risk of damage to human health or to ecosystems. Banning some herbicides and simultaneously encouraging diversity in others require sophisticated regulatory procedures that do not currently exist, even in the well-developed regulatory agencies of industrialized countries such as the United States' Environmental Protection Agency. Imposing bans also encourages corruption, as private agrochemical companies compete for approval and import licenses. A worst case scenario can be easily imagined: A private agrochemical company develops a rice variety that is resistant to a herbicide which it also produces. This herbicide is approved for import while all other herbicides are banned. The resistant rice variety and the selective herbicide are widely adopted, which significantly raises the probability over time of selecting for resistant weeds. Such a situation could only be worse if the herbicide itself were harmful to human health and to ecosystems.

Such an extreme, but possible, scenario suggests that regulation arguably should be based on a "dirty," excluded list of chemicals that are banned from use, rather than on a "clean list" of chemical formulations permitted for use. Selection of the list on which regulation is based has important implications for the degree of corruption that is likely to prevail.

Regulation of herbicide use will be a less dominant issue in the future if the package of technologies for managing weeds in ricefields can be expanded. Potential components of this technological package include biological controls, allelopathy, plant breeding for competitiveness in rice over weeds, and the use of biotechnology to confer resistance in rice to the more benign herbicides. Like the development of host plant resistance in rice to certain insects, the design of a technological package for weed management must remain dynamic so that it does not break down in the face of continuous pest pressure and ecological change. The current focus of the proprietary sector on the development of herbicides far outweighs its focus on other weed control techniques, such as biological controls or allelopathy (Cother 1996, Dilday et al 1996). Even within the realm of herbicide development, there is room for cost-effective granular formulations, which pose fewer risks than liquid formulations to human health and the environment (Shibayama 1996).

Private companies throughout the world naturally respond to potential profits and market access. The critical question is whether government policy and public sector research can influence the direction of technological change and farm practices in the domain of weed management. What currently appears to be lacking in Asian countries is a strong government commitment to ensuring that herbicides are used safely, and in combination with other weed control practices to minimize labor displacement and environment- and health-related risks. More than ever, this commitment is needed now, in the face of labor market pressures, rising real wages, and introduction of the new super rice varieties.

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