IRRI's Mission Statement

Our goal
To improve the well-being of present and future generations of rice farmers and consumers, particularly those with low incomes.

Our objectives
To generate and disseminate rice-related knowledge and technology of short- and long-term environmental, social, and economic benefit and to help enhance national rice research and extension systems.

Our strategy
We pursue our goal and objectives through
- interdisciplinary ecosystem-based programs in major rice environments
- scientific strength from discipline-based divisions
- anticipatory research initiatives exploring new scientific opportunities
- conservation and responsible use of natural resources
- sharing of germplasm, technologies, and knowledge
- participation of women in research and development
- partnership with farming communities, research institutions, and other organizations that share our goal

Our values
Our actions are guided by a commitment to
- excellence
- scientific integrity and accountability
- innovation and creativity
- diversity of opinion and approach
- teamwork and partnership
- service to clients
- cultural diversity
- gender consciousness
- indigenous knowledge
- environmental protection

IRRI 2000-2001

Rice Research: The Way Forward

Rice Research:
The Way Forward

Many viewing the cover of this latest IRRI annual report may think that scientists have ambitions to grow rice on some distant planet. However, although one day there may well be rice on Mars, this is not the message we want people to get from reading the following pages.

Instead, we hope that at long last people will realize that, while rice is the basis of a production system that feeds half the planet, it is also a system that allows a wonderful balance between humans and the environment.

Put simply, we at IRRI firmly believe that it is possible to feed three billion people in a safe and sustainable way that doesn't damage the environment, destroy traditional practices, or leave little of nature for our children.

How? The answer to this simple question is perhaps one of IRRI's best-kept secrets and also the reason for the environmental theme in this annual report. Since they first started work more than 40 years ago, the scientists at IRRI have (a little unfairly) mostly been seen as focusing solely on production increases as a way to ensure food security. However, production increases cannot be achieved in a vacuum. Instead, they very much rely on the environment in which rice is grown.

As a result of four decades of such work, IRRI has amassed a great store of knowledge on rice environments and ecosystems. As far as this Institute is concerned, the days of unsustainable high-input rice production are a thing of the past and the era of the rice farm as a sustainable, balanced ecosystem of its own is here to stay. The world's rice-growing regions should be seen as unique ecological regions no different from the great forests and vast oceans of the planet—especially as they cover about 11 percent of Earth's arable land and are the largest single area dedicated to feeding the world.

But before anyone decides that IRRI has washed its hands of its traditional goals and mandate, please let me assure you that this is not the case. Food security and improved incomes remain our fundamental goals for poor rice farmers and consumers. However, with the latest advances in science and technology, I'm pleased to report that these can now be achieved with little impact on the environment.

Using the scientific knowledge and expertise gained over the past 40 years, rice farms of the future will be not only clean and efficient producers but also safe and environmentally sensitive. Considering the enormous role that rice plays on this planet, in terms of both the area it covers and the number of people it feeds, this must be seen as a worthy goal deserving the support and commitment of all those involved in rice and its future development.

The urgency and importance of the problems facing rice farmers and consumers remain IRRI's primary focus—whether it be grinding poverty or a lack of food—but it's clear that these wars no longer need to be waged at the expense of the environment or human health. Clearly, rice research is the way forward not just for rice farmers and consumers but for the entire planet as well.

Ronald P Cantrell

Dr. Ronald P. Cantrell
Director General

IRRI Will Concentrate On Delivery and Impact

Early in 2000, IRRI undertook a landmark revision of its research program. The aim was to refocus our scientific efforts on a broad range of new imperatives.

More than ever before, there is a need to conserve natural resources in the face of continuing population growth and the inevitable intensification of rice production. But, as vital as this job is, IRRI's commitment to the alleviation of poverty remains unchanged.

It is therefore fortuitous that the biological sciences are providing an attractive array of new research opportunities. In this new environment, IRRI needs, first of all, to focus on those research opportunities that offer a real chance of tangible impact rather than those that do not. And fast-tracking that impact means that IRRI must also bridge the gap between research and extension.

Guided by these issues, the Institute's research activities have been restructured into just 12 projects, grouped within four programs: enhancing productivity and sustainability of favorable environments; improving productivity and livelihood for fragile environments; strengthening linkages between research and development; and genetic resources conservation, evaluation, and gene discovery.

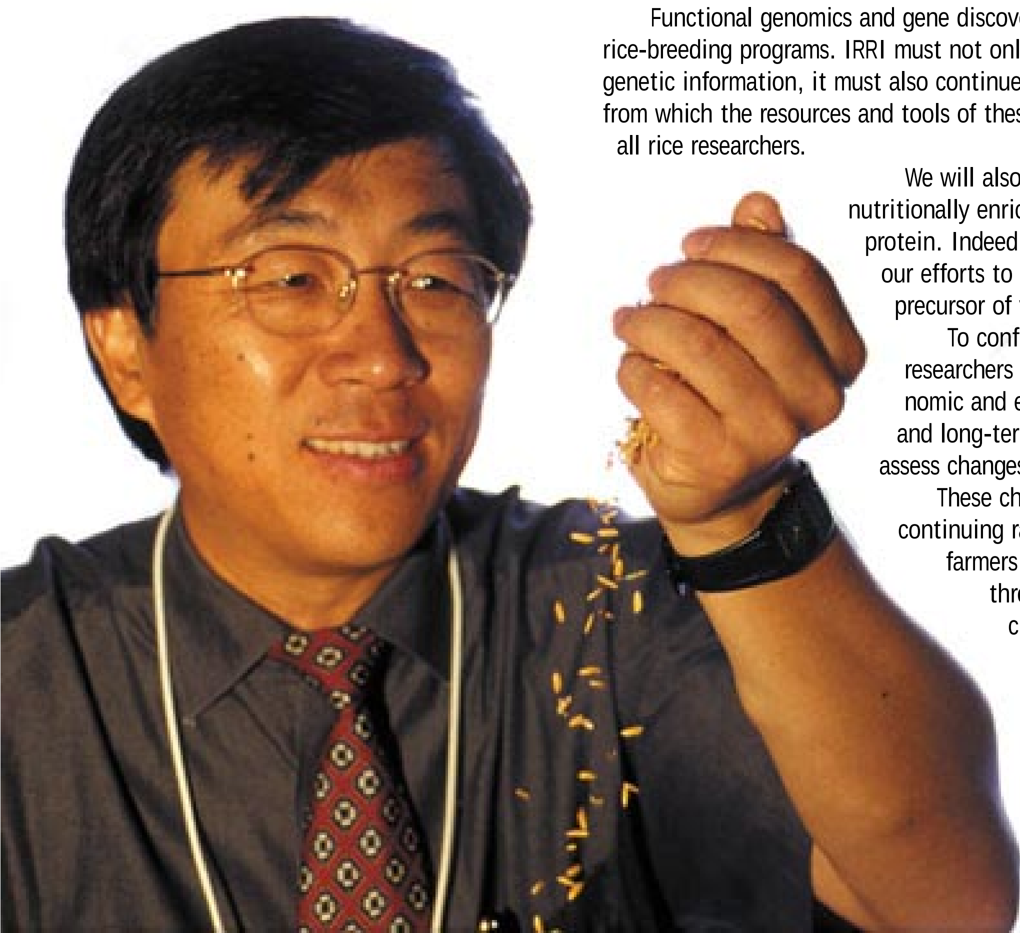
Our research effort will be guided by two principles: we will concentrate on product development and delivery, rather than simply talking about it, and we will mobilize all our efforts and innovative approaches toward achieving impact.

We must secure what I call IRRI's "heartland," that is, the International Rice Genebank and its deposits of germplasm, held in trust for future generations. The unfettered exchange of germplasm and information between the Genebank and rice scientists around the world must be maintained. In this, as in our entire research program, we must strive to maximize the benefits of our partnership and collaboration with national agricultural research and extension systems.

The time has also come for IRRI to transfer the knowledge and management tactics it has developed for intensive irrigated rice-growing systems to the rainfed lowland and upland ecosystems. This is clearly where we can most effectively have an impact on the livelihoods of the poorest rice farmers and consumers.

One of our first priorities will be the development of "aerobic" rice, which will not need standing water in order to grow. It will mark a fundamental change to rice cultivation within the rainfed and upland environments. Our goal is to have the plant varieties ready, together with crop management systems, within five to seven years.

Functional genomics and gene discovery are new sciences that are already driving rice-breeding programs. IRRI must not only be a prominent player in the search for new genetic information, it must also continue to develop an international public platform from which the resources and tools of these new sciences will remain freely accessible to all rice researchers.



We will also continue our very promising development of nutritionally enriched rice, dense in micronutrients and high in protein. Indeed, the eyes of the world are watching closely our efforts to produce rice rich in beta-carotene, the precursor of vitamin A.

To confront the challenges of the 21st century, IRRI's researchers will, more than ever before, study socioeconomic and environmental issues. We will make medium- and long-term projections of rice demand and supply, and assess changes in socioeconomic conditions and policies. These changes will give IRRI a head start in the continuing race to improve the lives of billions of rice farmers and consumers. We will strive to succeed through scientific teamwork, innovation, efficiency, and strong, harmonious relationships with our research partners around the world.

WangRen

Dr. Ren Wang
Deputy Director General for Research

Golden Rice:

"The Eyes of the World Are Watching"

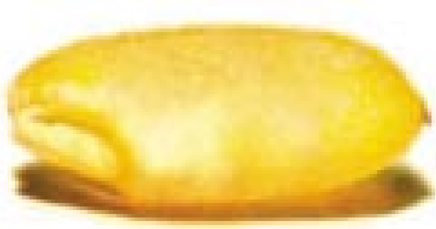
A major new chapter in IRRI's work for the well-being of present and future generations of rice farmers and consumers opened up on 19 January 2001.

The first research samples of the genetically modified provitamin A-enriched "golden rice" were delivered to the Institute's researchers by their German co-inventor, Dr. Ingo Potrykus. At the same time, the three genes that were used to achieve the transformation were also handed over to IRRI's plant biotechnologists by the other co-inventor, Dr. Peter Beyer, from Germany.

Work began immediately on what amounts to a race against time, and golden rice is just a start: IRRI's biotechnologists hope they will be able to create rice plants that deliver not only vitamin A but also iron and zinc *(see following story)* and, later, increased levels of protein.

The project stirs additional excitement because it represents the first major collaborative effort between the private-sector corporations that own many of the technologies and public-sector institutions such as IRRI that are capable of delivering their benefits, free of charge, to the poorest of the world's poor.

The genetically modified golden rice contains beta-carotene, the precursor of vitamin A. It was developed with the sole intention of combating vitamin A deficiency, which is responsible for about half a million cases of irreversible blindness and up to one million deaths per year among the poorest people in the world.



Back to Basics

The first job is to investigate the safety and efficacy of golden rice. In charge of the pioneering project is IRRI's chief plant biotechnologist, Dr. Swapan K. Datta. Although his work involves state-of-the-art genetic engineering, his first step involved a return to a basic understanding of the relationship between plants and their natural environment. From hundreds of popular, high-yielding indica rice varieties, he had to select the first candidates for genetic transformation.

"We don't choose these plants randomly, with nothing more in mind than a successful transfer of genes," Dr. Datta explains. "These must be popular and successful plants within particular environments, plants with which we are totally familiar, plants that we understand in totality."

The first move was to identify those parts of Asia most in need of a vitamin A dietary boost. Then local plant breeders were asked to help.

"One plant that we have chosen is BR29, from Bangladesh. It has good cooking quality and moderate disease and pest resistance, and it is well and truly adapted to its environment. The farmers are happy with it, the market is happy with it, consumers are happy with it. We, and our counterparts in Bangladesh, know this plant through and through. All we have to do is engineer BR29 with the beta-carotene pathway and, since we are totally familiar with the original plant, we will be able to quickly but thoroughly analyze the outcome of the genetic modification, and make sure nothing else has changed. We won't have to worry about pest and disease resistance, grain flavor, acceptability, or anything like that."

Dr. Datta points out that biotechnology research is, in many respects, the same as any other field of plant science, in that it demands a thorough understanding of both the living raw material and its relationship with the natural, social, and commercial environments in which it is grown.

As well as Bangladesh, the search for candidate plants has centered on Vietnam, India, the Philippines, and Mozambique in East Africa. Between six and ten varieties will be chosen for the first batch.

"We have a fundamental responsibility," Dr. Datta says. "We must be absolutely sure of the food safety and biosafety of the plants we produce."

For each of the varieties chosen for transformation, large numbers of different "lines" will be engineered. Some may be unhealthy, others may not produce enough seed, some may not produce enough beta-carotene, but some will have the desired characteristics.

When acceptable plants have been developed, they will be released to the national agricultural research and extension systems in their countries of origin so that they can proceed with their own analyses.

Within One Year

Dr. Datta believes that, within one year, his team at IRRI will have the first batch of transgenic golden rice plants. They will probably still be at the tissue culture level, but some may be growing in soil within secure greenhouses.

The three vital genes, meanwhile, have been "stored" in living bacteria, which are also busily multiplying their number. When the time comes, a speck of tissue weighing about one millionth of a gram will be transferred from the bacteria to the chromosomes of rice embryos, and researchers will begin the process of coaxing new life from the resulting tissue.

Dr. Datta explains that rice plants already have the pathway for producing beta-carotene. "It exists in the roots, stems, and leaves, but not in the seeds, so by adding appropriate genes we are directing the pathway to accumulate beta-carotene in the rice seeds."

The inventors, Drs. Ingo Potrykus and Peter Beyer, created their original vitamin A-enriched rice by implanting two genes from a daffodil and one more from a bacterium into a japonica rice variety called T309. It is not a commercial variety, but it is regularly used in biotechnology experiments because it is very responsive to tissue cultures.

Drs. Karabi Datta, Swapan Datta, Ingo Potrykus, and Peter Beyer.

Never Seen Such a Project

For the IRRI researchers involved, the golden rice project is already unlike anything they've ever worked on before.

"I've never seen such a project, ever," Dr. Datta says. "The eyes of the world are watching. Everyone wants to know about the work. We all know that if this is successful it may open up a new dimension in research collaboration with the private sector.

"Frankly, I enjoy the pressure. I think the private companies who handed us this technology have adopted a fantastic humanitarian attitude. We now have the responsibility of carrying the work forward."

IRRI's work with golden rice follows the donation of intellectual property licenses from Syngenta Seeds AG, Syngenta Ltd., Bayer AG, Monsanto Company Inc., Orynova BV, and Zeneca Mogen BV. Each company granted, free of charge, the use of technology employed in the research that led to the original invention, with the intention that golden rice should ultimately benefit poorer developing countries.

A humanitarian board, composed of several public- and private-sector organizations, has also been formed to help expedite the introduction of golden rice to developing countries. One of its seven members is IRRI's deputy director general for partnerships, Dr. William Padolina.

The Largest Human Feeding Trial:

300 Catholic Sisters Standing By

The unpredictable weather of the western Pacific has delayed plans for the largest human feeding trial ever conducted involving a staple food.

The trial, which will now begin early in 2002, aims to convince nutritionists that a variety of rice rich in iron and zinc, developed by IRRI in the Philippines, is capable of reducing the incidence of iron-deficiency anemia among countless millions of the world's poorest people.

It was to have begun in April 2001, but two typhoons swept across the Philippines as supplies of the all-important iron-rich rice were being grown for the trial, and the harvest was inadequate.

The rice, known simply as IR68144, has already been tested by 27 young religious sisters from a Manila convent, who ate it exclusively over a period of six months. The serum ferritin levels in their blood leaped, sometimes two or three times higher than normal. But nutritionists remained unconvinced, and that trial is now being regarded as a "dress rehearsal" for the main event.

Instead of the original 27, the new trial will involve 300 religious sisters from eight convents in the Philippine capital. The procedure has been refined and the trial will be supervised by nutritionists from Cornell University and Pennsylvania State University in the United States. It will be conducted by the Institute of Human Nutrition and Food (IHNF) at the College of Human Ecology, University of the Philippines Los Baños (UPLB), on behalf of IRRI's sister center, the International Food Policy Research Institute (IFPRI), in Washington, D.C.

Greater Significance

The trial is expected to be an event with far greater implications than earlier efforts to prove that the iron in IR68144 can be absorbed and used by the human body. Several of IRRI's sister agricultural centers are also developing staple foods rich in micronutrients, such as wheat, maize, and cassava, and the trial of IR68144 is being widely regarded as an attempt to prove the concept that staple foods enriched with micronutrients directly benefit human nutrition. If the trial establishes that proof, researchers will have convincing support for their claims for urgent funding.

The trial of IR68144 is now part of a larger initiative by the Consultative Group on International Agricultural Research, the U.S.-based organization responsible for funding IRRI and 15 other such research centers around the world. It is being coordinated by IFPRI and is funded by the Asian Development Bank, with additional support from Denmark and Canada.

IRRI's main involvement is growing and milling the trial quantity of IR68144, as well as supplying a similar quantity of a control rice with normal iron and zinc levels. The first attempt to grow sufficient rice for the big trial ended in disarray after two typhoons in 2000. Only 16 tons of the iron-rich grain were harvested and a further four hectares had to be planted in 2001. The rice will be milled at IRRI to avoid possible damage through overmilling and contamination.

In the trial, about half of the 300 sisters will be fed IR68144 and the rest will eat normal rice for up to nine months. The sisters, who are 20 to 35 years old, are particularly suitable for the experiment because of their disciplined lifestyle and modest diet, which normally leaves them slightly anemic.

A team of workers, including nutritionists, is being trained to supervise the preparation of the sisters' food during the trial. Each location will be linked with networking computers and new utensils will be supplied to the convent kitchens.

Revealing Every Detail

Despite the weight of scientific supervision, the effectiveness of the trial will depend heavily upon the tireless help of the sisters themselves, who must not only submit to regular weight checks and blood tests, but must also reveal every detail of their food intake, their physical condition, how they're sleeping, and even their mental state, during the lengthy course of the trial.

As well as trying to prove that the human body beneficially absorbs the iron in variety IR68144, a broad variety of other tests will also examine the interplay of minerals and nutrients within the body to discover whether, for instance, the presence of one enhances absorption and metabolism of another.

The scientific teams, including plant scientists, nutritionists, and statisticians, will, for the first time, also involve psychologists.

It's long been believed that iron deficiency reduces a person's work efficiency and powers of concentration. This will be put to the test by constantly examining the sisters' cognitive functions and capacity to concentrate.

The feeding trial is expected to end with a wealth of new detail about the huge complexities of human nutrition. Specifically, it is hoped that it will confirm the benefits to mankind of a new rice variety rich in both iron and zinc, which was bred quite by chance in an unrelated effort at IRRI to find rice with tolerance of low temperatures.

It's been estimated that about one-third of the world's population suffers from iron-deficiency anemia. About 60 percent of all pregnant women in Asia and 40 percent of schoolchildren are iron-deficient. It impairs immunity and reduces physical and mental capacities. It accounts for up to 20 percent of all maternal deaths.

The data from the feeding trial will be analyzed at Pennsylvania State University, with input from the IHNF at UPLB, Cornell University, and Adelaide University in Australia.

International Rice Parks

Rice production areas, especially those for lowland rice, can be seen as unique ecological regions no different from the great forests and vast oceans of the planet, except that they are major bastions of food production.

I would like to go so far as to introduce the concept of calling these areas "international rice parks" instead of commercial production zones or food factories. These rice parks cover 146 million hectares, or about 11 percent of the world's arable land. They sweep across borders and represent the largest single land use focused on feeding the world.

Dr. Ronald Cantrell, IRRI's director general,
speaking to a conference of the
Asia-Pacific Association of Agricultural Research Institutions
at Chiang Rai, Thailand, 8 November 2000

Soil

Rice-growing soils are arguably among the world's most vital natural resources. Certainly, flooded rice ecosystems are among the most sustainable uses of agricultural land on Earth.

A long-term experiment at IRRI's headquarters in the Philippines has delivered 111 crops of rice over 37 years of continuous production, and three crops every year still yield a total of ten tons per hectare. Yet the crops get no nitrogenous fertilizer and, despite the removal of crop residues, there has been no decline in soil organic matter, nor has there been any change in the ability of the soil to deliver nitrogen to the crops.

The future, however, has big demands for rice producers and they, in turn, will make extraordinary demands on their soil.

In many parts of Asia, rice production has already intensified to the stage where scientists are worried about the ability of the soil to meet further demands. Without nitrogenous fertilizers, yields are grossly insufficient to meet food needs, so nutrient inputs are essential. But there's increasing scientific evidence that excessive or ill-managed applications of nitrogenous fertilizer both enhance soilborne rice diseases and increase the plants' use of other soil nutrients. Under these conditions, the soil is "mined" for its nutrients and loses its ability to sustain heavy cropping.

Diversification of farming, by rotating flooded rice with dryland crops, may also cause problems. Extended periods of drying may lead to reductions in soil organic matter and harm the ability of the soil to supply nutrients.

Soil scientists are well on the way to understanding the hugely complex processes at work in rice-growing soils. Their evidence suggests that rice farmers of the future will need a far greater technical knowledge if they're to manage their most important resource—the soil—so that it nourishes intensive cropping without being irreversibly damaged in the process.

Bicol, Philippines

Land Preparation Is on the Level

One of IRRI's recent success stories, the Cambodia-IRRI-Australia Project (CIAP), will finish at the end of 2001 after 13 years in which it has helped Cambodia to recover from the devastation of war, reestablish its agricultural systems, and become an exporter of rice.

CIAP's story is replete with achievements, from restoring seed supplies of Cambodia's traditional rice varieties to introducing new techniques for soil, water, and crop management and training hundreds of new scientists to take over when it leaves.

One such achievement concerned farmers' land and the simple principle that, if it is to be flooded and puddled, the soil should have a perfectly level surface. What began as a mild interest soon became so successful that it turned into a virtual stampede.

IRRI agricultural engineer Joe Rickman recalls the conviction, in about 1995, that Cambodian rice farmers didn't know enough about land preparation. A closer look, through the weeds and patchy crops, showed that uneven fields were at the heart of the problem. They were parched in high spots and flooded in the hollows, rice crops were developing unevenly, weeds dominated drier areas, and, in the worst cases, grain yields were pitiful.

"We decided to try some land leveling, strictly behind closed doors at the start, on a 2.5-hectare block," Mr. Rickman explains. "We used tractors with back blades to level half of the block. The rest we left alone. We found that we doubled our yield on the leveled area and had better water control and better weed control.

"What we didn't realize was that farmers were looking over the fence. Very soon we were getting direct requests that we go and level their fields, so we decided that we'd better get the right equipment.

"We built a 2.2-meter leveling bucket to tow behind a tractor in the driveway of my home in Phnom Penh. It was the only place where we could get enough electricity to run a decent-sized welder.

"Then, out of the blue, I received a telephone call at 11:30 one night from an American company called Spectra Precision. They manufactured laser-leveling equipment and wanted to be part of what we were doing. I told them when we were starting and said, 'If you want to be on board, I'll see you there.'"

At the start of the next dry season, Joe McNamara from Spectra arrived in Phnom Penh with a collection of untested equipment; the untried steel bucket was hooked up to a tractor, and a group of Khmer farm workers undertook a high-technology land-leveling exercise.

"Just 12 months earlier, the only thing some of these operators had driven was a bullock," Mr. Rickman says, "but they learned quickly, and the equipment worked really well. So we then made an additional machine out of an old disc plow to repair and build the bunds around our freshly leveled fields.

"Then we put the tractor and the equipment on a truck and went out into the provinces. We found farmers willing to participate, and leveled one hectare of their land. Then, by way of a demonstration as well as an experiment, we took over half of that hectare and managed it, and its rice crop, to the best of our ability. In the first year, we did about 40 fields like this, in four provinces. Since then, on-farm demonstrations have spread to more than 120 fields in 13 provinces.

"All of a sudden, with all this new technology, yields were increasing by at least 30 percent and, in some cases, as much as 50 percent. Farmers were clamoring for their fields to be leveled; private companies were eager to get into the land-leveling business.

"Then, we were accused of bringing in equipment that the farmers couldn't afford," Mr. Rickman says. "We were still using the laser equipment because it was fast. So we had to rethink.

"We decided to set aside the new technology and train extension officers and farmers to level their fields using the equipment available to them. We taught them how to use walking tractors, oxen, and even buffaloes to level their fields, and we used garden hoses to monitor levels in the field. The deal was that we would teach them how to do it if they agreed to then go out and level at least one field in their district as a demonstration to others. Some of them went beyond that. They've now become trainers in their own right."

Mr. Rickman's group also organized field days and "farm walks" to demonstrate the leveling technology.

"It's difficult to say how much the leveling technology has meant to Cambodia's farmers on its own," Mr. Rickman says. "In the fields we monitored, we reduced water use by about 10 percent and reduced weed pressure by about 40 percent. Farmers have found that they can now use direct seeding more effectively, and their crops mature more evenly."

Further studies on newly leveled fields found that rice yields increased by 15 percent as a consequence of the leveling, and by another 15 percent if fertilizer was applied.

Joe Rickman became the head of IRRI's Agricultural Engineering Unit in the Philippines in 2001. However, there's no stopping his land-leveling technology. With IRRI's support, Thai and Indian farmers are now being taught how to level their fields.

Soil Salinity: Breeders Try Something New

IRRI scientists have begun a ground-breaking experiment in plant breeding that they hope will overcome the seemingly intractable problems of providing rice plants capable of thriving in saline soils.

For the first time, a breeding program that begins with the latest biotechnology will end only after several seasons in farmers' fields, when the farmers themselves become the final arbiters and select plants for their own conditions.

Soil salinity, in its many forms, is a growing problem throughout Asia. Often, flooded paddies raise local groundwater levels, bringing salts to the surface. Elsewhere, chemical processes within the soil itself result in both acidity and toxic levels of various minerals. And rising sea levels because of global warming are expected to transport saltwater inland, thus polluting coastal wetlands.

The new approach represents a challenge to plant breeders, who are used to developing new plants according to known parameters and delivering the finished articles for release to farmers. In the case of saline-tolerant plants, this procedure has rarely been successful.

According to IRRI plant breeder Dr. Glenn Gregorio, there has been scant recognition of the variety of soil conditions described broadly as "saline." He says that saline soils can be acid, acid sulfate, peat, or alkaline. Most are lacking in phosphorus and zinc, and some have toxic levels of iron or aluminum. This variety extends across the normal range of rice-growing environments, pest and disease problems, and grain qualities.

"In the past, national agricultural research and extension systems (NARES) have tended to select salinity-tolerant varieties for release by averaging their performance over a range of saline soils," Dr. Gregorio says. "This has worked for a few farmers where the plants were able to adapt to the soil conditions, but it's failed for the rest. A lot of people out there don't recognize the difference between salinity and alkalinity, much less the other differences.

"So we realized the need for a large range of plants capable of adapting to diverse soil conditions. What we've come up with is almost site-specific breeding."

IRRI's plant breeders began by developing a large number of plants whose genetic salinity tolerance has been proven by molecular-assisted selection. They are the raw material for the new approach, and the coastal wetlands of Bangladesh are the trial ground.

The project involves two procedures: farmer participatory variety selection and farmer participatory plant breeding.

In the first, a collection of salinity-tolerant varieties will be grown under different soil conditions by local farmers themselves and they will be asked to select varieties according to their performance on soils similar to their own. The chosen varieties will then be grown in national trials prior to release.

The second procedure is more radical. About 15 farmers, each with one hectare of land or less, have been chosen as the first farmer-breeders. Because they're poor and the experiment will use a large plot of their land, deals have been made to guarantee their normal domestic rice supplies.

In the first season, each farmer will receive seeds for as many as 20,000 different plants, to cover the widest possible range of adaptability. These plants will be traditionally bred crosses between salinity-tolerant varieties and popular high-yielding varieties. They will have undergone screening for salinity tolerance using molecular markers and advanced through six generations to ensure their genetic stability.

The farmers will be asked to watch carefully how the plants compete with weeds, how they develop and yield under their normal management practices, and how the grain suits their tastes. They'll be asked to identify the best plants in the crop, perhaps as many as 100 plants.

Researchers will then help the farmers gather seed from their selected plants and, in the following season, one row of seed from each selected plant will be grown in the same field. Once more, the farmers will watch carefully and select only the best rows, cutting the short-listed varieties down to about ten.

Seed will once more be collected from the chosen rows and, finally, the farmers themselves will plant these seeds in plots, using their own procedures and systems. At the end of the third season, they will select the best plot and that variety will thereafter be theirs to grow. The farmers will choose the variety that most successfully adapts to the specific conditions of their individual farms.

"We expect the technology to spread rapidly because the farmers themselves will be involved; they will regard their chosen varieties as their own," Dr. Gregorio says. "But I don't expect it to be easy. We will have to teach them to be brutal in their assessment of the plants. They must learn to discard the good ones and keep only the best.

"It's also going to be difficult for us, as plant breeders, to accept a different way of doing things," he adds. "It's not all science any more. We've got to learn to work with the farmers, to spend time with them, to use their language, and to listen to what they say."

Watching the procedure with great interest will be scientists from NARES in India, Thailand, Indonesia, and Sri Lanka. These are the countries most in need of successful salinity-tolerant rice varieties.

Precision Farming: A New Concept

Where it comes to providing staple food for huge numbers of people, no soil on Earth is more precious than that of the Indo-Gangetic Plains, lying between the tropical heart of the Indian subcontinent and the foothills of the Himalayas.

Here, 13.5 million hectares of land grow rice in the wet season and wheat in the dry winter season. In large part, it is a modern, mechanized farming system using recently developed, high-yielding varieties of both rice and wheat. A staggering one billion people depend on its output for their staple grain.

Since 1985, however, grain production from the Indo-Gangetic Plains has stagnated and there have been signs of declining productivity. This has prompted the questions: Is the intensively irrigated rice-wheat cropping system, in its existing state, basically unsustainable, and is the ecosystem beginning to degrade under the cropping pressure?

A large team of scientists says "no" to both questions, provided the farmers learn to be more efficient.

But the threat of declining productivity in such a vital area has drawn together researchers from the national agricultural research and extension systems of India, Pakistan, Nepal, and Bangladesh and scientists from international agricultural research centers such as IRRI, CIMMYT, ICRISAT, IWMI, and CIP and other institutions such as Cornell University, in the United States.

Glimpse of the Future

After several years of intensive study, under the umbrella of the Rice-Wheat Consortium for the Indo-Gangetic Plains, scientists have begun teaching farmers new agronomic techniques and crop management methods. These bring practical science to the farmers' fields and demand, in the process, that farmers learn new knowledge-intensive technologies. It is a glimpse of the future of agriculture across the entire Asian region. The scientists call it "precision farming," or "conservation farming," and their results so far suggest that it will increase crop productivity, reduce the costs of crop production, boost farmers' income, and maintain the quality of the farming system.

According to IRRI soil nutritionist Dr. J.K. Ladha, the sites showed evidence from some long-term experiments that soil nutrients had become depleted because of years of intensive cropping. Evidence also showed changes in the soil that reduced the availability of nutrients to the plants. On top of this, the inappropriate use of fertilizers was widespread.

"We found that soil nutrient characteristics varied, not only between regions and between farms, but from plot to plot," Dr. Ladha says. "There was no recognition of this, and fertilizer regimes were more or less general for entire regions or districts. Many farmers saw nitrogenous fertilizer as something that would boost their yields, regardless of whether the crop required it or not. Some farmers were putting on too much—sometimes 25 or 40 percent more than the recommendations, and this excessive use of nitrogenous fertilizer was threatening to pollute both the air and the water."

The range of measures being introduced to the rice-wheat system include laser-guided leveling of rice fields to save water; direct seeding of rice to cut the costs of crop establishment, save irrigation costs, and save labor; and incorporation of crop residues into the soil to improve fertility and protect the environment by retaining carbon and providing better conditions for the growth of microscopic life. There is also balanced nutrient management, and that's the most complex measure.

Under the precision-farming system, farmers are taught "field-specific nutrient management." They learn how to test their fields themselves for levels of the nutrients nitrogen, potassium, and phosphorus. Then, according to what they find, they apply enough potassium and phosphorus to avoid its depletion by another crop, and apply nitrogen throughout the growth of the crop according to the demand of the plants. This demand is measured by using leaf color charts that indicate the nitrogen level in the leaves of the plants. When the leaves turn a little yellow, they need more nitrogen.

The research teams have also conducted successful experiments with deep placement of nitrogen fertilizer tablets or briquettes, and with controlled-release fertilizers. They've concluded that both procedures are capable of reducing farmers' applications of nitrogenous fertilizer by up to 30 percent.

Rice on Dry Raised Beds

The researchers have also been experimenting with the cultivation of rice crops on raised irrigated beds, rather than in puddled soils with standing water, and this has achieved a water savings of around 40 percent. As well, it has integrated rice production more comfortably with the soil conditions needed by the following wheat crop.

Dr. Ladha acknowledges that poor farmers with low productivity will find it hard to adopt the new knowledge-intensive technologies over the coming ten years. "But these are the kind of people who need more of our help. They've been overlooked in the past. In Nepal, for instance, with good technical support, they can easily double their rice production."

Conclusions to date suggest that, by adopting field-specific nutrient management practices, farmers can increase their income by US$35 per hectare per crop in the first year, but by $50 per hectare per crop in the second year.

"Precision technologies that conserve resources have an enormous potential for increasing yields and nutrient efficiency in rice cultivation," Dr. Ladha says. "What's more, productivity improves over time, due to both a learning effect and a gradual improvement in soil fertility."

The research team is continuing its intensive monitoring of the rice-wheat ecosystem, further refining its understanding of soil, water, and nutrient processes, and continuing to fine-tune its advice to farmers on nutrient levels in various soils and the measures necessary to make continued intensive cultivation sustainable.

Water

Asia produces more than 530 million tons of rice every year. To produce just one ton of it requires between two and three Olympic-sized swimming pools full of water.

Nearly 90 percent of fresh water diverted for human use in Asia goes to agriculture and, of this, more than 50 percent is used to irrigate rice.

China's mighty Yellow River, which flows 4,600 kilometers through some of Asia's richest farmland, has run dry nearly every year since 1972. Such is the demand on its water that, in 1997, its final 600 kilometers were dry for more than four months.

In India, the Ganges and Indus rivers have virtually no outflow to the sea in the dry season, and inland, in the intensively cultivated states of Punjab and Haryana, groundwater tables fall about 70 centimeters per year.

Among them, China, India, and Pakistan have 120 million hectares of irrigated farmland upon which they depend for about half their domestic food production. Yet salinization has already damaged up to 17 percent of it, through mismanagement of irrigation projects. Salinization, the process by which salts accumulate in soil and make it unsuitable for most crops, is spreading worldwide at a rate of two million hectares per year.

Agriculture faces increasing competition from cities and industry for available water supplies. Yet rice production, the most water-intensive of all agricultural systems, needs to keep pace with population growth. Helping rice farmers to become more efficient users of water is a major issue now influencing much of IRRI's research.

Guilin, China

Where Does the Water Go?

Because farmers in large irrigation projects pay next to nothing for their water, nobody should expect them to become responsible and efficient in its use.

This is one prominent conclusion drawn by a group of IRRI researchers after four years of work in a large Philippines irrigation system. They aim to develop water-saving technologies able to be applied at the field level by individual rice farmers. But their studies have led them inevitably to consider a broader picture, and they've begun thinking of the problems associated with water use in an unconventional way.

Their studies have been driven by clear evidence that water for agriculture will soon be an essential commodity in short supply and, since rice production is easily the biggest user of agricultural water, rice farmers must learn to use it more efficiently. However, efforts to convince farmers of the need to be more efficient are not always met with understanding compliance.

Leading the IRRI team, water scientist Dr. Bas Bouman says that inefficiency is worsened by lack of cost.

"Upstream farmers in the irrigation system waste a lot of water, even though they know others downstream will go without as a consequence," he says. "The water system management has spent a lot of energy trying to make them more responsible in their use of water. But this has not worked."

Dr. Bouman says that economists have been advising for some years that efficient use will come only when a price is attached to water supplies. However, rather than stepping into what he acknowledges is the "sensitive area" of charging for irrigation water, Dr. Bouman's team is investigating a different approach.

It begins with the questions, Where does the water go after wasteful farmers have spilled it? And how can it be recovered and used again?

Although conventional water-saving approaches tend to concentrate on preventing water loss from canal systems and convincing farmers of the need for greater efficiency, the IRRI team has begun mapping water flows beneath the surface and listing the options available for intervention in water systems to control or avoid wastefulness and recover spilled water.

"As well as saving water at the field level, we're trying to reuse water efficiently," Dr. Bouman explains. "If water lost in the fields seeps in a certain direction, or into a river, can we pump it back again and use it elsewhere? Can irrigation systems bypass wasteful users?"

Of additional interest is the fact that the irrigation system in which they're working is currently being expanded from 100,000 to 120,000 hectares. Two new dams and an infrastructure of tunnels and canals will soon see it serving more than 50,000 families in Central Luzon.

"There is a problem common to most large irrigation systems," Dr. Bouman says. "Technical options are considered by engineers at the design stage, the project is built and delivered, and thereafter it receives little or no maintenance. Physical deterioration seems not to be considered."

"We want to list all possible options for interventions that will make for more efficient use of water across an entire irrigation system."

Meanwhile, the team has not relaxed in its job of helping individual farmers to become more efficient.

"A considerable number of farmers in this project have bought pumps to deliver additional water from ground wells or drainage canals," Dr. Bouman says. "They pay to run their pumps, and they're very careful about their water use.

"There are also groups that use a communal pump. They're also very careful. These are the people we want to help—the farmers who have to make conscious decisions on when and how to use irrigation water most efficiently."

Dr. Bouman says that, rather than trying to enforce rules and restrictions on the use of freely delivered irrigation water, system managers should be considering handing over parts of an irrigation system to groups of farmers, and allowing them to become self-regulatory.

"Aerobic" Rice: Preparing For a Water Crisis

Scientists at IRRI have begun the task of creating a high-yielding tropical rice plant that grows on dry but irrigated land instead of in flooded paddies. They have dubbed the new plant "aerobic rice" and given themselves five years to complete its development. But they face formidable challenges, including inexplicable "yield collapse."

The project is driven by the knowledge that water resources for agriculture are shrinking, as supplies are increasingly diverted to big cities for domestic or industrial use. Traditional rice cultivation requires that fields remain flooded for four to five months for every crop, and water losses through percolation into the soil, evaporation, and seepage are substantial.

IRRI has formed an Aerobic Rice Working Group, involving plant breeders, plant physiologists, and water and soil scientists, to meet the many difficulties of taking rice out of its natural environment and developing a complete management system for dryland crops using perhaps only half the water. Although rice varieties that grow in dry upland fields already exist, they cannot match the yield potential of conventional commercial varieties, nor do they respond to irrigation or fertilizers.

"We've got a long way to go," says water scientist Dr. Bas Bouman. "First of all, our plant breeders must come up with tropical varieties that grow in dry soil. Then we've got to understand the problem of yield collapse. After that, it's a matter of working out crop management: How much water does the crop need? How do we control weeds? And what nutrients does the crop need?"

The project has begun quickly, by studying aerobic varieties developed in northern China and Brazil. These were developed for subtropical and temperate climates, so the early aim is to test their adaptability to the tropics. They're being grown experimentally in China and the Philippines and will soon be grown in India, where water shortages are becoming a serious problem. Meanwhile, IRRI's plant breeders are working with many other rice varieties, selecting those that exhibit different reactions to drought, soil quality, and environmental conditions.

"We already have upland rice varieties that can withstand drought, but they're low yielders and they don't respond to fertilizer inputs," says water management engineer Dr. To Phuc Tuong. "Our aerobic rice must be able to withstand dry soil, respond to irrigation and to fertilizers, and deliver a high yield."

Another big problem is weeds. Normally, they're suppressed by flooding, but on dry land rice can easily lose the battle for dominance. So the working group expects weed tolerance to be a big issue.

But these problems may fade into insignificance alongside yield collapse.

In experimental dryland rice crops grown to date, the harvest is good in the first season but drops by about 20 percent in the second and may fall a further 70 percent in the third. Thereafter, plants don't develop properly, grow enough tillers, or set grain. Nobody knows why this happens, much less has an inkling of how it can be overcome.

Yield collapse doesn't occur when rice is rotated with other crops. This is how aerobic rice continues to play an important role in Brazil, where it is grown commercially under irrigation on 250,000 hectares. But IRRI plant physiologist Dr. Renee Lafitte, who is a member of the Aerobic Rice Working Group, believes that yield collapse may be a fundamental obstacle to the development of aerobic rice as a permanent, intensive crop.

"It's not simply a matter of finding the correct germplasm for new varieties that will be free of yield collapse," she points out. "I believe it's a problem of the agricultural system in which these plants are grown."

Dr. Lafitte says that among the areas that might benefit most from the development of aerobic rice is eastern India, where seven million hectares are devoted to annual crops of upland, or dry, rice. In this area, farmers who grow nothing but rice can't achieve harvests better than one ton per hectare, no matter how they try to improve their productivity.

"I believe that these low yields are actually a situation of yield collapse, and we should begin our efforts to develop aerobic rice by investigating what is happening in eastern India," she adds.

In another example, farmers in Mindanao, in the Philippines, were given a new upland variety to replace low-yielding local varieties. Many enthusiastically adopted the new variety in the first few years, and their yields grew, in some cases fourfold. Then, suddenly, they abandoned the new variety, reverting to the old ones. When asked why, they said the new variety had "broken down." This, Dr. Lafitte believes, was yield collapse.

"In some cases," she continues, "there were buildups of microscopic worms called nematodes in the soil that may explain the yield collapse. But we also see the same yield reductions in fields with no nematode problem.

"In situations where rice is grown in rotation with other crops, the problem doesn't seem to exist. So, do we need some kind of insistence upon farmers rotating their crops?"

Dr. Lafitte says that her work "at the border of plant breeding" will include intensive studies of the rice plant itself.

"Water shortages are going to become a major issue in the future," she says. "So we need to know what it is about the physiology of the rice plant that makes it demand so much water, and what it is that makes it so sensitive to fluctuations in water supply."

The imminent need for rice farmers to save water has already led to trials involving a variety of irrigation regimes and seeding techniques.

Dr. Tuong says that one technique practiced in China as an alternative to permanent flooding of rice fields involves flooding to five centimeters in depth every few days and allowing the water to recede before the next flooding. He says that conventional rice yields do not suffer under this method, and the crop uses 10 to 20 percent less water.

But aerobic rice is another thing altogether. One of the first tasks facing the working group is a geographic one. The researchers are mapping the areas where they believe their aerobic rice should be grown.

"Obviously, we'll target areas with water scarcity first, places such as northern China and some parts of India," Dr. Tuong explains. "But think of the Philippines, for instance. The dry season has only enough water to grow rice on half of the irrigated land. With aerobic rice, we could encourage farmers to make better use of their land and produce more food.

"If there is no need to flood fields, the benefits will not end with a savings in water. There will be much less effect on the environment. Water percolation from traditional flooded rice fields raises the groundwater table and can create salinity problems. If rice is grown in dry soil, much less percolation will occur."

The Fight Against Weeds

Weeds, the bane of any gardener's life, are looming as an even bigger problem for the future of Asian rice. So much so that IRRI has begun a concerted scientific effort to understand the complex relationships between rice plants and their unwanted competitors.

It has all come about because of shortages of water and farm labor, and a consequent move away from water- and labor-intensive transplantation toward direct seeding of rice crops.

The head of IRRI's Crop, Soil, and Water Sciences Division, Dr. James Hill, likes to refer to weeds as the "neglected pest" when it comes to rice research. Traditional transplanted crops are weeded by hand, so weeds don't create anything like the losses arising from disease epidemics or large-scale insect attacks. So they're not seen as a major threat.

"But they're always there, competing with the rice," he says. And that competition has lately taken on a greater significance.

He explains that transplanted rice seedlings in flooded fields have a major advantage because water controls the early growth of weeds. However, the old system of flooding and puddling rice fields before transplanting is threatened in many parts of Asia by increasing scarcity of water and the lack or high cost of farm labor, so farmers are turning to direct seeding of their rice crops. The seed is usually broadcast onto wet soil that is not flooded until the seedlings are 12 to 14 days old. But by then the weeds have become just as well established as the rice.

What's worse, those weeds that do best in shallow water or puddled soil are far and away the most competitive.

Dr. Hill says that IRRI's weed project team is trying to overcome the disadvantages of direct seeding by exploiting the life habits of the weeds themselves, and by learning to regain control over unwanted species by flooding the fields at different times. Trials with early flooding, within three to seven days after seeding, found that, although the water favored the rice crop and reduced the number of surviving weeds, it also reduced the number of surviving rice plants.

It may seem that just a few days wouldn't make much difference, but earlier flooding has a huge influence on the types of weeds that survive. "That's why it will be critical, when developing new rice varieties, to look for very early tolerance of submergence," Dr. Hill says.

He believes that, in creating new high-yielding rice varieties, plant breeders have unwittingly lost some of the plants' capacity to compete against weeds. His team's first task will be to begin studying the nature of plant competitiveness.

"What is it that helps plants to dominate their competitors?" he asks. "Although a few studies have tried to identify improved traits that would give rice a competitive advantage against weeds, we don't really know much about how rice varieties differ in early growth, let alone which traits are most important in giving them a competitive edge.

"Nevertheless, we're working with breeders to establish what traits can best be used to develop new, highly competitive plants," he says, "and we've got to achieve that without losing any of the attributes such as high yield and good grain quality that make these varieties popular with farmers and consumers."

Adding urgency to the project is the fact that, of all the agricultural pesticides in use in Asia, farmers' largest expenditure is on herbicides.

"Herbicides are an important component of integrated weed management and their use is rising rapidly," Dr. Hill says. "But along with it, weed resistance to herbicides is also rising swiftly. Ten or 15 major weeds of rice are now showing resistance to herbicides. We want to develop strategies against weeds that will minimize both herbicide use and the development of weed resistance to herbicides. Improving both the competitiveness of rice and its tolerance for submergence has potential for doing that. The potency of these herbicides is not going to last if farmers are completely dependent upon them."

air and sunlight

Human life ultimately depends on the peculiar combination of energy from the sun, the molecular composition of the atmosphere, and the physical and chemical structure of Earth's surface materials.

Plants use solar energy for photosynthesis, and this fuels the biological processes that manufacture the food on which human life depends. Earth's atmosphere, as well as being a source and a sink for the molecules essential to sustain life, wraps the planet in a "blanket" that helps regulate its surface temperature. At a "stable" average environmental temperature, the radiation entering Earth's atmosphere equals the amount leaving. Currently, that is not the case. Increasing concentrations of "greenhouse gases" in the atmosphere are absorbing more infrared radiation. "Global warming" and "climate change" are the consequences.

The greatest challenge facing mankind, and Asia in particular, is how to produce increasing amounts of food in an environmentally benign way. Recent research at IRRI has shown that methane emissions from flooded rice fields are much smaller than once thought. However, in the short term, increasing quantities of grain will require increasing amounts of nitrogen, from organic and inorganic fertilizers. Fertilizer-use efficiency is usually less than 50%, so gaseous nitrogen in the form of nitrous oxide will find its way into the atmosphere. Nitrous oxide is one of the worst greenhouse gases. It also damages the ozone layer.

Various solutions exist in theory. They are dependent, at least, on the latest biotechnology to make fundamental changes to the rice plant itself. Until these theories become reality, researchers will pay increasing attention to the delicate relationship between the world's rice crop and the atmosphere that supports all life on Earth.

Mt. Mayon, Philippines

The Consequences of Global Warming

Global climate change and its expected consequences in rice-growing regions have become a growing influence in much of IRRI's current research. Average temperatures are expected to rise by up to three degrees Celsius. There will be more carbon dioxide in the atmosphere, and increased ultraviolet radiation.

One fear is that yields could fall by 50 percent if air temperatures rise to 37 °C while the plants are flowering. So a search of germplasm has begun in the International Rice Genebank to see if genes exist that control the time of day at which rice flowers. The hope is to develop plants that flower only in the cooler parts of the day.

Not least among other concerns is the continuing scientific debate about the part rice farming plays in global warming by the emission of so-called "greenhouse gases." At one time, rice farming was thought to be one of the main culprits because of the amount of methane gas emitted into the atmosphere from flooded paddies.

However, research begun by IRRI in the early 1990s measured methane emissions from flooded paddies, and they amounted to only 12 percent of the global total, considerably lower than previously thought. Management practices have been developed to help minimize emissions, mainly involving water and crop-residue management. Methods have also been developed to assess the effects on emissions that result from changes in farming practices.

Alongside global warming, the growing scarcity of water for agriculture is a major environmental issue affecting world rice production. But there is little comfort in the fact that draining paddies at times during crop growth both reduces methane emissions and saves water.

Drying the flooded soil sometimes gives rise to an even worse gaseous emission: nitrous oxide. The gas is produced in a complex process involving nitrogen from both organic matter and fertilizers that remain in the soil as it becomes aerated when paddies are drained. Whereas one molecule of methane is 21 times worse than one of carbon dioxide in its contribution to global warming, nitrous oxide—better known as laughing gas—is 310 times worse than carbon dioxide.

So the question among IRRI's soil and water scientists is, Should the hardware and methodology used to fix the amount of methane rising from flooded paddies be shifted directly into measuring the nitrous oxide rising from rice soil that is partly dry and partly wet?

According to the deputy head of IRRI's Crop, Soil, and Water Sciences Division, soil chemist Dr. Guy Kirk, nitrous oxide emissions from rice fields are not a serious problem in continuously flooded systems. However, since rice farmers face the need to save water, this cannot be dismissed as a problem in the near future.

IRRI scientists are currently preparing for a water-scarce future by perfecting a rice plant that will grow in aerobic, or dry and aerated, conditions, much like wheat or maize *(see* "Aerobic" Rice: Preparing For a Water Crisis, *page 20)*. It is envisaged that the aerobic rice will be irrigated and will need fertilizer.

"Water-saving practices are going to push us toward nitrous oxide emissions," Dr. Kirk says. "But we don't yet have the necessary information to quantify the problem. We are therefore developing research plans.

"One problem is that nitrous oxide emissions are very transient, so you need continuous measurement to record them."

IRRI crop ecologist and modeler Dr. John Sheehy agrees.

"Interfering with water use by changing flooding to irrigation is rather difficult and dangerous because water stress is the main factor limiting yield in agriculture and, if irrigation is continuous, it's not likely to save water," he says. "Furthermore, we will have to consider the effect on gas emissions with every proposed change in crop management. We will have to ask, What is this going to do to nitrous oxide emissions, on the one hand, or methane emissions on the other? Like it or not, rice crops will always grow at the interface between aerobic (with oxygen) and anaerobic (without oxygen) conditions."

Dr. Sheehy is eager to investigate the benefits to rice farmers that may arise from global measures to mitigate emissions of greenhouse gases. He notes that provision has been made for so-called "clean development mechanisms," in which developed countries, or even polluting industries, can pay for projects that reduce emissions in other parts of the world.

The resulting reduction in emissions can then be reckoned as part of that developed country's promised contribution to global reduction. For instance, an industry that emits 100,000 tons of carbon dioxide into the atmosphere every year can pay for the planting of a new forest in another part of the world that will capture 100,000 tons of carbon in its trees, thereby reducing the industry's "carbon balance sheet" to zero. The developers of the forest reap the monetary rewards.

Trading in "carbon credits" began in January 2000, and Dr. Sheehy believes that the market will soon be worth billions of dollars per year.

"I think rice straw and rice hulls have potential in this area," he says. "We must be able to work out how to sequester the carbon in straw and hulls. Perhaps we turn it into building material or wood substitutes, and save trees. Perhaps we use it to produce ethanol, as a fuel, thereby reducing the need for petroleum.

"Rice farming produces 500 million tons of straw every year," Dr. Sheehy adds. "If the carbon in it is worth ten dollars a ton, that makes it worth five billion dollars. That's a bit better than dumping it back into the paddies and fueling methane emissions."

A New Plant for a Changed Climate

IRRI has been urged to direct its research efforts toward the creation of a new rice plant capable of thriving and producing heavier crops in a world changed by global warming.

It will be a world with higher temperatures, with more carbon dioxide and pollutants in the air, and where extremes of weather are commonplace. Less water will be available to agriculture, so the new plants will have to use less. And, because poor management of nutrients over vast tracts of rice land risks making the climate even worse, the new plants will have to use nitrogenous nutrients very efficiently.

The Institute's plant breeders have already created a new plant type in a scientific effort that has so far taken nearly 12 years' work *(see* Green Revolution Hero Bows Out*, page 42)*. It has been designed to boost the potential rice yield in the tropics, from the current 10 tons to 12 tons per hectare, as a first step toward meeting the huge additional demand for rice that will follow population increases over the next few decades. It is expected to be released in about four years. But already the Institute's biotechnicians and plant breeders have been urged to begin again, this time on a more challenging path: the creation of a more environmentally friendly rice plant that uses sunlight more efficiently to grow and produce grain.

According to IRRI crop ecologist and modeler Dr. John Sheehy, rice plants are less efficient in their use of solar energy than some other crops, such as maize. He contends that because of this there is a biophysical limit to the amount of grain a rice plant can yield.

"It is often suggested that continuation of existing trends in cereal yield will be sufficient to meet future demands for food," he says. "However, the linear trend of the past 30 years can be extrapolated only if there are no foreseeable limits to yield, and limits do exist."

He says that the potential yield is a theoretical figure never achieved on the farm. The best farmers can reach is about 80 percent of the figure, so the present practical maximum yield for rice with a 110-day growth period grown on ordinary farms in the tropics is 8 tons per hectare. With the introduction of new cultivars and improvements in agronomy, the maximum limit on the farm may be raised to 9.6 tons per hectare. But this, he says, will be the absolute limit.

"The current technology is going to run out of steam in about ten to 15 years. Present rice plants will be unable to convert any more solar energy into biomass and grain. They will have reached their limit."

Dr. Sheehy takes this scenario and places it alongside predictions of future conditions for rice farming and estimates of future demand.

"The population of Asia is expected to increase by 44 percent in the next 50 years," he says. "At present, more than half the people in Southeast Asia have a calorie intake inadequate for an active life, and ten million children die annually from diseases related to malnutrition. Yet simply to maintain our present per capita consumption, we will need 44 percent more rice within 50 years. The area for rice cultivation is continually being reduced by expansion of cities and industries, to say nothing of soil degradation. So we will need rice plants to deliver maybe 50 or 55 percent more."

Dr. Sheehy points out that more efficient farmers will soon reach the yield limit, and the job of filling future needs will depend upon the less efficient farmers lifting their productivity. This prospect, he says, casts a dark shadow over future food security.

"We're trying to improve yields against a background of climate change and increasing competition for resources such as land and water. If, by using all the tools available to modern biotechnology, we can create a new plant that addresses many of these problems, then we should be doing it."

He recalls that, in the past, higher yields have depended on increased use of organic and inorganic fertilizers to supply nitrogen to the plants. But this, he says, no longer represents the way forward because the use of organic fertilizer often stimulates the emission of methane and inorganic nitrogen fertilizers can stimulate the emission of nitrous oxide. Along with carbon dioxide, these are the two most damaging greenhouse gases and any proposal to boost rice production simply by increasing fertilizer use would risk making the world's climate even worse.

Dr. Sheehy believes, along with a growing body of scientific opinion, that the only way to achieve the rice harvests needed for the future is to change the biophysical structure of the rice plant, making it a much more efficient user of energy from the sun. Plants use solar radiation to grow—to develop leaves, roots, stems, flowers, and seeds in a process known as photosynthesis.

Rice has what is known as a C_3 photosynthetic pathway, less efficient than that of maize, which has a C_4 pathway. Converting a plant from C_3 to C_4 would involve a rearrangement of cellular structures within the leaves and more efficient expression of various enzymes related to the photosynthetic process.

"All the components for C_4 photosynthesis already exist in the rice plant," Dr. Sheehy says, "but they're just distributed differently and are not as active."

He believes that a significant part of IRRI's biotechnology and functional genomics programs should be targeted specifically at the conversion of rice to a C_4 photosynthetic pathway. Work should also begin on screening likely candidates in the more than 100,000 germplasm samples held in the International Rice Genebank for varieties that lean toward a C_4 anatomy, or that have greater enzyme efficiency.

Dr. Sheehy believes that current trends leave about 15 years in which to invent a C_4 rice, and that IRRI should be encouraging the formation of an international partnership to use all available biological tools to achieve it within that time frame.

"Plants with a C_4 photosynthetic pathway are better equipped to cope with the climate changes that are expected as a consequence of global warming," he says. "They operate well at high temperature, they're extremely water-efficient, and they require less nitrogen.

"This is the single most important change that can be made to rice, and there's no doubt that, eventually, it will happen. If IRRI doesn't do this, and others succeed, then people will be asking, 'Where were you guys?'"

biodiversity

Increased rice production has generally been achieved by planting a few improved plant varieties over large areas. This monoculture cropping has reduced the biodiversity of the rice landscape and has created genetic uniformity that exposes rice crops to attacks by disease pathogens and insects. Once a pest or pathogen has adapted to one plant, it is ready to attack the rest of the crop.

Pest management has depended upon the development of disease- and pest-resistant varieties, and the use of pesticides. But when a single pest-resistant variety is planted over large areas, the insects and pathogens soon learn to overcome its natural resistance. Likewise, insect pests and disease organisms develop resistance to pesticides, and farmers are tempted to increase their application of chemicals.

Traditional rice-growing environments with a rich diversity of plant varieties rarely suffer serious epidemics or insect outbreaks. Natural checks and balances among plants, herbivores, predators, pathogens, microbial antagonists, weeds, and other organisms prevent the increase of one population at the expense of the rest. However, traditional agriculture would never have succeeded in feeding the world's modern population.

The challenge is to maintain the high productivity of modern rice varieties while reversing the trend toward monoculture, and promoting a greater diversity of plant varieties growing in any single field. Taking this a step further, scientists have already brought economics and social acceptance into the equation, and they're working out which varieties should be grown side by side for ease of crop management, to maximize profitability, and to provide a natural hedge against domination by any single destructive species.

Tashigang Dzongkhag, Bhutan

A Clean and Simple Success Story

Of all the new technologies developed by IRRI scientists, few have spread like wildfire to transform rice-farming practices over thousands of hectares in just three years.

But such has been the success of an IRRI project called "Exploiting Biodiversity for Sustainable Pest Management." It has used a simple ploy to dispel a serious fungal disease that was threatening China's rice crop and, at the same time, has boosted yield and farmers' income and has substantially reduced the use of fungicides.

What began in 1997 as a small-scale trial now covers about 42,500 hectares in Yunnan Province and is being adopted by farmers in a further ten provinces representing China's rice-growing heartland. *The New York Times* has referred to it as the largest agricultural experiment of all time.

This technology involves a practice called "interplanting," which is based on the knowledge that monoculture crops—large areas of one plant species—are acutely vulnerable to attack from diseases and insect pests. After a pathogen adapts itself to the physiology of one plant, it is then ready and able to attack the remainder of the crop. If, on the other hand, the pathogen is surrounded by dissimilar plants, it is unlikely to achieve a population explosion and the scale of its depredations is limited.

In 1997, the fungal disease blast was threatening to wreak havoc on the Chinese rice crop. So, a team of IRRI scientists led by Dr. Tom Mew, head of the Institute's Entomology and Plant Pathology Division, in collaboration with scientists from Yunnan Agricultural University, interplanted its first crop of hybrid rice and glutinous rice, four rows of one, followed by one row of the other. The striped fields of two-tone green have now grown to represent a significant part of the entire Chinese rice crop.

The success of the system has astounded even those closely involved. Incidence of blast has been dramatically reduced, and farmers claim to be enjoying additional income of up to US$150 a hectare.

There has been an equally dramatic reduction in pesticide use. Before the interplanting experiment, farmers were known to spray fungicide up to seven times on one crop. Follow-up surveys have found that 87 percent of farmers using the interplanting system are using less fungicide.

Dr. Mew says that the next move will be to introduce the technology to northeastern Thailand, Vietnam, and the Philippines, where, as well as minimizing disease damage and reducing the use of pesticides, he hopes that the biological control of blast by interplanting will offer another vital benefit.

He says that natural resistance to blast, carefully bred into rice plants by incorporating resistance genes, lasts only three to five years in monoculture crops because the blast pathogen quickly adapts itself to the resistant plants. However, when the virulence of the fungal attack is blunted by providing a diversity of rice varieties in any field, the resistance can last a lot longer.

This may be particularly important in northeastern Thailand, where farmers grow a well-known traditional variety called Khaaw Dok Mali, or jasmine rice. Although there are about 38 varieties of Khaaw Dok Mali, only 12 of them are known to have blast resistance genes. If these genes are incorporated, one after another, into field crops, but last only about four years each, then the known stock of resistance genes will run out within 50 years.

"For the current generation of farmers, that's fine," Dr. Mew says. "But what about their children? If blast is still a problem, what do we do?"

He hopes that, as well as minimizing blast damage in the new areas and cutting back on pesticide use, his interplanting procedure will extend the effectiveness of blast resistance genes in a famous and popular rice variety.

The Misuse of Pesticides

Reducing the use of pesticides has become an urgent issue in many rice-growing countries, and IRRI scientists have developed some unusual but extremely successful approaches to the problem.

They're working against a background of official and scientific reports that continue to outline a horror story of misuse, widespread sickness among farmers, and exploitation of inadequate government controls.

The damage is being compounded by the fact that many pesticides commonly available in Asia are classified by the World Health Organization as extremely hazardous and are either banned or severely restricted for use in the developed world.

Repeated calls have been made for a tightening of regulatory controls and increased farmer education and, these days, these tend to be based on economic issues, rather than the more obvious environmental costs of pesticide use.

For instance, a report prepared for the Institute of Agricultural Economics in Hanover, Germany, estimates that nearly 40,000 farmers in Thailand suffer from various degrees of pesticide poisoning every year, and that their associated health costs amount to more than US$300,000. It goes on to estimate that the external costs of pesticide use in Thailand, including health, monitoring, research, regulation, and extension, amount to as much as $127.7 million per year.

A similar report called "The impact of pesticides on farmer health: a medical and economic analysis in the Philippines" (Pingali, P.L. et al., 1995) claims that the value of crops lost to pests is invariably lower than the cost of treating diseases caused by pesticides. It says that the health costs incurred by farmers exposed to pesticides are 61 percent higher than those of farmers who are not exposed.

The Thai report details the proliferation of trade names used there in marketing agricultural chemicals. One chemical is marketed under 296 different trade names, another under 274, and, as the report points out, this makes transparency for users and monitoring and control by government agencies nearly impossible.

The effects on the Thai environment are equally dramatic. Studies have shown pesticide residues in more than 90 percent of samples of soil, river sediment, fish, and shellfish. Seventy-three percent of tangerines tested in one survey contained pesticide residues, and more than a third of all vegetables were contaminated with organophosphorus insecticides.

Against this backdrop, an IRRI team is helping to introduce to Thailand an education program that has already proven very successful in Vietnam.

Under the banner of the Rice Integrated Pest Management Network, the campaign reduced insecticide use in Vietnam's Mekong Delta by an estimated 72 percent. What's more, the number of farmers who believed that insecticides would bring higher yields fell from 83 percent to just 13 percent.

As in Vietnam, the new Thailand campaign will involve cartoon characters, billboards, information handouts, and, most importantly, brief and humorous radio programs. Local actors will play out a series of brief comedies, using rustic situations and solid scientific facts, to make their audience laugh. The basic premise is that farmers' perceptions, rather than economic rationale, are used in most pest management decisions.

"We want to motivate farmers to think of the benefits of not using pesticides," says IRRI entomologist Dr. K.L. Heong. "Most of the farmers in the project area spray their rice crops three or four times. In fact, some of them are not even using insecticides against insects. They're using them to kill snails, because they believe they've got no other option. Pesticide use is regarded as a big problem in the Thai countryside. We are trying to reduce it by one half."

Dr. Heong will be helping local researchers to develop the antipesticide campaign. It will be centered on the town of Singburi, north of Bangkok, in Thailand's famous "central rice bowl."

integration

As Earth's population continues to grow beyond the six billion mark, pressure on the quality of our natural environment also continues to grow. As demands on our soil, water, air, and biodiversity increase, our ability to adjust one part of this life support system without simultaneously affecting the rest is diminished. We therefore need to do more than carefully manage each of our natural resources: we need to integrate those management regimes so that, with every contemplated scientific intervention, the effects on all natural resources are taken into account. Hence, integrated natural resource management.

Many Asian rice-farming traditions will undergo widespread changes within the next 20 years. There will be a far greater business orientation, mechanization will begin to replace manual labor, land ownership will be consolidated, and regulations will increase to control the exploitation of natural resources. On top of these will be a tide of agronomic measures and new plants with which farmers will struggle to satisfy demand.

But these changes involve practical application, whereas the biggest revolution of all may be more a philosophical one: a recognition that nothing must be achieved at the expense of further damage to the environment.

By 2020, we hope that the world's rice producers will supply enough rice to feed half the world's population. More certainly, a large number of them will be practicing a form of agriculture that is environmentally sustainable.

IRRI, Philippines

Achieving a Balance

The single most important question facing agricultural science today is whether the farmers of the world can feed humanity without irreversibly damaging the natural environment.

Most opinions suggest, with some confidence, that they can. But the confidence is tempered with caution, because Earth's finite natural resources are being widely mismanaged and there are no straightforward solutions to the problems.

So IRRI has joined a scientific movement that is coming to grips with the crucial need for sustainability and balance in the world's farms and fields. One of its cornerstones is the recognition that pressures upon natural resources have become so intense that no single aspect of a farming system can be changed or manipulated without it affecting the rest, even including social and institutional considerations.

This calls for a new approach, integrated natural resource management (INRM), which aims at making agricultural production environmentally, socially, and economically sustainable.

At the heart of IRRI's commitment to the concept is Dr. Suan Pheng Kam, the Institute's Malaysian-born specialist in geographic information systems (GIS). Dr. Kam is team leader of a project titled "Ecoregional approaches for integrated natural resource management and livelihood improvement."

Past Research

In the 1960s, even when research focused on yield alone, it was driven purely by the need to feed hungry people and it still had its environmental payoffs. The much larger harvests from the new rice varieties with which IRRI contributed to the Green Revolution meant that farmers didn't have to break in new land to make enough money to live comfortably. The Intercenter Working Group on Climate Change says that the Green Revolution saved more than 400 million hectares of forest and grasslands from conversion into farms. As a consequence, the atmosphere was spared the emission of an estimated 600 million tons of carbon per year over the past 30 years.

The "additional benefits" of the Green Revolution were probably not even considered in the 1960s. Therein lies a basic difference between agricultural research then and now. With the current heightened environmental consciousness, the development and use of new agricultural technologies to enhance agricultural productivity should be carefully considered in the light of their satisfying the food needs of the world's population while maintaining Earth's environmental balance and protecting its natural capacity to produce more.

"We need to understand how an agricultural system works," Dr. Kam continues, "and understand that how farmers use and manage their land, soil, and water is driven by their livelihood needs and aspirations, and moderated by institutional policies.

"IRRI has been contributing significantly to natural resource management (NRM) research and to protecting the integrity of the rice-growing environment. Its forte has been NRM research at the field and farm level, building strong scientific foundations for the management of crops, soil, nutrients, water, pests, diseases, and weeds.

"There has also been a concerted move toward more integrated approaches, such as integrated pest management and integrated nutrient management, taking into account interactions among nutrients, water, plant varieties, and the environment," Dr. Kam says. "This is one dimension of integration in NRM that will produce field-level technologies aimed at more efficient use of natural resources and agricultural inputs, making rice production more environment-friendly."

Increasing Impact

However, she says that this research tends to be site-specific, and the challenge is to make INRM capable of benefiting large numbers of farmers, particularly the poor, across large areas and within reasonable time frames.

"In many Asian situations," Dr. Kam adds, "rice is not the only crop that farmers grow, cropping is not the only agricultural activity that they engage in, and farming is not their only source of income. So the way farmers act and the decisions they make may not be based simply on rice."

So researchers team up with development and extension workers, including nongovernment organizations (NGOs), to identify farmers' technology needs based on an understanding of their constraints and opportunities. Then, different combinations of technologies, "a basket of options," will be offered, tested by the farmers in their own fields, and chosen according to their circumstances. This approach hastens the transformation of INRM research results into practical technologies that are more readily acceptable to farmers because they participate and adapt to meet their needs.

This approach is already being tried out in the Mekong River Delta in Vietnam, on the Indo-Gangetic Plains of India, in northeastern Thailand, and in the Red River Basin in Vietnam.

However, Dr. Kam says that, to ensure long-term sustainable agriculture, the natural resource base needs to be maintained over broader geographical areas.

"If we're investigating integrated pest management, to reduce the use of pesticides," she adds, "we're talking about biological control of some kind, and obviously you're not dealing with one individual farm, you're dealing with the entire landscape.

"If you're developing a technology that is labor-intensive, you may have to consider the availability of labor at the community or even regional level.

"Managing water at the farm level may affect an entire irrigation system. Conversely, operating an irrigation system correctly may influence all the farms within it. So these things must be tackled at both the farm and policy level."

A Step Closer to Farmers

Farmers in general put their immediate concerns of food security and increased productivity above the broader effects of their activities on the environment or the longer-term concerns of ensuring that natural resources remain in good shape for future generations.

INRM research also needs to be targeted at local and national agencies and policymakers. Computer-based analytical systems and models have been developed to help these people explore optimal land uses and resource allocations according to different regional objectives. These tools have already been tested at six sites in five countries. They have been well received, and their use has even been extended to areas outside the pilot sites in a few cases.

INRM also takes IRRI a major step closer to the end users of its research and, to those involved in "building the bridge between research and extension," it's a step long overdue. One of them is the head of IRRI's International Programs Management Office, Dr. Mark Bell.

"Scientists often say, 'I have the answer to a particular problem, but the farmers haven't adopted it,'" Dr. Bell says. "I ask, 'What was the benefit to farmers in adopting it in the first place?' And they often cannot answer.

"If farmers don't adopt a particular piece of technology, then there are two broad reasons: either they don't know about it or it simply doesn't appear to meet their needs. Often researchers haven't listened to what farmers want. They haven't communicated clearly, or there's been no consideration of the kind of incentives farmers need to adopt a new technology. To us it has to be science-logical, whereas to farmers it has to be lifestyle-logical. If a technology can be proven to save them money, lower their risk, give them greater yields, or reduce their workload, then we're providing the correct incentives for its adoption."

Dr. Bell's office is involved in identifying new partners in the rice-growing countries to help deliver technological innovations to the end users, the farmers. Many organizations with the potential to bridge the gap between scientists and farmers are these days found among NGOs and private companies, whereas, in the past, IRRI relied solely on the national agricultural research and extension systems of rice-growing countries to communicate new technologies to farmers.

Green Revolution Hero Bows Out

The man who is often referred to as one of the fathers of the Green Revolution in rice farming, Dr. Gurdev Khush, retires this year as head of IRRI's plant breeding program after working for the Institute for 34 years.

It is a measure of Dr. Khush's stature as the world's foremost rice breeder that, in any rice field, anywhere in the world, there's a 60 percent chance that the rice was either bred at IRRI under his leadership or developed from IRRI varieties.

It is a measure of the man that, on the eve of his retirement, he hotly denies that IRRI should be recognized solely as a center for germplasm development, and not for its extensive research in the field of natural resource management.

"Less than 30 percent of IRRI's budget over the years has been spent on crop improvement and enhancement of germplasm," he declares. "The rest has been spent on the multitude of issues that might, these days, be regarded as integrated natural resource management." With a smile, he adds, "We used to call it agronomy."

"The idea that IRRI is only a breeding center is a misconception," he continues. "We focus our research programs on the known needs of farming communities. Natural resources, and their management, are the very first things we consider. The issues that drive a breeding program include yield, diseases, pest management, responsiveness to nutrients, and tolerance for abiotic stress and weeds. All of these things have to do with the natural environment."

New Plant Type

In his 34 years at IRRI, Dr. Khush has become one of the world's most decorated scientists, winning the Japan Prize in 1987, the World Food Prize in 1996, and both the Wolf Prize from Israel and the Padma Shri Award from his native India in 2000.

In his final months at IRRI, he received news that, at a ceremony in the Great Hall of the People in Beijing, the State Council of China had awarded him the China International Scientific and Technological Cooperation Award for 2001.

Dr. Khush's final work, the creation of IRRI's new plant type, is almost complete. The plants are already yielding strongly in temperate areas of China, and they are expected to be ready for farmers in tropical Asia by 2005. Developing the new plant type has taken nearly 12 years of hard and sometimes disheartening work. It is designed to yield up to 12 tons per hectare in irrigated tropical conditions, but adjusting its genetic characteristics to match tastes and environmental conditions has been more difficult than expected. Nevertheless, it's almost "ready for the road."


"I expect it to move very quickly into farmers' fields once it is released," Dr. Khush says. "It will give farmers the chance to increase their yields, so it will spread quickly. Already it is yielding 13 tons per hectare in temperate China."

Looking back on his three and a half decades with IRRI, Dr. Khush says he has come to love the Institute as his home. "It provided me an excellent opportunity for professional development and allowed me to contribute to world food security."

He believes that IRRI will have an important role to play in developing technologies for food security, environmental protection, and poverty alleviation for many years to come. He also believes that the Institute should be developing collaborative arrangements with private-sector corporations.

"IRRI has tremendous assets that the private sector does not possess, such as genetic resources, knowledge, and links with the national agricultural research and extension systems of rice-growing countries. The private sector, on the other hand, has resources to invest in cutting-edge science and the generation of technologies. So, the roles of IRRI and the private sector should be synergistic."

A Farmer's Son

Gurdev Singh Khush was born the son of a farmer in the village of Rurkee, in Punjab, India, in 1935. After excelling at high school, he went on to graduate from Punjab Agricultural University with a bachelor's degree in science, majoring in plant breeding.

Determined to further his studies in the United States, the young Khush borrowed money from relatives and went to England, where he worked as a laborer in a canning factory to earn his fare to America. There, he obtained a scholarship to study genetics at the University of California, Davis, and did so well that he gained his Ph.D. in genetics in less than three years. He was not yet 25 years old.

Dr. Khush then spent seven years at the University of California, Davis, researching the cytogenetics of tomatoes. He joined IRRI as a plant breeder in August 1967, when he was 32, and immediately began to make his mark on food production in a hungry developing world.

He has since played a key role in developing more than 300 rice varieties in IRRI's race to keep rice production ahead of population growth. One of them, IR36, was released in 1976 to become the most widely planted variety of rice, or of any other food crop, the world has ever known. It was planted on 11 million hectares in Asia in the 1980s, yielding an additional five million tons of rice a year, boosting rice farmers' incomes by US$1 billion, and, because of its resistance to pests, saving an estimated $500 million a year in insecticide costs.

IR64 later replaced IR36 as the world's most popular rice variety and IR72, released in 1990, became the world's highest-yielding rice variety.

The Nobel laureate, Dr. Norman Borlaug, has summed up Dr. Khush's career by saying, "The impact of Dr. Khush's work upon the lives of the world's poorest people is incalculable."

Busy Retirement

Dr. Khush will move to California upon his retirement at the end of August, but he won't be away from IRRI for long. He will return for a few months every year to work as a consultant.

Aside from this work, Dr. Khush looks forward to a busy retirement. He intends, first, to write about 10 research papers from information he has been unable, for lack of time, to compile. Then he intends to write a book on aspects of rice culture, possibly for use in high schools. After all that, he might consider an autobiography.

As well, Dr. Khush has been invited to serve on the boards of several companies, but he hasn't accepted anything yet. First, he intends to spend more time with his family. His wife, Harwant, has a Ph.D. in educational management, his son Ranjiv is a molecular biologist, his eldest daughter Manjeev and youngest daughter Kiran are medical doctors in San Francisco, and a third daughter, Sonia, is an economist with the Save the Children Foundation in Washington, D.C.

Genomics: The Way of the Future

The years 2000 and 2001 have seen wildfire growth in the new scientific field of genomics, which is expected to revolutionize the breeding of future food crops.

Rice, the staple grain for half the world's population, remains at the forefront of the latest advances and, through judicious planning and participation, IRRI has consolidated its role in the tide of discovery as well as promoting access to the new science for the rice-growing world.

The high point was the announcement in January 2001 that the multinational agribusiness corporation, Syngenta, had completed the sequencing of the rice genome, and was happy to release its results to freely benefit poor farmers and consumers in the developing world.

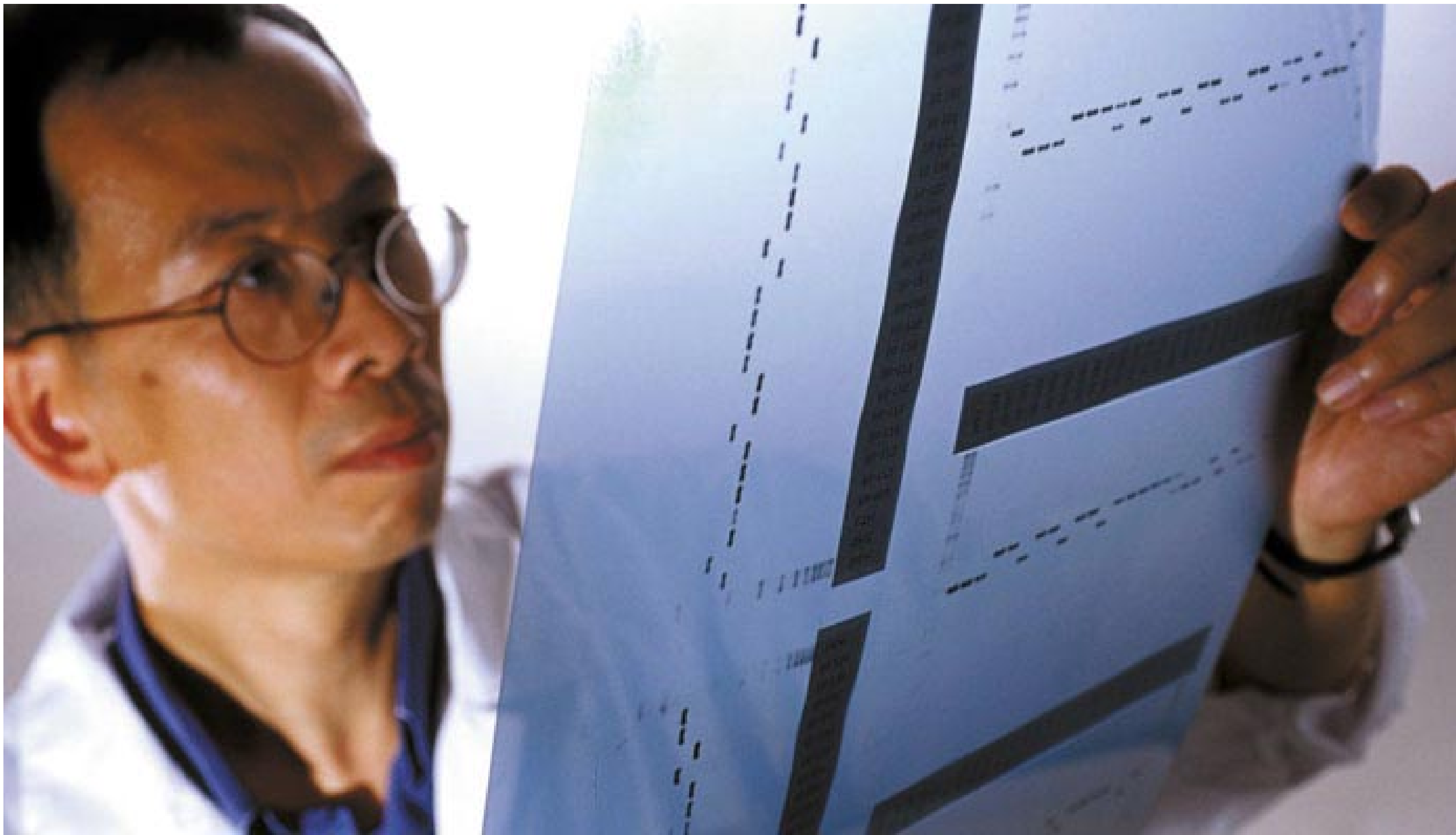
The announcement came when an international effort to sequence the genome was progressing well. This effort was expected to complete one of the largest chromosomes in early 2001. Sequencing involves the painstaking ordering of DNA sequences that encode about 50,000 genes in the rice genome. The genome of rice has 12 chromosomes consisting of 430 million base pairs of DNA. Each gene consists of about 3,000 base pairs.

Rice is the first of the world's major food crops to have its genome fully sequenced. The end result is a "map" that identifies every gene on the 12 chromosomes.

The next big step is discovering what the genes do: how they function, how their functions combine with those of other genes, and for what purpose. This is called "functional" genomics, and this is where IRRI holds a unique research position.

One way to track down the function of any one gene is to simply delete the gene from the chromosomes of a rice plant using chemical or irradiation processes, then examine the plant as it grows. By looking for what is missing, what characteristics the plant does not have, researchers are able to deduce the function of the missing gene. The plants are called "deletion mutants," and IRRI now has a collection of 18,400 of them, with different genes deleted. By the middle of 2002, the collection will have grown to about 40,000.

Dr. Hei Leung.



The Institute's functional genomics project is also developing a large collection of what are called "introgression lines," plants that carry a wide range of unique chromosome segments implanted from commercial varieties and wild rice. These will be used in the discovery of the functional diversity of the genes, and to understand the overall genetic, biochemical, and physiological systems in the rice plant.

Backed by the unique collection of rice germplasm in the International Rice Genebank, IRRI researchers are multiplying their collection of modified plants—what they call their "genetic resources"—so that mutants and introgression lines can be supplied to other institutions assisting them in the challenging task of assigning functions to all the rice genes.

According to the plant pathologist and geneticist leading the IRRI team, Dr. Hei Leung, the Institute has benefited from the rice sequencing projects of both the private and public sectors. It has been working with information as it has become available. The international consortium led by Japan is expected to finish its sequencing effort in two to three years, and this is particularly significant because of its anticipated accuracy and the fact that it will be completely open to public access.

Dr. Leung's favorite analogy for the functional genomics project is that, after the genome is fully sequenced, scientists will have a dictionary full of words, with each word representing a gene, but with no definitions giving the words meaning or purpose.

Functional genomics will help overcome disease.

The job of the IRRI team is to give a meaning to every "word," to find a function for every gene. Already, by studying the deletion mutants and introgression lines, Dr. Leung's team has identified several genes giving the plants enhanced resistance to various types of organisms that cause disease. Mutants were isolated for genetic analysis after displaying tolerance for submergence. The team has also produced plants containing small chromosome segments from wild species that confer resistance to multiple diseases and insects.

The scientists also found introgression lines and mutants that grew and yielded well in soil with too much or too little water. They studied the drought-response process in rice plants being grown under different water conditions, and identified a variety of proteins produced by the plants in the process of responding to drought and salinity stress. Such studies allow them to better understand the way rice plants respond to stress, and to find genes for use in plant breeding. For example, more than 100 genes that can help the plants defend themselves against pathogens have been found and are already being used to select better disease-resistant rice varieties.

Dr. Leung says that an exciting aspect of genomics is that tools for gene discovery are constantly being improved. He and his team hope eventually to begin using "gene chips," or "microarrays," in their search for an understanding of genetic function. This relatively new technology involves massing about 20,000 genes on one display slide. This so-called "chip" can then be used as a sensor to detect genetic messages that are turned on or off when the plants are exposed to stress.

The expression of the genes can be recorded and analyzed to give a total picture of how the plant behaves under different conditions. In this way, scientists will be able to identify hundreds or even thousands of genes that may combine and interact to achieve a particular function, such as tolerating drought, resisting disease, or producing more nutritious grains.

"This technology allows us to discover in weeks what would, in the past, have taken maybe two years of work,

looking at the genes one at a time," Dr. Leung says.

Of paramount importance in IRRI's functional genomics project are efforts to protect the interests of rice farmers and consumers from the private exercise of intellectual property rights, which could lead to increased prices or delays in the extension of benefits to the public.

To broaden access to information, IRRI has launched a database on the Internet to describe the biological characteristics of its collection of deletion mutants. Another similar database has been developed for information on stress-response genes. These will be linked to genome sequence databases to facilitate information exchange.

The Institute has also established an International Rice Functional Genomics Working Group (http://www.cgiar.org/irri/genomics/) as a first step toward developing a public research platform to accelerate gene discovery. Dr. Leung says that more than 14 research groups, including laboratories and institutions from the international rice research community, have agreed to contribute resources and expertise, and to promote the sharing of genetic stocks.

"Contributions from the IRRI team are now crucial to the success of this public research platform," he says. "We must produce tangible things, make discoveries, and develop materials to give away. Within three years, I want researchers around the world to see the benefits of working with us. We don't want to be the only player on the field, but we would like to be the preferred player because of IRRI's mission and the quality of our work."

He says that it's critical that the national agricultural research and extension systems (NARES) from rice-growing countries become involved in the working group.

"We need to make sure that this is not seen by the NARES as research beyond their reach. They must have a common place in which to work with someone they know and trust. We will make all our genetic resources and tools available to our partners."

So far, the process of unraveling the secrets of the rice genome has been a harmonious combination of public and private efforts, and Dr. Leung says he's been impressed with the readiness of private organizations to contribute.

"I think they've gradually realized that rice improvement is a longer-term process than they thought, and that there are no quick returns. They've also recognized that their benefits will accrue from better welfare for rice consumers in the developing world."

Dr. Leung believes that it will take about ten years for scientists to complete the writing of the functional genomics "dictionary." It will begin with the assignment of functions to every gene in the rice genome, but he points out that the true biological function of the genes is beyond that, and he quotes a few figures to illustrate the vastness of the job.

"There are 50,000 genes, but the function of each may vary in every rice variety because the genetic background of one is different from that of another. Just think, the International Rice Genebank has 110,000 different samples of rice germplasm."

Ultimately, plant breeders may be able to refer to a database to find precisely which genes they need to achieve specific plant characteristics. Then, using "maps" of the genome, they'll select the genes and mix them, according to their plans, and the resulting plant should be just what they're looking for. But Dr. Leung concludes that, "like words in poetry, the creative composition of genes is the essence of successful plant breeding, and it will come down to how well we can use the dictionary."

IRRI: "University Without Walls"

IRRI's new determination to tailor its research programs for maximum impact is having a profound effect on the Institute's Training Center.

For some years, advice from many quarters has been urging IRRI to convert the Center into a "university without walls," to pass on the results of the Institute's scientific research. But, until the Internet made substantial inroads into rice-growing countries, this was not practicable.

In 2000, however, the enormous task of digitizing the Center's entire training library began in earnest and, using the endless reach of cyberspace, the IRRI university without walls will soon be reality.

"I can't reach every farmer in Asia," laments Training Center Head Dr. Paul Marcotte, "but I can get to anyone who owns or can beg, hire, or borrow a personal computer with Internet access. We're not bound by the walls of a classroom anymore."

The Center will soon have a staff of about ten experts creating a university faculty at IRRI to deliver rice-related information via the Internet. They will include agriculturists, distance learning experts, and information technologists. As well, a fresh effort has been made to find out what training services are needed in rice-growing countries.

Expert Consultation

In January, about 50 people were invited to an "expert consultation" conference in Thailand. They included the heads or directors of training from the national agricultural research and extension systems (NARES) in 15 countries stretching from Madagascar through South, Southeast, and East Asia to Korea. Representatives from nongovernment organizations in each of the countries were also invited, along with IRRI's country representatives.

"We wanted to know what their training needs were and what they needed from us," Dr. Marcotte says. "We also asked them about the impact of IRRI's training in their countries. We have never conducted a training needs assessment in this fashion before." And the outcome? The first priorities of most participants were training of

trainers, integrated nutrient management, integrated pest management, and research station management.

The NARES representatives were also asked to detail their information technology capabilities.

Demand for IRRI training courses has, meanwhile, reached unprecedented levels, and the Training Center is working at full capacity to convert the entire gamut of its training resources to digital form for use on the Internet, on compact discs, and in the classroom.

Its first electronic training or information packages were available a few years ago and most have been updated.

The most popular is called TropRice. It offers noninteractive, grass-roots "how to" information for farmers, including details on plant varieties, planting times, management practices, and even economic assessments. In its original form, it was spoken in English, but it has since been translated into Thai, Vietnamese, and Indonesian and is widely and freely used throughout South and Southeast Asia. It has been updated about six times to keep abreast of advances in technology and is kept under constant review. Among many other places, it is used in universities in Indonesia, at Thailand's Kasetsart University, and at farmer field schools throughout Bangladesh.

TropRice has been supplemented by electronic information packages on hybrid rice and reaching toward optimum productivity. A start has now been made on the creation of TropRice Two, a version that will allow researchers in rice-growing countries to contribute changes and incorporate the results of their local research.

Electronic training courses prepared by the Training Center include "Digital Literacy for Rice Scientists" and "English for Agriculture." Both are interactive.

Staggering Scope

Another course, called "Experimental Design and Data Analysis," illustrated the staggering scope of electronic distance training. It was offered for the first time earlier this year. A printed study guide supported the Internet lessons.

"We used a virtual classroom, but in multiple locations," Dr. Marcotte explains. "We were teaching the course as if we were in a classroom with 20 pupils. We had real-time lectures, exercises were set, there were question-and-answer sessions, and we even gave homework. We are restricting our on-line courses to 100 students at the same time because of manageability problems, but the amazing thing is that we could deal with as many as 1,000 students. Our ability to reach people has accelerated by geometric progression."

The Center is now working on the creation of a series of major training modules that will be offered freely on the Internet, or on CDs.

The first, titled "Growth Stages of the Rice Plant," was completed in 2000 and the second, "Stem Borer," earlier in 2001. Both offer the latest scientific information supported by color photographs.

Work is currently under way on "Farm and Experimental Station Management," "Pests, Weeds, and Diseases," and "Integrated Natural Resource Management."

"We are painstakingly working our way through the current state of knowledge in rice science," Dr. Marcotte says. "By creating these modules, these clusters of training tools, we'll have stand-alone products to put on the Internet. They are very large pieces of information. Imagine the issues in 'How do you run a farm?' There are a huge number of techniques and procedures, but we have all that information, and we'll make it freely available."

The new training thrust at IRRI is buoyed by a structural change that, for the first time, brings training under the research umbrella.

"Training is now correctly placed for impact," Dr. Marcotte says. "We're in coalition with people in the field. In reality, this is a new day for training at IRRI. We're not just talking about it, we're doing it."

High Numbers in Training

A total of 126 rice scientists and professionals took part in IRRI's degree and postdegree on-the-job training program in 2000. They represented 26 countries in Asia, Africa, Europe, and North America, although 87 percent of them came from Asia. Twenty-two of these completed their Ph.D. program, six their M.S. program, and 36 their respective on-the-job training courses or internships.

Ninety-five scientists also upgraded specific skills by participating in 11 group training courses conducted by the Training Center at IRRI headquarters in the Philippines. They represented 14 countries in Asia, Africa, and Europe.

During 2000, IRRI also organized 20 group training courses for a total of 590 scientists employed by the NARES of rice-growing countries. Eighteen of these courses were held in the countries concerned. Two others, however, one in Thailand and the other in China, were international courses attended by 27 scientists from ten Asian countries. The courses brought to 4,000 the number of rice scientists and professionals IRRI has trained in their home countries over the past ten years.

IRRI expects to assist about 130 degree and postdegree scholars and on-the-job trainees during 2001, and about 25 training courses will be held at headquarters in the Philippines.

The Unsung Heroes: Quality Is a Way of Life

If any one group of people were to be singled out as the "unsung heroes" of IRRI's research effort, it would probably be the staff of the Institute's Analytical Services Laboratory.

The modern facility with the daunting workload is run by an effervescent Filipina grandmother whose pride in the laboratory is rooted in the fact that, ten years ago, she took a leading role in its design.

Ms. Bernardita Mandac joined IRRI's staff 32 years ago with a master's degree in plant biochemistry and an idealistic urge to support IRRI's mission. Today, she heads a service that is a linchpin to much of the Institute's research, and is known to one and all, simply, as Bernie.

With her staff of ten, she maintains an extraordinary turnover. The laboratory is called upon to analyze soil, plants, fertilizers, solutions, and water, and the staff now performs about 28 analyses per person per day—a total of about 35,000 individual tests during 2000.

The workload has been worse. Much worse. In 1998, for instance, she had a staff of about 30 people, and they performed 61,000 tests in one year.

"When we reached 60,000 we had to call for emergency help," she recalls. "We had two people in here just to do the dishes! The scientists always want their data yesterday."

Throughout, the Analytical Services Laboratory has maintained the highest of standards. "Quality is a way of life here," Bernie explains. "It has to be ingrained. And we're a team. If one of us goes wrong, then the whole team falls down. But it's not hard to keep our standards high. They all know how I can scream if they do anything wrong."

Perhaps the secret of Bernie Mandac's success is running the laboratory like it was her home, and caring for her staff like they were her family. She has one son, two daughters, and one granddaughter, all living within walking distance of IRRI's headquarters. Is there any conflict between motherhood and her job? "I will look after my kids first," she says, almost fiercely. "My family always comes first."

She recalls the difficulty of being a working mother with a young family. "I was lucky because I always lived across the street," she says. "One of my girls at the laboratory had trouble feeding her new baby. I couldn't do without her, so the baby and her housemaid moved in here.

"It takes a lot of guts to do these things, and to be able to compete with men," she adds.

Her work philosophy is one of looking beyond the performance of a simple analytical service. "I'd like to see the laboratory geared to the solution of problems by providing analytical tools to researchers, rather than serving only to provide data for others to interpret."

Bernie Mandac is also working toward a personal dream. Her husband of 25 years, Abe, is an adviser to a United Nations drug control program in Myanmar. He took the two-year assignment so that he and Bernie could develop their 10-hectare retirement property at Isabela, in Northern Luzon.

"He's a Filipino farmer at heart," she says, wistfully. "We want to try our hand at agroforestry."

The Unsung Heroes:

The "Spider Man" of Los Baños

Doctor Alberto Barrion, "Bert" to his friends, is a man with a great fondness for spiders.

His desk is crowded with jars full of defunct arthropoda; he has spent much of his life visiting them in the dank and gloomy undergrowth of countless rice fields, and he is the proud curator of IRRI's arthropod reference collection.

But spiders are simply the stars in Bert Barrion's teeming world of rice-field insects. For 24 years he has been an entomologist on the staff of IRRI's Entomology and Plant Pathology Division and, in 2000, he was named Outstanding Local Scientist by the Consultative Group on International Agricultural Research in Washington, D.C., for his contributions to IRRI research.

In his present position as a senior associate scientist, Dr. Barrion plays a prominent role in the vital research field of integrated pest management. He preaches antipesticide sentiments with an almost evangelical zeal. And, just occasionally, one is left to wonder whether he feels more for the farmers or for the beneficial insects of the rice-growing environment.

"Farmers generally know that pesticides will kill pests," he says. "What they don't know is that many of these chemicals are nonselective, broad-spectrum products. They kill everything. They're detrimental to the environment; they're even a risk to the farmer and his family.

"What we're promoting is natural biological control of rice pests. Rice paddies have a very rich array of beneficial arthropods—predators, parasites, and parasitoids—and, if the rice environment is regarded in a holistic way, then encouraging these beneficial arthropods, instead of wiping them out, is clearly the best way to control pests."

He goes as far as reassuring farmers that they shouldn't panic and run for the insecticide when they see pests on their rice crop. "If you kill all the bad ones, there won't be any food for your beneficial friends," he explains. "Insecticides should only be used when there's an outbreak of some kind, because that means that, for some reason, biological control is no longer working."

Dr. Barrion's work has led to the use of naturally occurring biological control agents to control insect pests, resulting in increased farm profits without resort to chemical pesticides.

Much of his career has been an effort to understand the complex relationships between the tiny, often unseen, creatures that live in tropical rice fields. One of his best known publications is an insect identification kit for rice pests and their natural enemies, used widely by scientists, researchers, and students.

In the course of his studies, he keeps finding new, previously unrecorded creatures. He's named eight genera and 270 species of spiders new to science, and he's working on describing 28 new taxa. His review of Philippine chalcidoids, the tiny wasps that kill the eggs of rice leafhoppers and planthoppers, yielded 23 species. Of these, eight genera and 15 species are new Philippine records. In the search for names, he only has to pick up the IRRI staff list.

Three of the latest are *Oligosita cantrelli* (after IRRI's director general, Dr. Ronald Cantrell), *Paracentrobia wangi* (after IRRI's deputy director general for research, Dr. Ren Wang), and *Oligosita mewi* (after the head of IRRI's Entomology and Plant Pathology Division, Dr. Tom Mew). All are tiny parasitoid wasps native to the Philippines rice-farming ecosystem.

Dr. Barrion is the head of IRRI's taxonomy laboratory. He is recognized as one of Asia's top entomologists and araneologists.

Only the Best Seeds

It couldn't be simpler: plant only the best seeds and you've got a far better chance of a good harvest. It's a principle being taught to farmers in Bangladesh, and one that has already proven capable of boosting that country's annual rice harvest by an astounding two million tons of grain a year.

Although most farmers are preoccupied with soil, the weather, water supplies, or fertilizers, IRRI scientists are urging them to pay more attention to something they nearly always overlook: the condition of their seeds.

It's a project being led by Dr. Tom Mew, head of IRRI's Entomology and Plant Pathology Division, whose work in China has already seen a major rice disease problem overturned by a simple exercise in biodiversity (*see* A Clean and Simple Success Story, *page 32*). In this case, he is collaborating closely with the head of IRRI's Social Sciences Division, Dr. Mahabub Hossain, and with the Bangladesh Department of Agriculture, the Bangladesh Rice Research Institute, and four nongovernment organizations.

Dr. Mew explains that farmers in South and Southeast Asia have long reported a problem that many know as "dirty panicles," especially from wet-season crops. There is an apparent decline in the productivity of seeds saved from previous harvests, and farmers have felt compelled to change their seeds or face continuing crop deterioration.

The problem appears to have come hand-in-hand with more intensive cropping and a lack of farm labor. Both factors tempt farmers to overlook their once scrupulous but time-consuming care in choosing and storing seeds for the following season's crops. Instead of being painstakingly selective, they've been content to simply scoop a stock of seed from the general harvest.

This practice has coincided with a trait common to modern rice varieties: they don't wait for good weather and flower even if it is raining heavily. When they are at their most vulnerable, the developing grains fall under constant attack from diseases and insect pests. Seeds harvested from such crops often carry the consequences of these attacks into the following season.

Dr. Mew says that the situation becomes worse when the seeds must wait in poor storage conditions for up to nine months before planting, allowing molds and other contaminants to further diminish their quality.

"Nobody thinks of seed health," Dr. Mew says. "In rice production, we tend to think only of crop management. But if the seeds are not good, then the farmers are building their agriculture on a poor foundation. The genetic potential of the plants will never be reached."

Working closely with their local partners over the past two years, the IRRI team has taught 560 Bangladeshi farmers how to sort their seeds and reject the poorly filled, diseased, and contaminated ones. They were taught how to recognize poor grains by their physical appearance. Commonly, at least half their seed was discarded. In some cases, more than 80 percent of it was in very poor health.

"Then they were told to grow a plot of the good, healthy seeds alongside their normal unsorted seeds," Dr. Mew says. "Even at the start, the good seeds germinated uniformly and the ground cover was very rapid. The farmers needed to hand-weed the crop from the good seeds only once, and the rest of it several times."

When it came to the harvest, farmers whose yields had previously amounted to 5.1 tons per hectare were reaping about 5.8 tons per hectare by using the healthy seed. Across the entire 560 farms, yields from the sorted seeds were, on average, nine percent higher. Applied to the entire Bangladesh rice crop, this would mean an increase of two million tons of grain.

Dr. Mew says that his team hopes to give "hands-on" seed health training to enough Bangladeshi farmers, especially the women farmers, to guarantee that the technology spreads to all of Bangladesh's 13 million rice farms.

Dr. Erik Sacks.

Rice Plants That Do Not Die

Curious new plants growing in IRRI's experimental fields at Los Baños in the Philippines are living evidence of how close the Institute's researchers have come to creating a perennial rice plant. The leaves look like rice, but the plants grow in sizable clumps, and vigorous stems creep outward on the surface of the soil, putting down new roots and growing fresh leaves at every node.

So far, the plants have been growing for nearly two years and they've been harvested about four times.

According to the leader of the Institute's perennial rice project, Dr. Erik Sacks, some of the plants could probably live indefinitely, if properly cared for. However, much still needs to be done to prepare them for the often harsh conditions of upland cultivation.

Researchers have been working for six years to create an upland rice plant that doesn't die at the end of one season, and that can be grown in virtual "hedgerows" across mountain slopes. The aim is a perennial that delivers a crop and is cut back every season, but which continues to grow to deliver another season's harvest, and so on.

The "hedgerow" idea would prevent erosion by providing living barriers to soil movement on sloping land, helping to stop not only the loss of precious topsoil in upland regions but also the silting of rivers and irrigation systems downstream. Farmers would have a rice crop at least once a year without all the hard labor and expensive inputs of annual cultivation.

Dr. Sacks says that some of the most promising plants will soon be sent for field trials in China and India so that their reaction to real upland conditions can be assessed.

These plants are the result of a traditional breeding effort involving thousands of crosses of wild and domesticated species from Asia and Africa. One of the ancestors of modern rice, a wild Asian species called *Oryza rufipogon,* is the parent believed to have gifted the new plants with their seeming perenniality.

The aim now is to give the new plants panicle characteristics that are more like those of cultivated rice. In addition, adding resistance to pests and diseases and to attack by microscopic worms called nematodes will help ensure that the plants survive and yield. They will also need the capacity to compete with weeds. It may be another five years before they are ready for handing over to national agricultural research and extension systems and, from them, to upland farmers.

Meanwhile, among the thousands of crossbred plants in the project, some big surprises have occurred. Some plants not only developed root systems capable of keeping them alive for several years, but they also survived experimental drought stress and, on top of that, yielded more grain than expected.

Dr. Sacks explains that, in ordinary rice plants, many of the plant's carbohydrates are dedicated to the process of flowering and developing seeds; little surplus energy remains for vigorous growth after harvest. So the new plants are under close scrutiny to find out how they gathered all their energy *(see next story)*.

An Unexpected Offspring

Breeding new varieties of rice normally involves a painstaking process of trial and error in which countless thousands of crosses are made between huge collections of parent plants. With each batch of newcomers, plant breeders hope to find the genetic traits they are trying to create.

In the mix and match of countless genes, surprises are sometimes in store. Occasionally, breeders inadvertently create plants with attributes totally unrelated to the aim of their project, but nonetheless fascinating and valuable. In the effort to create a perennial rice plant, IRRI's plant breeders may have stumbled upon a plant with an enhanced capacity for using sunlight.

For many years, scientists have theorized that the productivity of rice could be boosted if its photosynthetic pathway—the way plants use energy from the sun to fix carbon from the atmosphere—could be made more efficient *(see* A New Plant for a Changed Climate, *page 28)*.

Maize and sorghum are both plants with what is known as a C_4 photosynthetic pathway. In most respects, it is more efficient than the C_3 pathway of rice, wheat, and potatoes. Recently, biotechnicians in Japan and the United States have been transferring genes from maize into rice in an attempt to create a C_4 rice.

The question sparking interest at IRRI is whether or not the new plants bred in the search for perenniality have unexpectedly progressed a step or two down the path toward greater photosynthetic efficiency.

A recent arrival from China to IRRI's scientific staff, Dr. Ming Zhao, a plant physiologist, has been examining first- and second-generation plants that were among the best performers in the perennial rice project. He has found an uncommonly high photosynthetic rate among second-generation plants, markedly higher than that of the plants' parents and their first-generation family.

The rate at which a plant assimilates carbon dioxide in sunlight is the usual measure of photosynthesis. In normal rice plants, it is about 36 units, compared with maize, whose rate is slightly more than 50. The experimental, second-generation rice plants, grown in the hope that their mix of genes would make them perennial, register carbon dioxide assimilation rates as high as 46 units, about 90 percent of the rate of maize grown under similar conditions.

The next step will be a comparison of the second-generation plants with their third-generation offspring. If there is a strong association between the photosynthetic performances of parents and progeny, then the researchers will feel confident that the special ability is a genetic trait, rather than something anomalous that may disappear within a few generations.

Dr. Ming is optimistic. "This new material may be very good for improving modern varieties," he explains. "Improved photosynthesis can have the outstanding benefits of high yield along with greater efficiency in the use of both water and nitrogen."

Hybrids for the Rainfed Lowlands

IRRI's hybrid rice breeding program has also set its sights on the rainfed lowland ecosystem.

Until now, tropical hybrids have been bred only for irrigated cultivation. They're a recent appearance in tropical Asia, requiring fresh seed purchases with every crop and special care in cultivation, but they yield up to 20 percent more than the best semidwarf inbred varieties, upon which the rice crop of Asia depends.

China has about 15 million hectares planted in hybrid rice, mainly in its subtropical and temperate regions. That is about half the country's rice-growing area. Vietnam has become the leading grower of tropical hybrids in Asia, with nearly 300,000 hectares. It is followed by India (180,000 ha), Bangladesh (30,000 ha), the Philippines (15,000 ha), and Myanmar (5,000 ha). Indonesia, Sri Lanka, Thailand, and Korea are just beginning to show an interest, along with Egypt.

IRRI's hybrid rice breeder, Dr. Sant Virmani, says that the Institute has projects aimed at boosting yields from hybrid seed production plots and making the development of hybrid technology more efficient.

However, having perfected a range of hybrids for irrigated farming, researchers are now turning to the rainfed lowland ecosystem, where any increase in yields will have a direct impact on poverty.

Breeding hybrids for this ecosystem, which is often beset by droughts, floods, or both, has now become a concerted effort. Already, some newly developed experimental hybrids have been sent to research stations in India, Thailand, and the Philippines.

At the same time, IRRI's researchers are also developing a package of agronomic measures aimed at helping farmers who adopt hybrid technology. These mainly involve seeding and seedbed management, along with nitrogen management.

"We want to see how far we can spread this technology," Dr. Virmani says. "To get the maximum out of hybrids, we have to make sure the farmers can use an agronomic package."

Unlike many other areas of IRRI's research, the tropical hybrid program stirs considerable interest from private companies. This is because of the need to continually produce new seed, whereas in conventional rice cultivation farmers simply plant seeds saved from the previous season's crop.

First-generation hybrids benefit from a phenomenon known as hybrid vigor. They perform better than both their parents. But this lasts for only one generation, and seeds kept from hybrids lose their superior yield and produce a nonuniform crop with mixed grain types.

Private companies are attracted to hybrid rice technology because of the opportunity to profit from seed production. There is another reason, prompted by the one-season-only restriction.

"Some big multinational companies with genetically altered rice plants in the pipeline can protect their investment in these plants by using them as one of the parents of a hybrid," Dr. Virmani says. "Then they cannot be copied. The farmers have to buy new seeds every season."

He says that IRRI's hybrid program will take advantage of any developments in the conventional breeding program. For example, hybrid breeding has already begun with IRRI's new plant type lines and hybrids will be developed from vitamin A, or "golden rice," lines as soon as they are available.

Gathering Genetic Resources

The year 2000 was a busy one for IRRI's Genetic Resources Center (GRC) and the International Rice Genebank.

Among other things, it saw the completion of a six-year project called "Safeguarding and Preservation of the Biodiversity of the Rice Genepool." According to the head of the GRC, Dr. Michael Jackson, the project had a major impact on the worldwide conservation of rice germplasm. More than 24,700 samples of cultivated rice and 2,400 samples of wild rice were collected during 165 missions in 22 countries in Asia, sub-Saharan Africa, and Costa Rica.

Despite it having been the project's final year, the Genebank still received for safekeeping nearly 700 samples of *Oryza sativa,* the predominant Asian rice species, together with 84 samples of different wild species from the Lao PDR, Tanzania, the Philippines, and Costa Rica.

More than 80 percent of the cultivated samples and nearly 70 percent of the wild samples collected under this project are now preserved in the International Rice Genebank.

During 2000, thousands of new samples were grown and their seeds multiplied and tested for germination and health before they became "accessions" in the International Rice Genebank. The Genebank's "active" collection received 4,035 new accessions, and the "base" collection, where the seeds remain in long-term storage at minus 20 ºC, received 4,716 new accessions.

Germplasm from new samples was multiplied and 1,978 *O. sativa* accessions and about 130 *O. glaberrima* accessions were rejuvenated. Seed stocks of about 1,000 wild species and newly acquired samples were also successfully increased in the nursery screenhouse.

Staff at the Genebank also prepared routine descriptions of 1,640 *O. sativa* accessions and 345 samples of wild species.

The Genebank distributed almost 7,000 seed samples during 2000 in response to 173 requests from scientists from 24 countries. Of the samples sent out, 1,661 were of wild species.

The International Rice Genebank Collection Information System (IRGCIS), which contains the International Rice Genebank's database and manages all seed stocks and exchanges of germplasm, was also updated during the year to allow greater flexibility of data management resources. This also provided a better link to the Systemwide Information Network for Genetic Resources (SINGER) on the World Wide Web (http://www.singer.cgiar.org).

Domestic Water Contamination

A survey of groundwater contamination by agricultural chemicals in Luzon, the Philippines, has shown that the threat to human health from fertilizers and pesticides is not as high as generally believed.

The survey, conducted by IRRI scientists over at least ten years, involved drawing monthly samples from more than 50 domestic wells used to supply families with drinking and household water. The water came from shallow aquifers beneath agricultural land. The researchers also investigated the history of agrochemical use at each of the three sites involved.

Two of the sites were in irrigation projects in the provinces of Laguna and Nueva Ecija, where most farms grow two rice crops per year. The third site was in the northern province of Ilocos Norte, where rice is grown in the wet season and sweet pepper in the dry.

The researchers found that in the irrigation projects average fertilizer use had risen fivefold, from less than 20 kg per hectare in the mid-1960s to between 80 and 90 kg per hectare in the wet season and 100 kg per hectare in the dry season in the mid-1990s. Over the same period, there had been a roughly equivalent rise in pesticide use, settling downward to between 0.65 kg and 1.4 kg of active ingredients per hectare in the 1990s.

In Ilocos Norte, the wet-season rice crop received an average of 60 to 110 kg of nitrogenous fertilizer and 0.6 kg of active pesticide ingredients per hectare in the 1990s. But the sweet pepper crop was given about 446 kg of nitrogenous fertilizer and 6.1 kg of active pesticide ingredients per hectare.

Out of 633 well samples taken in the irrigation projects, less than half had detectable levels of nitrate, and only one sample exceeded the World Health Organization (WHO) safe limit of 10 parts per million in drinking water. There was no evidence of any accumulation of groundwater nitrate from 1989 to 2000.

At the Ilocos Norte site, nitrate concentrations varied from 5 to 12 parts per million, with the WHO safe limit for drinking water being exceeded in July, October, and November. The relatively high contamination was attributed to the high use of nitrogen fertilizer in the sweet pepper crop. Low levels of nitrate coincided with a high incidence of wet-season rice cultivation.

The researchers found that average pesticide concentrations in domestic wells at all three sites were generally one or two orders of magnitude below the WHO safe limit of 0.1 parts per billion for single pesticides. However, there were isolated instances at all sites where the level of a single pesticide was as much as 40 times higher than the WHO limit.

They concluded that human health was not threatened by nitrate concentrations in drinking water beneath irrigated, double-cropped rice systems and that pesticide residues did not generally exceed safety limits.

They added that both the environment and the history of the study areas suggested that the results of the survey could be characteristic of many parts of tropical Asia where rice-based cropping had intensified since the 1960s.

Targeting the Rainfed Lowlands

More than 700 million of Asia's poorest people get up to 80 percent of their calories from rice grown in fragile environments such as rainfed lowlands. The soils here are poor, each new season brings risks of drought or flood, or both, and then there are pests and diseases. But, even with all this difficulty, the rainfed lowlands make up about a quarter of the world's total rice-growing area.

Modern high-yielding rice varieties do not adapt well to these ecosystems, so farmers grow traditional varieties that yield about two tons per hectare, less than half the average harvest from irrigated farms.

IRRI's scientists have begun the task of developing for rainfed lowlands modern high-yielding varieties of rice that show enhanced seedling vigor and are better able to withstand submergence, drought, sodium, iron, and aluminum toxicity, phosphorus and zinc deficiency, pests, and diseases. They are also formulating better crop management practices.

Armed with recent advances in biotechnology, IRRI's scientists are working with an almost impatient confidence. Their efforts are buoyed by the knowledge that productivity improvement in the rainfed lowlands will more effectively combat poverty than any other process.

Among the problems of the past was identifying dominant environments in the diverse rainfed lowlands to provide substantial targets for plant breeders. Conversely, plant breeders needed to choose from scores of genotypes and genetic traits those best suited to particular environments.

According to IRRI crop physiologist Dr. Len Wade, the quandary was well illustrated in an experiment in 1995. Thirty-one rice varieties were grown at nine locations in Thailand, India, and the Philippines to test yields. Researchers found that 40 percent of yield variation was due not simply to site conditions or plant characteristics, but rather to complex interactions between the plants and their environments.

It was impossible to match suitable varieties with every one of millions of rainfed rice farms. So, working with researchers in five countries, Dr. Wade and the head of IRRI's biometrics unit, Dr. Graham McLaren, sought "repeatable patterns of risk" within the myriad interactions between scores of rice varieties and hundreds of possible growing environments.

Instrumental in the new research will be recent advances in molecular biology, including the tagging and characterization of genes and gene transfers, improved methods in physiology, and better tools for data analysis. The potential gains to food security, human nutrition, poverty reduction, and environmental protection are immense.

Using about 48 rice varieties, the 1995 experiment was expanded to spread over 37 environments in India, Bangladesh, Thailand, Indonesia, and the Philippines.

Patterns of interaction between the plants and their diverse environments have been plotted. The like behavior of different varieties has led to the formation of groups and, from each of these, one variety has been chosen as a representative "reference line."

From the original 48 varieties, the team now works with just 10 reference lines. Plant breeders aiming to develop new plants for specific rainfed environments can link plant characteristics and genetic traits with environmental factors. They can multiply and use the reference lines themselves, or breed new plants with similar patterns of adaptability.

The achievement has not been lost on plant breeders in national research systems. Such has been the demand for full sets of the reference lines that IRRI's besieged seed multiplication program is taking orders for delivery next year.

Dr. Wade says that over the next three to five years the reference lines will be grown in a the widest possible variety of environments, and their reactions carefully measured.

"We're now using the plants to assay the environmental conditions," Dr. Wade says. "We might think that two soils are very different, but if one plant variety does equally well on both, then the soil difference means nothing to that plant. Such groupings simplify the targets for plant breeders."

After the Fighting, "Seeds of Life"

IRRI has joined an international effort to restore principal food crops to war-ravaged East Timor.

The project, called "Seeds of Life—East Timor," follows the tide of violence that swept the territory in late 1999, after the people voted for independence from Indonesia. The fighting caused widespread destruction of property and massive displacement of the population. In its wake occurred an acute shortage of planting materials for new crops.

Funded by the Australian Centre for International Agricultural Research (ACIAR), the three-year Seeds of Life project is a collaborative effort involving the United Nations Transitional Administration in East Timor, World Vision, Catholic Relief Services, and five of the 16 CGIAR centers: IRRI, CIMMYT, CIAT, CIP, and ICRISAT.

It seeks to restore East Timor's crops of rice, maize, cassava, cowpea, soybean, mungbean, potatoes, sweet potatoes, and peanuts.

According to the coordinator of the International Network for Genetic Evaluation of Rice, Dr. Edwin Javier, IRRI has supplied 15 varieties of irrigated lowland rice, 11 varieties for rainfed lowlands, and 13 varieties of upland rice. All were chosen for their potential adaptability to the East Timorese environment, and sufficient seed was supplied for small replicated field trials.

The seeds were planted between December 2000 and March 2001. Dr. Javier returned to East Timor in April 2001 to monitor the field trials, and will return later in the year, when the experimental crops are mature and ready for harvest.

The varieties most suited to local conditions will then be identified, with three or four varieties chosen from each category. More seed from each will then be multiplied in IRRI's fields in the Philippines and shipped back to East Timor for the next stage in the project.

Local farmer-cooperators will then grow the three or four selected varieties in each of the targeted ecosystems, and will be asked to select the variety they think is best suited to local conditions, local tastes, and local management practices.

Seed production from the most popular varieties will then be organized locally and, with continuing IRRI and ACIAR support, rice production in East Timor will begin to recover from the ravages of war.

Assisting various nations around the world to recover from devastating conflicts has become a familiar role for IRRI.

In the late 1980s, the seeds of Cambodia's traditional rice varieties were found in safekeeping in the International Rice Genebank at IRRI and were returned to that country so its agricultural production could begin a 20-year struggle toward self-sufficiency following years of war.

IRRI also sent shipments of seeds to Rwanda, in central Africa, where years of internal warfare had left the country's agricultural and social systems in chaos.

Ethiopia was another nation that received seeds from the International Rice Genebank in an effort to feed its war-weary population.

Sharing Rice Resources

The International Network for Genetic Evaluation of Rice (INGER) continued its leading role in the worldwide distribution and sharing of rice genetic resources during 2000.

A total of 729 breeding lines were organized into seven ecosystem trials and three stress trials. The latter aimed to screen the plants for their tolerance of problem soils and resistance to blast and tungro disease.

About half of the seeds for the trial nurseries had come from the national agricultural research and extension systems (NARES) of 35 countries. The other half came from international agricultural research centers (IARCs), including IRRI.

As well, 281 nursery sets were sent out to 29 countries for evaluation at test growing sites. Most of them went to countries in Asia, but others were sent to Ethiopia, Mozambique, Senegal, Bolivia, Brazil, Suriname, Venezuela, and Italy. Some also went to the West Africa Rice Development Association (WARDA).

INGER also prepared 12 sets of yield nurseries covering irrigated lowland, rainfed lowland, and upland ecosystems for the "Seeds of Life—East Timor" project, funded by the Australian Centre for International Agricultural Research *(see opposite page).* In response to requests from rice scientists worldwide, 509 seed samples were also processed and distributed to 24 countries and to researchers at IRRI and WARDA.

Eleven types of nurseries were prepared for distribution during 2001. They were composed of 859 breeding lines that came from researchers in 32 countries, as well as five IARCs. A total of 432 nursery sets were produced for distribution in 2001.

During the year, INGER began to distribute electronic field books to collaborators for recording data from INGER nurseries. These will serve as data entry tools to the International Rice Information System (IRIS) and the INGER Information System, INGERIS. Development and testing of the INGERIS, and its link to IRIS, were completed, and a new seed inventory system was developed.

Of the many rice varieties tested in the 1999 INGER trials, 287 were used as parents in the hybridization programs of ten countries. They had originated from breeding programs in 27 countries. As well, 519 breeding lines were selected for follow-up yield trials by NARES in 13 countries.

Institutional Activities

New Medium-Term Plan

To hasten the impact of IRRI's research, the new MTP provides strong bridges between the Institute's research activities and the national agricultural research and extension systems (NARES) of rice-growing countries and IRRI staff posted outside the Philippines.

The new MTP consists of 12 focused projects across four programs. They renew IRRI's commitment to the conservation of genetic resources, improvement of germplasm with classical methods, integrated pest management, integrated nutrient management, and ecoregional research. This research places increased emphasis on the more fragile environments and the associated problems of biotic and abiotic stresses.

The new plan also outlines the Institute's commitment to the new science of functional genomics to solve the old problems of agronomic performance and to address some new opportunities for improving the nutritional quality of rice. As well, it identifies new opportunities and approaches in the effective transfer of technology.

New Positions

Two critical positions, head of the Plant Breeding, Genetics, and Biochemistry (PBGB) Division and IRRI's first intellectual property specialist, were filled. The appointees are Dr. David Mackill and Dr. Thanda Wai, respectively.

On 31 December 2000, Dr. Gurdev Khush officially retired as head of the PBGB Division and leader of various research programs. He will continue to serve as IRRI's principal plant breeder and as a member of the management team until the end of August 2001. Dr. Khush served as PBGB Division head for nearly three decades. Dr. Sant Virmani is serving as PBGB interim head until the arrival of Dr. Mackill.

Awards and Honors

The list of awards to individuals was headed once more by Dr. Gurdev Khush, in the year before his retirement. Dr. Khush received the B.P. Pal Gold Medal and the Padma Shri Award, both from his native India. He also received the Wolf Prize from the President of Israel, and was awarded honorary doctorates from Cambridge University in the U.K. and from Assam Agricultural University in India. Dr. Khush was also made an honorary professor of the University of Tehran, in Iran, and an honorary researcher of the China National Rice Research Institute.

Drs. James Hill and Roland Buresh, both from IRRI's Crop, Soil, and Water Sciences Division, were made fellows of the American Society of Agronomy, and entomologist Dr. K.L. Heong received an honorary doctorate of science from the University of London.

The Prime Minister of Cambodia bestowed a Distinguished Collaboration Award on Dr. Harry Nesbitt, leader of the Cambodia-IRRI-Australia Project, and the Officer Award for Collaboration on INGER coordinator Dr. Edwin Javier and agricultural engineer Joe Rickman.

Entomologist Dr. Alberto Barrion received the Outstanding Local Scientist Award for 2000 from the CGIAR in Washington, D.C. As well, he received the Pest Management Council of Philippines Pest Management Award for 2000 and the Gawad Saka Special Citation from the Philippines' President.

Intellectual Property

In 2000, the second phase of the Institute's intellectual property management review (IPMR) was completed, including an IP audit. It focused on the IP implications of germplasm-related technologies deployed by IRRI, functional genomics and bioinformatics activities carried out by IRRI researchers, the new plant type, and use of third-party proprietary technologies to enhance the nutritional value of rice.

The results indicated that IRRI's capacity in trait discovery, in collaboration with its NARES partners, is an important inventive activity.

In considering the IP implications of these issues, the IPMR investigated the extent to which defensive publication or defensive registration might be used to deal with some IP problems. One theme running through the review was the necessity for IRRI to consider its IP management in the wider context of its membership in the CGIAR.

The IPMR identified a need to consolidate the office of the deputy director general for partnerships (DDG-P) as IRRI's "single-door" IP unit, handling all IP issues and acting as a depository of IP documents.

Knowledge Management and Information Technology

In 2000, IRRI established a task force to explore the creation of a global knowledge system for rice. The question of whether enough people will have access is no longer of concern. Rather, the concern is whether or not IRRI can be ready soon enough, with expertise and leadership, to help its partners integrate into a global knowledge system.

The task force recommended that IRRI should not only plan for a global knowledge system for rice, but it should clearly define its role in such a system. It recommended that IRRI become actively involved with other institutions planning or creating global knowledge systems on agriculture and development and, by doing so, ensure the involvement of its NARES partners.

The task force concluded that, by taking advantage of the opportunities afforded by new information and communication technologies, IRRI can integrate its research and information activities with those of its partners, thus achieving a true science partnership from the rice fields of Asia to the molecular laboratories and supercomputers of the developed world.

IRRI's Outreach Programs

The International Programs Management Office (IPMO) has made significant progress in improving the day-to-day management and coordination of IRRI's outreach activities, as well as their integration with activities at headquarters in the Philippines.

In 2000, IRRI had substantial research activities in 18 countries and maintained liaison offices in ten countries. However, the full range of its international activities covered more than 70 countries.

Scientific Publishing

IRRI's four Web sites—the IRRI home site (www.cgiar.org/irri), Riceweb, Riceworld, and the IRRI Library site—continue to grow in popularity. There were nearly 210,000 visitors to the Web sites during 2000. They made more than 780,000 "hits," or movements within the sites. More than 100,000 files of popular information products were downloaded, including installments of the discussion paper series, stories from the 1999-2000 annual report, and sections of the *International Rice Research Notes* and annual program reports. IRRI-developed software also proved popular. An example was more than 1,000 downloads of the popular IRRISTAT program for statistical analysis.

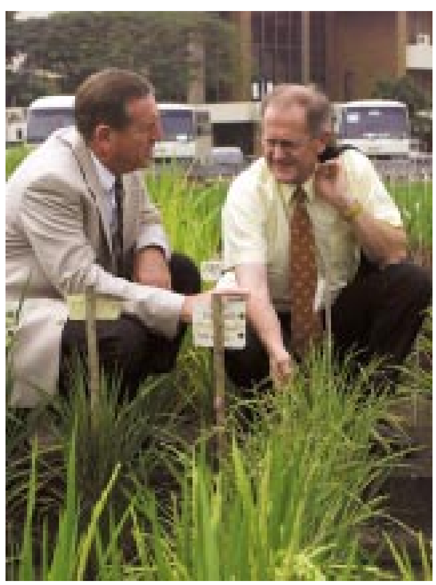
During the year, the Web sites were enhanced by the addition of electronic versions of the three 2000 issues of the *International Rice Research Notes, the Program Report for 1999*, and recent IRRI conference and workshop proceedings. New sections were created for rice genomics, rice bioinformatics, decision support tools, and software downloads.

Sixteen titles were produced and distributed, including seven IRRI books, four installments of the IRRI discussion paper series, and one installment of the limited proceedings series. One of the books, *Redesigning Rice Photosynthesis to Increase Yield*, was a dual imprint with Elsevier Science.

More than 139,000 photographs in the IRRI archives, dating back to 1960, were assessed, classified, catalogued, and indexed. Of these, about 3,500 of the best images were scanned and made available for searching and downloading via Institute computers.

Public Awareness, Visitors, Exhibitions, and Conferences

After a fire in 1999, the Riceworld Museum was closed for part of 2000 but reopened in time for the Institute's 40th anniversary activities in April. However, the Chandler Hall Auditorium, which was also damaged by the fire, remained closed throughout 2000 and reopened in early 2001.



Dr. Ron Cantrell and Swiss Foreign Minister Joseph Deiss.

During the year, the public awareness unit produced 28 press releases and 27 photo releases, delivered more than 100 broadcasts on "The IRRI Hour" radio show, produced the 1999-2000 annual report, *The Rewards of Rice Research*, and a 2001 wall calendar, "Rice Science for a Better World." The unit also created a new Internet homepage and produced four editions of "The IRRI Hotline."

The Institute also welcomed about 50,000 visitors to its headquarters including ten state ministers, 35 ambassadors and members of the diplomatic corps, and 15 representatives of donor and international organizations such as the United Nations Development Programme, Food and Agriculture Organization of the United Nations, and Asian Development Bank.

The 40th anniversary events kicked off with an international rice research conference titled "Rice Research for Food Security and Poverty Alleviation," beginning on 31 March. It attracted 243 researchers from 35 countries. Events culminated with the Fourth International Rice Genetics Symposium in late October, which brought 507 participants from 32 countries. It is believed to have been a record gathering at IRRI headquarters.

Library

During 2000, more than 8,000 references were added to the rice bibliography database, bringing the total to more than 188,300. The on-line catalog grew to 60,715 bibliographic records. To provide electronic access to rice literature prior to 1970 and to benefit scientists who have no Internet access, the International Bibliography on Rice Research, 1951-2000, was published in CD-ROM format in December.

The library added 277 rice dissertations to its collection, most of which came from China and major European countries, and acquired 33 videocassettes for the audiovisual learning center. The main library collection now contains 116,655 monographs and 1,536 active serial titles.

IRRI Board of Trustees 2001

Board of Trustees 2001 with IRRI senior management.

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(as of 31 Dec. 2000)

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Wazhong Tan, *PhD, project scientist*[1]
Xiaoping Yu, *PhD, project scientist*[1]
Wenjun Zhang, *PhD, project scientist*[1]
Zeng-Rong Zhu, *PhD, project scientist*

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Sena Balachandran, *PhD, project scientist*[4]

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John Bennett, *PhD*, *senior molecular biologist*
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Im-Soo Choi, *PhD, visiting scientist*[3]
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Karabi Datta, *PhD, plant biotechnologist*
Yoshimichi Fukuta, *PhD, plant breeder*
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Woon-Go Ha, *PhD, collaborative research fellow*[4]
Shailaja Hittalmani, *PhD, visiting scientist*[3]
Louise Friis Bach Jensen, *MS, collaborative research fellow*
Kuk-Hyun Jung, *visiting scientist*[3]
Kyung-Ho Kang, *PhD, collaborative research fellow*[4]
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Bo-Kyeong Kim, *collaborative research fellow*[1]
Nguyen Thi Lang, *PhD, visiting scientist*[4]
Deung-Don Lee, *PhD, collaborative research fellow*[4]
Moon-Hee Lee, *PhD, IRS seconded from RDA-Korea*
Zhikang Li, *PhD, plant molecular geneticist*
Lijun Luo, *PhD, visiting scientist*[4]
Chang-Xiang Mao, *PhD, project scientist*[4]
Kenneth McNally, *PhD, affiliate scientist*
Hanwei Mei, *collaborative research fellow*[3]
Shin Mun-sik, *PhD, collaborative research fellow*[1]
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Tilathoo Ram, *PhD, project scientist*[4]
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Yu Sibin, *PhD, project scientist*[1]
Sanjay Singh, *PhD, project scientist*
You-Chun Song, *PhD, collaborative research fellow*[3]
Jumin Tu, *PhD, project scientist*
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Parminder Virk, *PhD, affiliate scientist*
Xu Weijun, *PhD, project scientist*
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Li Xiaofang, *PhD, visiting scientist*[3]
Bi Xuezhi, *PhD, project scientist*
Seiji Yanagihara, *PhD*, *rice breeder*[4]

Public Awareness

Duncan I. Macintosh, *AB, head*
Olivia Sylvia O. Inciong, *MS, manager, public awareness*
Mario M. Movillon, *MS, manager, visitors, exhibition, and conference services*

Social Sciences

Mahabub Hossain, *PhD, economist and head, program leader, rainfed lowland rice ecosystem research*
Sushil Pandey, *PhD, agricultural economist and deputy head*
David Dawe, *PhD, agricultural economist*
Christopher Edmonds, *PhD, affiliate scientist*[1]
Esteban Godilano, *PhD, project scientist*
Chu Thai Hoanh, *PhD, affiliate scientist*
Aldas Janaiah, *PhD, project scientist*
Suan Pheng Kam, *PhD, GIS specialist*
Nguyen Tri Khiem, *PhD, project scientist*[1]
Li Luping, *collaborative research fellow*[3]
Piedad F. Moya, *MS, senior associate scientist*
Thelma R. Paris, *PhD, affiliate scientist*

Training Center

Paul Marcotte, *PhD, head*[4]
Abdul Karim Makarim, *PhD, project scientist*[4]
Madeline B. Quiamco, *PhD, senior associate scientist*

Staff Based in National Agricultural Research and Extension Systems

Bangladesh

Sadiqul I. Bhuiyan, *PhD, IRRI representative for Bangladesh and water scientist*

Cambodia

Harry J. Nesbitt, *PhD, agronomist and team leader*
Peter G. Cox, *PhD, agricultural economist*

China

Sheng-Xiang Tang, *PhD, liaison scientist for China*

Paul O'Nolan, Dr. Tom Mew, Dr. Sant Virmani, and Dr. Emil Javier.

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R.K. Singh, *PhD, representative and liaison scientist*

Indonesia/Malaysia/Brunei Darussalam

Mahyuddin Syam, *MPS, communication specialist and liaison scientist*

Japan

Hiroyuki Hibino, *PhD, liaison scientist*
Kazuko Morooka, *BA, librarian*

Lao PDR

John M. Schiller, *PhD, agronomist and team leader*
Bruce A. Linquist, *PhD, upland research specialist*

Madagascar

Martha M. Gaudreau, *PhD, cropping systems agronomist and team leader*[1]

Myanmar

Arnulfo G. Garcia, *PhD, cropping systems agronomist and IRRI representative*[1]

Thailand

Boriboon Somrith, *PhD, liaison scientist*

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[1]Left in 2000.
[2]On study leave.
[3]Joined and left in 2000.
[4]Joined in 2000.
[5]Transferred from Agricultural Engineering Unit.
[6]Transferred from Cambodia-IRRI-Australia Project.

How to Contact IRRI Offices

Bangladesh
E-mail: irri@bdonline.com
Phone: (880-2) 882-7210, 881-3842
Fax: (880-2) 882-5341
Contact: Dr. Sadiqul I. Bhuiyan

Cambodia
E-mail: irri-cambodia@cgiar.org
Phone: (855-23) 219-692
Fax: (855-23) 219-800
Contact: Dr. Harry J. Nesbitt

China, People's Republic of
E-mail: irricaas@public.east.cn.net
Phone: (86-10) 6218-4732
Fax: (86-10) 6217-5611
Contact: Dr. Sheng-Xiang Tang

India
E-mail: irri@vsnl.com
Phone: (91-11) 582-5802, 582-5803
Fax: (91-11) 582-5801
Contact: Dr. R.K. Singh

Indonesia, Malaysia, Brunei Darussalam
E-mail: irribogr@indo.net.id
Phone: (62-251) 334-391
Fax: (62-251) 314-354
Contact: Dr. Mahyuddin Syam

Japan
E-mail: irrijp@jircas.affrc.go.jp
Phone/fax: (81-298) 386-339
Contact: Dr. Hiroyuki Hibino

Lao PDR
Vientiane
E-mail: j.m.schiller@cgiar.org
Phone: (856-21) 412-352, 414-373
Fax: (856-21) 414-373
Contact: Dr. John M. Schiller

Luang Prabang
E-mail: b.linquist@cgiar.org
Phone/fax: (856-71) 212-310, 212-765
Contact: Dr. Bruce A. Linquist

Myanmar
E-mail: irri.mya@mptmail.net.mm
Phone: (95-1) 663-590
Fax: (95-1) 642-341
Contact: Dr. Mark Bell

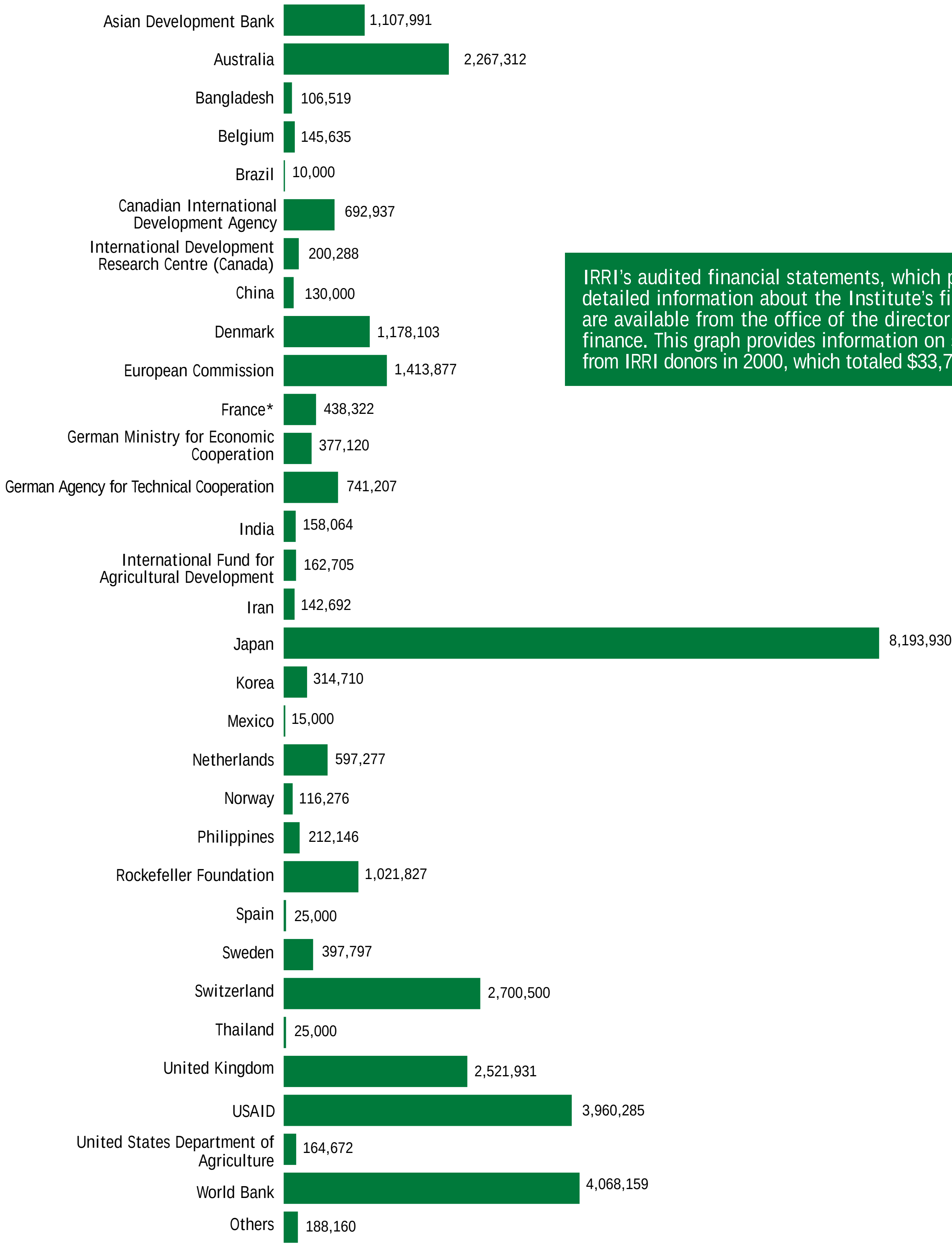
Thailand
Bangkok
E-mail: irri-bangkok@cgiar.org
Phone: (66-2) 579-5249, 579-9493, 561-1581
Fax: (66-2) 561-4894
Contact: Dr. Boriboon Somrith

Ubon
E-mail: irriubon@cscoms.com
Phone: (66-45) 344-100, 344-101
Fax: (66-45) 344-090
Contact: Dr. Surapong Sarkarung

Vietnam
E-mail: irri-hanoi@netnam.org.vn
Phone: (84-4) 823-4202
Fax: (84-4) 823-4425
Contact: Dr. Mark Bell

IRRI Financial Statement (US$)

IRRI's audited financial statements, which provide detailed information about the Institute's finances, are available from the office of the director for finance. This graph provides information on support from IRRI donors in 2000, which totaled $33,795,442.



** The Government of France also provided personnel and other services valued at F2.19 million.*