



Rice Research and Production in the 21st Century

Symposium Honoring Robert F. Chandler, Jr.

Edited by W.G. Rockwood

IRRI

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Foreword

Many of the tributes that can be made to the life and accomplishments of Bob Chandler can be found in these proceedings. His dedication to the gigantic effort for keeping hunger and poverty in Asia at bay is reflected in his work in founding the International Rice Research Institute (IRRI) and the Asian Vegetable Research and Development Center (AVRDC). His special genius for organizing and leading goal-oriented research was instrumental in bringing about not only the Green Revolution but also a revolution in how international agricultural research is organized and supported.

M.S. Swaminathan, IRRI's fourth director general, noted in a frontispiece to the Chandler book *An Adventure in Applied Science: A History of the International Rice Research Institute* that Chandler was "obviously modest when referring to his own contributions. It is therefore the duty of others who are aware of the history of agricultural progress . . . to chronicle the seminal role of Dr. Chandler." These proceedings do that.

Readers who are most interested in Bob Chandler the man will find Part I rewarding. A longtime Chandler colleague and friend chronicles Chandler's humble beginnings in rural Maine and his early years as a member of a somewhat itinerant family. Professional colleagues give readers of these proceedings a close-up personal look at the life and management styles that Chandler brought to the two international institutions he founded, and the respect and love engendered among their teams of scientists. Other colleagues remember how Chandler touched their lives throughout his long and distinguished career from university professor to his post-retirement activities in other international institutions.

Those readers most interested in rice, rice science, and innovations in both research methodologies and institutions will find enrichment in Parts II-IV. And beyond these proceedings, read Chandler's books—*An Adventure in Applied Science* (noted above and available online via the IRRI Web site at www..irri.org/ChandlerBook/Adventure.htm) and *Rice in the Tropics: A Guide to National Development.*

Edwin B. Oyer
Ithaca, New York
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Acknowledgments

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Bob Chandler's Memorial Symposium

E.T. York

First, let me say how pleased my wife and I are to be back at Cornell where we spent some 2.5 delightful years right after World War II while I was working on a graduate degree. Cornell will always have a warm spot in our hearts. I'm very pleased to be in Kennedy Hall today. Keith, for whom the building was named, and I were fellow graduate students and played together on the Agronomy Department softball team. Colin McClung, Bob Miller, and others were fellow graduate students at that time.

Secondly, may I say how delighted I am to have an opportunity to participate in this Chandler Memorial Symposium. Like most of you, my life has been impacted most positively by the legacy of Bob Chandler.

I came to Cornell in 1946 to study under Dr. Richard Bradfield, the preeminent soil scientist in the world at that time. For the first few weeks, I shared an office with Earl Stone, who was Bob Chandler's graduate student. I was immediately impressed with Dr. Chandler, a young vibrant and vigorous professor of Forest Soils. However, before I could take his course, he went to the University of New Hampshire where he was dean of the College of Agriculture and then president of the university. He later joined the staff of the Rockefeller Foundation.

Dr. Bradfield worked extensively with the Rockefeller Foundation in that era, in fact serving on the Foundation board. He did some of the early work for Rockefeller in helping establish an agricultural program in Mexico, which ultimately led to the creation of CIMMYT. I'm sure Dr. Bradfield was instrumental in getting Bob Chandler to join Rockefeller Foundation. The later work of Bradfield, Chandler, and other stalwarts of agricultural science—Warren Weaver, George Harrar, F.F. Hill, and George Gant of Ford Foundation—is interestingly detailed in Chandler's book (1982) titled *An adventure in applied science.*

In 1961, while serving as administrator of the Federal Extension Service, I accompanied Secretary of Agriculture Orville Freeman on an around-the-world trip to study international agricultural issues. While in the Philippines, we visited Los Baños, the site of the newly created International Rice Research Institute (IRRI), which at the time had only one building—a large Quonset structure that provided office, laboratory, and storage space. We heard about Bob Chandler's plans and dreams for IRRI and felt that with his leadership there were great potentials for IRRI.

Since that time, I have visited IRRI several times, including the period I served on the Technical Advisory Committee (TAC) of the Consultative Group (CG) system. Over the past 40 years, I have seen Bob Chandler's dreams become reality as IRRI came to be widely recognized as the flagship of the CG system.

Then about 10 years ago, I had an opportunity to observe more of the Chandler legacy while chairing a comprehensive program and management review of the Asian Vegetable Research and Development Center (AVRDC), which like IRRI started under Bob Chandler's leadership. I was again most impressed with his legacy at AVRDC.

Bob and Sunny eventually became citizens of Florida, and some 3 years ago the IRRI alumni held a reunion, which I was privileged to host, at the University of Florida. The highlight of that meeting was celebration of Bob's 90^{th} birthday on June 22. So, if Bob had lived he would be celebrating his 93^{rd} birthday exactly one week from today.

Others will discuss details of Bob's contributions, but let me conclude my opening remarks by saying that few, if any, people with careers in agriculture-related fields have made more significant contributions to the well-being of mankind than Bob Chandler.

Reference

Chandler Jr., RF. 1982. An adventure in applied science: a history of the International Rice Research Institute. Manila (Philippines): International Rice Research Institute. 233 p.

Notes

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In search of research entrepreneurship: a tribute to Robert F. Chandler, Jr.

N.E. Borlaug and C.R. Dowswell

It is a pleasure to participate in the Chandler Memorial Symposium and address the topic of Bob Chandler's legacy as a research manager and institution-builder. This topic is especially appropriate at this time, when so many agricultural research systems concerned with the developing world seem to be in crises.

I first met Bob Chandler in 1947, when he took leave as a professor of Forest Soils at Cornell and came to Mexico as a soil scientist with the Mexican Government-Rockefeller Foundation Agricultural Program. I was quickly impressed with his intellectual and leadership skills. It was in Mexico, I believe, that he became convinced of the urgent need for, and challenge of, assisting food-deficit developing nations to improve their agriculture and food supply.

Within the year, he was appointed dean of the College of Agriculture and director of the Agricultural Experiment Station at the University of New Hampshire. He served in that capacity for 3 years. He then became president of the University, a position he held for 4 years. Our paths come together again, when he joined the Rockefeller Foundation in 1954, serving as assistant director, and later associate director, for the Agricultural Sciences Division.

In his years with Rockefeller Foundation, Bob worked as sort of a roving agricultural staff member, traveling extensively in Asia and Africa, and, to a lesser extent, in Latin America. In 1959, he was asked to establish the International Rice Research Institute (IRRI). He served as its director until 1972, when he officially retired because of his age. But he continued with the Rockefeller Foundation for another 3 years, and given a special assignment to establish and serve as the first director of the Asian Vegetable Research and Development Center (AVRDC) in Taiwan.

Bob Chandler's legacies, as a research manager and institution-builder, are many. However, I focus my comments on his role as founding director of IRRI. I was privileged to visit him during this formative period and we had many discussions, especially concerning international germplasm exchange and testing, and the training of young scientists of developing nations.

In establishing IRRI and in shaping its research agenda, Bob took full advantage of the Rockefeller Foundation's experience in international agricultural research and development, first in Mexico and in South America and Asia. The Ford Foundation's role, especially on the financial side, was also central to the launching and rapid success of IRRI.

None of us involved in the creation of the first four international agricultural research centers—IRRI, CIMMYT, IITA, and CIAT (and others that followed—and the creation of the Consultative Group on International Agricultural Research (CGIAR) will forget the leadership of the late George G. Harrar of the Rockefeller Foundation and the late F.F. Frosty Hill of the Ford Foundation. They, in turn, were guided by the wise counsel of scientist-giants, such as E.C. Stakman, Paul Mangelsdorf, and Richard Bradfield, among a list of luminaries too long to mention fully.

A remarkable convergence of research talent and mentoring came together in the creation of IRRI. It was a new type of international agricultural research organization, clear in focus and purpose, which applied the best available scientific knowledge to expand the food supply for much of the world. Bob Chandler was one of those pioneers whose boundless energy and enthusiasm—and complete dedication to a cause—helped to make rice available for hundreds of millions of people in the developing world.

Institution-building

One of Bob Chandler's outstanding leadership qualities was his attention to careful staffing. The way he combined very experienced rice researchers, like Hank Beachell, Akira Tanaka, and S.H. Ou in the early years, to mentor younger scientists like Peter Jennings and later, Gurdev Khush, was brilliant. An anecdote from Colin McClung captures Bob's philosophy on staffing:

"Find the person who has the background and wants to do the job and give him an environment in which he can excel. The person had to be well qualified in the basics of his field but prior knowledge of rice was far less important under Chandler management than a desire to take the ball and run with it. In retrospect, it may be hard to believe but there was a concern when Gurdev Khush was being considered for employment at IRRI. Did he really want to be rice breeder or would he prefer to be a geneticist who worked out principles and left the job of developing varieties to others? Gurdev's response was unequivocal and the rest is history." Gurdev Khush today is the world's most successful rice breeder.

Chandler and his program directors at IRRI brought together a range of scientists with different professional skills that complemented each other and added value to the collective whole. Weekly seminars and symposia were enormously valuable in fostering cross-discipline understanding of the research program (Colin McClung, pers. commun.). This was an interdisciplinary institutional structure with a purpose.

The in-service and degree-related training programs instituted under Chandler's leadership were another great contribution, and followed in the tradition of Rockefeller Foundation agricultural programs. Trainees were involved fully in the grubby fieldwork of rice cultivation—from planting to harvest. They helped prepare the international nurseries that went out each year to national rice research programs in Asia and beyond. David Hopper captured well the spirit (pers. commun.):

> "The trainees became IRRI's best ambassadors to the farmer and the agricultural science community throughout the region. On the return of each to their home institutions, they brought back genetic material and the new practices to make this material more than double traditional 'best yields.' It was not just a revolution in rice production; for many in Asia, it was also a revolution in teaching applied agricultural practices."

Strategic planning in Chandler's day was not a formal corporate activity, yet it certainly went on, and Chandler was instinctively good at it. Colin McClung (pers. commun.) described Bob's style well:

> "Bob put in place a plan very early in the development of IRRI that was particularly effective in orienting the new organization and keeping it on track in a complex and constantly changing environment. He did it with the input of staff, trustees, and others, often without them being really aware of it. He never mentioned the subject as such, or called a meeting to discuss it, but plans were steadily improved, modified, and refined."

Chandler was also an agricultural development leader, unafraid to venture into what I often call "the no man's land" of economic policy. He took the case of rice modernization to political leaders with evangelical zeal. He knew that science alone would not bring a green revolution to Asian agriculture. Battles would have to be fought at the level of public policy. Farmers would need access to inputs, such as the seeds of the new high-yielding varieties, fertilizer, pesticides, and the credit to buy them. They would also need price incentives to adopt these modern inputs and adequate access to markets to sell their surpluses. This was not a message happily received by those who favored the status quo. But Bob worked tirelessly to bring these institutional and market changes to fruition.

Research entrepreneurship

Bob Chandler was not inclined to talk about himself, or his style of management. He talked instead about the results of research being achieved by IRRI scientists.

"On my trips to IRRI, I was struck by the fact that there was no doubt that Robert Chandler was the Director General, but there was also no doubt that each scientist, indeed, each employee enjoyed the freedom to undertake his or her duties and to challenge the DG's judgment as the results unfolded.

Chandler was truly a classic leader of a top-caliber scientific research institution. Would that there were many more leaders cut to his mold." (W. David Hopper, pers. commun.)

All I can say to David's comment is "Amen." Bob Chandler is gone in body but not in spirit. My concern now is how we keep this sort of research leader and the sort of agricultural institution he headed so effectively for more than a decade, alive, dynamic, and thriving.

Keeping the CGIAR relevant

Frosty Hill, a key force in the creation of the international agricultural research center (IARC) system, told me in 1968 as we traveled across the Punjab looking at the wheat revolution and reflecting about the future of the not yet founded CGIAR, "Norm, enjoy this moment while you can. From my experience with other institutions, I doubt that the international centers will have more than 25 years of productive life, before they succumb to the twin ills of bureaucracy and complacency." He added, "If this happens, my guess is that it will probably be easier to build a new set of institutions rather than try to reform the old ones."

I find myself increasingly asking the question, are Frosty's predictions coming true? I hope not, but I must confess that I am not sure, especially with the reports I read, and the stories I hear, about the multitude of CGIAR committees, review panels, and meetings. These continue to grow, taking more and more of the time of research directors and program leaders away from the more productive work of the centers—to generate new technology for farmers—both small scale and large.

I understand that more than 400 people now attend the CGIAR Centers' Week and mid-term meetings. How things have changed since the first Centers' Day (not week), which Bob Chandler and I attended in Washington in 1971. I would be surprised if we were more than 35 people present in the room. Moreover, virtually everyone at the table could speak for his or her organization, including making financial pledges, almost literally on the spot. Basically, it was an informal gathering of scientists and investors, in which the center directors reviewed their recent work and progress and laid out their financial requirements for the coming year, or years. Representatives from the donor organizations, often the CEOs themselves, listened to the technical presentations and financial requirements of the centers, and made their commitments in a spirit of trust and respect. Then everyone returned home and went to work.

Although IARC and national agricultural research system (NARS) scientists have advanced the frontiers of knowledge over the past four decades, I believe their more significant contribution has been the integration of largely known scientific information. Its application in the form of improved technology has raised farmers' incomes and overcome pressing crop production problems and food shortages. This should continue to be their primary mission. Moreover, impact on farmers' fields should be the primary measure by which to judge the value of IARC and NARS work.

Unfortunately, agricultural science—like many other areas of human endeavor—is subject to changing fashions and fads generated from both within the scientific community and imposed upon it by external forces, especially the politically induced ones that affect the actions of financial donors. Increasingly, I fear, the CGIAR centers, and NARS as well, are falling prey to development bandwagons that will not solve Third World food production problems. One dangerous trend, I believe, has been the shift among donors away from promoting and supporting new high-quality agricultural research and technology generation and toward funding to foster social and environmental reforms that the CGIAR has no comparative advantage in addressing.

In his path-breaking book, *Transforming traditional agriculture*, and in other writings, the late T.W. Shultz, Nobel laureate in economics, argued forcefully about the importance of modernizing traditional agriculture, not maintaining it.

"When farmers are limited to traditional factors of production they . . . can make little or no contribution to economic growth because there are few significant inefficiencies in the allocation of factors, and because the investments made to increase the stock of traditional factors would be a costly source of economic growth . . . . Accordingly, there would be virtually no entrepreneurial function, routine management would suffice.

But agriculture is not in such an equilibrium state. On the contrary, the transformation of agriculture into an increasingly more productive state, a process that is commonly referred to as 'modernization,' entails changes in what farmers do as new and better opportunities become available."

Clearly, our objective should be to establish the policies and institutions that will make it profitable for small-scale farmers to undertake modernizing investments to increase the productivity of agriculture. Much yet needs to be done on the policy-making front. How can African agriculture modernize, for example, with farm gate fertilizer prices three to five times higher than the world price, and farm gate grain prices one-half the world price? What incentive would any farmer have to buy these inputs at such prices? Why are we just accepting horrendous market failures such as these? Where is our righteous indignation?

I hear much minimalist talk today in CGIAR centers about helping farmers just to "feed themselves," rather than really "prospering" from their efforts in agriculture. Such thinking is likely to slow future agricultural production, accelerate environmental degradation, and contribute to social and political chaos, not only in the developing world but in rich, complacent nations as well, where adequate food supplies and high standards of living are taken for granted.

Let there be no mistake about it, unless small-scale farmers see the possibility to make substantially better incomes from agriculture in the future, and also to reduce the terrible drudgery that traditional agriculture entails, they will abandon farming by the millions, and migrate to the cities to join the battalions of unemployed urban poor. The social, political, and human health meltdowns that could ensue from such a chaotic exodus might well threaten human civilization.

Agricultural research has become a substantial enterprise over the past century. It is so extensive that no research director can keep abreast of the many advances in science and no scientist can stay on top of all the changing conditions in agricultural production. Certainly, there are many management problems that must be addressed to improve the efficiency of agricultural research. But what needs to be done is far from clear.

I agree with T.W. Shultz that most working scientists are research entrepreneurs and that centralized control is an anathema to research progress. Yet this seems to be the direction that CGIAR donors and leadership want to take the international centers. I quote Shultz,

> "In the quest for appropriations and research grants, all too little attention is given to that scarce talent which is the source of research entrepreneurship. The convenient assumption is that a highly organized research institution firmly controlled by an administrator will perform this important function. But in fact a large organization that is tightly controlled is the death of creative research. No research director . . . can know the array of research options that the state of scientific knowledge and its frontier afford.
>
> Organization is necessary. It too requires entrepreneurs . . . . But there is an ever-present danger of over-organization, of directing research from the top, of requiring working scientists to devote ever more time to preparing reports to 'justify' the work they are doing, and to treat research as if it was some routine activity."

In today's world, CGIAR directors general and program leaders are forced to spend more and more time chasing money, while demonstrating to a growing multitude of critics—many of whom have little idea what farmers and developing countries really need from research—that their centers are politically correct. The result is that CGIAR leaders spend less and less time on the ground with their scientists, national counterparts, policymakers, and farmers monitoring what is happening—or not happening.

Some of the recent IARC downsizing, while painful, has probably been for the better, since many centers had grown too big. However, in this process, staff morale often has declined considerably. In particular, the perception that good career opportunities no longer exist within the CGIAR system needs to be dispelled. Thirty-five years ago, the centers were able to attract the best and the brightest outstanding young scientists who wanted to direct their talents to helping to solve Third World agricultural problems. Is this still true today?

I believe that the CGIAR centers must attempt to retain the best and brightest of their staff for as long as they can. This notion of forced staff turnover, following a rigid formula, is one of the craziest and most nonsensical ideas I have ever heard. An outstanding senior IARC leader is much more than a scientist. He, or she, must have strong networking (communications) skills and also have a good understanding of development. These talents take considerable time to develop.

Another worrisome trend in the CGIAR system in recent years has been the weakening of links with NARS, most of which are in greater financial and management crisis than the IARCs themselves. The CGIAR centers cannot be a substitute for effective national research systems, much of which, because of the nature of research on food crop technology for small-scale farmers, will continue to require public-sector funding. Thus, any strategy to maximize CGIAR investments in technology generation and transfer for food crops in the developing countries must find ways to fund adequately—and with stability—the NARS as well. Funding one without the other will not result in maximum impact.

One important IARC function is to serve as hub for various research networks. In addition to research collaboration on specific problems, IARC networking functions include germplasm and information exchange, which should include, I believe, continuing opportunities for practical in-service training for mid-career researchers from national programs, as well as visiting scientist opportunities for senior-level visiting scientists. Even with all the advances in information technology, there is still a need for face-to-face contact. This means that NARS scientists need to visit the IARCs fairly frequently, while IARC scientists need to spend significant time visiting NARS scientists and touring agricultural areas.

In closing, permit me to quote from an article written by Andre and Jean Mayer, titled *The Island Empire*, which appeared in the summer 1974 issue of *Daedalus*, and remains relevant in the 21st century and to this meeting:

> "Few scientists think of agriculture as the chief, or the model science. Many, indeed, do not consider it a science at all. Yet it was the first science—the mother of all sciences; it remains the science which makes life possible; and it may well be that, before the century is over, the success or failure of Science as a whole will be judged by the success or failure of agriculture."

The record of agricultural research and development over the past 50 years has been outstanding in many parts of the developing world. We have been able to keep food production ahead of population growth, especially in Asia, and to raise farm incomes and simultaneously lower the real cost of food to the consumer. In particular, the adoption by hundreds of millions of farmers of productivity-enhancing technology in rice, wheat, maize, and other important food crops has especially benefited the poor.

But we need to keep working vigorously to keep food production ahead of population growth, and in a way that benefits farmers and consumers alike, without damaging the resource base. In this quest, we must be ever vigilant against the negative efforts of pseudo-scientists and "neo-Luddites," many of whom, it seems, want to stop science in its tracks. My last conversation with Bob Chandler, in October 1998, was exactly on this subject. His concern was about all of the nonsense maliciously being spread around in the popular press about biotechnology, and the negative effect this sort of reactionary thinking could have on agricultural progress.

Finally, let me express a fervent hope that those still working on the food production front will find new motivation and dedication in our work by remembering the stellar way in which Bob Chandler lived his professional and personal life.

Notes

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The Chandler family heritage: excerpts from a memoir

E.B. Oyer

Many of us in this room had the pleasure of knowing and working with Bob Chandler. It is a distinct honor and sincere pleasure to come together and to share details from his writings. All of us who worked under Bob's direction know that one of his rules of administration was to answer every letter he received. My remarks come from our personal correspondence over the last quarter century of Bob's life.

We shared good books and Bob's response, written on August 16, 1992, on that of Lewis Thomas titled *The Fragile Species* is germane to our gathering today. I quote from Bob's letter:

> I particularly liked his statement on page 75 about old age, 'It is an absolutely unique stage of human life—the only stage in which one has both the freedom and the world's blessing to look back and contemplate what has happened during one's lifetime instead of pressing toward new high deeds. It is one of the three manifestations of human life responsible for passing along our culture from one generation to the next. The other two are, of course, the children who make the language and pass it along and the mothers that see to it that whatever love there is in a society moves into the next generation.'
>
> Bob then explained:
>
> . . . my niece, Ann Chandler Barden . . . asked that I write a small piece about life with my parents, because she is interested in family history . . . . I wish so much that I had asked questions about my ancestors when my grandparents were alive. Now I'm scrambling from one small town to another here in Maine trying to find out

more about my great-grandfather, Amasa Loring, who was a Congregational minister and an able historian.

Bob prepared an 18-page document for his niece titled "*Some recollections of life with my parents, Robert Flint Chandler and Harriet Loring Chandler*" and it is from that document, dated March 10, 1992, that the following excerpts are taken.

> Mother and Dad were married in Portland, Maine, on September 14, 1904. They were the first couple in the city to ride from their wedding reception to the railroad station in an automobile . . . .
>
> At some time in 1905 (latter part of the year I believe), the folks moved to Gorham, New Hampshire, where Dad worked for a mill in Berlin, NH. On May 20, 1906, Loring Olmstead Chandler was born at 5:10 a.m. in their rented upstairs apartment at 14 Mechanic Street in Gorham. He weighed 10 pounds at birth.
>
> On February 11, 1907, the folks moved to Columbus, Ohio, where Dad had obtained a position as structural detailer for the Jeffrey Manufacturing Company . . . . On June 22, 1907, I was born at 444 Vermont Place in Columbus. I was premature by 5 or 6 weeks and weighed only a little over 5 pounds (roughly half of what Loring weighed). They had great difficulty in getting me to eat properly and I went down to 4.5 pounds before I started to gain weight. It was 5 months later before I weighed 10 pounds. When Grandmother Chandler saw me for the first time, she quipped, "If it wasn't for his head, he wouldn't be worth saving."

I remember Bob telling of a comment his mother made sometime in his later life to the effect "He was in a hurry to get here and hasn't slowed down yet." Bob's mother was homesick in Columbus and anxious to live back in Maine. She returned there with Grandmother Chandler and the two boys soon after Bob's birth. Bob's mother and grandfather looked for employment for Bob's dad and found an opportunity at the Portland Upholstery and Decorating Company. He moved the family possessions back to Maine on September 25, 1907.

> The next fact I know about is that Dad came down with tuberculosis. I have a photo of our family at the T.B. sanitorium in Henron, Maine, during the summer of 1908. We lived in a tent. At that time, the only cure known for tuberculosis was rest and fresh air.

With improved health, Bob's father learned early in 1910 of an opportunity to survey land on the Flathead Indian Reservation in Polson, Montana.

> While on the train on our way to Polson, I came down with a serious attack of pneumonia. My fingers were turning purple and when the train stopped at Great Falls, my parents got off and rushed me to a doctor's office and then to a hospital.
>
> My first recollection of life was in Polson. I remember mother shooting a porcupine that kept invading the tent in which we lived, taking our food. I remember as well being stung by a hornet or bee and being quite frightened by a Flathead Indian dance because of the loud chanting and the beat of the tom-toms.
>
> From Polson we moved to Spokane, Washington, where my father had obtained a position in the engineering department of the Washington Power Company . . . . On September 13, 1911, my sister, Audrey, was born . . . . On June 3, 1912 Grandfather Loring passed away in Portland, Maine, from a heart attack. Mother, with her three children, boarded the train in Spokane and for 5 days and 5 nights, we rode across the country to attend the funeral of my grandfather.
>
> I am uncertain about the details after this except to state that we never moved back to Spokane. Dad sold the house and came to Portland. He may have had another bout with tuberculosis. In any case before long we were living in New Gloucester where I continued to live until after I was graduated from high school in 1924 . . . .
>
> One of the highlights of our stay in Spokane was when Col. Theodore Roosevelt (formerly President Roosevelt, of course) came to town. This was on April 8, 1911 (Dad made quite a thing of it in his diary). At 2:30 in the afternoon, we all went out to watch him pass by in a parade. I remember him wearing a tall silk hat and bowing graciously to the crowds that lined the streets . . . . Speaking of Teddy Roosevelt, the teddy bear was "invented" during his last term as president (after a 1907 cartoon depicting the president sparing the life of a bear cub). Loring and I had two of the earliest teddy bears that were made. One afternoon we took them out in the areas back of our house in Spokane and placed them at the opening of two gopher burrows, thinking, I suppose, that they might go down the holes to live.
>
> Halley's comet appeared in the sky in 1910. Mother and Dad took Loring and me onto our front lawn in Spokane to see it. They said to us, 'Now remember this comet, for if you live to be old men,

you will see it again.' Indeed we did see it 76 years later in 1986, although, unfortunately, it was not nearly as spectacular as it was in 1910.

Regarding the family's return to Maine in 1912, Bob writes: "We lived in Grandfather and Grandmother Chandler's house. My sister Elizabeth (Betty) was born there on March 19, 1914. When Loring and I heard her first cries the night she was born, we asked Dad to quiet down the cats. Of course we were then told that we had a new baby sister . . . .

In the spring of 1915, my parents bought the Foxcroft House . . . . We drilled a 100-foot-deep well and built a pump house, which also served as Dad's workshop. We moved into the house in September 1915 . . . . I should mention our schooling. All of us children attended the one-room schoolhouse at the lower corner. It was located just below the general store that is still there. My recollection is that we started going to school in the fall of 1912 when I was 5 and Loring was 6 years old. We continued to be in the same class from then until we were graduated from high school in 1924 . . . .

The teacher we had for the longest time was Mrs. Woodbury. She was a good disciplinarian and an excellent teacher, giving us a fine start in the fundamentals of reading, writing, and arithmetic. There were 35 to 40 students in all nine grades, so no classes were large. All, however, were in one room, thus providing good training in concentration. There was always a class up front reciting while the rest of the pupils were studying. School didn't let out until 4 p.m., but we had an hour off for lunch and two 15-minute recesses, one in mid-morning and the other in mid-afternoon. The school had no running water, but there was a pail of drinking water at the back of the room with a common dipper for everyone to use. Toilet facilities consisted of an outdoor privy in the back of the schoolhouse . . . .

On September 25, 1916, we children were told not to come home for lunch but to go to our grandparents' house. When we returned home after school, we found that we had a new baby sister, named Esther Evelyn. Now we were a family of seven, Mother, Dad, and five children . . . .

Until 1915 we had no automobile, using our gentle horse, Jeanette, for getting around town. That summer the Shakers at Sabbathday Lake decided to sell their 1908 model Selden touring car and purchase a Pierce Arrow (a fine luxury car at the time). Grandmother

> Loring, who was living with us then, offered to buy the Selden for us. I remember well the day Mr. Wilson of the Shaker Community drove it to the house. We all went out to look at it. Grandmother Loring said to Mr. Wilson jokingly, "If I'm buying this car for my son-in-law, I want to know just one thing and that is how to stop it." Mr. Wilson simply shut off the engine by turning the ignition switch, and the deal was closed. The price was $300 . . . . We kept this car until 1917 when Dad bought a slightly used 1916 model Studebaker touring car (seven-passenger capacity with only four cylinders). This was to be our family car until the fall of 1924 when the folks moved to Florida.

In citing the family's attendance at Aunt Sara's graduation from Bates College in June 1917, Bob wrote:

> I particularly recall the ceremony of passing a pipeful of smoking tobacco from person to person among the graduating seniors as an expression of the common bond between them. When the pipe reached Aunt Sara, she simply put her handkerchief over her mouth and passed it on to the next person. Many of the other girls did the same thing. Smoking among women was rare in 191 7 . . . .
>
> In 1915 or 1916, I took piano lessons. It was not for long, however, because some of the boys made fun of me, calling me a sissy. I was over-sensitive and couldn't stand the ridicule. I begged Mother to let me stop taking lessons. Finally, she did, but I remember her saying, "Now when you grow up, please don't ever say, 'I could have played the piano if my mother had made me take lessons.' If I had continued, as Mother wanted me to, I could have played well enough to have obtained considerable pleasure from it. As it is, all that I can do is play simple tunes by ear, although with some enjoyment . . . .
>
> The winter and spring of 1920-21 was an eventful period for our family. Dad accepted a job with the North Carolina Highway Department to lay out a new road between Glenville and Tuckasegee, N.C. (now a part of Route 107) . . . we moved to Glenville where Dad was to start the actual surveying of the new road. The town was so small that it had no high school. Loring and I had to attend a private boarding school in Cullowhee, 16 miles from Glenville. There was no public transportation and we walked the 16 miles when we went home to visit our family.

> The school in Cullowhee is now Western Carolina University, but at that time it accommodated high school students and those who were in the first two years of college. Many of the students were from the local area and went home at night, but there were two dormitories for boarding students, one for girls and one for boys. There were four or five of us boys who were quite young and we were housed in one wing of the girl's dormitory.
>
> Loring and I were the only persons in the school with Republican parents and the only northerners. I recall once, when we were getting ready to play tennis, I said 'I'll be ready as soon as I put on my sneakers.' Some other boy, who was from North Carolina, responded, 'Is that some damn-yankee word?' (They called them tennis shoes) . . . .
>
> A railroad was being built to pass through Cullowhee. They used many cans of black pelleted powder for blasting. There was always a little powder left in each can—perhaps an ounce or so. Loring and I were the ring-leaders in going along the route of the railroad-to-be collecting it. We used it to make small "bombs." Our technique was as follows: We put a small quantity of powder in the bottom of a used tin can. We then inserted a fuse made of twisted newspaper. After that we stuffed the can with sod.
>
> Once a week or so, in the evening just as it was getting dark, we lit the fuses, and with a loud bang the cans shot into the air. We continued to put on a show for resident faculty and students until the local authorities got wind of what we were up to and put a stop to it.

Indeed, Bob and his brother Loring did not forget this technique. Mary Ann and I joined the Chandlers at their home in Massachusetts to celebrate the Bicentennial on July 4, 1976. Bob's brother Loring had an antique cannon that had been moved from Fort Ticonderoga on Lake Champlain to Boston at the beginning of the Revolutionary War. After inserting a fuse and powder, the barrel of the canon was stuffed with grass clippings and sod and fired.

> The school at Cullowhee did not have high scholastic standards and Loring and I were not inspired to do any better than our peers. In Latin, for example, we were still learning the fifth declension when we left in March 1921 to return to Maine. As a consequence, we had to be tutored by Mary Worthley during the summer in order to start second-year Latin (Caesar) in New Gloucester High School in

the fall . . . . Let me reminisce a bit about our lives in New Gloucester in the teens and twenties of the 20th century.

The principal entertainment in town consisted of attending plays put on by the Grange or the high school. The talent was far from great, but Grandfather never missed one (he called them "draymas"). A little later in the period, silent movies were shown in the town hall every two weeks or so, accompanied occasionally by someone on the piano to provide the correct emotional atmosphere. We had our first radio in either 1923 or 1924. When my grandparents got their first one, Grandfather, who normally went to bed no later than 9 p.m., stayed up until 11 o'clock, absolutely fascinated by the fact that words and music could come over the air.

Much of the life of the Chandler family (in 1924 there were 25 Chandlers living in New Gloucester) revolved around the activities of the Congregational Church. All of them went to church and Sunday school. Grandfather was a deacon and Uncle Roland, Grandfather's youngest brother, was superintendent of the Sunday School.

I particularly remember the boy's club that we had under the guidance of the Rev. Henry Worthley, who was the minister when Loring and I were in high school. One of our club's summer excursions was in 1923 when we went to New Hampshire and climbed Mt. Washington. We took the short, steep way up Tuckerman's Ravine and walked down the carriage road. On the way down, we met some people walking up and they gave us a newspaper telling of President Harding's death.

I've been accused of idealizing my parents. I guess there is something to that. Of course Mother and Dad were no more perfect than the rest of us are. I felt that Dad was gentler and more considerate of Mother than she was of him, her nature being rather volatile and his quiet and patient. Nevertheless, they were always in love and missed each other dreadfully when they had to be separated. I'm confident that I can truthfully say that none of us ever felt that we were unloved. Furthermore, I never noted any show of favoritism among the six of us; we were all treated fairly and alike. We were very fortunate to be brought up in such a good home environment.

Until 1923, the roads in New Gloucester were not plowed. They were rolled after every snowstorm. This packed the snow so that the horses and sleighs could travel more easily. I still recall the lovely

> sound of sleighbells ringing from the traffic by our house, especially after dark . . . . That same year, electricity came to town. Previously we had to use kerosene lamps and lanterns for illumination. Another event in 1923 was the arrival of my fourth sister Sally Barbara. She arrived on August 18th in a hospital in Portland, being the only one of us who was not born at home.
>
> Loring and I were graduated from high school in June 1924. All 13 of us in the class performed in the graduation ceremonies. I gave an essay on Alaska and Loring gave the address to undergraduates, which was cleverly done. Loring was ahead of me in imagination and writing and speaking talent. I recall how nervous I was speaking before all those people! Seven of the 13 graduates went on to college, a rather good record for those days.
>
> The principal of the high school in our senior year was Mr. Frank Fortier. He was a graduate of the University of Maine in the class of 1912, and was the State champion in the one-mile run. Because of his interest in track, he started the first-ever track team at New Gloucester High School. We did much of our practicing and time trials at the racetrack at the Fairgrounds. I played on the baseball and basketball teams but I was no star. I did much better in track.
>
> I remember a meet with Pennell Institute in Gray. I won the mile and half-mile races (both the same afternoon), Loring was the champion in the 100-yard and 220-yard dashes, as well as the shot put and hammer throw. Elliot Small won the quarter-mile race. Although there were other members of our team who participated in the meet, none of them placed, so really three men won the meet for New Gloucester High.

In the summer following his graduation from high school, Bob's father's health again deteriorated and it was decided that a part of the family would go to Florida at least for the winter so they sold all their livestock and went to Clermont, Florida, by train. Bob writes:

> Dad's health improved and he noted that there was a demand for civil engineers to survey residential lots in Clermont . . . . He did rather well and at one time was so busy that he ran two 3-man crews of surveyors.
>
> I left Florida in the spring of 1925, lived with my grandparents in New Gloucester, and entered the University of Maine in the fall . . . .

When I entered the University of Maine as a freshman, I didn't know what to select as a major. I decided to start in Engineering, with the idea of following in my father's footsteps. I remained in the College of Engineering for the first full year. However, toward the end of my freshman year, I decided that my real interests were in agriculture. I told the Dean of the College of Engineering that I would be registering in the College of Agriculture when I returned in the fall. This I did and eventually majored in Horticulture, with a specialty in Pomology.

Grandfather provided the funds for my college education. At that time, $750 a year was sufficient to cover tuition, fees and room and board. I joined the Beta Theta Pi fraternity and lived in the Beta House, after the first 2 weeks on campus. Being an innocent little country boy, I developed and matured more during the 4 years at the University than at any similar period in my life . . . . I was graduated "with distinction" in June 1929. As Class Chaplain, I composed and delivered a prayer during the Commencement Exercises. Mother and Dad drove up for the occasion in their 1926 Essex sedan.

In the spring of 1929, the State Horticulturist in Maine died. The Commissioner of Agriculture, Mr. Frank Washburn, and the head of the Division of Plant Industry of the Maine Department of Agriculture, Mr. Richard Newdick, came to Orno and interviewed candidates to fill the vacant position. There were eight seniors in Horticulture and all of us were interviewed. I was fortunate to be offered the position and I accepted with alacrity. The beginning was at $1800 a year, which was sufficient for me to get along comfortably. I lived in a private home and got bed and breakfast for $4.00 a week . . . . I decided (in 1931) to leave my position in Maine and undertake graduate study toward the Ph.D. degree at the University of Maryland in College Park.

Bob was married to Eunice Copeland, a fellow student whom he had met at the University of Maine, in May 1931 and after a 2-week honeymoon left for Maryland:

We were to spend the next 3 years living on a monthly stipend of $83.33. Our son, David, was born in a hospital in Washington, D.C. on January 31, 1933; and I completed the requirements for my degree which was conferred on June 3, 1934 . . . . Jobs were scarce and, since there were no certain openings at colleges or universities, I applied for a National Research Council Fellowship to undertake

> post-doctoral studies at the University of California in Berkeley, to prepare myself to become a specialist in forest soils (I won't go into the complicated details as to why I shifted from pomology to forest soils).
>
> I was granted the fellowship . . . and left New Gloucester in mid-June 1934 in our 1928 Buick (a used car that I bought in Maryland for $90), with a trailer holding our worldly possessions in tow (I had made the wooden box-like body myself and mounted it on a used Model T Ford chassis—the back half, of course). The National Research Council gave us $160 to cover our traveling expenses from Maine to California. When we reached Berkeley, we had just $2.50 left, but fortunately the Council paid stipends in advance, so we were solvent again!

Two of Bob's sisters (one of whom found employment) and his parents joined them in Berkeley and Bob continues:

> My stipend was $180 per month, which had to provide the living costs for six people. It wasn't easy, but we managed to break even.
>
> It was a good year for me professionally, for I had the privilege of working under Professor D.R. Hoagland, at that time the most eminent plant nutritionist in the USA. I took advanced courses in soil science and forestry and conducted a research project on factors affecting the return of vegetation on copper smelter-denuded areas in Shasta County, California . . . . By March 1935 I was urgently seeking a permanent position. I had applied for several openings but none was certain . . . . Fortunately, in early June I received an offer from Cornell University to occupy the position of assistant professor of forest soils, beginning July 1, 1935. I immediately accepted the post, got into our 1928 Buick and headed for Ithaca, NY . . . .
>
> When I left Berkeley in June 1935, I didn't know that I was not to see Mother again. She passed away in July 1937 from a blood clot that went to her lungs following an operation. We saw Dad once more in March 1938 when we made a trip to California during my vacation period at Cornell. He died on March 11, 1941 at age 60, having spent the last two and a half years of his life in T.B. sanitoriums in California.
>
> Separate memorial services were held for them in New Gloucester and their ashes were buried in the New Gloucester Cemetery. Mother had requested some years earlier that when they passed

away the gravestones on their lot would be of natural stone from our land on the Foxcroft place. We complied with this request, of course, and placed bronze plaques on the stone giving their names and dates of birth and death . . . . Sunny and I have a lot in the same cemetery and when our days on this planet are ended, we shall join the many Chandlers whose remains are there, beginning with Peleg Chandler, who moved to New Gloucester from North Yarmouth, Maine, in 1762.

Notes

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The Chandler years at IRRI

L.M. Vergara and B.S. Vergara

Robert F. Chandler, Jr. was a man in a hurry. Within 3 years after arrival at IRRI with his wife Sunny on September 7, 1959, the buildings and grounds of IRRI were ready and a team of outstanding and experienced scientists plus ambitious and promising young scientists were hard at work. IRRI was formally dedicated February 7, 1962 to alleviating the hunger of the ever-burgeoning population of the rice-eating countries of the world.

Who is this man Robert F. Chandler, Jr.? What was he like? To speak of Bob Chandler is to speak of life. He had a flair for living, working hard, and enjoying life to the fullest.

People who were at IRRI during the early years speak of the "good old days." Everybody worked, and everybody laughed. Dr. Chandler could cause worry lines to appear and could also cause laughter wrinkles to deepen. Scientists were heard complaining at coffee breaks but they did so only among themselves. They did not want to dishearten him or give him extra problems, so they kept their peace. All because they loved him.

He inspired staff members to perform at their best, often pointing out emphatically that the success of the program depended on the contribution of each individual in the organization. He stressed the importance of high quality and urged all to take pride in IRRI.

He believed IRRI would likewise be judged by the way it was kept, how its staff behaved and dressed, and the appearance of its surroundings. He urged decorum and propriety in the manner of dressing and behavior. The smallest pebble on the driveway and the lowliest grass on the lawn received the same attention as the most refined scientific equipment. He was scrupulous about grammatical and spelling mistakes, and typographical errors. And he treated the brilliant rice scientist and the lowly rice farmer with the same regard.

Dr. Chandler placed top priority on research and the IRRI scientists. Administrative and support services existed only to facilitate research efforts. Administration to him was there to coordinate, not to control.

He made quick and good administrative decisions and never encroached on decisions he believed department heads and individual scientists should make. He made suggestions but left the decisions to the department heads. He gave one and all free rein of their programs, and their budgets too.

Dr. Chandler never walked anywhere normally. He walked so fast that the people walking with him had to run. He was like the wind and we were like tumbling weeds behind him. He would enthusiastically slosh in muddy fields, or peer into a microscope, to recognize the importance of research and to show trust in his scientists. And by so doing, he transferred his enthusiasm to them. He stressed the points he wanted to make with words and with gestures. He would stoop low to show the short, high-yielding rice plant, and stand on tiptoe to stress how high he wanted IRRI's excellence to soar.

High morale and esprit de corps extended to the IRRI families. Dr. Chandler gave careful attention to the home atmosphere because he knew an unhappy home would mean an unhappy, unproductive scientist. He would end a meeting at 5 p.m. saying, "Go home. It's time for family and a martini."

Bob Chandler emphasized group entertainment. Parties were short on speeches, more of dancing. When Taal volcano erupted, RFC as we referred to him, organized a trip to the crater. A boat was rented to take brave souls of IRRI to the island that was then spewing ashes and lava. When the trembling group reached the rim of the crater, RFC produced ice-cold martinis to toast their feat. He organized hikes to the top of Mount Makiling and no one could beat RFC to the top.

To strengthen relations with the neighboring University of the Philippines College of Agriculture, and the whole town of Los Baños, Bob and Sunny Chandler attended and participated in college functions and gave time and resources to depressed areas of Los Baños. Bob Chandler did his utmost to maintain good relations between IRRI, the college, and the town, which paved the way to a healthy environment for collaborative research.

Above all, Bob Chandler was a plant lover. He participated in the annual garden shows in Los Baños, creating a quiet nook where he displayed his flowers and plants. He funded, carted plants and soil, and landscaped his area himself. He is remembered by Philippine plant enthusiasts as having introduced the bougainvillea Mary Palmer, and different cultivars of anthurium, one of which to this day the local people call Chandler anthurium.

A delicate white, speckled with pink, orchid bred by Dr. Vicente Saplala, is registered in Kew Gardens as *Dendrobium* Robert F. Chandler, Jr.

With Bob Chandler at the helm, IRRI became the foremost center for rice research in the world. Rice production was revolutionized. Improved rice germplasm was distributed to countries with problems of malnutrition and famine. Extensive training programs were introduced to improve farm technology. Training involved students and research scholars from all parts of the world, with the objective of forming knowledgeable core groups who would in turn transfer the new rice technology to others. The research achievements are numerous:

- Establishment of the rice germplasm collection, now the most complete in the world.
- Development of rice threshing equipment that replaced the difficult task of hand threshing.
- Development of a method of rapid screening of varieties at the seedling stage for resistance to leafhoppers and planthoppers, now a standard procedure.
- Increase in the resistance of rice to blast and bacterial diseases.
- A better understanding of the chemistry of flooded rice soils.
- Initiation of multiple cropping research in rice, now a standard practice in many rice-growing areas where one crop used to be the norm.
- Better understanding of plant growth responses in rice in relation to yield, the basis for plant types.
- Establishment of a library of the world's literature on rice, still the premier source of literature for many rice researchers.
- Establishment of numerous screening methods for the evaluation, including rice quality, of rice germplasm and breeding materials.

The achievement that created the biggest stir was the introduction of IR-8-288-3, dubbed miracle rice by the Philippine press. IR8 was introduced on November 28, 1966, a mere 6 years after IRRI's inception.

With IR8, the green revolution in rice was on a roll. Bob Chandler received numerous awards for his personal efforts in the fight against hunger, among them:

- International Rice Year Award for outstanding research on rice from the Indian Council of Agricultural Research, 1966
- Star of Distinction from the Government of Pakistan, 1968
- Doctor of Humanities degree from the Central Luzon State University in the Philippines, 1971
- Doctor of Letters, University of Singapore
- Star of Merit, Republic of Indonesia

- Golden Heart Award, Republic of the Philippines
- Order of Brilliant Star, Government of the Republic of China
- Presidential End Hunger Award, United States
- World Food Prize, 1988
- Ramon Magsaysay Award for International Understanding, 1969 (received by Dr. Chandler for IRRI)
- UNESCO Science Award (shared with CIMMYT), 1971

During IRRI's l0th anniversary celebration in 1972, the administration building was named Chandler Hall in his honor. At about the same time, the Provincial Board of Laguna passed a resolution adopting Robert F. Chandler as a son of the Province of Laguna, the Philippines.

Foremost of Bob Chandler's accomplishments is his winning Sunny Chandler, a loving helpmate. She was his great source of inspiration, spiritual strength, and a sense of humanity.

The International Rice Research Institute is Robert F. Chandler, Jr. It is the enduring symbol of his passionate idealism. It is a testament to his desire to help fulfill the hopes of hungry millions for a new and comfortable life. In the words of M.S. Swaminathan, "We owe a debt of gratitude to Bob and Sunny Chandler, for their labor of love and for their message of hope."

Notes

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The Chandler years at the Asian Vegetable Research and Development Center

N.S. Talekar and S.C.S. Tsou

Dr. Robert Chandler was appointed founding director of the Asian Vegetable Research and Development Center (AVRDC) in September 1971 and assumed the position on 1 July 1972, a day after his retirement as founding director of the International Rice Research Institute. In the intervening period, he was able to guide AVRDC's construction and it was only natural that he would use ideas that had served IRRI well. As a result, there is striking similarity in the layout of IRRI and AVRDC.

In designing AVRDC's physical infrastructure, Dr. Chandler corrected one mistake made at IRRI. He put the library in the laboratory building instead of the administration building. He wanted the library as close as possible to the scientists so they would use it more often and increase their chances of "running into each other." As AVRDC staff size and facilities increased, it was suggested that the library be moved to the administration building. Instead, an annex was added to the laboratory building and the library remains in its original place.

Dr. Chandler insisted on construction of buildings requiring minimal maintenance, preferring to spend more for sturdy buildings if it would reduce the cost of maintenance. That practice has helped AVRDC immensely, especially in view of the astronomical increase in the cost of labor over the past two decades. And none of AVRDC's buildings suffered damage during Taiwan's killer earthquake of 21 September 1999. We are grateful for the Chandler foresight.

Early years at AVRDC

Dr. and Mrs. Chandler arrived in Taipei on 1 August 1972. AVRDC housing was still under construction, so the Chandlers stayed in the Emperor Hotel in Taipei. Dr. Chandler met with government officials in Taipei and worked with Mr. Luh and Mr. Chin, who had established offices at the Sino-American Joint Commission on Rural Reconstruction (JCRR), the forerunner of the Council of Agriculture, Taiwan's *de facto* Ministry of Agriculture. The JCRR chairman was AVRDC board chairman, Dr. T.H. Shen, who was also a member of IRRI's Board of Trustees.

The Chandlers stayed in Taipei for about a month before moving to Tainan to supervise interior decoration and furnishing of their house. The move to Tainan coincided with the arrival or Dr. and Mrs. Edwin Oyer. Both couples stayed in the venerable Tainan Hotel, practically the only refuge for expatriates venturing into that ancient southern city. The Chandlers and Oyers moved into their AVRDC residences in October 1972.

Mr. Luh and Mr. Chin also moved to Tainan. They, along with newly hired local staff, set up makeshift offices, essentially cubicles, in a large room in the newly constructed service building, which they shared with all of AVRDC's cars, trucks, tractors, and other farm equipment. Almost three decades later, some of the AVRDC old-timers still speak nostalgically of those humble cubicles. They also speak fondly of the many lunches they shared at their favorite noodle shop in Shanhua—a haven they dubbed the Shanhua Hilton.

The original budget for infrastructure proved adequate for construction of only an administration building and staff housing. Dr. Chandler and Associate Director Luh managed to convince Taiwan's food processing industry association to donate money for construction of a laboratory building. And the Kresge Foundation donated money for construction of the trainees' dormitory, which included a cafeteria, where trainees and many of AVRDC's staff still eat their meals. The building contractor agreed to construct a swimming pool, for free, if AVRDC would provide the pool equipment. All in all, despite limited budget, AVRDC had the buildings necessary to conduct research and house its senior staff.

In planning the research and administrative structure of AVRDC, Dr. Chandler emphasized that

- a strong problem-oriented research program will be initiated, geared to the needs of the poorer countries of Asia;

- a qualified group of young scientists and extension workers from tropical to subtropical Asia will receive training by a staff of carefully selected, energetic, creative agricultural scientists; and
- the Center will devote its efforts not only to the production problems of the farmer but also to the development of a stronger vegetable industry in the region concerned, thus bringing greater prosperity and nutrition to both rural and urban people (Chandler et al 1972).

Dr. Chandler always sought opportunities for farmers to improve their livelihood. He was perhaps mindful of the fact that, despite considerable improvement in yields of rice, wherein his leadership of IRRI played no small part, small rice farmers had not received proportional benefits; they were still classified as subsistence farmers. At times he appeared agitated over this. While discussing the subject at a staff meeting in early 1975, he again emphasized the need for us scientists to bear in mind our responsibility to help farmers improve their incomes through cultivation of vegetables. He said:

> The farmer is our client, it is he whom we must serve; any other objective is trivial compared with our aim to improve the well-being of the rural population and to strengthen agricultural production.

That statement remains AVRDC's preamble. He saw cultivation of vegetables after rice as one way to fill the income gap. And, as a scientist, he saw an opportunity for using applied science to achieve this.

By mid-1973, the administration and laboratory blocks were ready. On 17 October 1973, the Center was officially opened with Taiwan's Vice President C.K. Yen presiding over the inaugural ceremony attended by members of the diplomatic corps and government officials flown in from Taipei.

AVRDC's programs

Among pundits of international agriculture, conventional wisdom held that for an international agricultural research center to make significant impact, it must concentrate on one or, at the most, two crops. This was not possible with vegetables. The provisional planning committee entrusted with establishing AVRDC had identified 26 species in Southeast Asia that deserved attention.

Dr. Chandler later explained his philosophy in identifying crops, among the more than 100 species classified as vegetables, in a paper presented in Hyderabad, India: "If an international agricultural research organization is to benefit the small farmer and the urban poor, it must select the crops for study that are important food items and that have severe production constraints to be overcome. Furthermore, consideration of such barriers to yield should be limited to those that, beyond reasonable doubt, can be reduced through first class intensive scientific research. Another essential in establishing a research program is that attention be restricted to only a few crops; otherwise it is unlikely that there will be a significant impact on any one crop" (Chandler 1974).

Based on these criteria, plus careful consideration of the nutritional and income generation capacity of the crops, AVRDC selected tomato, Chinese cabbage, sweet potato, potato, soybean, and mungbean. The target area of our research was to be countries in the tropics, beginning with Southeast Asia. Although the International Potato Center (CIP) was working on the potato, AVRDC emphasized developing heat-tolerant potato clones for the tropical lowlands. That work was done in close collaboration with CIP, whose program was confined to the highlands, where most of the potato in the tropics is grown. Indeed, as envisioned by Dr. Chandler, after we developed a heat tolerant clone, we turned the entire program over to CIP, which was then preparing for a move into tropical Asia.

Although we had six crops, compared with only one at IRRI, Dr. Chandler established a departmental structure similar to IRRI's. He did not see a need to change—he felt that scientists should work as a team to solve problems and they did. Toward the end of his term, certain scientists became reluctant to share credit with their colleagues, but that was due to personality conflicts, which are always difficult to avoid.

Emphasis on crop improvement

Dr. Chandler was a strong believer in crop improvement (breeding) to overcome production constraints. He believed in tapping the world's genetic resources in a massive way, followed by a thorough screening program to identify germplasm with resistance to, or tolerance for, production constraints, wide adaptability, and superior yielding ability.

Progeny from crosses between such germplasm and local cultivars were tested over wide areas, and the outstanding selections used where they proved their worth. To plant pathologists and entomologists, Dr. Chandler used to say, "The solution is in the seed (resistant cultivars) and not in the pocket (purchase of pesticides)." After almost 30 years, crop improvement remains AVRDC's major research approach, and we have made significant strides in crops such as mungbean, tomato, and Chinese cabbage, to fulfill his vision.

Interdisciplinary research

Dr. Chandler was a practitioner of interdisciplinary research. He emphasized the importance of plant breeders, plant pathologists, entomologists, and plant physiologists working as a team. In hiring new AVRDC staff, he insisted on the prerequisite that candidates be willing to work together. If he suspected otherwise of any candidate, the hiring would not proceed. After nearly 30 years, this still holds true at AVRDC. Our breeders, pathologists, and entomologists work as teams.

Academic scrutiny

Dr. Chandler emphasized academic importance of research, although many times it was of secondary importance to AVRDC's programs. He encouraged his scientists to publish, whenever they could, from the research they were doing for AVRDC. He thought it a duty of each scientist to promote and strengthen his profession. During annual review presentations, if he noticed work worth publishing, he would instruct the scientist to write a paper. This, at times, did not fit well with everyone, but for all of us fresh PhD hires, it was very, very encouraging.

Open-door policy

Dr. Chandler had an open-door policy. He was willing to talk with any employee of any rank at any time. He especially loved to go to the field or to the laboratory to see, first hand, any promising experimental result. If a scientist called to tell him of some new finding—which in those early years included sources of resistance to a disease or insect pest, or tolerance for high temperature—he would immediately go to the laboratory or field to see the results. He believed in keeping the gap between the administration and the scientists as narrow as possible. He would let the scientists and their assistants know that they were truly important to AVRDC. He always believed that it is the job of the administrator to facilitate the work of the scientists by providing an environment for creative research. He let it be known, though indirectly, that he gave his scientists the best salaries and the best working conditions, so there should be nothing to prevent them from striving for excellence. Many times, some important letter, written by a scientist or administrator and copied to him, would be returned covered in corrections written in ink, with instructions on how the letter should have been written. This applied to everyone, not just the majority of those who were non-native English speakers.

Respect for fellow professionals

Dr. Chandler respected the professional integrity of his staff. He rarely overruled the professional judgment of AVRDC scientists or administrators. At times, on certain issues, he would not agree, and might raise his voice and get upset. But after he came to appreciate the opposing point of view, he would go to the staff member and apologize. That was an extremely rare act in the culture of the Far East.

IRRI and AVRDC relations

Relations between IRRI and AVRDC were close during the Chandler years. He emphasized that rice would remain the king of the food crops in the humid tropical lowlands, and that AVRDC's crops and technologies must fit rice-based cropping systems. In this context, all of our yield trials of elite progeny continue to be planted after rice.

Each new staff member was required to make IRRI his or her first overseas travel assignment. The purpose was to learn how IRRI and its scientists worked, and to try and foster similar approaches at AVRDC. Some of us dubbed it the "IRRI pilgrimage." We learned from IRRI scientists, which helped us to minimize the mistakes that beginners make. IRRI Director General Nyle C. Brady served as a member of AVRDC's Board from 1974 to 1978. That tradition, for some reason, was discontinued after 1978.

AVRDC and the CGIAR

The Consultative Group on International Agricultural Research (CGIAR) was formed around the time AVRDC was in its final stages of establishment. There was a natural expectation that AVRDC would become a CGIAR member. However, an important political event killed that expectation. Between the time Dr. Chandler accepted the directorship and his arrival at AVRDC, China was admitted to the United Nations and Taiwan had to vacate its seat in that world body. Dr. Chandler was disappointed but not discouraged. He had good rapport with several international aid agencies and thought he could get funding from them. During International Centers' Week in 1972, Dr. Chandler made a pitch for AVRDC's admission to the CGIAR, but some members opposed.

AVRDC Board chairman, Dr. T.H. Shen, pressured Taiwan and the United States Agency for International Development (AID) to continue their support. Eventually they devised a formula whereby 40% of the Center's funding would come from AID, 30% from Taiwan, 10% from the Asian Development Bank (ADB), and the remaining 20% would come from the other member countries—Japan, Korea, Philippines, Thailand, and Vietnam. Through Professor Yoshiaki Ishizuka, a fellow soil scientist and an IRRI Board member, Dr. Chandler was able to keep Japan in and, in fact, see its contribution gradually increase. Thailand remained a loyal supporter and through Philippine Minister of Agriculture, Arturo Tanco, an AVRDC Board member, Dr. Chandler secured solid backing from the Philippines. South Korea, then not a member of the UN, insisted that a temperate climate vegetable substation be established in Korea. ADB financed the establishment and running cost of that substation in the early years. The founding members stayed and remain reliable supporters of AVRDC to this day, although a few have changed their mode of support.

All of this said, without Dr. Chandler's good standing and fortitude during this tough time, AVRDC might have been finished before it began. AVRDC was made an associate member of the CGIAR in 1974, which enables us to participate in International Centers' Week activities, and thus increase our visibility among international donors.

Dzai-jyan to AVRDC

Dr. Chandler accepted the AVRDC job for a 2-year period and was due to retire by the end of June 1974. However, at the urging of all AVRDC staff and the Board of Directors, he agreed to continue for another year. Before his return to the United States in June 1975, Dr. Chandler was awarded the Order of the Brilliant Star by the Government of the Republic of China on Taiwan, for his services to Taiwan and the region. The Chandlers returned to their home in Massachusetts on 15 June 1975.

The Chinese never use their word that means good-bye. They only say *dzai-jyan*, which means, we will meet again. Indeed, the Chandlers did visit AVRDC again, most notably for the Center's 10th and 20th anniversary celebrations in 1983 and 1993.

References

Chandler Jr., RF. 1974. The potential impact of research on vegetable production. In: Report of the FAO/UNDP International Expert Consultation on the Use of Improved Technology for Food Production in Rainfed Areas of Tropical Asia. Rome: Food and Agriculture Organization of the United Nations.

Chandler Jr., RF, Oyer EB, Luh CL. 1972. The Asian Vegetable Research and Development Center: its background, program, budget proposal and present stage of development. Shanhua, Taiwan: Asian Vegetable Research and Development Center. 30 p.

Notes

Authors' address: AVRDC, P.O. Box 42, Shanhua, Taiwan 741.

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Chandler the mentor

R. Beahrs

Bob Chandler was the most impactful mentor that anyone could ever hope for, and I feel greatly privileged to have had the opportunity to know him and to reap the benefits of that type of relationship. I know that many of you can relate to that sentiment.

In many ways, we probably share a great deal in what we learned from him. Warmth, empathy, and a willingness to teach—and yet he also conveyed a steely expectation of excellence on all initiatives we worked on together.

There was no one that I would have hated to disappoint more than Bob Chandler. His own words reflect that he set the bar high for everyone:

> "I am sure that at times our IRRI staff felt that I was overly blunt, but I believe they appreciated the fact that I was never devious or manipulative and that we were only anxious to set out and maintain high standards for every institute activity, whether it were a matter of writing a letter, driving a car, cooking or serving meals, cleaning the buildings and ground, or conducting research. Our feeling was that only in an environment where the best was needed from and expected of everyone could each employee, no matter what the assignment, feel that he or she was playing a significant role."

In another way, my experiences with Bob were likely different from yours because I'm not a scientist. I wasn't even a very good science student—and that's putting it kindly.

Nevertheless, I appreciate fully the impact and importance of Bob's work and, by inference, that of all of you as well. Mothers and fathers of the green revolution—what a legacy that is.

And yet, so much development work remains. I came to know Bob while serving with him on the board of the Near East Foundation. It's wonderful to see some fellow board members here today—Chuck Roberts, Bob Herdt, and Colin McClung. At that time, the exponential increases in agricultural yields derived from the green revolution were leveling off. I asked Bob where the future opportunities might lie. Bob offered his belief in agroforestry as an area of endeavor that could help meet the pressing demands of the world's poorest. He believed that agroforestry could serve to combine the skills of scientists with the extraordinary insights of the indigenous farmer—those often living on less than a hectare of land. In fact, Bob was an early trustee of the International Center for Research in Agroforestry (ICRAF), which makes it particularly significant to me to now serve in that capacity.

More important than Bob's insights was the fact that he took time to respond to every letter I wrote him—and there were many. He did so in great detail with single-spaced typed letters that continued for many pages. What insights! He took the time to teach a scientifically illiterate business executive the fundamentals and principles of agroforestry.

He wanted us to focus on enhancing the public's appreciation of the critical importance of development issues. This is a lesson that should resonate for all of us. There are so many unexploited opportunities but adequate financial resources will never be obtained, unless the issues are understood by those with the power to mobilize in both the north and the south.

The complexity of these challenges could leave us mired in frustration, but one of the Chandler legacies is that we can't allow ourselves to be distracted from the important work at hand. I've told an anecdote that reflects this. When Bob felt a conversation with fellow IRRI scientists wasn't properly focused or prioritized, he forcefully asserted, "Just remember, our job is to help people feed themselves."

To me, that statement says so much about Bob—focus, priority, passion. And underlying it all is his belief that one should never give up; be relentless in your pursuit of excellence.

Scientists continue to seek answers to the challenge of increasing yields and restoring the environment. As a business executive, I feel Bob's admonition by personally wanting to work with scientists for new and better ways to sell the value of your research and the impacts it can have. It's not enough to wring our hands in anxiety because the story isn't getting out: "Just remember, our job is to help people feed themselves."

Once more Bob's words eloquently enforce the importance of broadening the impact of your work.

> "I feel that because of the prestige the CGIAR centers have attained, the directors general, and sometimes the scientists themselves, can play a significant role in influencing government officials to alter national policies to speed up agricultural development. The need for family planning clinics, for farm-to-market roads, for additional support for agricultural research and extension programs, for production incentives such as price supports and subsidizing of inputs, are examples of important requirements in many developing countries. Although none of these items is the direct responsibility of the CGIAR centers, I feel strongly that the centers should show a deep interest in government policy and should use their influence to affect change where needed. I dare say that the substantial increases in wheat production in Third World countries would not have occurred nearly so soon had not Dr. Norman Borlaug influenced top government officials to take strong and affirmative action to facilitate the spread of modern wheat varieties and the necessary cultivation practices."

I am pleased to tell you about two steps ICRAF has taken to honor Bob's legacy. In fact, it's probably relevant that ICRAF's outstanding director general, Pedro Sanchez, who was a graduate student at IRRI more than 30 year ago, has said that he has patterned his job as a result of observing Bob run IRRI.

ICRAF's first step to honor Bob is the creation of a replicable model of community nursery development that will be scaled up in partnership with national agricultural research systems and others to reach tens of millions of farmers. It is ICRAF's intention to seek much of the funding from nontraditional donors for the purpose of expanding the impact of this research that current finances have supported. The initial nursery is in Zimbabwe and named The Robert F. Chandler, Jr. Community Nursery.

Second, as some of us involved with ICRAF have read some of Bob's papers, such as those I've quoted from today, we feel that they should be accessible to as broad an audience as possible. Thus they will be posted on ICRAF's web site. We encourage others to help us make other appropriate works of Bob available there as well.

I can't help but muse a bit about Bob's place in history. Perhaps 20 years ago, a book was written with conjecture about the 100 most important personages of all time. Religious leaders from Mohammed and Christ to St. Paul and Buddha dominated the top 10 places. But #2 was Isaac Newton, reflecting the critical importance of scientific inquiry and its related benefits.

During a visit to Newton's home in England, I was struck by the fact that my wife Carolyn and I were virtually alone—there were no other visitors. How sharply this contrasts with the masses that sweep through the Vatican or Mecca each year.

On my last visit to Bob and Sunny at their home in Florida, I felt a similar sensation. How quiet and peaceful their home surroundings were, despite the intellectual energy and love of life within. Herein resided a man that the World Food Prize presenters noted, "impacted the diet and food security of a billion people."

At times, our society seems swamped in excess. People go to great lengths to make statements to reflect just how wealthy and significant they are. To me, that probably reflects insecurity about who they really are. Perhaps Bob's greatest legacy lies in the startling contrast to excess and insecurity. He led a life of extraordinary achievement, but he did so while projecting an awareness of what was truly important in life. As we all face the many options about what road to take, our memories of Bob—what he stood for and how priorities should be ordered—will always help light the way.

Notes

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The Asian rice economy in transition

R. Barker and D. Dawe

In the years following World War II, there was growing concern about the food problem in Asia. The population was growing at close to 3% per annum and potential for further expansion of cultivated area was limited. Attention focused on the need to increase the yield of rice, the primary dietary staple. The International Rice Research Institute was established in 1960 with a clear mission (IRRI 1982a):

- *to conduct research on the rice plant, on all phases of rice production, management, distribution, and utilization with a view to attaining nutritive and economic advantage or benefit for the people of Asia and other rice-growing areas of the world through improvement in quality and quantity of rice.*
- *to develop and educate promising young scientists from Asia and the other major rice-growing areas of the world along lines connected with or relating to rice production, distribution, and utilization, through resident and joint training programs under the guidance of well-trained and distinguished scientists.*

The work of IRRI and other Asian scientists in developing new rice varieties (and CIMMYT in wheat) coupled with the widespread use of ever cheaper forms of chemical fertilizer and a rapid expansion in irrigated area, achieved what came to be known as the green revolution. And indeed it was a revolution that could be seen with the naked eye, as across Asia, the traditional tall rice varieties were rapidly replaced by higher yielding semidwarf varieties. The impact on consumers was also visible as retail food grain prices fell sharply from their highs in the early 1970s.

The food security achieved by the green revolution was but a critical first step in Asia's transition from an agricultural to an industrial society. In the 1960s, two-thirds of the labor force and one-third of the gross domestic product (GDP) for most Asian countries was in agriculture. As those economies grew, agriculture became an ever smaller portion of the total economy. This is the normal pattern of development. Rice remains the dominant staple in the Asian diet, however, and the most widely grown crop. It contributes one-third to one-half of agricultural value added and 50–80% of calories consumed by people in much of the region (Hossain and Pingali 1998). Large numbers of poor Asians still cannot afford an adequate diet. But the well-to-do consumers are diversifying their diets and rice-farming households are looking for new sources of income to compensate for low returns to rice production due to the decline in price.

The introduction of new technologies and growth in production continue but at a much slower pace. More than a decade of low and stable world rice prices has led to complacency among policymakers and a slackening of investments in research, irrigation, and other factors that would promote productivity growth in the rice sector. There is concern, particularly in the scientific community, that rice production may not keep pace with the growth in demand due to population, let alone meet the needs of the growing number of the poor who lack adequate purchasing power.

The comparative advantage in rice production is shifting away from the regions that were the early beneficiaries of the green revolution back to those major river deltas where labor is cheap and water plentiful—the Mekong, the Ganges-Brahmaputra, and potentially the Irrawaddy. Many governments are faced, on the one hand, with internal pressures to subsidize rice production to maintain food security and, on the other hand, with external pressures to remove tariff restrictions and liberalize trade.

We describe the transition in the Asian rice economy from several dimensions. We examine in turn

- the trends and sources of growth in rice production,
- the beneficiaries of technological change and impact on poverty alleviation and negative impacts on environment and health,
- diversification in consumption and production away from rice, and
- the shift in comparative advantage and expanding world rice trade.

We conclude with a discussion of the needs and potential gains from continued investments in rice research and a retrospective look at the reasons for the success of IRRI, "the house that Chandler built."[1]

[1]Bob Chandler was a diehard Red Sox fan. But we are sure that he would appreciate this analogy to Yankee Stadium, "the house that (Babe) Ruth built" after he was traded from the Boston Red Sox to the New York Yankees in 1919.

Trends and sources of growth in production and productivity

The growth in rice production over more than three decades since the release of the first high-yielding rice variety, IR8, in 1966 and the factors explaining that growth are well documented (Barker and Herdt 1985, Pingali and Hossain 1998, Pingali et al 1997). Today, there is general concern in many quarters about the slowdown in rice production growth and the potential implications for food security and poverty alleviation.

How was it possible to achieve a 3% per annum growth in Asian rice production for more than two decades, a growth rate far exceeding what had ever been previously achieved?

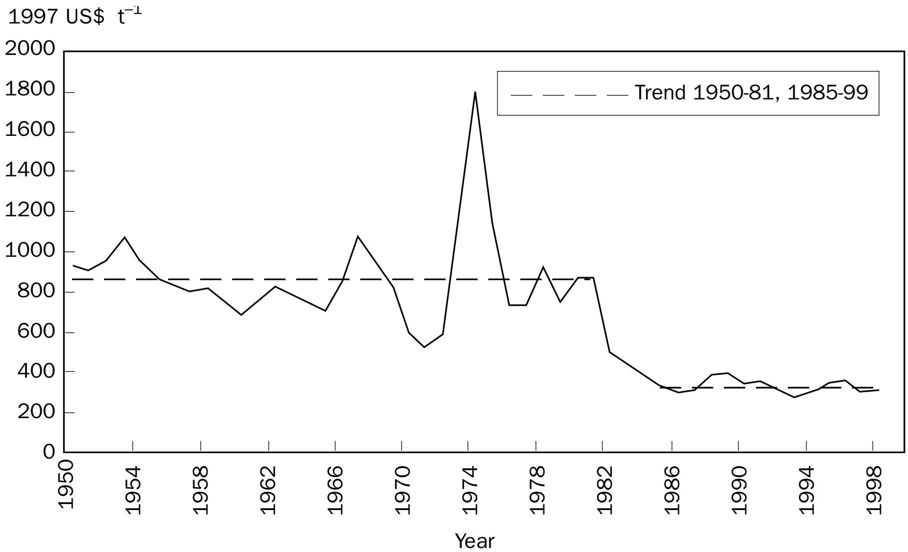
Political imperatives and climatic shocks

In the post-World War II era, the concern of the West regarding the deteriorating food situation in Asia and its implications for political stability was driven to a large degree by cold-war politics. The Great Game (see Hopkirk 1991) that had dominated the struggle between Great Britain and Russia for control of Asia in the 19th century was very much alive, albeit in a new format and with a different cast of players. Among the governments of Asia and the West and the international development agencies, the priority was clear—*increase cereal grain production in Asia.* A consensus gradually emerged as to how to get the job done as the pieces of the green revolution technology began to fall into place.

Two weather events, which have now come to be known as *Los Niños* (which lead to shortfalls in annual rains throughout much of the world) served to catalyze the commitment to the food security goal. The first of these occurred in the Indian subcontinent in the mid-1960s, where a shortfall in grain production threatened famine. The second occurred as a result of a shortfall in crop production in 1972, leading to a sharp rise in world rice prices (Fig. 1) and forcing Thailand, the world's largest rice exporter, to ban exports for several months in 1973.

Technological change

The so-called green revolution is most commonly associated with the development of the *modern semidwarf varieties* of rice and wheat (MVs). However, two other critical components of the green revolution technology are *fertilizer* and *irrigation.* As with new varieties, so also with these other two factors, there has been a steady stream of technological improvements contributing to rice productivity growth. Because the inputs were highly



1. Real world rice prices (FOB Bangkok).

complementary, efforts to apportion the share of the output growth to each have proved difficult. An analysis by Herdt and Capule (1983) suggested that the MV effect, fertilizer effect, irrigation effect, and other factors (a residual) contributed almost equally to growth in production. Included in "other factors" would be the extraordinary investment of the West in human capital development in Asia. This often overlooked investment helped to provide the policy and institutional changes needed to facilitate the development and spread of the new technology. This would help to account for the speed with which these technologies spread. For example, as discussed in more detail in the final section of this paper, the importance given to training in agricultural research and extension explains in large part IRRI's success.

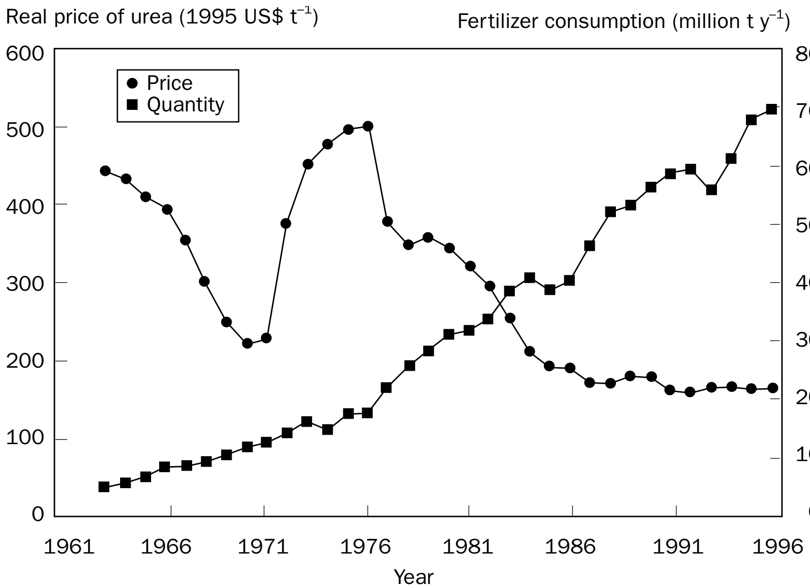
Varietal improvement. At the time that IRRI began operations in 1962, no one would have predicted that a breakthrough in rice yield potential could be achieved in just 4 years. The serendipitous early discovery of the dwarfing gene in the Taiwan collection led to the release in 1966 of the first semidwarf variety, IR8. Traditional tall varieties (about waist high) yielded a biomass consisting of 80% straw and 20% grain, while the grain to straw ratio in the semidwarfs (about knee high) was 50/50. These shorter, stiffer straw varieties gave a higher yield response to fertilizer without lodging at harvest time. Equally important, the new varieties matured in just 120 days or less compared with 150 days for the traditional varieties. The release of IR8 established a yield ceiling in open-pollinated rice in the tropics that has lasted to this day.

The susceptibility of IR8 to pests and diseases quickly shifted the emphasis to breeding for resistance. The release of IR36 a decade after IR8 (1976) marked another milestone, characterized by the development of the second generation of insect- and disease-resistant MVs. It was estimated in the early 1980s that more than 10 million hectares were planted to IR36 (IRRI 1982b). However, this led to concerns that the genetic base of the new varieties was too narrow, increasing the downside risk of widespread crop loss in a single year (Evans 1986). The release of IR64 in 1985 with more than 40 land races in its ancestry provided insurance against risk of this nature.

To date, drought and the impact of *El Niño* and *La Niña* weather conditions remain the major source of year-to-year variation in crop production. Breeding for marginal environments with frequent droughts or adverse soil conditions is more complex. There are those who argue that aided by biotechnology, the greatest potential for productivity gains (and poverty alleviation) in the future lies in the rainfed environments. Others anticipate that a future breakthrough in the yield ceiling will continue to favor the irrigated areas and that these areas will produce an ever larger share of the world's rice.

Advances in fertilizer technology. Since the advent of the green revolution in the 1960s, chemical fertilizers have had a central place in transforming farm production in Asia. Asian fertilizer consumption has risen from 7 million nutrient (N, P, K) tons in the 1965 to 17 million in 1975, the year of the "fertilizer crisis," to 39 million in 1985 and 69 million in 1995, essentially doubling every 10 years. The extraordinary growth in fertilizer consumption, more than 7% per year for three decades, was due to a steady decline in the price of fertilizer (Fig. 2) and learning by farmers about the benefits of fertilizer when used with MVs.

The major factor explaining this reduction in cost has been a stream of discoveries in applied chemistry and mechanical engineering relating to the production of superphosphates, phosphoric acid, and above all, ammonia, which is converted into N fertilizer (Tomich et al 1995). One of the most dramatic developments occurred in 1963 just before the green revolution. The shift from piston to centrifugal compressor tripled the optimum plant size for manufacturing urea, further dropping the cost of production. Given the speed of technological change and the sophistication and capital-intensive nature of the technology, the developed countries have a comparative advantage in fertilizer production. Some Asian countries, ignoring this fact and seeking to become self-sufficient in fertilizer, have constructed plants, often with

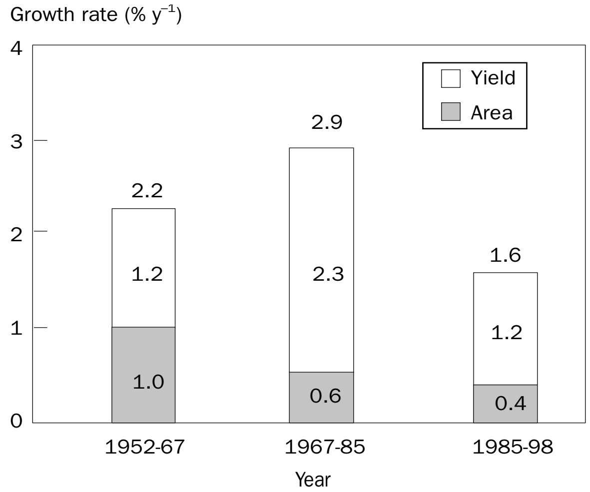


2. Relationship between world price of urea and total fertilizer consumption in Asia, 1961-96.

assistance from the developed countries, that were obsolete almost the day they were completed.

Technological advances in irrigation and water management. Technological advances in irrigation can be divided between (i) those relating to development of surface water or canal irrigation systems largely through public investment and (ii) those relating to the exploitation of groundwater largely through private investment. Prior to World War II, Asian irrigation was dominated by so-called run-of-the-river systems by which water was diverted by barrages to provide supplemental irrigation to insure the main wet-season crop. Advances in the technology of large dam and reservoir construction in the western United States prior to World War II became the foundation for surface irrigation system development in Asia in the post-World War II period. High rice prices justified the substantial investment in large public-sector irrigation systems in the 1970s. But the subsequent decline in rice prices, rising construction costs, and growing opposition of the environmentalists have led to a sharp decline in investments since the mid-1980s (Rosegrant and Pingali 1994).

By contrast, advances in technology and declining costs have resulted in a continuing rapid expansion of tubewells (and more recently in other micro-irrigation technologies such as sprinkler and trickle irrigation). In India and China, for example, well over half of the total area irrigated is served by



3. Changes by area and yield toward production growth in Asia, 1952-67 to 1985-98.

tubewells. Farmers, often reluctant to pay irrigation fees for unreliable deliveries of canal irrigation water, are willing to pay full cost for pump irrigation that can facilitate the shifts from rice to higher valued crops. But unregulated expansion of tubewells is leading to a serious overexploitation of groundwater, particularly in the semiarid regions that include two of the major breadbaskets of Asia, the Punjab and the north China Plain.

Growth in production and yield

The growth in rice production and yield is shown in Figure 3 for the green revolution years (1967-85) and for the pre- and post-green revolution years. Following a rapid growth in production of close to 3% in the green revolution period, the growth rate declined by almost one-half. The considerable variation over time and space in the rate of adoption of the new technology and growth in production is illustrated in Table 1. Insular Southeast Asia, China, and other select regions such as the Indian Punjab were the early beneficiaries of the green revolution technology. By 1980, 50% or more of the rice area in these regions had been planted to the MVs (Herdt and Capule 1982). In other parts of Asia including Bangladesh and eastern India, the adoption has been much more recent and the growth in yields has been more rapid after 1985. Vietnam has shown a strong growth in land area and yields since 1985. Surprisingly, Thailand, the world's largest exporter of rice, has had the lowest rate of MV adoption among all major Asian countries, approximately 15% in 1995. Yield growth and fertilizer consumption have also

Table 1. Average annual compound growth in rice area, yield, and production for Asia and selected countries or regions, 1966-85 and 1985-98 (IRRI 1995).

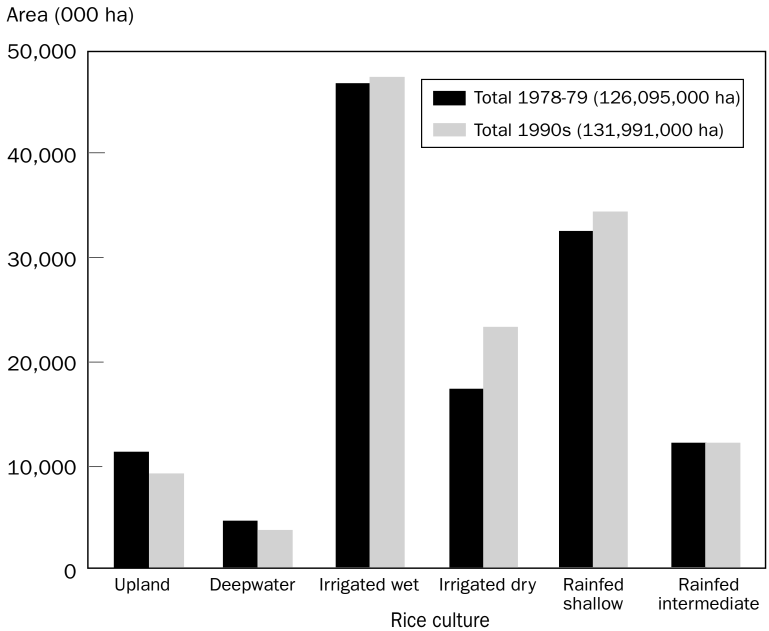
		1966-85	1985-98
Asia	Area	0.6	0.4
	Yield	2.3	1.2
	Production	2.8	1.6
Early adopters			
China	Area	0.3	-0.3
	Yield	2.9	1.3
	Production	3.1	1.0
Indonesia	Area	1.3	1.1
	Yield	3.9	0.7
	Production	5.3	1.8
Philippines	Area	0.2	0.7
	Yield	3.5	1.2
	Production	3.6	1.8
Punjab (India)[a]	Area	9.5	2.3
	Yield	4.9	0.4
	Production	14.8	2.6
Late adopters			
Bangladesh	Area	0.4	-0.1
	Yield	1.4	2.0
	Production	1.8	1.9
Vietnam	Area	0.9	1.9
	Yield	2.3	2.6
	Production	3.2	4.6
West Bengal (India)[a]	Area	0.5	1.1
	Yield	1.7	2.8
	Production	2.1	3.9
Low adopter			
Thailand	Area	1.7	0.4
	Yield	0.7	0.8
	Production	2.5	1.2

[a]Growth rates are for 1985-96 period.

been low, as Thailand has chosen to expand rice area and continue to grow low-yielding but high-quality export varieties.

Much of the variation in timing of MV adoption seems to be associated with developments in irrigation and water management. Investments in large irrigation schemes occurred in the 1970s and early 1980s in many parts of Asia and the expansion of the dry-season rice area gave a major boost to production. But the shifts in cropping pattern and adoption of irrigation technologies that allowed the delta areas to avoid the low yields associated with deepwater rice and take advantage of more favorable growing seasons came much later.

The rice area in Asia has remained almost constant since the mid-1980s. The continued expansion of tubewell irrigation has resulted in a major portion of new irrigated area being used for crops other than rice. However,



4. Summary of rice areas by type of culture for Asia (Huke and Huke 1997).

the portion of the rice area that is irrigated increased between the late 1970s and the early 1990s from 51 to 56%. This was the result of a decline in both upland and deepwater hectarage, a trend that seems likely to continue (Fig. 4).

What explains the slowdown in growth?

What explains the slower growth in production, area, and yield since 1985? The most obvious cause is the dramatic drop in world rice prices between 1981 and 1985 (Fig. 1). Marking the successful introduction of green revolution technologies, supply grew more rapidly than demand. Over the past 15 years, world prices have remained remarkably stable, allaying earlier fears that adoption of the green revolution technology would result in greater yield and price variability. A new equilibrium in supply and demand seems to have been reached at a lower price and slower growth rate.

The slower growth is influenced by both supply and demand factors. On the supply side, in many areas of Asia, the yield gains from adoption of the new technologies had been almost fully exploited and, typically in these areas, intensification of rice production has been leading to the over-exploitation and degradation of soil and water resources. It is no longer possible to sustain a growth in production at 2.5 to 3% per year. In addition, with sharply lower domestic rice prices and rising wage rates, farmers have found it far less profitable to produce rice. Simultaneously, the growth in demand for rice was declining due both to a rise in incomes and fall in the rate of population growth. The factors that have contributed to slower growth and the implications for rice research are discussed in more detail in the sections that follow.

Productivity, poverty, and sustainability

The words "poverty alleviation" or "poverty eradication" do not appear in the earlier mission statements of either IRRI or the CGIAR. Yet, there was certainly an implicit belief that success in raising rice production in Asia and increasing farm incomes would have a positive impact on poverty alleviation by averting famine and providing food security for millions of people. Michael Lipton (1989, p. 400) an early critic of the green revolution, wrote more recently that "if social scientist had in 1950 designed a blueprint for pro-poor agricultural innovation, they would have wanted something like the modern varieties: labor-intensive, risk-reducing, and productive of cheaper, coarser varieties of food staples." Even better would have been a range of MVs benefiting less-favored, rain-parched areas. But if initial emphasis had been given to the marginal areas, such emphasis could not have produced enough extra food in the 1960s to avert disaster.

A 25-31 March 2000 article in the *Economist* states that "the green revolution's tool kit probably saved more than a billion people from starvation." However, even today, despite convincing evidence to the contrary, a large share of public opinion views the green revolution as having made the rich richer and the poor poorer. This fact notwithstanding, there are legitimate concerns about the benefits and costs associated with the green revolution in the past and, more particularly, with future technological change in agriculture. In the next two sections, we look at the plus side of the ledger—how the increase in rice productivity has helped the poor. In the third section, we discuss the negative impacts of the green revolution technology and issues related to sustainability in growth of rice production.

How has the increase in rice productivity helped the poor?

Research that leads to an increase in the productivity of rice contributes to poverty alleviation through pathways that lead to benefits for rice producers, agricultural laborers, and consumers. Initially, higher productivity results in higher profits for farmers and more employment, particularly for agricultural laborers and for those in farm-related businesses. The early adopters benefited the most because initially the growth in production was too small to affect the rice price. Subsequently, as the adoption of new technologies spread and rice prices fell, the farmers with the largest marketed surplus suffered the largest decline in income.

Due to the sheer size of the rice economy and the importance of rice in the Asian diet, productivity gains in rice compared with any other agricultural commodity grown in Asia have the widest potential impact on poverty reduction. The lower prices for consumers are the inevitable result of growth in production that outstrips growth in demand. Lower rice prices for consumers benefit the poor—including urban poor, rural landless, and nonrice farmers—disproportionately because rice makes up as much as 70% of their calorie intake. A lower rice price stimulates employment in the industrial and service sectors of the economy, drawing labor out of agriculture. For many economies, the structural transformation has not been smooth particularly where slow growth in the nonfarm sector fails to create sufficient jobs to employ the surplus agricultural labor. However, this transformation in the economy, described later in more detail, is essential for long-term poverty alleviation.

As the MVs spread, initial concerns focused on equity rather than productivity impacts on poverty reduction. Large farmers and landowners were seen to be benefiting at the expense of the small farmers, tenants, and the landless. More than two-thirds of the published research on what MVs do to the poor was focused on this issue (Lipton 1989). There is convincing evidence, particularly in the case of rice (where nearly all farms are small), that in those environments where MVs have been widely adopted, the benefits have accrued to the well-to-do and poor alike (Barker and Herdt 1985, David and Otsuka 1994). The poor consumers, for whom rice represents a much larger share of total calorie consumption, often have benefited disproportionately.

The new technology did favor irrigated areas over marginal environments. A study of the effect of modern rice technology on income distribution based on case studies in seven Asian countries concluded that factor and product market adjustments largely counteract the potentially adverse effects of differential MV adoption across production environments (David and Otsuka 1994). For example, either seasonal or permanent labor migration to irrigated areas has been a common phenomenon in Asia.

It is scientifically more difficult to develop varieties for unfavorable production environments. However, a pro-poor strategy must target those unfavorable environments where there is potential for success. This is illustrated by recent gains in production in the river delta areas of eastern India, Bangladesh, and Vietnam made possible by the introduction of irrigation technology and a change in cropping pattern that allowed a shift from low-yielding deepwater rice to MVs. By contrast, there is a general consensus that crops other than rice normally would be better suited to the upland (nonpaddy) areas.

Measuring the impact on poverty alleviation

The period from 1965 to 1985 saw a large fall in poverty (as measured by numbers of people below the dollar-a-day poverty line) based on rising food yields, employment, and public agricultural research effort but all four have stalled since then (Lipton 1999). The decline in numbers below the dollar-a-day poverty line from 1970 to 1990 is shown for six East and Southeast Asian countries in Table 2. The majority of the poor are in the rural area and it is in these areas that the decline in poverty has been most dramatic.

The decline in percentage of people below the poverty line in South Asia has been equally dramatic. This is best illustrated in a study conducted by Datt and Ravallion (1998a). The research is based on surveys of poverty and consumption conducted periodically by the National Sample Survey for the 15 major states in India spanning the period 1957-58 to 1990-91. The study links the reduction in rural poverty to growth in farm productivity in India. Figure 5 compares the downward trend in the squared poverty gap index (SPG)[2] with the upward trend in yield. There is an 88% correlation, but there was a considerable lag with the decline in poverty not occurring until after 1975.

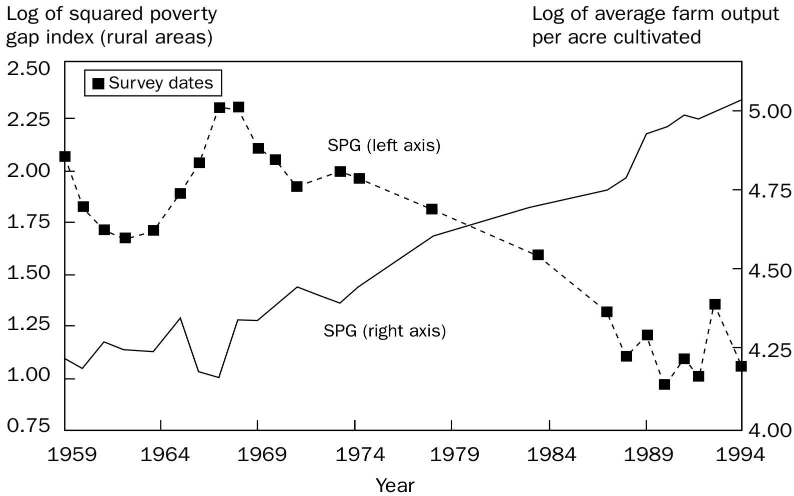
In a separate study based on the same data, Datt and Ravallion (1998b) identify factors that explain why some Indian states have performed better than others. They conclude that while the trend rate of growth of average farm yields is important, starting endowments of physical infrastructure and human resources—higher irrigation intensity, higher literacy, and lower initial infant mortality—all contribute to higher long-term rates of poverty reduction in rural areas. With the exception of Bihar and Assam, the rice-growing states have performed at or above the average in rural poverty reduction.

In contrast to Southeast Asia, the absolute numbers of the poor in South Asia are stagnant or continue to grow. For example, the number of rural poor in India in 1994 was still nearly 250 million, essentially unchanged from 1970, despite data showing that the incidence of poverty in rural India has fallen from 55 to 37% over the same period (Fan et al 2000). India exports rice, while large segments of the population still lack the purchasing power to

[2]The poverty gap (PG) is the average distance of the population below the poverty line—defined in this study as the level of average per capita expenditure to achieve a nutritional norm of 2,400 calories per person per day. For the squared poverty gap (SPG), the distances below the poverty line are squared so that the measure will penalize inequality among the poor.

Table 2. Absolute poverty, 1970-90, for selected countries (Lipton 1999).

		Number of absolute poor (millions)			Incidence of poverty (%)		
		1970	1980	1990	1970	1980	1990
China	Total	275	220	100	33	29	9
	Rural	267	211	95	39		11
	Urban	8	9	5	5		2
Poor in rural areas					97	96	95
Indonesia	Total	70	42	27	60	29	15
	Rural	56	33	18	58	28	14
	Urban	14	9	9	73	29	17
Poor in rural areas					82	80	66
Korea	Total	7	4	2	23	10	5
	Rural	6	1.5	0.4	28	9	4
	Urban	1	2.5	1.6	16	10	5
Poor in rural areas					84	37	20
Malaysia	Total	2	1	0.4	18	9	2
	Rural	1.7	0.9	0.3	21		4
	Urban	0.3	0.1	0.1	10		1
Poor in rural areas					85	85	85
Philippines	Total	13	14	13	35	30	21
	Rural	11	11	10	42	35	27
	Urban	2	3	3	20	18	11
Poor in rural areas					85	75	77
Thailand	Total	9.5	7.9	9	27	17	16
	Rural	9	7.4	8.5	30	19	20
	Urban	0.5	0.5	0.5	9	5	4
Poor in rural areas					94	94	94
Six countries	Total	377	289	152	35	23	10
	Rural	351	265	132	40	27	12
	Urban	26	24	20	13	9	5
Poor in rural areas					93	92	87



5. Squared poverty gap and average farm yield, rural India 1959-94 (Datt and Ravallion 1998b).

provide an adequate diet. This hidden food gap in cereal grains due to lack of effective demand is projected in one study to reach 160,000 tons in South Asia in 2020 (Conway 1997).

Negative impacts and sustainability

The intensification and rapid growth in rice production has led to a growing number of environmental and health problems and raised questions about our capacity to sustain growth in production for the foreseeable future. Pingali et al (1997) provide a comprehensive analysis of these problems and their environmental and health impacts.

The various problems affecting sustainability of production were a result of the intensification process imbedded in the green revolution technology. The new technology led not only to an increase in yields, but with the development of irrigation, made it possible to grow two or three crops of rice where only one had grown before. As the ecology of the rice field changed, a range of environmental problems emerged gradually over time. Solutions have been found with varying degrees of success but have often proved to be only temporary. A continuing research effort has been needed simply to maintain the yield potentials (so-called maintenance research).

Following the initial release of the MVs, there were serious pest and disease problems—most notably the brown planthopper and tungro virus. This resulted in the development of more insect- and disease-resistant varieties (e.g., IR36) and in the very successful efforts of the FAO to mount a campaign in integrated pest management (IPM) (FAO 1990). Soil nutrient problems such as zinc and phosphorus deficiencies led to increased research on nutrient balances. Soil degradation and water pollution problems were traced to the increased use of chemicals. Chemicals have also had negative impacts on human health, livestock, and fish culture. Clearly some of the emerging problems or side effects have extended well beyond those related simply to rice cultivation.

One of the most recent and less tractable problems to arise relates to the management of water resources. Until recently, most people believed that we would always have enough water to grow food, to drink, and to support industry. However, we need only to be reminded by the current drought in India that many countries are entering a period of severe water shortage (Barker et al 1999). Many of the water problems such as salinity, waterlogging, and overexploitation of groundwater are largely confined to the semiarid regions. However, these regions include two of the major breadbaskets of Asia—the Punjab and the north China Plain—where rice and wheat are commonly grown in rotation. Furthermore, the growing scarcity and competition for water will be pervasive, extending well beyond the semiarid regions and profoundly affecting the way we value and utilize water resources.

A common perception is that in rice production, enormous quantities of water are being "wasted." However, the rice plant consumes about the same amount of water as other cereal grains. Much of the water that is "lost" from one farmer's rice field is used elsewhere, perhaps in the next farmer's field, perhaps as return flow, or through groundwater extraction further down the basin.

This fact notwithstanding, most irrigation systems in monsoon Asia have been poorly designed, managed, and maintained (Pingali et al 1998). Through better management practices at the farm and system level, there appears to be ample scope for increasing the productivity of water (Guerra et al 1998). There is growing research interest in *integrated water resource management* (IWRM), which focuses on allocation of scarce water resources at the basin level among competing uses—irrigation, municipal, industrial, hydropower generation, and environment. IWRM research is also concerned with the competing and complementary relationship between canal and groundwater development in the basin. IRRI and the International Water Management Institute (IWMI) are currently working with colleagues at a site in China to determine how the Chinese have been able to reduce the allocation of water to irrigation from the main reservoir from 70 to 30% without reducing rice output.

Another piece of the water puzzle relates to the development of technologies and water management practices for the rainfed and drought-prone areas largely untouched by the green revolution. This includes a combination of breeding for drought tolerance and managing limited water supplies to be sure that adequate water is available at critical stages of growth such as flowering. Scientists disagree as to the potential gains that can be achieved from research on the unfavorable environments. Pingali et al (1997) suggest that a pro-poor research prioritization should partition IRRI research resources 50/50 between the irrigated lowland environments and less-favorable rice-growing environments.

In summary, the gradual emergence and recognition of problems related to the intensification of rice production has broadened the research agenda of IRRI and other research institutes. Maintenance research to ensure the *sustainability* in rice production to meet future demands is a continuing process that extends beyond initial focus on higher yields and productivity to assess the potential impact of productivity gains on environment and health and on poverty alleviation.

Table 3. GDP and labor force in agriculture—1960s and 1990s.[a]

Region/country	GDP in agriculture (%)		Labor force in agriculture (%)	
	1960s	1990s	1960s	1990s
East Asia				
China	40	21	82	70
South Korea	37	7	66	18
Taiwan	28	3	56	10
Southeast Asia				
Indonesia	54	17	75	57
Malaysia	30	13	60	25
Philippines	26	22	62	43
Thailand	40	11	84	64
Vietnam	–	40	–	70
South Asia				
Bangladesh	53	31	86	61
India	47	26	75	62
Sri Lanka	28	23	56	47

[a]Sources: World Bank, World Development Reports, and Council of Agriculture, Taiwan.

Agriculture and structural transformation

All countries are striving for a successful transformation—the gradual evolution of an economy from one based primarily on agriculture to one in which the large majority of labor and output is in the industrial and service sectors (Timmer 1997). Diversification and commercialization of agricultural systems are part and parcel of the process of transformation. But for such a transformation to take place, there must initially be a rise in agricultural productivity to generate food surpluses and free up labor and other resources needed to support growth in the nonagricultural sector. Whether through the improvement in rice production following the Meiji restoration (1888) in Japan, the introduction of high-yielding Ponlai varieties in Taiwan in the 1920s, or the spread of the green revolution technology in South and Southeast Asia in the 1960s and 1970s, the starting point has been much the same. That is to say, for most Asian economies, the initial step in this transformation has been an increase in land and labor productivity in the production of rice.

This structural transformation in the Asian economies is depicted in Table 3. Over the past 30 years, the share of GDP and the percentage of the labor force in agriculture have been declining, more rapidly in some countries such as South Korea, Taiwan, Indonesia, Malaysia, and Thailand, more slowly in others such as the Philippines and Sri Lanka. Due to the slow absorption of labor into the nonfarm sectors in these later two countries, a substantial portion of the labor force has looked overseas for work and remittances have become a significant foreign exchange earner and source of household income.

For most Asian countries in the 1990s, GDP in agriculture was 25% of total GDP, but 50% or more of the labor force remains in agriculture. The 2 or 3 to 1 ratio of labor force to GDP in agriculture shows that labor productivity is higher in the nonagricultural sector, and that labor will continue to be pulled toward the more productive nonagricultural sector.

It is somewhat of a paradox that the success in increasing rice productivity leads not only to further changes in production practices but to a gradual decline in the importance of rice in both consumption and as a source of farm household income. This is accompanied by both diversification of consumption and production, and the move from a largely subsistence to a commercial or market-oriented agriculture.

The demographic transition

Historically, structural transformation has been accompanied by *demographic transition* (Tomich et al 1995). In the first phase of the transition, mortality rates decline but fertility remains high and the rate of population growth rises significantly. In the second phase, rapid population growth ends as population growth declines to levels nearer the greatly reduced mortality rate.

Table 4 shows the trend in annual growth in population for East Asia, Southeast Asia, South Asia, China, and India for three time periods. Although the decline has been most dramatic in China, clearly South and Southeast Asia are rapidly entering the second stage of the demographic transition. Due to the downward trend in population growth and rising incomes, we can expect the growth in demand for rice to decline. However, the growth in the labor force will remain high in the immediate future and finding gainful employment for this expanding workforce will be the major concern of most

Table 4. Annual population growth (%) in Asia, 1965-70 and 1990-95.[a]

Region/country	1965-70	1990-95
East Asia	2.5	1.2
Southeast Asia	2.5	1.7
South Asia	2.4	1.9
China	2.6	1.1
India	2.3	1.8

[a]Source: FAOSTAT database.

Table 5. Change in percentage of calories from rice in total per capita calorie supply for Asian countries, ranked by percent change from 1965 to 1995 (IRRI 1995).

Country	1965	1995	Change	Change (%)
Asia	38	33	–4	–12
Japan	42	23	–19	–45
Malaysia	49	31	–19	–38
South Korea	51	34	–17	–33
Thailand	69	47	–23	–33
Philippines	44	38	–6	–13
China	37	34	–4	–10
Sri Lanka	43	39	–4	–9
Vietnam	72	68	–5	–6
Bangladesh	76	73	–3	–4
Nepal	37	37	–1	–2
Cambodia	76	76	0	0
India	33	33	0	1
Myanmar	73	76	3	4
Indonesia	47	51	4	8

governments. The greatest pressure will occur in South Asia, where, as noted in the previous section, the number of people below the poverty line will continue to grow.

Changes in food consumption patterns

There is an inherent desire for diversity in dietary patterns among most populations of the world. For many of the poor in Asia, rice remains the priority in the diet, composing 70% or more or the calories supplied. But as incomes increase, the proportion of rice in the diet declines, giving way initially to wheat and more gradually to consumption of livestock and other products. For most of Asia, this means a growing level of imports and the challenge is to find agricultural exports to offset this import bill.

In Table 5, countries have been ranked according to the percentage decline in rice as a portion of the calories supplied in the diet from between 1965 and 1995. The rate of decline is clearly associated with the rate of economic growth, with Myanmar experiencing no decline at all and, at the other extreme, Japan experiencing a decline of 50%.

Changes in farming practices

Earlier we indicated how the spread of the semidwarf high-yielding varieties had brought a visible change in the rice fields. More visible changes have followed. As the rate of growth in yield has declined, the demand for labor in the nonagricultural sector has grown. The growth in labor productivity, due initially to the increase in rice crop yields, is now being achieved largely

Table 6. Labor input in rice production (days ha^{-1}), Central Luzon, 1966-94.[a]

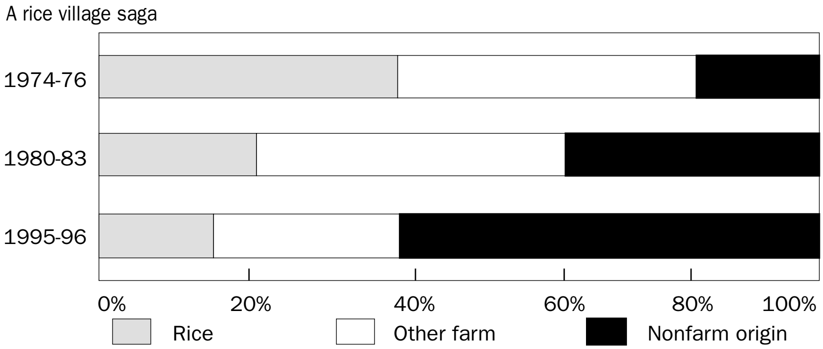
	1966	1970	1979	1986	1990	1994	1998
Preharvest labor	40	53	49	52	40	40	34
Family	21	32	22	14	14	13	9
Hired	19	21	27	28	26	27	25
Harvesting-threshing labor	20	21	28	19	29	28	25
Family	2	3	2	1	5	6	4
Hired	18	18	26	18	24	22	21
Total	60	74	77	61	69	68	59
Family	23	35	24	15	19	19	13
Hired	37	39	53	46	50	49	46

[a]Sources: Estudillo et al 1999; data for 1998 are updates from latest IRRI survey.

through adoption of labor-saving technology. Table 6 shows the change in mandays of labor for rice production in a survey of Central Luzon farms. Between 1966 and 1979, labor input increased as more labor was needed for crop care activities and for the harvesting of the increase in rice production. After 1979, labor input declined and this decline can be expected to continue.

This rising and then falling trend in labor input reflects the fact that in the early stages of the agricultural transition in Asia, labor was in surplus. The green revolution technologies created jobs by increasing the labor requirements for a single crop, by making it possible in many areas to grow two crops of rice, and by generating employment off the farm in a host of farm- and nonfarm-related activities. As the transition proceeds and the demand for labor in the nonfarm sector grows, wage rates rise and there is a growing demand at the farm level for labor-saving technologies. With more than 50% of the total labor force still in agriculture, there is the danger that the adoption of labor-saving technologies may move faster than the ability of the nonfarm sector to absorb labor. The temporary setback in demand for nonfarm labor as a consequence of the Asian financial crisis in 1998 illustrates this point. Lipton (1999) cautions that the top priority for anti-poverty research should be to raise yields in ways that substantially raise the demand for labor. Attempts to save on labor with research into direct seeding, mechanical rice transplanters, weedicide screening, and mechanical threshing are conducive to despair as a use of aid funds in Asian research centers. The issue is largely a matter of timing. As economies grow, the point is reached where there is no longer a surplus but a shortage of labor in the agricultural sector.

The speed of adoption of these labor-saving technologies has varied by region, but the unmistakable trend is marked by the gradual disappearance in many regions of practices and techniques that have been used for centuries in



6. Changes in source of rural household incomes in Laguna village, Philippines (adapted from Hayami and Kikuchi 2000).

the production of rice. The tractor is replacing the water buffalo for land preparation; direct seeding of rice is replacing transplanting; herbicides are replacing hand weeding; the mechanical thresher is replacing traditional hand threshing of paddy.

Indeed, the traditional Philippine song: "planting rice is never fun, work from morn' to the setting sun; cannot stand, cannot sit, cannot rest for a little bit." seems to have been a harbinger of things to come. While the youth no longer look to rice farming as a way of life, those left behind to tend the rice fields are adopting new practices to lighten the burden and increase the productivity of their labors.

Change in source of rural household incomes

While rice is becoming a smaller part of the total economy, for rice farmers it also is becoming a smaller share of household income. The study by Hayami and Kikuchi (2000) of a Laguna, Philippines, village over three decades documents the direction of this change (Fig. 6). The share of income from rice fell from 50% in the 1970s to 15% in the 1990s. The share of income from other farm activities fell, but more gradually, and by the 1980s, it exceeded income from rice. The income from nonfarm activities rose from 10% to more than 60%.

Surveys identifying sources of household income were conducted in six villages in two locations in Thailand in 1987 and 1994 (Isvilanonda and Hossain 1998) and in four villages in the Philippines in 1985 and 1997 (Marciano et al 2001). The villages represented three rice-growing ecosystems—irrigated, rainfed, and upland. The results are summarized in Table 7. Despite the shorter period of time, the pattern is much the same as in the

Table 7. Change in percent income from rice, other farming, and nonfarm selected villages in the Philippines and Thailand (Marciano et al 2000, Isvilanonda and Hossain 1998).

	Irrigated		Rainfed		Upland	
Philippines	1985	1997	1985	1997	1985	1997
Rice	42	29	55	41	25	17
Other farming	18	6	26	10	42	22
Nonfarm	40	65	19	49	33	61
Thailand	1987	1995	1987	1995	1987	1995
Suphan Buri						
Rice	56	21	53	17	53	27
Other farming	36	31	27	18	8	36
Nonfarm	8	48	20	65	39	37
Khon Kaen						
Rice	46	8	28	8	30	19
Other farming	10	5	14	7	19	32
Nonfarm	44	87	58	85	51	49

Laguna village. The importance of rice as a source of household income declines and nonfarm income increases in all three rice-growing environments.

One needs to be cautious about generalizing from these village case studies particularly as regards the speed and magnitude of change. For example, the location of the village will have much to do with opportunities for nonfarm employment. A sample survey was conducted in Bangladesh consisting of 1,245 rural households in 1988 and 1,316 rural households in 1995 (Hossain 1998). The pattern of change was similar but more gradual with the share of income from rice falling from 28 to 24% and the share of income from nonagricultural activities rising from 37 to 46%.

Diversification in the agricultural sector

Successful agricultural development requires the diversification of agriculture away from the staple crops such as rice for which demand gradually declines. For smaller countries, diversification must be associated with the development of export markets. Diversification of agriculture can occur at the farm level, or in the agricultural sector as a whole, with different regions of a country specializing in different crops.

By and large in Asia, the diversification of rice farms to crops other than rice has been difficult. This is because the surface irrigation systems have been designed and managed to provide adequate supply water for rice but not to provide water when needed for nonrice crops. The systems are said to be "supply-" rather than "demand"-driven. A notable exception has been Taiwan (Levine et al [2001]). Here, the irrigated area remained fairly constant from the mid-1960s to the mid-1980s. But during this period, the area in rice and sugar cane fell by almost 50% and was replaced by fruits, vegetables, and feed grains, allowing the value of agricultural production to continue to rise and the value of exports—including livestock—to contribute significantly to foreign exchange earnings. The ability of farmers to make these crop adjustments was due in large measure to the major government investments in land consolidation and in irrigation and drainage infrastructure during the 1950s and 1960s that allowed water to be rotated at the 10-hectare level. Many Chinese irrigation systems have been designed with the same high degree of infrastructure articulation and of water control and management needed to facilitate diversification from rice to other crops.

But for much of the rest of Asia, diversification of irrigated agriculture is largely occurring through private farmer investment in tubewells and more recently in micro-irrigation systems such as sprinklers, surge, and trickle irrigation. As noted earlier, groundwater irrigation has been growing more rapidly than surface irrigation in a number of countries and the cost of these micro-irrigation technologies has been falling rapidly. Large sections of the new irrigated area are not being cropped with rice. The initial exploitation (and now overexploitation) of groundwater occurred largely in the semiarid regions but is now gradually spreading to the monsoon areas.

Several Asian countries have been successful in developing nonirrigated crops for export. Following an initial success in development of rubber exports, Malaysia in the 1970s and 1980s captured 80% of the world's palm oil market. While Thailand remains the world's largest rice exporter, they successfully developed export markets in cassava, maize, and sugar. Vietnam has become the world's second largest exporter of rice, but also the fourth largest exporter of coffee.

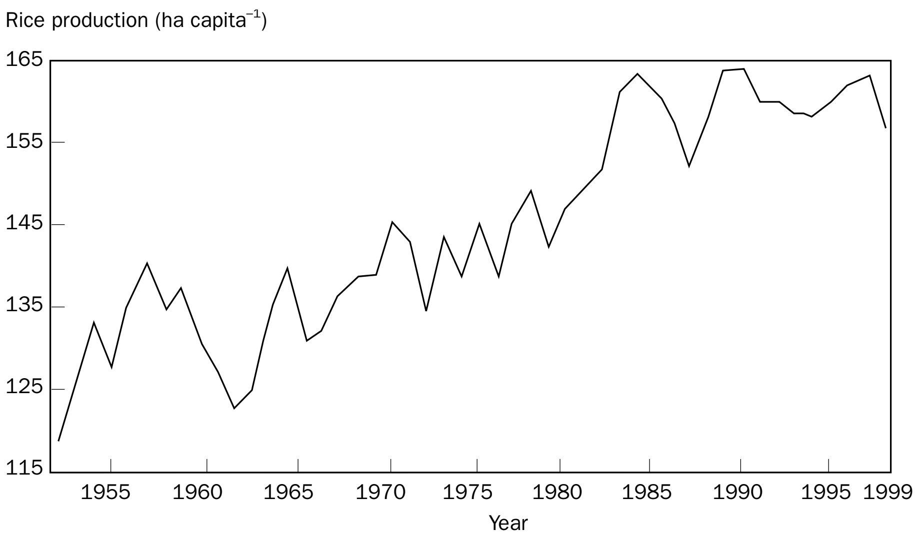
The world rice market, changing comparative advantage, and domestic rice policies

High and unstable world rice prices in the 1960s and 1970s provided a major incentive in Asian importing countries to adopt green revolution technology and strive for rice self-sufficiency. Major investments in irrigation gave those countries and regions outside of the major river deltas of Asia at least a temporary comparative advantage in producing rice. For political reasons, the collapse of exports from Myanmar, Cambodia, and Vietnam added further uncertainty to the world market. But the successful adoption of the new technologies and the growth and maturation of the Asian rice economies have dramatically changed the picture.

The world rice market

The opening of the Suez Canal in 1856 promoted the development of rice exports from the major river deltas of Southeast Asia—the Irrawaddy, Chao Phia, and Mekong. The dominance of Burma, Thailand, and Indochina in the world rice trade continued until after World War II, providing a major source of foreign exchange earnings for these countries. Rice exports remained small as a portion of total production—3 to 5%. After World War II, rice exports to South and Southeast Asia rose to exceed more than half of the total. Through the 1950s to the mid-1960s, rice export prices remained stable. The withdrawal of Burma, Cambodia, and Vietnam from the export market and shift in policies in Thailand and the rice importers led to wide fluctuations in world prices. The rice importers adopted policies to stabilize their domestic prices thus shifting instability to the world market. Between 1961 and 1980, the coefficient of variation in world rice prices was 30%, while the coefficient of variation for domestic rice prices in most Asian countries was less than half of that (Siamwalla and Haykin 1983).

A combination of factors led to a surge in per capita rice production (Fig. 7) between 1981 and 1985. This resulted in the sudden plunge in world rice prices to less than 50% of their previous levels (Fig. 1). One might ask why the steady upward trend in per capita production prior to the early 1980s had not led to a much earlier decline in world prices. The most likely reason is that Asian countries were much poorer in this earlier period, which meant

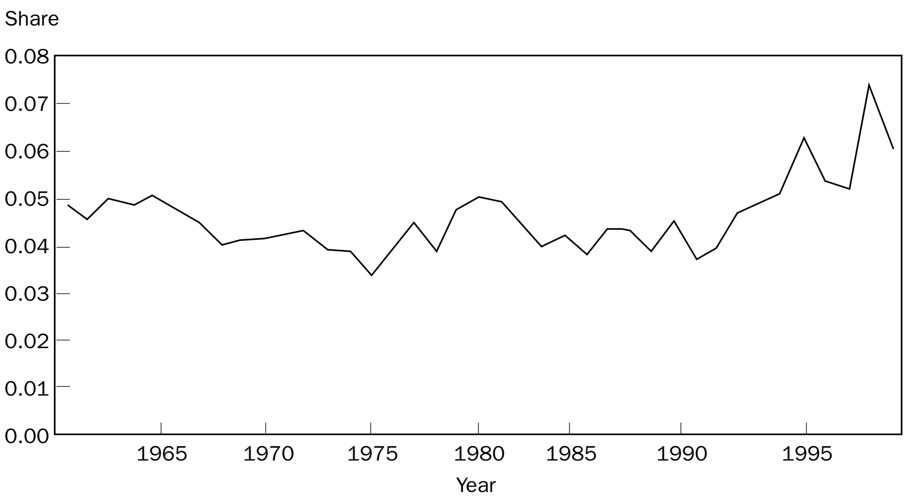


7. Per capita Asian rice production, 1951-97.

that income elasticity of demand was still positive. Thus, growth in rice production had to keep pace not only with population growth but also with income growth. Increases in per capita production were necessary to keep world prices constant in real terms. As the economies have grown, population growth has been declining (Table 4) and the proportion of rice in diets also is declining (Table 5). Future growth in demand is projected to be roughly equal to the now lower rate of population growth (Rosegrant et al 1995).

For the last 15 years, world rice prices have remained low and relatively stable. The greater importance of irrigation in rice production and improved pest and disease resistance in MVs has tended to reduce variability in production per capita. The reemergence and strengthening of the commercial orientation of major rice-exporting nations and the move toward freer trade and increasing integration will improve the performance of the world rice market. In addition to Thailand and Vietnam, with luck Cambodia and Myanmar (Burma) may emerge to become important players once again in the near future.

Finally, between 1995 and 1999, there has been a sharp increase in world market rice exports (Fig. 8). The average world export in 1990-94 was 14.3 million metric tons, and in 1995-99, 22.5 million metric tons. Although there has been a steady growth in demand for exports in Africa and Latin America, this sudden spurt is due to a doubling of demand in OPEC countries and tripling of demand among Asian importers—largely due to shortfalls in production in Indonesia and the Philippines in 1998. Whether or not this



8. World rice exports as a share of world rice production, 1961-99.

volume of trade will be maintained or continue to grow will depend on the continuing growth in demand outside of Asia, and upon the decision of Asian importers regarding the level of protection to provide to domestic rice production.

Comparative advantage

The introduction of new technology increased the comparative advantage in rice production for many of the Asian importing countries. Asia's total imports of rice declined from an average 4.5 million metric tons in 1965-75 to approximately 3 million metric tons in 1985-95. In the former period, Asian exports represented approximately half of world exports while in the latter period, they represented only 25%. More recently, Asian imports have once again been on the rise, but it remains to be seen whether this trend will continue.

Since the early 1980s, many Asian importers have begun to lose their comparative advantage. Recent studies of economic comparative advantage have been conducted in the Philippines (Estudillo et al 1999) and in Sri Lanka (Kikuchi et al 2000). In both studies, there has been an upward trend since the 1980s in domestic costs of rice production, due largely to an increase in wage rates. The domestic cost of production per metric ton of rice has risen above the level of the cost of importing a ton of rice. For these countries, the benefit-cost ratios no longer justify the investment in new irrigation facilities on economic grounds.

By contrast, comparative advantage in the deltas, which include the traditional exporting countries, has been strengthened. Recent improvements in water management and the development of groundwater have facilitated the introduction of green revolution technology and accelerated growth in rice yields in Vietnam, Bangladesh, and West Bengal. Due to low wage rates, reflecting the lack of demand for nonfarm labor, and plentiful water, the deltas will maintain a strong comparative advantage in rice production for the foreseeable future.

Domestic rice policies

Domestic rice policymakers face two decisions—at what level to set the price of domestic rice and how to ensure price stability. Setting the level of the domestic rice price became a more difficult political issue when world rice prices fell substantially in the middle of the 1980s. The more developed Asian rice-producing countries have all made essentially the same choice in recent years: keep domestic prices above world rice prices. Japan and Korea currently have very high nominal rates of protection and provide the most

Table 8. Nominal protection rate for rice in nine Asian countries, 1960-95 (David and Huang 1996, IRRI 1995).

Country	1960-70	1970-80	1980-88	1988-95
Japan	70	148	443	496
South Korea	17	65	243	431
Taiwan	–12	6	101	246
Philippines	31	–3	6	39
Bangladesh	68	51	32	18
Indonesia		3	27	18
Sri Lanka	36	42	–4	8
Thailand	–28	–28	11	5
India	19	–5	–3	–17

dramatic examples of this choice (Table 8). This choice may have been due in large part to substantial appreciation of the national currency (the yen and won), since higher real domestic rice prices have been only a minor contributor to higher nominal rates of protection (Timmer 1993). Thus, whether other countries follow the path of high protection taken by Japan and Korea may depend on what happens in the future to world rice prices and exchange rates.

It is not clear how this conflict between high protection for rice and increased trade liberalization will be resolved. While the Uruguay Round of the GATT was a major milestone for international agricultural trade, no Asian rice producers have yet made major binding international commitments in the direction of allowing equilibration between world and domestic prices. Perhaps the most significant commitments have been made under the ASEAN Free Trade Agreement (AFTA). Indonesia and Malaysia have agreed to end nontariff barriers (NTBs) on rice by 2010 with a maximum tariff of 20% for intra-ASEAN trade. The Philippines has also agreed to the removal of NTBs by that date, but with an as yet unspecified maximum tariff. These agreements could have major effects on rice producers and consumers in those countries, especially since the world's two leading rice exporters (Thailand and Vietnam) are members of ASEAN. Yet there remain safeguard provisions whose effects could in principle be quite important. Large domestic protection for the traditional Asian rice importers would retard the development of a vibrant international market for rice.

Ensuring domestic rice price stability has become an easier task in the past decade for at least two reasons. First, world rice prices were more stable during the past 15 years than they were from 1965 to 1980. In fact, world rice prices were more stable than world wheat and maize prices from 1985 to 1999, which was not true in the earlier era when the world rice market gained a reputation for severe instability. Second, even after accounting for the setback due to the recent economic crisis, most countries in the region have experienced significant economic growth and structural transformation during the past 30 years. As a result, the importance of rice to consumers, producers, and the macroeconomy is correspondingly less.

Nevertheless, rice price instability will not go away as a problem in the eyes of policymakers. For one, with the increased liberalization of financial markets, free trade in rice would expose consumers and producers not only to instability on world rice markets, but also exchange rate instability. More important, there are still many poor consumers and farmers for whom rice still constitutes a substantial share of their expenditures (for net buyers) or income (for net sellers). Large sudden price movements will profoundly affect the effective purchasing power of these poor individuals, and there is a legitimate role for government to smooth such fluctuations.

Projections and reflections

Asia's transition from an agricultural to an industrial society is well advanced. Despite the setback caused by the Asian financial crisis in 1998, economic development and the structural transformation appear to be back on course. Growth in agriculture has supported industrial growth. Incomes have risen and population growth rates have declined, accompanied by a gradual decline in per capita demand for rice. There have been significant gains in poverty reduction. Rice prices have been low and stable for more than a decade. The declining budgets for research suggest that many donors are asking why they should continue to invest in rice research. This is a reasonable question and one deserving serious consideration.

Why continue investing in rice research and related technological developments?

The short answer to this question is *sustainability* and *poverty reduction.* As noted in an earlier section, the intensification of rice production and rapid growth in output have been achieved at a significant cost in terms of environmental degradation and pollution. The engine of agricultural growth has slowed or stalled. How much of this is due to declining prices, to the near full exploitation of existing technological potential, or to the environmental degradation? For example, what will be the impact of overexploitation of groundwater and falling water tables in the Punjab and north China Plain on Asian food supplies? We don't know the answer to questions such as this. But we face a Catch 22 (see Heller 1962). At today's low world food grain prices, it does not seem to pay to invest in research and development that will lead to sustainable gains in productivity in the future. But given the long gestation period for most research and development efforts, failure to invest could lead to higher food prices and even erase some of the gains in poverty reduction achieved in the past.

A second, more compelling and challenging reason for investing in research and development relates to the need to extend productivity gains and poverty reduction to those segments of Asian society and the rest of the developing world who have not benefited from the green revolution. The projected number of people in South Asia who cannot afford an adequate diet will still be large for the foreseeable future. Under the baseline assumptions of IFPRI's IMPACT model, which projects a slight decline in world rice prices by 2020, there will still be more than 50 million malnourished children below the age of six in India and Bangladesh at that time, accounting for nearly half the population in that age cohort (Rosegrant et al 1995). If world prices were to rise, the situation would be much worse. If we ignore this issue, then a large segment of Asian society will fail to participate in economic growth.

We emphasize that reduction in poverty will be achieved in the future as it has in the past by sustained growth in agricultural productivity. In CGIAR circles where "poverty eradication" is now the main theme, this point seems to be poorly understood. Lipton (1999), referring to what he calls "mission creep" in the CGIAR, reports investments to increase productivity fell from 74% in 1972-76 to 39% in 1997-98.

What are the prospects for further gains in rice productivity?

Major advances in varietal improvement designed to break the yield ceiling established by IR8 include a new plant architecture and the development of hybrid rice that is adaptable to the tropics (Dawe 1998). Compared with current MVs, the new plant type (sometimes referred to as 'super rice') will have fewer tillers but these tillers will have longer panicles bearing more grains, plus sturdier stems and deeper roots to support the increased grain weight. The grain-bearing panicles will also sit lower relative to the tops of the leaves to reduce shading and enhance photosynthetic activity.

Hybrid rice will give a yield advantage of about 15–20% over inbred lines. Hybrids have been grown for 20 years in China and until recently covered half of China's rice-growing area. It appeared that hybrids were poised to spread rapidly in India, but consumers have regarded the quality as inferior to popular inbred lines and the price has been discounted by more than 10% (Janaiah and Hossain 2001).

Whether the above technologies will have a major impact on production and productivity is uncertain. However, biotechnology—tissue culture, gene mapping, gene transfer, etc.—has now become an important avenue for advances in plant breeding. Owing to the advent of molecular mapping and the ability to scan the genomes of wild species for new and useful genes, we may now be in a position to unlock the genetic potential of these germplasm resources (Tanksley and McCouch 1997). In the case of rice, for example, exotic germplasm is a likely source of new and valuable genes capable of increasing yield and other complex traits important to agriculture.

However, the ability to capture intellectual property rights has led to rapid private-sector investments in biotechnology and, in some instances, a virtual buy-out of public-sector research capacity at the universities. The concern is that the priorities of the private firms are likely to draw funding away from important crop improvement work that would benefit the developing countries and in particular the poorer segments of these economies.

The Rockefeller Foundation over the past 15 years has been supporting biotechnology research on rice by more than 50 researchers from advanced and developing countries. They and other interested researchers have met every 18–24 months to review progress, exchange experiences, and make arrangements for training opportunities in one another's facilities. More than 400 scientists from developing countries have been trained at the PhD or postdoctoral level in this effort. The recent development of varieties fortified by vitamin A and iron demonstrate the potential of such work not only in the traditional lines of improving yields, insect and disease resistance, etc., but also in nutrition and health. Hopefully the Foundation's program will ensure that support for research in rice biotechnology will remain a public-sector priority.

As a result of the growing scarcity and competition for water and the persistent poverty in drought-prone areas, more research is needed that ties together management of scarce water resources, agronomic practices, and development and selection of suitable rice varieties. New technology and management practices are needed to increase rice productivity in many of the water-stressed areas bypassed by the green revolution.

Reflections on the legacy of Bob Chandler

In this final section of the paper, we would reflect briefly on the role of IRRI and the course set by its first director in helping to build the foundation for rice research in Asia. Most of us associate IRRI with the development of the semidwarf or MV of rice. But by the time IRRI was established, much progress had already been made in this direction. We knew about the progress being made in developing modern wheat varieties. We were less aware of the fact that the Chinese were developing semidwarf varieties. The new technology was just around the corner, which explains why in just 4 short years, IRRI was able to release IR8 or, as the saying goes, "get to first base." While not minimizing IRRI's role in technology development, we would like to suggest that much of IRRI's success and unique contribution was in the development of trained manpower that built a research and extension foundation in the national programs and enabled the rapid dissemination of the new technologies.

IRRI was established initially for 25 years. A major objective was not only to solve the then current food problem but *to develop capacity in rice research to allow developing countries to solve their own problems.* This would require a major effort in manpower training at all levels from hands-on extension to PhDs. The founding fathers from the Ford and Rockefeller foundations decided to locate IRRI in Los Baños, knowing that both the foundations were supporting major programs to strengthen agricultural research at the University of the Philippines College of Agriculture (UPCA) in Los Baños. The Ford Foundation's contribution was through a 10-year grant to the University of the Philippines and Cornell University (1962-72) to develop an exchange program to strengthen graduate training (Turk 1974).

What emerged was a de facto joint venture between IRRI and the University of the Philippines Los Banos (UPLB, formerly UPCA). UPLB graduates formed the foundation of IRRI's excellent research support staff. Early emphasis was given to training at all levels. IRRI staff served as members of graduate student committees at UPLB and helped to supervise their research and some IRRI staff taught courses at the University. Other graduate students did thesis research at IRRI, receiving their degrees from universities in other countries. The number of trainees at IRRI is summarized in Table 9. The impact on the development and dissemination of new rice technology has been enormous.

Those who remember with a sense of nostalgia IRRI, Los Baños, and the rice fields of Asia during the Chandler days will be shocked and perhaps a little dismayed at the changes that have taken place. One is reminded of the words of the famous American author, Thomas Wolfe (1940), "you can't go home again . . . back home to the old forms and systems of things which once seemed everlasting but which are changing all the time." IRRI has, of course, played an important role in bringing about these changes. The

Table 9. Short-term group training, degree and nondegree training at IRRI,1962-99.

Short-term group training	
Trainees (no.) 1962-99	5,823
Degree and nondegree training (1962-99)	
Completed (no.)	
PhD	345
MS	569
OJT or interns	1,114
Affiliate scholars (no.)	
PhD	135
MS	81
Total	2,244

process of transformation described in this paper extends well beyond the rice fields. Gains in agricultural productivity have supported wider economic development. But rice remains the single most important crop in Asia, and continued advances in rice research will bring benefits to millions, particularly the poorer segments of Asian society.

Fortunately, the research foundation is strong. Today, it is impossible to go anywhere in the rice-growing world and not find people that have been to Los Baños. In short, the house that Chandler built has rooms all over the rice-growing world. This is the legacy of Bob Chandler.

References

Barker R, Seckler D, Amarasinghe U. 1999. The world's water: emerging issues in an era of growing scarcity. Choices Fourth Q. (special issue)

Conway G. 1997. The doubly green revolution: food for all in the 21st century. UK: Penguin Books Ltd. 335 p.

Datt G, Ravallion M. 1998a. Farm productivity and rural poverty in India. J. Dev. Stud. 34(4):62-85.

Datt G, Ravallion M. 1998b. Why have some Indian states done better than others at reducing rural poverty? Economica 65:17-38.

David CC, Otsuka K. 1994. Modern rice technology and income distribution in Asia. Boulder, CO (USA): Lynne Rienner Publishers. 473 p.

Dawe D. 1998. Reenergizing the Green Revolution in Rice. Am. J. Agric. Econ. 80:948-953.

Estudillo JP, Fujimura M, Hossain M. 1999. New rice technology and comparative advantage in rice production in the Philippines. J. Dev. Stud. 35(5):162-184.

Evans LT. 1986. Yield variability in cereals: concluding assessment. In: Hezell P, editor. Summary proceedings of a workshop on Cereal Yield Variability. Washington, D.C.: International Food Policy Research Institute.

FAO (Food and Agriculture Organization). 1990. Midterm review of FAO intercountry programme for development and application of integrated pest control in rice in South and Southeast Asia. Rome (Italy): FAO.

Fan S, Hezell P, Thorat S. 2001. Government spending, growth and rural poverty in rural India. Am. J. Agric. Econ. (in press)

Guerra LC, Bhuiyan SI, Tuong TP, Barker R. 1998. Producing more rice with less water from irrigated systems. IRRI Disc. Pap. Ser. 29. 19 p.

Hayami Y, Kikuchi M. 2000. A rice village saga: three decades of green revolution in the Philippines. New York (USA): Barnes & Noble and Manila (Philippines): International Rice Research Institute. 274 p.

Heller J. 1962. Catch-22. UK: Jonathan Cape Ltd.

Herdt RW, Capule C. 1983. Adoption, spread, and production impact of modern rice varieties in Asia. Manila (Philippines): International Rice Research Institute. 53 p.

Hopkirk P. 1991. The great game. UK: Oxford University Press.

Hossain M. 1998. Rice research, technological progress, and the impact on the rural economy: the Bangladesh case. In: Pingali PL, Hossain M, editors. Impact of rice research. Manila (Philippines): International Rice Research Institute. p 311-342.

Hossain M, Pingali PL. 1998. Rice research, technological progress, and impact on productivity and poverty: an overview. In: Pingali PL, Hossain M, editors. Impact of rice research. Manila (Philippines): International Rice Research Institute. p 1-25.

IRRI (International Rice Research Institute). 1982a. Articles of Incorporation of the International Rice Research Institute, Inc. as amended October 14, 1982. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1982b. IR36, the world's most popular rice. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1995. World rice statistics. 1993-94. Manila (Philippines): IRRI. 260 p.

Isvilanonda S, Hossain M. 1998. Recent changes in Thailand's rural economy: a case study of six villages in the Central and Northeast regions. Paper presented at the workshop on Prioritization of Rice Research in Asia, 20-22 Apr 1998, International Rice Research Institute, Los Baños, Philippines.

Janaiah A, Hossain M. 2001. Adoption of hybrid rice technology in India: an economic assessment of early farm-level experiences. In: Peng S, Hardy B, editors. Rice research for food security and poverty alleviation. Proceedings of the International Rice Research Conference, 31 March-3 April 2000, Los Baños, Philippines. Los Baños (Philippines): International Rice Research Institute. p 231-240.

Kikuchi M, Barker R, Samad M, Weligamage P. 2000. Comparative advantage of rice production in an ex-rice importing country: the case of Sri Lanka, 1968-1997. Paper presented at the Asian Society of Agricultural Economists Conference, 18-22 Oct 2000, Jaipur, India.

Levine G, Sheng KH, Barker R. 2001. The evolution of Taiwanese irrigation: implications for the future. Int. J. Water Resour. Dev. (in press)

Lipton M. 1999. Reviving global poverty reduction: what role for genetically modified plants? Paper presented at the Sir John Crawford Memorial Lecture, The CGIAR Secretariat, Washington, D.C.

Lipton M, Longhurst R. 1989. New seeds and poor people. London (UK): Unwin Hyman.

Marciano EB, Gascon F, Cabrera E, Hossain M. 2001. Technology impact on distribution of rural household income and poverty: insights from a repeat village study representing different rice ecosystems in the Philippines. In: Peng S, Hardy B, editors. Rice research for food security and poverty alleviation. Proceedings of the International Rice Research Conference, 31 March-3 April 2000, Los Baños, Philippines. Los Baños (Philippines): International Rice Research Institute. p 603-615.

Pingali PL, Hossain M, Gerpacio R. 1997. Asian rice bowls: the returning crisis. UK: CAB International.

Rosegrant MW, Pingali PL. 1994. Policy and technology for rice productivity growth in Asia. J. Int. Dev. 6(6):665-688.

Rosegrant MW, Sombilla MA, Perez N. 1995. Global food projections to 2020: implications for investment. Food, Agriculture and the Environment Discussion Paper 5. Washington, D.C.: International Food Policy Research Institute.

Siamwalla A, Haykin A. 1983. World rice market structure, conduct and performance. Research Report 39. Washington, D.C.: International Food Policy Research Institute.

Tanksley SD, McCouch SR. 1997. Seed banks and molecular maps: unlocking genetic potential from the wild. Science 227:1063-1066.

Timmer CP. 1993. Rural bias in the East and Southeast Asian rice economy: Indonesia in comparative perspective. J. Dev. Stud. 29(4):149-176.

Timmer G. 1997. Farmers and markets: the political economy of new paradigms. Am. J. Agric. Econ. 79:621-627.

Tomich TP, Kilby P, Johnston BF. 1995. Transforming agrarian economies: opportunities seized, opportunities missed. Ithaca (NY): Cornell University Press.

Turk K. 1975. The Cornell-Los Baños story. Ithaca (NY): New York State College of Agriculture and Life Sciences.

Wolfe T. 1940. You can't go home again. New York: Harper & Brothers.

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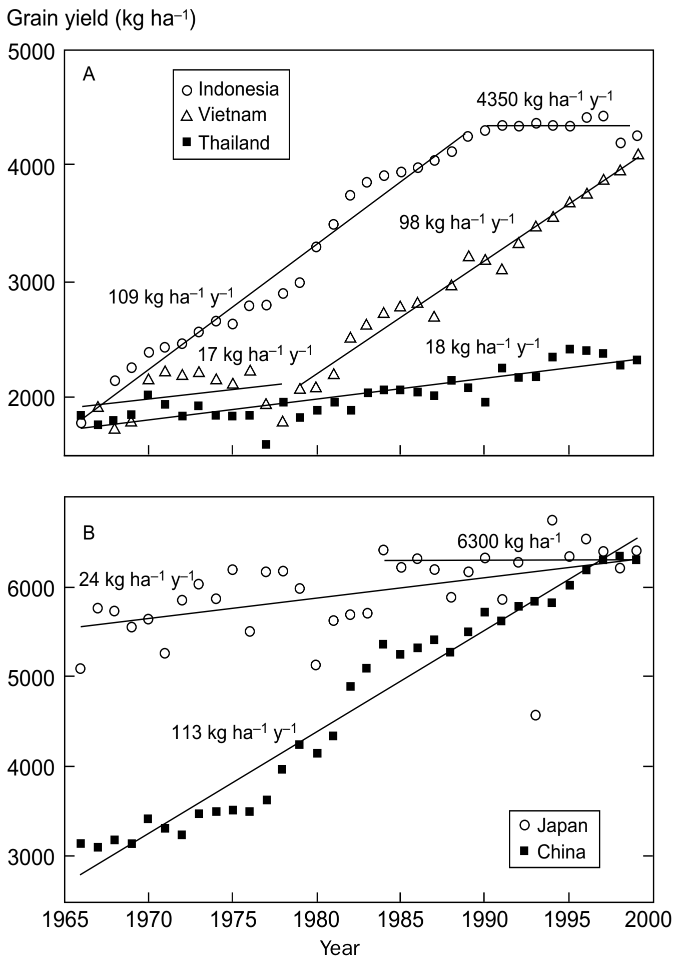
Evolving rice production systems to meet global demand

K.G. Cassman and A. Dobermann

The changes that have occurred in rice production systems during the past 30 years provide a point of departure for our discussion about how rice production systems will evolve in the 21st century. Fundamental to this discussion are assumptions about the projected global demand for rice, the availability and quality of land and water resources on which to produce it, and scientific breakthroughs that will influence the means of production.

In exploring these issues, we focus attention on irrigated rice because most of the increase in global rice supply has come from irrigated systems, which presently account for more than 75% of global production (IRRI 1993). In contrast, increased production from less favorable rainfed systems has been relatively small because of severe biophysical constraints—including drought, flooding, and poor soils—limit the magnitude of yield gains from the seed and fertilizer technologies that were the driving forces of the so-called green revolution. Comparison of yield trends in Thailand, Indonesia, and Vietnam illustrate this point (Fig. 1A). In Thailand, rainfed rice predominates, soils are of poor quality, and the rate of gain in average yield is small. In contrast, most rice is grown with irrigation in Indonesia and Vietnam and the rate of yield gain has been much greater than in Thailand.

We presume that feeding rapidly growing urban populations in Asia will depend largely on the yield advances obtained from irrigated rice systems. We are not optimistic that scientific breakthroughs in genetic improvement will greatly improve tolerance of the rice plant for biophysical stresses such as drought, flooding, or macronutrient deficiencies. As a result, we do not expect the magnitude of increase in production from less-favorable rainfed systems to have a significant impact on global rice supplies.



1. National average rice yields from 1966 to 1999 in several Asian countries (data obtained from *http://apps.fao.org*). Annual rates of gain are obtained from linear regression. An apparent yield plateau is indicated for Indonesia (A) (1990-99) and (B) Japan (1984-99).

Rice supply and demand projections

Recent estimates of rice demand indicate that a compound annual growth rate of 1.2% is needed to meet expected rice consumption in 2020 (Rosegrant et al 1998). There is general consensus that there is little scope for expansion of rice production area because urbanization will likely offset any expansion of rice production on land not presently farmed. Protection of remnant natural ecosystems and preservation of the biodiversity they contain are also valid concerns, especially in Asia, where population density is already high. Hence, the projected increase in rice demand must be met almost entirely by greater output per unit area on existing rice land.

Increased production per unit land area can be achieved by obtaining higher yields per crop and by increasing the number of crops grown each year on the same land. Continuous rice cropping with two and sometimes three crops each year on the same land is the predominant land use in the humid and subhumid lowland tropics and subtropics of Asia. Further increases in the number of rice crops per year above present cropping intensity will provide relatively little increase in total rice output. In addition, an increase in irrigated area is unlikely to occur in Asia because of increasing competition for water resources from other economic sectors and concerns about the environmental, social, and economic costs of large irrigation projects. Therefore, with little potential for increasing cropping intensity or net expansion of irrigated area, meeting projected rice demand will depend on sustaining an adequate rate of gain in average rice yields on existing irrigated land.

The ability to maintain adequate rates of yield gain largely depends on two factors: 1) the genetic yield potential of available rice varieties, and 2) the size of the exploitable gap between average farm yields and the genetic yield potential ceiling. Yield potential is defined as the yield that can be achieved with adapted varieties when water, nutrients, and pests are nonlimiting to crop growth (Evans and Fischer 1999).

The challenge of increasing rice yield potential

Release of IR8 in 1966, plus the semidwarf varieties that soon followed, marked the beginning of the green revolution in Asia. These new rice varieties provided a quantum leap in yield potential when compared with the traditional land races they replaced because of shorter stature, lodging resistance, greater harvest index, and responsiveness to nitrogen (N). With continuous rice cropping, however, the early IR varieties became sensitive to a number of insect pests and diseases. In response, breeding programs focused on incorporating disease and insect resistances into the next generation of IR varieties—an effort that was remarkably successful (Khush and Coffman 1977, Khush 1990). Today, IR germplasm releases contain strong resistance to a number of major disease and insect pests, and host-plant resistance provides the foundation of integrated pest management (IPM) in irrigated rice systems (Heong et al 1995).

While the emphasis on improving pest resistance was justified during the 1970s and 1980s, it diverted attention from the challenge of increasing yield potential. Recent studies suggest there has been little increase in the yield potential of inbred rice varieties released since IR8 (Peng et al 1999). Because average irrigated rice yields are predicted to approach the existing yield potential ceiling in the early decades of the 21st century, the explicit goal of increasing rice yield potential became a high research priority in the late 1980s (IRRI 1989). Indica x indica hybrids were developed with a 7–10% increase in yield potential above that of the best inbred varieties such as IR72 (Peng et al 1999). This increase, however, is not sufficient to maintain an exploitable yield gap for the next 20 years. Hence, a new IRRI project was established involving collaboration among geneticists, physiologists, agronomists, entomologists, and plant pathologists to develop a new plant type with a 25–50% increase in yield potential compared with the best inbred indica varieties (Peng et al 1994).

Increased sink size was postulated as the most important trait for increasing rice yield potential. A plant type with fewer tillers, thicker stems, larger panicles, and greater lodging resistance was proposed. Although considerable progress has been made in identifying germplasm sources for developing this new plant type, validation of its higher yield potential has been thwarted by lack of insect and disease resistance in the germplasm. In addition, the sink limitation hypothesis, which was the basis for the design of the new plant type concept, has not been corroborated (Kropff et al 1993). More recent research has identified early vegetative growth rate and the ability to maintain high N concentration in the leaf canopy as crucial factors for alleviating 'source' limitations to rice yield potential (Sheehy et al 1998, 2000).

While the goal of increasing rice yield potential continues to warrant a high research priority, it is not certain that a major breakthrough is imminent. Promising avenues currently under investigation include incorporating genes that confer C_4 photosynthesis into the rice plant (Ku et al 1999) and improving lodging resistance so that higher leaf N concentration can be maintained to improve radiation use efficiency during the most rapid crop growth periods (Sheehy et al 2000).

But incorporation of these traits and development of adapted varieties will require considerable time and research investment. It is noteworthy that the challenge of increasing yield potential in other crops also has been underestimated. For example, there is little evidence of increase in the yield potential of maize hybrids grown in the USA during the past 30 years, despite a much larger research investment in maize improvement than for rice (Duvick and Cassman 1999).

In summary, efforts to raise the yield potential ceiling deserve a high research priority but we assume only small, incremental increases will be achieved during the next 20–30 years—in contrast to the quantum leap that initiated the green revolution. Even modest gains of perhaps 10–15% in yield potential, however, will require considerably more research investment than presently devoted to this goal and improved crop management practices are needed to support yield stability at higher levels of productivity. Therefore, we speculate that increased production from irrigated rice systems in the next 20–30 years will come largely from improved crop, soil, water, and pest management to close the existing gap between average and potential yield levels.

Rate of yield gain and the exploitable yield gap

It becomes increasingly difficult to move average farm yields up the yield curve as average yields increase toward the yield potential threshold (Cassman 1999). This is illustrated by the fivefold greater rate of gain in rice yields in China than in Japan since the mid-1960s (Fig. 1B). In Japan, average rice yields were exceeded 5 t ha^{-1} at the beginning of this time series versus initial average yields less than 2 t ha^{-1} in China. Despite the relatively high prices paid for rice in Japan, average rice yields have leveled off at 6.3 t ha^{-1} since the mid-1980s—a yield level roughly 80% of the climate-adjusted yield potential (Matthews et al 1995). A similar leveling off in average yields at about 6.3 t ha^{-1} is evident in Korea since the early 1980s (data not shown)—which is again roughly 80% of the climate-adjusted yield potential (Shin and Lee 1995). Stagnation of average farm yields at some level below the genetic yield potential ceiling occurs because it is not possible for farmers to implement the degree of precision in crop management operations, on a commercial scale, required to achieve maximum possible yields.

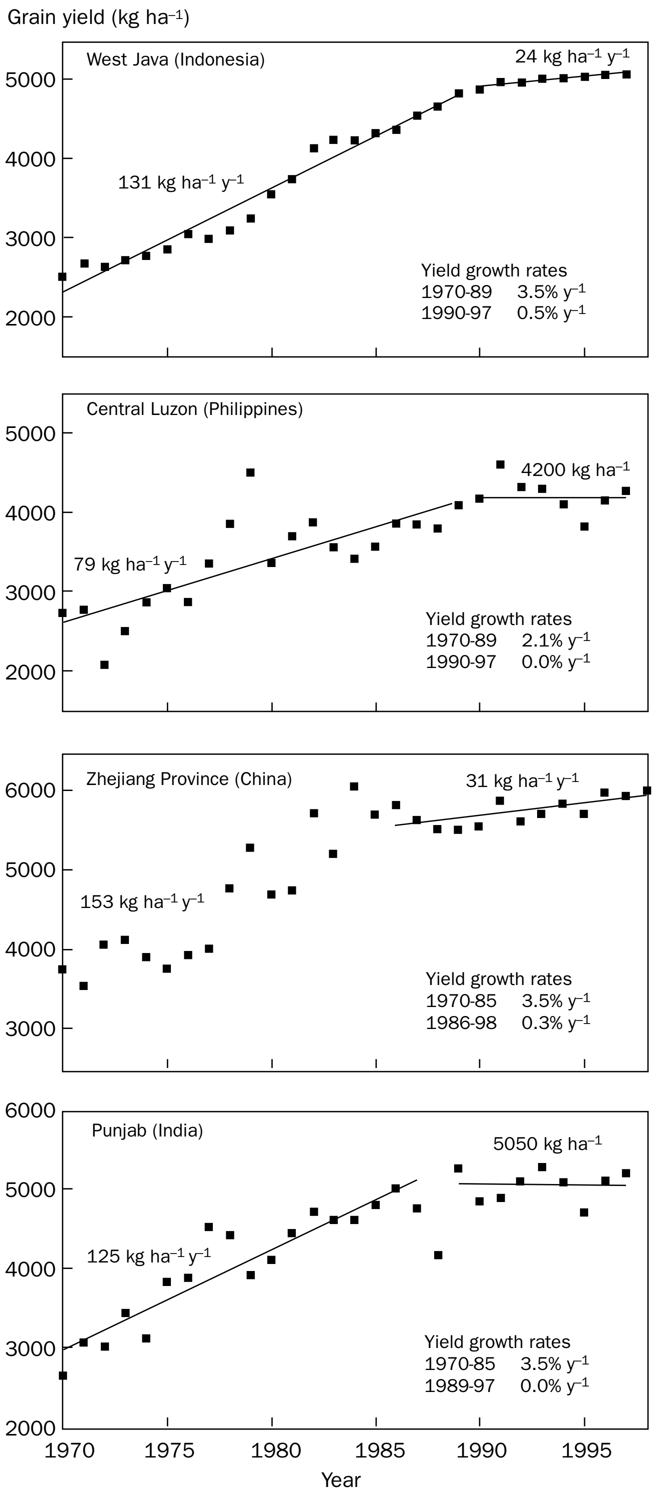
Assuming that 80% of the climate-adjusted yield potential represents a realistic upper threshold for the maximum average yield that can be achieved on a regional or country basis, the exploitable yield gap on a regional or national scale is the difference between average farm yields and the 80% yield potential value. Hence, we propose that the rate of yield increase will decrease to zero as average yields approach the 80% threshold and the exploitable yield gap disappears. Although the yield trend in China does not appear to be leveling off, average yields above 6 t ha^{-1} have only recently been attained (Fig. 1B). At issue is whether China can maintain the same linear rate of yield increase as average yields exceed 6 t ha^{-1}, or whether yield stagnation will set in. We suspect that stagnation somewhere near the 80%

yield potential threshold will soon become evident in China because the average climate-adjusted yield potential is about 8 t ha^{-1} for inbred varieties and 8.8 t ha^{-1} for hybrids in the intensive double-crop rice production areas (Dufeng and Shaokai 1995).

Nearly all rice is produced in irrigated systems in China, Japan, and Korea. In Indonesia, about 75% of rice output is produced with irrigation, which makes it more difficult to estimate an appropriate yield potential ceiling, given the additional limitations of drought and flooding that occurs in rainfed systems. It appears, however, that yields in Indonesia have stagnated at about 4.3 t ha^{-1} since the late 1980s (Fig. 1A). At issue here is whether yield stagnation is occurring prematurely at levels well below the 80% yield potential limit.

Examination of irrigated rice yield trends at regional or district levels where farmers were early adopters of modern rice production technologies suggests that premature stagnation, or a marked decrease in the rate of yield gain, is a relatively common phenomenon (Fig. 2). In each of the regions shown in Figure 2, rice is the predominant crop and is grown almost entirely in irrigated systems. In addition, soils are relatively fertile and the climate is favorable for rice production. In spite of these natural resource endowments, stagnation or a marked deceleration in yield gain is evident at yield levels well below the climate-adjusted 80% yield potential threshold. Yield trends display a remarkably similar pattern, with a rapid rate of increase during the first 15–20 years after adoption of modern rice production technologies in the late 1960s, followed by an abrupt deceleration or stagnation in the past 10–15 years. For example, dry-season yield potential in Central Luzon averages about 10 t ha^{-1} (Kropff et al 1993), yet average dry-season yields have leveled off at about 40% of this value. Premature stagnation at yield levels well below 80% of yield potential results from lack of adoption of crop management practices that are responsive to the dynamic ecological conditions that characterize intensive rice systems. More responsive, information-intensive management, field-specific approaches are needed to fully exploit the existing yield gap in irrigated rice systems of Asia. We describe the crucial components of a precision agriculture approach for small-scale irrigated rice systems in a subsequent section.

For irrigated rice in developing countries of Asia, average yield was 5.2 t ha^{-1} in 1995, which is about 64% of the climate-adjusted yield potential of 8.1 t ha^{-1} as estimated by the ORYZA1 simulation model for modern inbred rice varieties in these agroecosystems (Matthews et al 1995). Assuming a 10% yield potential advantage for indica x indica hybrid rice (Peng et al 1999), today's average yields would be 58% of the yield potential ceiling for hybrid rice. For



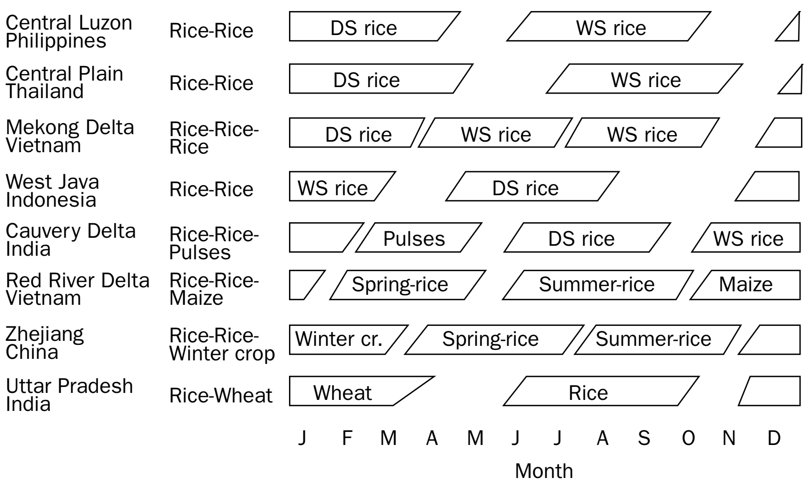
2. Yield trends of irrigated rice in four states, provinces, or regions in which farmers were early adopters of modern rice production technologies during the late 1960s. Rice is grown in continuous annual double-crop systems in West Java, Central Luzon, and Zhejiang Province and yield trends are shown for the highest yielding season, which is typically the dry-season or late rice crop. In Punjab state, farmers practice an annual rice-wheat rotation. Annual rates of yield increase are estimated from a piece-wise linear regression. An apparent yield plateau is indicated for Central Luzon (1990-97) and Punjab (1989-97). Data obtained from Social Sciences Division, IRRI.

both inbred and hybrid rice, annual yield gains of 1.2%, which are required to meet predicted rice demand, will cause the exploitable yield gap to disappear by 2020 in most of the major irrigated rice production regions unless scientists can develop new varieties with greater yield potential. Even a modest 10–15% increase in yield potential will be of critical importance to the goal of sustaining rice production increases.

Irrigated rice systems today

As previously mentioned, intensification of irrigated rice systems during the past 35 years involved both an increase in the number of crops grown per year on the same piece of land—made possible by irrigation and rice varieties of short duration—and greater yield per crop cycle. Higher yields resulted from the combination of increased yield potential of modern varieties compared with the land races they replaced, improved crop nutrition made possible by fertilizer application, and improved pest management to minimize losses from weeds, insects, and disease. More detailed discussion of the intensification process is provided elsewhere (Cassman and Pingali 1995).

Two features distinguish irrigated rice systems on the eve of the 21st century: 1) the small amount of time that land is fallowed, and 2) a lack of crop diversity (Fig. 3). Continuous rice systems with short fallow breaks are practiced in the major rice-producing regions of tropical and subtropical Asia.



3. Predominant cropping systems and the annual cropping calendar in several major irrigated rice production areas of South, Southeast, and East Asia.

Among these are West Java of Indonesia, Central Luzon of the Philippines, the Central Plain of Thailand, the Mekong and Red River deltas of Vietnam, and the Cauvery Delta of Tamil Nadu, India. Farmers in some of these regions are moving toward three rice crops each year although the total area where such cropping intensity is practiced is relatively small. In parts of China, such as Zhejiang Province, a nonrice crop is grown during the winter season in rotation with spring and summer rice crops. Recent trends, however, indicate that farmers are eliminating the winter crop because of labor shortages (G. Wang, Zhejiang University, pers. commun.). In contrast, inclusion of a nonrice crop continues to be a common practice in irrigated systems of the Cauvery Delta, the Red River Delta, and the rice-wheat zone of northern India and south-central China.

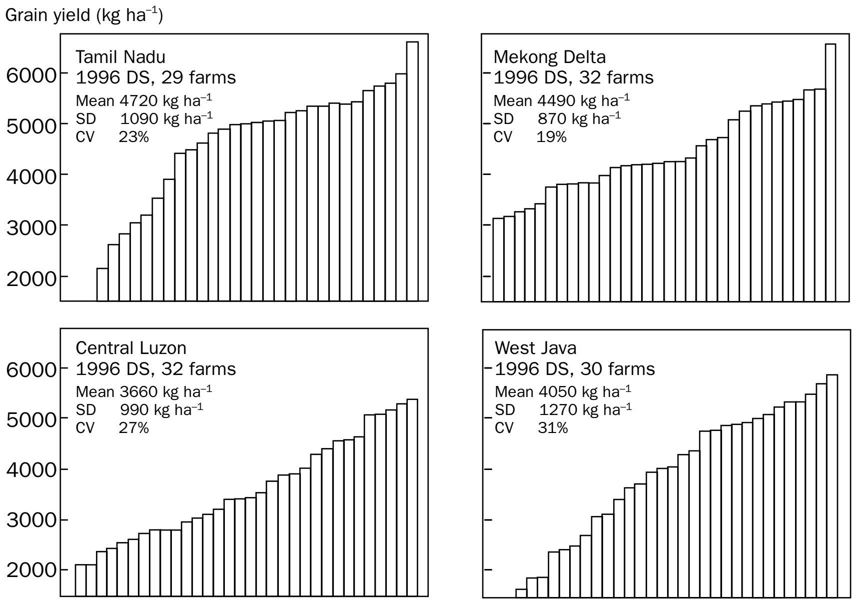
Biophysical production constraints

Irrigated rice yields in the developing countries of Asia are limited by a number of factors. The most widespread limitations are nutrient deficiencies, pest damage, soil constraints, and water relations (Greenland 1997).

Nutrient deficiencies

The greatest constraint to increased yield of irrigated rice is N deficiency caused primarily by poor N fertilizer-use efficiency. N deficiency is an ubiquitous characteristic of irrigated, lowland rice soil. The uptake efficiency from applied N in farmers' fields is typically less than 30% (Dobermann 2000). Recent on-farm research has shown that the low N recovery efficiency results from imbalance among the crop demand, the supply of N from soil, and amount of applied N (Adhikari et al 1999, Cassman et al 1998). Although the yield obtained without N fertilizer varies greatly among farms on similar soil types because of differences in soil N supply (Fig. 4), farmers do not adjust the amount of N fertilizer applied to these fields in accordance with the soil N supply (data not shown). This situation occurs because standard N fertilizer recommendations are provided on a district or regional basis and do not account for the tremendous field-to-field variability in soil N supply that exists in these seemingly uniform lowland rice soils. Precise balance between crop N demand and the N supply from indigenous soil resources and applied fertilizer is required to increase yields, optimize profit, and minimize environmental concerns associated with N losses.

Although green manures, such as legume cover crops or azolla, can provide significant quantities of biologically fixed N_2 (BNF), their use is declining rapidly because they are not cost-effective compared with N



4. Irrigated rice yields without N fertilizer as measured in replicated plots located within farmers' fields in four irrigated rice production areas. Each bar represents the mean yield from three replicate plots per farmer's field. Fields were on similar soil types within each production area. Differences in rice yield largely represent field-to-field variation in the indigenous soil N supply available to the rice crop. Data from Reversing Trends of Declining Productivity (RTDP) database, IRRI.

fertilizer (Ali 1999). Increased labor requirements and loss of time available for production of a grain crop discourage adoption of green manure technologies. In addition, residual benefits from green manures in terms of improved soil quality or increased soil N supply in continuous irrigated rice production are relatively small (Cassman et al 1996). The lack of longer term benefits from green manure appears to reflect the unique N- and carbon-conserving properties of flooded rice systems as discussed in the following section.

Long-term experiments and on-farm studies have documented the need to maintain an appropriate balance of other macronutrients, in addition to N, to sustain rice yields (Dobermann et al 1998, Witt et al 1999). In most regions, the amount of phosphorus (P) applied by Asian rice farmers is sufficient to sustain present rice yields and there has not been serious P depletion of soil (Dobermann 2000). Local soil P depletion only occurs in areas where fertilizer P use is below the current average removal of about 18 kg P ha^{-1} crop^{-1}, e.g., parts of Central Luzon, Philippines, or rice-wheat areas in Nepal. In contrast, potassium (K) input has not matched K removal in most areas and K deficiency is becoming a more widespread problem. We estimate that about 80% of the intensive rice fields in Asia have a negative K balance, with an average of about –25 to –30 kg K ha^{-1} $crop^{-1}$. Other mineral deficiencies (e.g., S, Zn, and Mg) occur in certain irrigated rice areas in Asia, but they hardly represent a general constraint and can be alleviated easily once they are properly diagnosed (Dobermann and Fairhurst 2000).

Soil quality

Several basic properties of wetland soils have contributed and will continue to contribute to the biophysical sustainability of rice farming systems (Greenland 1997). These include

- Avoidance of acidification because of the physical chemistry of flooded soil systems.
- Nutrients tend to be leached into lowland soil rather than out of it because of their landscape position.
- Phosphorus is maintained in more readily available forms than in aerated, upland soils.
- Significant input of N is derived from BNF.
- Relatively little threat of erosion because fields are well leveled and surrounded by bunds.

In spite of these advantages, the maintenance of soil quality is still important, given the need to sustain a vigorous rate of gain in rice yields into the foreseeable future.

Soil quality can be defined by a subset of physical, chemical, and biological properties that have the greatest influence on rice yield and input-use efficiency. Trends in soil quality can be quantified by monitoring changes in those soil properties over time. A unique characteristic of lowland soils that are continuously cropped with rice in flooded soil is the conservation of both organic matter and N. Conservation occurs even when all aboveground crop residue is removed (Cassman et al 1995). Some long-term experiments document a significant C and N sequestration with time. The ability to maintain, or even accumulate, C results from additional inputs of C from photosynthetic biomass (e.g., algae) in the soil-floodwater system, and the reduced degradation rates of humus that results from anoxic soil conditions. The maintenance or accretion of N despite high removal rates with harvested grain results from large inputs of N from BNF and the stabilization of applied fertilizer N in young humus. In contrast, C and N sequestration does not occur when rice is rotated with a nonrice cereal crop, such as wheat as in the rice-wheat systems of the Indo-Gangetic Plain, unless additional organic inputs are applied as manure or green manure (Duxbury et al 2000).

The C and N sequestration capacity of continuous rice compared with a rice-maize rotation was recently quantified in an IRRI field study (Witt et al 2000). Nitrogen losses exceeded inputs from fertilizer and BNF in the rice-maize system such that there was a 3% decline in soil N. In contrast, soil N increased by 10–14% in continuous rice systems. The difference in N conservation resulted from smaller losses of N fertilizer and greater input of BNF-N in the continuous rice system. Despite the conservation of C and N, however, soil N supply available to the rice crop is not closely associated with organic matter or soil N content (Cassman et al 1998). Instead, factors such as soil aeration, crop residue management, and tillage practices have a greater influence on the N supply from indigenous soil N reserves (Witt et al 2000).

Soil constraints such as salinization and iron toxicity are of a more local concern and not widespread in irrigated rice systems of Asia. Avoidance or remediation of these constraints begins with good water management, including an appropriate amount of drainage.

In summary, maintenance of soil quality should not be a major constraint to sustaining yield gains in irrigated rice systems if soil fertility can be maintained and nutrients applied in precise balance with crop demand. Meeting the nutrient requirements of the rice crop and maintaining adequate soil fertility will require a field-specific nutrient management approach to account for the large field-to-field variation in the indigenous soil nutrient supply, especially for N. Improved understanding of factors governing N cycling in lowland rice soils will be needed to develop cost-effective, field-specific N management.

Insects, diseases, and weeds

Continuous cropping in tropical and subtropical climates fosters the buildup of insect and disease populations because the host-free period is minimal and temperature rarely exceeds tolerance thresholds of pest organisms. For this reason, a number of insect pests and diseases become endemic and cause severe yield reductions unless control measures are taken. For many of the most important leafhoppers and foliar feeders, adequate host plant resistance has been incorporated into more recent rice varieties and the need for pesticide application is minimal (Heong et al 1995), especially when varieties are rotated to avoid selection for specific biotypes that can overcome the sources' host plant resistance. We now know to avoid continuous widespread use of a single variety. At one time, for example, IR36 was grown on more than 10 million hectares of irrigated rice in Asia and quickly became susceptible to the brown planthopper and viral diseases transmitted by leafhoppers.

Other insect pests, such as the stem borer, are more difficult to control because adequate host plant resistance has not been found in rice germplasm. The incidence of these insect pests must be carefully monitored to allow timely application of insecticide when populations exceed thresholds at which economic losses occur. Use of biotechnology approaches to transfer novel sources of resistance to these insects holds promise to reduce dependence on pesticide for managing them.

Several rice diseases also become endemic to intensive rice systems and can cause severe yield loss when climatic conditions favor an epidemic. For some, such as blast, host-plant resistance has been identified and incorporated into recent varieties. With those, fungicide as control measures are not needed, except when climatic conditions are extremely conducive to infection and the crop is well supplied with N. In contrast, adequate host-plant resistance for sheath blight has not been identified in rice germplasm, and it is difficult to avoid yield loss without preventative measures when climatic conditions are conducive to disease progression. Like blast, sheath blight incidence and yield loss are more severe in crops that are well supplied with N (Cu et al 1996). Prophylactic fungicide treatment is required to consistently achieve high yield levels, especially when climatic conditions favor disease progression. Here again, identification of novel resistance genes to endemic diseases such as sheath blight and their transfer to rice using molecular approaches should be a high research priority.

Yield loss from weed competition is also a widespread constraint, especially in broadcast direct-seeded rice for which hand weeding or cultivation is not economically feasible. As labor costs increase, adoption of direct seeding increases because it requires much less labor than transplanting. Increased herbicide use has coincided with the adoption of direct seeding. But even with widespread adoption of direct seeding, the large majority of irrigated rice is still transplanted in Asia.

Water-use efficiency

Another potential threat to sustaining yield gains of irrigated rice is timely access to adequate amounts of irrigation water. Rapidly growing urban populations and increased industrial and recreational demand compete for water resources allocated to agriculture (Postel 1998). Because water-use efficiency in irrigated rice systems is relatively low and a large proportion of available freshwater resources is presently used for rice production, we anticipate that increasing competition for water will drive innovation in water-conserving technologies.

Evolution of irrigated rice systems to 2020

The driving forces of change in irrigated rice production systems during the next several decades in the developing countries of Asia can be summarized as follows:

- Economic development will continue to increase personal income.
- Although diets will change dramatically as incomes rise, rice demand will increase at a compound annual rate of 1.2%.
- Population growth will occur primarily in urban areas.
- There will be little, if any, net increase in rice cropping area or in the amount of irrigated land available for rice production.
- Labor costs will continue to rise faster than the cost of energy (and N fertilizer).
- Increases in rice yield potential will be relatively small and even small increases will require a major increase in research investment above present levels.
- Competition for water resources will intensify.

Given these trends, yield gains must be sustained even as average yields approach the 80% yield potential threshold. Although farmers in Japan and Korea have demonstrated the ability to maintain rice yields at this threshold, they receive a price that is 4–5 times greater than the present world market price for rice. Such high prices allow rice farmers in these countries to use high levels of fertilizer and pesticide inputs. The fact that Korea and Japan account for 50% of the global insecticide market for rice while producing only 4% of global rice supply illustrates this point (Wood Mackenzie Consultants 1993). Hence, we believe the Japan-Korea model of intensive rice production is not valid for developing countries for three reasons:

1. The cost of rice production would increase substantially;
2. A significant increase in rice prices would be required to offset the increased cost of production, which would have the largest negative impact on poor urban and rural consumers; and
3. Environmental quality would be degraded unless farmers achieve large increases in the efficiency with which inputs are utilized to obtain the required advances in yield.

For example, to increase rice yields at an annual rate of 1.2% will require a 30% increase in average irrigated rice yields to nearly 7 t ha^{-1} by 2020. This yield level is 86% of the climate-adjusted yield potential of existing inbred varieties and about 79% of the yield potential of indica hybrid rice. Without an increase in N fertilizer-use efficiency, N fertilizer rates must increase by 114% to achieve the 30% increase in yield (Dobermann 2000). Such high rates of N fertilizer use and low uptake efficiency would promote losses of N from denitrification, which contributes to the greenhouse gas load in the atmosphere (Bronson et al 1997) and nitrate losses to ground and surface water resources (Buresh et al 1989).

Given these economic and environmental concerns about input use in irrigated rice systems, we argue the need for a quantum leap in the sophistication of crop and soil management practices to achieve a precise match of genotype to environment while utilizing field-specific tactics to ensure that input requirements are met without deficiency or excess in time and space. We also speculate that the premature stagnation in rice yields that occurs in some favorable, irrigated rice domains (Fig. 2) results from lack of a precision agricultural approach that can accommodate the tremendous season-to-season variation in climate, which determines yield potential, and field-to-field variation in soil nutrient supply (Fig. 4), insect and disease pressure, and other factors affecting yield and input requirements.

Precision agriculture for small-scale rice farmers

Mechanization

Timely tillage, planting, and harvest are often hindered by lack of labor at appropriate times. Rising labor costs and labor shortages have driven a shift from transplanted to direct-seeded rice in a number of major rice-producing regions. We expect this trend to continue in both continuous rice systems and in the rice-wheat systems. Because establishment of direct-seeded rice requires a finer degree of leveling than transplanted rice, mechanized tillage operations are needed to facilitate the soil-leveling process. Early incorporation of crop residues during the fallow period when soils are aerated, which requires increased mechanical power for tillage of unsaturated soils, also appears to improve the congruence between the indigenous soil N supply and the N demand in the subsequent rice crop and may reduce N fertilizer requirements (Witt et al 2000). Conservation tillage in rice-wheat systems will also require a degree of mechanization.

Timeliness of harvest operations is pivotal in annual double-crop and triple-crop systems to allow planting of the following crop at the optimum time in relation to weather patterns. Because labor requirements for manual harvest are substantial and increase in proportion to yield level, mechanization will be needed to achieve higher yields and timely planting. Timely planting is particularly important in systems that have a relatively short turnaround time between crops, such as for wheat following rice in the rice-wheat systems of India and China, and in the triple-crop systems of the Mekong and Red River deltas of Vietnam and southeast China (Fig. 3).

To accommodate mechanization, average field size must increase. While the typical size of a managed field unit today is 0.2–0.50 hectare, we expect this to double or triple within the next 20 years if economic growth and labor costs increase as expected. Appropriate equipment of relatively small size will be needed.

Water management

Competition for water resources will force major changes in crop management of irrigated rice systems. Reducing the amount of time soil remains flooded and the depth of floodwater has the greatest impact on water requirements for irrigated lowland rice (De Datta 1981, Bhuiyan et al 1995). Both tactics often lead to increased weed pressure because maintenance of a standard floodwater depth of 5–10 cm contributes to the control of weeds not adapted to anaerobic soil conditions. Therefore, water-saving management strategies must be closely linked with improved weed management practices, which will entail increasing reliance on herbicides because the cost of labor is increasing much faster than the cost of herbicides (Pingali et al 1997). The shift to mechanized tillage operations will provide opportunities for direct row-seeding to establish the dry-season rice crop, similar to sowing methods in Australia and the southern USA. This planting method allows a crop establishment period without standing water and interrow cultivation for weed control.

More radical changes in the way irrigated rice is grown will be required if competition for water intensifies to such an extent that allocation for rice production is greatly reduced. Ultimately, there may be need for systems that produce rice in aerated soil that is saturated with water only when heavy rainfall causes ponding or after intermittent flood irrigation. Flush irrigation to saturate the soil and then allow soil moisture depletion until a subsequent irrigation is required would greatly reduce irrigation requirements. Sprinkler irrigation would allow even further increases in water-use efficiency. Irrigation systems such as these, however, will require a tremendous body of research to develop new rice varieties specifically adapted to this type of culture because present rice varieties do not yield as well when grown in soil without standing floodwater throughout most of the growing season (Bhuiyan et al 1995). In addition, research must also identify appropriate weed, disease, and nutrient management tactics because substantial modification of existing practices developed for flooded soil culture will be required.

Integrated nutrient, insect, and disease management

Increasing awareness of the high degree of variation and dynamic changes in soil nutrient supply and pest pressure among fields within relatively homogeneous environments has caused rice researchers to reassess the manner in which management recommendations are developed (Cassman et al 1998, Dobermann and White 1999). In the past, standard guidelines and rules of thumb were extended to farmers on a regional basis without modification for field-specific characteristics. We hypothesize that this standard recommendation approach cannot sustain yield increases as average yields approach the 80% yield potential threshold because they are not sensitive to the large differences in nutrient supply and pest pressure among fields and thus cannot optimize yield and input-use efficiency concomitantly. Moreover, the margin for error for yield reductions from lodging or increased disease sensitivity caused by excessive N fertilizer is relatively small. Therefore, management of N, insect, and disease pests must respond to in-season conditions rather than follow a prescribed set of standard guidelines.

A responsive, field-specific management approach will require farmers to monitor crop growth stage, N status, and pest pressure to precisely identify when N topdressings, insecticide, or fungicide application are required. As average yields increase toward the yield potential ceiling, farmers will need to monitor crop growth and N status and have access to predictions of growth stage, crop stage, and yield potential from crop simulation models that use real-time weather data and weather projections. This information is crucial for estimating the N fertilizer requirement and the proper timing for N topdressings and prophylactic treatment against endemic diseases when weather conditions are conducive to disease progression.

We believe that the revolution in information technology will make it feasible for smallholder rice farmers in Asia to access the needed information. Without access to this information, it will not be possible to sustain the rate of yield gain needed to meet rice demand.

Rice farmers currently have limited means for adjusting fertilizer rates according to the nutrient supply from indigenous sources (soil, water, atmosphere) or to seasonal climatic fluctuations. In collaboration with scientists in six countries, however, IRRI researchers are currently testing field-specific nutrient management tactics that focus on managing spatial and temporal variability in nutrient supply (Dobermann and White 1999, Witt et al 1999). Development of robust but simple, user-friendly decision-making tools are crucial for implementing this approach. Real-time N management appears to be necessary for optimizing N nutrition at high yield levels. Considerable progress toward this goal has been made using plant-based technologies such as the chlorophyll meter, simple leaf color charts, and strategies based on tiller counts at critical growth stages.

Diversification and rice cropping intensity

Opportunities to diversify irrigated rice systems are limited because the lowland soils on which most rice is produced are prone to waterlogging during the wet (monsoon) season. Rice is by far the best adapted food crop for these lowland soils in the wet season. Although alternative crops can be grown successfully in the dry season, a significant shift out of dry-season rice would place a larger burden on rice production in the wet season, which has a smaller yield potential because of lower solar radiation. A significant decrease in dry-season rice area would require average wet-season yields to exceed the 80% yield potential threshold by a large margin. We do not believe it is possible to consistently achieve such yield levels on a regional or countrywide basis even if farmers adopt sophisticated, precision-agriculture approaches.

In peri-urban rice production areas, it is likely that farmers will shift out of dry-season rice production, and perhaps quit rice production entirely, because greater economic returns can be obtained from vegetable and fruit crops for urban markets. Depending on the amount of land involved, this shift to other crops in peri-urban areas could have a significant impact on rice supplies as cities expand to accommodate the tide of urban migration.

Despite the potential to reduce N fertilizer requirements, continued decreases in the use of green manure crops are expected unless there is a major trend reversal in the relative costs of labor and energy. Therefore, except in peri-urban areas, we envision continuous rice cropping to remain the predominant food production system in the tropical and subtropical lowlands of Asia. If rice prices increase because of shortages, a shift from double to triple rice cropping is likely to expand beyond existing areas in the Mekong Delta and the Central Thailand Plain.

We do not envision that more diverse cropping systems are required to sustain the needed increases in rice yields in lowland rice systems in which soils remain flooded during most of the cropping season because the soil-floodwater system provides a unique environment that supports a high degree of biodiversity (Simpson et al 1994), sequesters carbon and N (Cassman et al 1995), and preserves soil quality (Greenland 1997). If, however, water shortages force rice to be grown without flooded soils—using intermittent irrigation as discussed in a previous section—we would predict that greater diversity in crop rotations will be required to sustain rice yields without the benefits conferred by the flooded soil system.

Biotechnology and rice germplasm

The degree to which biotechnology influences the productivity of irrigated rice will depend on whether the use of molecular genetics, molecular physiology, and marker-assisted selection can accelerate progress in the improvement of complex traits, such as yield and drought resistance. Both traits are under multigenic control and we are not optimistic that molecular approaches will lead to substantial improvements in these traits in the foreseeable future. In contrast, we envision considerable impact from molecular approaches to increase host-plant disease and insect resistance. Resistance can often be improved by manipulation of a limited number of genes and useful genes conferring resistance can be found in both rice germplasm and in other organisms. Genomics, transformation, and marker-assisted selection will accelerate gene identification and incorporation into adapted varieties to achieve improved host-plant resistance. Greater tolerance for sheath blight and stem borer is a high-priority target for this research.

Molecular approaches to improve grain quality traits will also contribute to the economic viability of rice systems if farmers can profit from the greater end-use value. Increased profitability will be pivotal to provide the capital farmers need for mechanization and the adoption of precision agriculture approaches in crop management. Significant changes will be required in rice markets to maintain identity preservation of grain with improved end-use quality and to ensure that farmers obtain a portion of the increased value.

Conclusions

Sustaining yield gains in irrigated rice systems to meet projected demand will prove to be a greater challenge than is generally recognized. It becomes more difficult to maintain yield gains as average yields approach the yield potential ceiling, and rice yield potential has increased little since the release of the first modern varieties in the 1960s. Yield stagnation in several major irrigated rice production regions and countries illustrates this point. A quantum leap in sophistication of management of all production factors will be required to sustain yield gains from present levels to the commercially feasible threshold of about 80% yield potential. Although research to increase rice yield potential must remain a high priority, gains are likely to be small and incremental in the foreseeable future. The need to maintain increases in rice output will afford few opportunities for diversification such that continuous irrigated rice cropping will remain the predominant production system except in peri-urban areas. Molecular genetics and biotechnology will be pivotal for improving pest resistance to achieve stable production at high yield levels in continuous rice systems and to improve nutritional quality and end-use value. Increased investment in research and extension will be required to sustain the level of ecological intensification that must be achieved by several hundred million rice farmers in Asia.

References

Adhikari C, Bronson KF, Panaullah GM, Regmi AP, Saha PK, Dobermann A, Olk DC, Hobbs P, Pasuquin E. 1999. On-farm soil N supply and N nutrition in the rice-wheat system of Nepal and Bangladesh. Field Crops Res. 64:273-286.

Ali M. 1999. Evaluation of green manure technology in tropical lowland rice systems. Field Crops Res. 61:61-78.

Bhuiyan SI, Sattar MA, Khan MAK. 1995. Improving water use efficiency in rice irrigation through wet-seeding. Irrig. Sci. 16:1-8.

Bronson KF, Neue HU, Singh U, Abao EB. 1997. Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen, and water management. Soil Sci. Soc. Am. J. 61:981-987.

Buresh RJ, Woodhead T, Shepherd KD, Flordelis E, Cabangon RC. 1989. Nitrate accumulation and loss in a mungbean/lowland rice cropping system. Soil Sci. Soc. Am. J. 53:477-482.

Cassman KG. 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96:5952-5959.

Cassman KG, Pingali PL. 1995. Intensification of irrigated rice systems: learning from the past to meet future challenges. GeoJournal 35:299-305.

Cassman KG, De Datta SK, Amarante S, Liboon S, Samson MI, Dizon MA. 1996. Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources on tropical lowland rice. Exp. Agric. 32:427-444.

Cassman KG, De Datta SK, Olk DC, Alcantara JM, Samson MI, Descalsota JP, Dizon MA. 1995. Yield decline and the nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal R, Stewart BA, editors. Soil management: experimental basis for sustainability and environmental quality. Boca Raton, FL (USA): Lewis/CRC Publishers. p 181-222.

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann A, Singh U. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56:7-39.

Cu R, Mew TW, Cassman KG, Teng PS. 1996. Effect of sheath blight on yield in a tropical, intensive rice production system. Plant Dis. 80(10):1103-1108.

De Datta SK. 1981. Principles and practices of rice production. New York (USA): John Wiley & Sons. 618 p.

Dobermann A. 2001. Future intensification of irrigated rice systems. In: Sheehy JE, editor. The quest to reduce hunger: redesigning rice photosynthesis. Manila (Philippines): International Rice Research Institute. 293 p.

Dobermann A, White PF. 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. Nutr. Cycl. Agroecosyst. 53:1-18.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE. 1998. Management of phosphorus, potassium, and sulfur in intensive, irrigated rice systems. Field Crops Res. 56:113-138.

Dobermann A, Fairhurst TH. 2001. Rice: nutrient disorders and nutrient management. Singapore: Potash and Phosphate Institute and International Rice Research Institute. 191 p.

Dufeng Z, Shaokai M. 1995. Rice production in China under current and future climates. In: Matthews et al, editors. Modeling the impact of climate change on rice production in Asia. Wallingford (UK): CAB International. p 217-235.

Duxbury JM, Abrol IP, Gupta RK, Bronson KF. 2000. Analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In: Abrol IP et al, editors. Long-term soil fertility experiments in rice-wheat cropping systems. Rice-Wheat Consortium Paper Series 6. New Delhi (India): Rice-Wheat Consortium for the Indo-Gangetic Plains. p 7-22.

Duvick DN, Cassman KG. 1999. Post-green-revolution trends in yield potential of temperate maize in the north-central United States. Crop Sci. 39:1622-1630.

Evans LT, Fischer RA. 1999. Yield potential: its definition, measurement, and significance. Crop Sci. 39:1544-1551.

Greenland DJ. 1997. The sustainability of rice farming. Wallingford (UK): CAB International. 273 p.

Heong KL, Teng PS, Moody K. 1995. Managing rice pests with less chemicals. GeoJournal 35:337-349.

IRRI (International Rice Research Institute). 1989. IRRI toward 2000 and beyond. Manila (Philippines): IRRI. 142 p.

IRRI (International Rice Research Institute). 1993. IRRI rice almanac. Manila (Philippines): IRRI. 66 p.

Khush G. 1990. Varietal needs for different environments and breeding strategies. In: Muralidharan K, Siddiq EA, editors. New frontiers in rice research. Hyderabad (India): Directorate of Rice Research. p 68-75.

Khush G, Coffman WR. 1977. Genetic evaluation and utilization (GEU), the rice improvement program at the International Rice Research Institute. Theor. Appl. Genet. 51:97-110.

Kropff MJ, Cassman KG, van Laar HH, Peng S. 1993. Nitrogen and yield potential of irrigated rice. Plant Soil 155/156:391-394.

Ku SB, Agarie S, Nomura M, Fukayama H, Tsuchida H, Ono K, Hirose S, Toki S, Miyao M, Matsuoka M. 1999. High-level expression of maize phophoenolpyruvate carboxylase in transgenic rice plants. Nat. Biotechnol. 17:76-80.

Matthews RB, Horie T, Kropff MJ, Bachelet D, Centeno HG, Shin JC, Mohandass S, Singh S, Zhu Defeng, Moon Hee Lee. 1995. A regional evaluation of the effect of future climate change on rice production in Asia. In: Matthews et al, editors. Modeling the impact of climate change on rice production in Asia. Wallingford (UK):CAB International. p 95-139.

Peng S, Cassman KG, Virmani SS, Sheehy J, Khush GS. 1999. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. Crop Sci. 39:1552-1559.

Peng S, Khush GS, Cassman KG. 1994. Evolution of the new plant ideotype for increased yield potential. In: Cassman KG, editor. Breaking the yield barrier. Proceedings of a Workshop on Rice Yield Potential in Favorable Environments. Manila (Philippines): International Rice Research Institute. p 5-20.
Pingali PL, Hossain M, Gerpacio RV. 1997. Asian rice bowls: the returning crisis. Wallingford (UK): CAB International. 341 p.
Postel SL. 1998. Water for food production: will there be enough in 2025? Bioscience 48(8):629-637.
Rosegrant MW, Leach N, Gerpacio RV. 1998. Alternative futures for world cereal and meat consumption. Washington D.C. (USA): International Food Policy Research Institute.
Sheehy JE, Dionora MJA, Mitchell PL, Peng S, Cassman KG, Lemaire G, Williams RL. 1998. Critical nitrogen concentrations: implications for high-yielding rice (*Oryza sativa* L.) cultivars in the tropics. Field Crops Res. 59:31-41.
Sheehy JE, Mitchell PL, Dionora MJA, Peng S, Khush GS. 2001. Nitrogen increases radiation conversion factor and unlocks the yield barrier in rice. Plant Prod. Sci. (in press)
Shin JC, Lee MH. 1995. Rice production in South Korea under current and future climates. In: Matthews et al, editors. Modeling the impact of climate change on rice production in Asia. Wallingford (UK): CAB International. p 199-215.
Simpson IC, Roger PA, Oficial R, Grant IF. 1994. Effects of nitrogen fertilizer and pesticide management on floodwater ecology in a wetland ricefield. I. Experimental design and dynamics of the photosynthetic aquatic biomass. II. Dynamics of microcrustaceans and dipteran larvae Biol. Fertil. Soil 17:129-146.
Witt C, Cassman KG, Olk DC, Biker U, Liboon SP, Samson MI, Ottow JCG. 2000. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling, and productivity of irrigated rice systems. Plant Soil 225:263-278.
Witt C, Dobermann A, Abdulrachman S, Gines HC, Wang GH, Nagarajan R, Satawthananont S, Son TT, Tan PS, Tiem LV, Simbahan GC, Olk DC. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63:113-138.
Wood Mackenzie Consultants, Ltd. 1993. Global rice pesticide market. Basel (Switzerland): Plant Protection Division, Ciba-Geigy Ltd.

Notes

Authors' address: Department of Agronomy, University of Nebraska, Lincoln, NE 68583-0915.
Citation: Rockwood WG, editor. 2001. Rice research and production in the 21st century: symposium honoring Robert F. Chandler, Jr. Los Baños (Philippines): International Rice Research Institute. 224 p.

Is rice and wheat productivity falling in Asia?

P.L. Pingali

Phenomenal growth of cereal crop productivity in the developing world, particularly for rice and wheat in Asia, occurred during the last three decades. High levels of investments in research and infrastructure development, especially irrigation infrastructure, resulted in the rapid intensification of cropping of the lowlands. The irrigated and the high-rainfall lowland environments consequently became the primary source of food supply for Asia's escalating population. The emergence of the rice-wheat system in South Asia as the most important source of food supply is a testament to the success of the green revolution in wheat and rice.

Recent signs, however, indicate a slowdown in productivity growth of rice and wheat, especially in the intensively cultivated lowlands of Asia, and particularly in the intensively cultivated rice-wheat zones of South Asia. Slackening of infrastructure and research investments and reduced policy support partly explain the slowdown. We argue that in addition to the above factors, degradation of the lowland resource base due to intensive use also contributes to declining productivity growth rates. Intensification *per se* is not the root cause of lowland resource-base degradation, but rather the policy environment that encouraged inappropriate land use and injudicious input use, especially water and chemical fertilizers.

Trade policies and output price policies, as well as input subsidies, have contributed to the unsustainable use of the lowlands. The dual goals of food self-sufficiency and sustainable resource management are often mutually incompatible. Policies designed for achieving food self-sufficiency tend to undervalue goods not traded internationally, especially land and labor resources. As a result, food self-sufficiency in countries with an exhausted land frontier, particularly the countries of South Asia, came at a high ecological and environmental cost. Appropriate policy reform, both at the macro as

Table 1. Rice and wheat production (million t) in South Asia, 1950-97.

Rice production	1950-52	1960-62	1970-72	1980-82	1990-92	1993-95	1996-98
Bangladesh	10.9	14.1	15.6	20.9	27.1	26.3	28.2
India	32.4	49.2	62.3	77	109.4	120.5	123.1
Nepal	2.5	2.3	2.2	2.3	3.1	3.3	3.7
Pakistan	1.2	1.6	3.4	5	4.8	5.7	6.5
South Asia	47.0	67.2	83.5	105.2	144.4	155.8	161.5
Wheat production							
Bangladesh	<0.1	<0.1	0.1	1.1	1.1	1.2	1.5
India	6.7	11.3	25	38.9	55.7	61.6	65.8
Nepal	<0.1	0.1	0.2	0.4	0.8	1.0	1.0
Pakistan	3.1	4.0	6.9	11.7	15.8	16.3	17.4
South Asia	9.8	15.4	32.2	52.1	73.4	80.1	85.8

well as at the sector level, will go a long way toward arresting and possibly reversing the current degradation trends.

Looking back

In 1950-52, rice production for all of South Asia was only 47 million tons. By 1996-98, it was 161.5 million tons, with India the largest producer at 123 million tons. We note a similar story with wheat production. Production increased from 9.8 million tons in 1950-52 to 85.8 million tons in 1996-98, with India the largest producer at around 66 million tons (Table 1). Between 1966 and 1998, the annual growth rates of rice (2.75%) and wheat (4.9%) production in South Asia exceeded the annual rate of growth in population (2.22%), indicating an increase in the per capita availability of the two cereals.

The dramatic increase in production came from the intensification of land use and yield growth, with the former attributable to investments in irrigation infrastructure and the latter to the adoption of modern seed and fertilizer technologies.

While the production of wheat and rice increased at a rapid rate, real food prices declined steadily since the mid-1960s. A similar decline in the real price of rice was observed in India and across Asia. The temporal decline in basic food prices was especially beneficial to urban consumers, particularly the urban poor, as well as the rural poor who tend to be net purchasers of food.

The major factors that contributed to the initial success of the green revolution and to the emergence of the rice-wheat system as an important source of food supply were

- introduction of the high-yielding, semidwarf varieties of rice and wheat (modern germplasm);
- infrastructure investments, especially irrigation systems;
- political commitment; and
- policy support.

The latter two were as important as the first two in the rapid dissemination and adoption of modern technologies and the rapid growth in food production. The commitment to achieving food self-sufficiency was the driving political force that made the green revolution happen in South Asia. Micro- and macroeconomic policies that promoted rapid productivity growth through the adoption of modern wheat and rice technologies were established in the mid-1960s.

In the early years, input price subsidies and output price supports were essential as they helped stimulate farmers to adopt new technologies. Free irrigation water, cheap fertilizers, subsidized power supply, and low-interest farm credit were some of the crucial supports provided by South Asian governments that made intensive rice-wheat production profitable. But prolonging the policies of input price subsidies into the post-green revolution period resulted in a distortion of farm-level incentives for efficient input use and led to much of the degradation observed today.

While micro policies played an important role in leading South Asian farmers to unsustainable agricultural practices, macro policy scenarios were just as important. Because food self-sufficiency was the motivating factor for many of the policy measures during the 1970s and 1980s, macroeconomic policies protected cereal prices through import restrictions and tariffs. Domestic prices were kept artificially high and excessive productive resources were devoted to the production of rice and wheat. These were safe crops that would get farmers assured prices at subsidized input prices. Thus there was no real incentive for farmers to diversify from the rice-wheat rotation.

Ecological consequences of intensification

Intensive rice-wheat rotation on the lowlands resulted in the changes in production systems. Those were

- seasonal wet and dry crop cycles over the long term,
- increased reliance on irrigation and inorganic fertilizers,
- asymmetry of planting schedules, and
- greater uniformity in the varieties cultivated.

Over the long term, these changes imposed significant environmental costs due to negative biophysical impacts.

The most common environmental consequences of lowland intensification are

- buildup of salinity and waterlogging;
- depletion or pollution of water resources;
- formation of a hardpan (subsoil compaction);
- changes in soil nutrient status, nutrient deficiencies, and increased incidence of soil toxicities;
- increased pest buildup, pest-related yield losses, and associated consequences of increased and injudicious pesticide use.

A brief description of each of these problems and the possibilities for reversing them are discussed below. At the farm level, long-term changes in the biophysical environment are manifested in terms of declining total-factor productivity, profitability, and input efficiencies. Many of the degradation problems mentioned above were policy-induced and the result of inappropriate and inefficient land, water, and input use practices.

Salinity and waterlogging

Intensive use of irrigation water in areas with poor drainage can lead to a rise in the water table due to the continual recharge of groundwater. This leads to salinity buildup in semiarid and arid zones and to waterlogging in the humid zone. Salinity results from an excess of evapotranspiration over rainfall, which causes a net upward movement of water and the concentration of salts on the soil surface. The groundwater need not be saline for salinity to build up; it can occur due to the long-term evaporation of continuously recharged water of low salt content (Moorman and van Breeman 1978).

Poor irrigation system design and management are primary factors leading to salinity problems. Irrigation water provided free, or at low cost, to the farmer tends to aggravate the problem. Dogra (1986) estimates that nearly 4.5 million hectares in India are affected by salinization, and a further 6 million hectares are affected by waterlogging. In the short term, salinity buildup leads to reduced yields while in the long term, it can lead to abandoning of croplands (Samad et al 1992, Postel 1989, Mustafa 1991).

In high-rainfall areas, such as in east India, induced salinity buildup is not as much a problem because the rain flushes out the accumulated salts. However, excessive water use and poor drainage cause problems of waterlogging in that zone. Waterlogged fields have lower productivity levels because of lower decomposition rates of organic matter, lower nitrogen availability, and accumulation of soil toxins. In the case of wheat, low plant populations in some areas can be attributed to waterlogging, especially waterlogging during germination and emergence stages of wheat. Hobbs et al (1996) report that waterlogging reduced yields in the Nepal Tarai by 0.5 t ha^{-1}.

Groundwater depletion

Development of groundwater resources has been a significant driving force for agricultural intensification in many parts of Asia. The massive expansion of private-sector tubewell irrigation in Bangladesh, India, and Pakistan is the most successful example of private-sector irrigation development. A groundwater revolution in Bangladesh beginning in the 1980s was a key stimulant to rapid agricultural growth in the 1980s and early 1990s. Nearly 1.5 million hectares of land were newly irrigated after 1980, in significant part from installation of shallow tubewells spurred by deregulation of tubewell imports (Rogers et al 1994).

Excess use of free irrigation water can lead to rising water tables and salinization, but it can also lead to falling water tables in tubewell areas and create negative environmental and productivity consequences. The problem of overuse of groundwater often occurs because individual irrigators have no incentive to optimize long-run extraction rates.

While mining of both renewable and nonrenewable water resources can be an optimal economic strategy, groundwater overdrafting is excessive in many intensive agricultural areas in Asia. And the overdrafting is exacerbated when electricity for tubewell operations is subsidized. Government intervention to prevent depletion of groundwater in the developing world has proven difficult to implement, subject to corruption, and in many cases, very costly.

The most successful tubewell development has been through small-scale private investment, which is widely dispersed and difficult to monitor. A small-scale tubewell revolution took off in Bangladesh only after private tubewell imports and markets were deregulated. Restrictions on well sites slowed growth in tubewell adoption during 1985-87 (Rogers et al 1994). India has been ineffective at implementing licensing laws at the state level, where ownership of all water resources resides. Pakistan has no legal system for licensing groundwater withdrawals, and limited attempts to give ownership of underlying aquifers to municipalities have been challenged in the courts (Pingali and Rosegrant 1998).

Changes in soil nutrient status

The most commonly observed effect of intensive rice-wheat systems is a decline in the partial factor productivity of N fertilizer (Hobbs and Morris 1996). Work at IRRI (Cassman et al 1995) indicates that the declining partial factor productivity of N in rice monoculture systems is due to a decline in the N-supplying capacity of intensively cultivated wetland soils. Rice-wheat systems could be facing a similar phenomenon. Fertilized rice and wheat obtain 50–80% of their N requirement from the soil; rice obtains an even larger portion, mainly through the mineralization of organic matter (De Datta 1981). The soil's capacity to provide N to the plant declines with continuous (two to three crops per year) flooded rice cultivation systems. Declining soil N supply results in declining factor productivity of chemical N, since soil N is a natural substitute for chemical N. The magnitude of yield forgone due to declining soil N supply is estimated by Cassman and Pingali (1993). Using long-term experiment data from IRRI, Cassman and Pingali (1993) estimate the decline in yields to be around 30%, over a 20-year period, at all N levels.

In addition to N, P, and K are the two other macronutrients demanded by rice and wheat. Phosphorus and K deficiencies are becoming widespread across Asia in areas not previously considered to be deficient. These deficiencies are directly related to the increase in cropping intensity and the predominance of year-round irrigated production systems. In China, for example, an estimated two-thirds of agricultural land is now deficient in P, while in India nearly one-half of the districts have been classified as low in available P (Stone 1986, Tandon 1987, Desai and Gandhi 1989). Desai and Gandhi note that this is due to the emphasis on N rather than a balanced application of all macronutrients required for sustaining soil fertility. The result of unbalanced application of fertilizers has been a decline in the efficiency of fertilizer use over time (Desai and Gandhi 1989, Stone 1986, Ahmed 1985).

Soil micronutrient deficiencies and toxicities

Perennial flooding of ricelands and continuous rice monoculture as well as the rice-rice-wheat rotation lead to increased incidence of micronutrient deficiencies and soil toxicities. Zinc deficiency and Fe toxicity are the ones most commonly observed in the tropics. Waterlogging and salinity buildup, often caused by poor water pricing and water management practices, aggravate these problems. In Asia, Zn deficiency is regarded as a major limiting factor for wetland rice on about 2 million hectares (Ponnamperuma 1974).

Zinc deficiency is also important among the micronutrient deficiencies in the rice-wheat zone. These are mainly soils of low Z content. Soils that are not initially of low Z content also show signs of induced Z deficiency due to perennial water-saturated conditions and continuous cropping. Drainage, even if temporary, helps alleviate this deficiency by increasing Zn availability (Lopes 1980, Moormann and van Breeman 1978).

Most irrigated lowlands do not start off with any soil toxicities but toxicities build up in some soils due to continuous flooding, increased reliance on poor-quality irrigation water, and impeded drainage, especially on soils where a hardpan is formed due to alternating wet and dry cycles. Iron toxicity is the most commonly observed soil toxicity due to intensive irrigated crop cultivation.

Once diagnosed at the farm level, micronutrient deficiencies are relatively straightforward to correct. Diagnosis is not easy, however, and quite often micronutrient deficiencies are misdiagnosed as pest-related damage. In the case of soil toxicities, farm-level diagnosis is equally complicated and corrective actions are not as straightforward. In both cases, however, the problem ought to be attacked at the cause rather than the cure stage. Periodic breaks in rice monoculture systems or rice-rice-wheat systems (two crops of rice followed by a crop of wheat) and improved water-use efficiency go a long way toward reducing the incidence and magnitude of the above problems.

Long-term changes in soil physical characteristics

Seasonal cycles of puddling (wet tillage) and drying lead over the long term to formation of hardpan (compacted subsoil that is 5–10 cm thick at depths of 10–40 cm) in rice soils. A striking example of the problem of hardpans is found in the rice-wheat cropping system of South Asia where there is poor establishment of wheat following rice. If the hardpan is broken through deep tillage and soil structures are improved through the incorporation of organic matter, it reduces the productivity of the subsequent rice crop by reducing water-holding capacity of the soil. Thus, intensification has reduced the flexibility of dry-season crop choice by changing the soil physical structure.

Increasing losses due to pests

The use of purchased inputs for plant protection was not important for cereal production prior to the mass introduction of modern varieties. Farmers had traditionally relied on host plant resistance, natural enemies, cultural methods, and mechanical methods such as hand weeding. Agricultural intensification in general and continuous cropping of cereals in particular increased the incidence of weed, insect, and disease problems (Pingali and Gerpacio 1997, Hobbs and Morris 1996).

In the case of rice, relatively minor pests—leaffolder, caseworm, armyworm, and cutworm—started to cause noticeable losses in farmers' fields as area planted to modern varieties increased. Hence the rapid increase in insecticide use in intensive rice monoculture systems (Rola and Pingali 1993). In the case of wheat, insecticide use is not prevalent and fungicide use has been largely avoided by the development of varieties with resistance to major diseases. However, some diseases, such as *Helminthesporium sativum* (spot blotch) are on the rise in intensive wheat production zones, as well as in the rice-wheat zone.

Soilborne diseases are also becoming an increasingly important factor in constraining yield growth in the rice-wheat areas of the Indo-Gangetic plains. On the other hand, the incidence of kernel bunt, an important disease problem in wheat, has been reduced with the advent of rice-wheat system, because the saturated soil for rice is unfavorable for disease buildup.

Crop-management and pesticide-use practices have exacerbated insect and disease problems that have emerged. Injudicious and indiscriminate pesticide application is related to policies that made chemicals easily and cheaply accessible. Heong et al (1992) argued that prophylactic pesticide application has led to the disruption of the pest-predator balance and a resurgence of pest populations later in the crop season. Rola and Pingali (1993) argued that pesticide use has been promoted by policymakers' misperceptions of pests and pest damage. Policymakers commonly perceive that modern variety use necessarily leads to increased pest-related crop losses and that modern cereal production is therefore not possible without high levels of chemical pest control.

Ecologically safe methods of weed management continue to be a major concern for the rice-wheat system. *Phalaris minor* became the major weed problem with the advent of the rice-wheat cropping (Hobbs and Morris 1996). Homogeneity of cropping patterns across large areas contributed to the rapid buildup and spread of *Phalaris*. Breaking up the cropping pattern reduces the weed buildup and herbicide resistance problems. Cropping pattern choices, however, are made on economic grounds rather than on sustainability grounds.

The widespread availability of insect- and disease-resistant varieties for the major cereals has reduced the productivity benefits and the profitability of applying insecticides and fungicides. Pingali and Gerpacio (1997) provide a current review of the impact of host plant resistance for the major cereals and Rola and Pingali (1993) provide specific evidence for rice. Even where resistant varieties are used, one could anticipate pest problems due to a narrowing of genetic diversity on farmers' fields. When many farmers, in the same area, choose to grow the same high-yielding variety, or ones with similar resistance genes, there is a lower level of genetic diversity than will most effectively protect against the emergence and spread of new disease strains (Heisey et al 1997).

Increasing diversity on farmers' fields, however, is not a simple proposition. The socially optimal level of diversity might differ quite substantially from the private optimum due to potential yield tradeoffs and the cost of frequent varietal replacement.

Policies for reversing the current degradation trends

Meeting future food requirements in Asia requires sustained productivity growth. Continued high levels of investments in research and infrastructure, as well as institutional and policy reforms, are needed.

While resource base degradation is increasingly observed in the rice-wheat belt, intensification *per se* is not the root cause of environmental and ecological damage. Severe environmental degradation in intensified agriculture occurs mainly when incentives are incorrect due to bad policy or a lack of knowledge of the underlying processes of degradation.

Government intervention in the cereal market, especially through output price support and input subsidies, provided farmers incentives for increasing cereal productivity. In addition to highly subsidized irrigation water, farmers benefited from cheap fertilizers, pesticides, and credit. The net result was that rice monoculture systems as well as rice-wheat systems were extremely profitable through the decades of the 1970s and the 1980s, despite a long-term decline in the real world rice and wheat prices through that period.

Input subsidies that keep input prices low directly affect crop management practices at the farm level. They reduce farmer incentives for improving input-use efficiency, which often requires farmer investment in learning about the technology and how best to use it. As Asian countries liberalize their agricultural sectors and move away from the single-minded pursuit of food self-sufficiency, one can expect positive resource base and environmental benefits.

Many of the degradation problems observed in the intensively cultivated rice-wheat lands are not irreversible and appropriate policies will provide farmers the incentives to invest in more sustainable land and crop management practices. Techniques for improving fertilizer-use efficiency, for example, are available but will only be viable at the farm level when fertilizer subsidies are removed. The same is the case for the adoption of zero-tillage, integrated pest management (IPM) techniques, or more judicious water management. Table 2 provides details on policy interventions that contribute to resource base sustainability.

Water subsidies (and power subsidies for operation of tubewells) should be phased out, with more realistic water charges in all sectors, in order to create incentives for efficient and more environment-friendly water allocation. In the longer term, markets in tradable water rights should be established where feasible. Establishment of secure water rights for water users is an important foundation for the establishment of economic incentives for efficient water allocation. Moreover, responsibility for irrigation water management should be devolved where possible to autonomous local institutions with user representation or joint ownership, or both. Full financial responsibility should be granted, including right to charge for water and services (Pingali and Rosegrant 1998).

To complement the approaches to crop management improvement in reducing fertilizer-related degradation problems, fertilizer subsidies should be removed to eliminate the incentive for unbalanced and excessive use. The financial costs of fertilizer subsidies to government treasuries are high. The true economic costs can be even greater because subsidies soak up funds that could be used for alternative investments. The reduction and eventual removal of fertilizer price subsidies can substantially improve the efficiency of fertilizer use.

Nonprice policies for fertility management are also important, including location-specific research on soil fertility constraints and agronomic practices, improvement in extension services, development of improved fertilizer supply and distribution systems, and development of physical and institutional infrastructure (Desai 1986, 1988).

For various environmental and human health reasons, the IPM program has been vigorously pursued, particularly for rice. To make IPM more attractive, pesticides should never be subsidized because, as in the case of fertilizers, farmers would have no incentive to invest time in acquiring IPM skills. Removing all explicit and implicit subsidies on pesticides is essential to reduce pesticide use on farms.

With the progression toward global integration, the competitiveness of domestic cereal agriculture can only be maintained through dramatic reductions in the cost per unit of production. New technologies designed to significantly reduce the cost per unit of output produced, either through a

Table 2. Policy interventions for reversing ecological-environmental degradation problems.

Resource base degradation problem	Possible-probable causes	Farm-level indicators of resource degradation	Economic impact	Possible technology intervention	Policy change
Buildup of salinity-waterlogging	Poor design of irrigation systems	Reduced yields and reduced factor productivities		Improved irrigation system and design	Pricing irrigation water at its true cost
	Intensive use of irrigation water	Reduced cropping intensities		Increased water-use efficiency	
		Abandoned rice lands in the extreme	Declining trends in total factor productivity		
			Declining profitability of rice and wheat cultivation		
			Increased social costs of negative externalities on environment and human health		
Hardpan (subsoil compaction)	Increased frequency of puddling (wet tillage)	Reduced flexibility; nonrice crop production in the dry season		Improved farm-level drainage systems	Pricing irrigation water at its true cost
				Increased water-use efficiency	

Table 2 continued.

Resource base degradation problem	Possible-probable causes	Farm-level indicators of resource degradation	Economic impact	Possible technology intervention	Policy change
Changes in soil N- supplying capacity	Changes in organic matter quantity and quality	Declining efficiency of N fertilizer use		Crop diversification	Output price reform
	Long-term flooding/ water saturation of rice soils	Reduced yields, reduced factor productivities		Increased fertilizer-use efficiency	Removal of fertilizer subsidies
				Balance application of all nutrients	
Increased pest buildup and pest-related yield losses	Continuous rice monoculture	Increased pesticide use		Improved varieties with host plant resistance	Removal of pesticide subsidies
	Increased asymmetry of planting schedules			Appropriate varietal turnover	Investments in farmer education
	Greater uniformity in varieties grown			Adoption and use of IPM	

shift in the yield frontier or through an increase in input efficiencies, would substantially enhance farm-level profitability of cereal crop production systems. Increasing input-use efficiency would also contribute significantly to the long-term sustainability of intensive food crop production and help arrest many of the problems we describe.

References

Ahmed N. 1985. Fertilizer efficiency and crop yields in Pakistan. Phosphorus Agric. 89:17-32.

Cassman KG, Pingali PL. 1993. Extrapolating trends from long-term experiments to farmers' fields: the case of irrigated rice systems in Asia. In: Measuring sustainability using long-term experiments. Proceedings of the working conference at Rothamsted Experimental Station, (UK), 28-30 Apr 1993.

Cassman KG, De Datta SK, Olk DC, Alcantara J, Samson M, Descalsota J, Dizon M. 1995. Yield decline and the nitrogen balance in long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal R, Stewart BA, editors. Soil management: experimental basis for sustainability and environmental quality. Advances in soil science. Boca Raton, FL (USA): CRC Press. p 181-222.

De Datta SK. 1981. Principles and practices of rice production. New York, NY (USA): Wiley-Interscience Publication, John Wiley & Sons. 618 p.

Desai GM. 1988. Development of fertilizer markets in South Asia: a comparative overview. Washington, D.C. (US): International Food Policy Research Institute.

Desai GM. 1986. Fertilizer use in India: the next stage in policy. Indian J. Agric. Econ. 41:248-270.

Desai GM, Gandhi V. 1989. Phosphorus for sustainable agriculture growth in Asia—an assessment of alternative sources and management. In: Proceedings of the Symposium on Phosphorus requirements for Sustainable Agriculture in Asia and Pacific Region, 6-10 Mar 1989, Los Baños, Philippines. Manila (Philippines): International Rice Research Institute.

Dogra B. 1986. The Indian experience with large dams. In: Goldsmith E, Hildyard N, editors. The social and environmental effects of large dams. London (UK): Wadebridge Ecological Center. p 201-208.

Heisey PW, Smale M, Byerlee D, Sonza E. 1997. Wheat rusts and costs of genetic diversity in the Punjab of Pakistan. Am. J. Agric. Econ. 79:726-737.

Heong KL, Aquino GB, Barrion AT. 1992. Population dynamics of plant and leafhoppers and their natural enemies in rice ecosystems in the Philippines. Crop Prot. 11:371-379.

Hobbs P, Morris M. 1996. Meeting South Asia's future food requirements from rice-wheat cropping systems: priority issues facing researchers in the post-Green Revolution era. Natural Resource Group Working Paper 96-01. Mexico DF (Mexico): Centro Internacional de Mejoramiento de Maíz y Trigo.

Lopes AS. 1980. Micronutrients in soils of the tropics as constraints to food production. In: Priorities for alleviating soil-related constraints to food production in the tropics. Manila (Philippines): International Rice Research Institute and Ithaca, NY (US): New York State College of Agriculture and Life Sciences, Cornell University. p 277-298.

Moormann FR, van Breeman N. 1978. Rice: soil, water, land. Manila (Philippines): International Rice Research Institute. 185 p.

Mustafa U. 1991. Economic impact of land degradation (salt-affected and waterlogged soils) on rice production in Pakistan's Punjab. PhD dissertation, University of the Philippines Los Baños.

Pingali PL, Gerpacio RV. 1997. Toward reduced pesticide use for cereal crops in Asia. Economics Working Paper 97-04. Mexico DF (Mexico): Centro Internacional de Mejoramiento de Maíz y Trigo.

Pingali PL, Rosegrant MW. 1998. Intensive food systems in Asia: can the degradation problems be reversed? Paper presented at the Pre-Conference Workshop on Agricultural Intensification, Economic Development and the Environment, 31 Jul-1 Aug 1998, Salt Lake City, USA.

Pingali PL, Hossain M, Gerpacio RV. 1997. Asian rice bowls: the returning crisis? Wallingford, Oxon (UK): CAB International. 341 p.

Ponnamperuma FN. 1974. Micronutrient limitations in acid tropical rice soils. In: Bornemisza E, Alvarado A, editors. Soil management in tropical America. Raleigh (US): Soil Science Department, North Carolina State University. p 330-347.

Postel S. 1989. Water for agriculture: facing the limits. Worldwatch Paper *93*.

Rogers P, Lydon P, Seckler D, Keith Pitman GT. 1994. Water and development in Bangladesh: a retrospective on the flood action plan. Synthesis report by the Irrigation Support Project for Asia and the Near East. Washington, D.C. (US): Bureau for Asia and the Near East, United States Agency for International Development.

Rola AC, Pingali PL. 1993. Pesticides, rice productivity, and farmers' health—an economic assessment. Manila (Philippines): International Rice Research Institute and World Resources Institute. 100 p.

Samad M, Merrey D, Vermillion D, Fuchs-Casrsch M, Mohtadullah K, Lenton R. 1992. Irrigation management strategies for improving the performance of irrigated agriculture. Outlook Agric. 21:4:279-286.

Stone B. 1986. Chinese fertilizer application in the 1980s and 1990s: issues of growth, balances, allocation, efficiency and response. In: China's economy looks toward the year 2000. Washington, D.C. (US): Congress of the United States. p 453-493.

Tandon HLS. 1987. Phosphorus research and agricultural production in India. New Delhi (India): Fertilizer Development and Consumption Organization.

Notes

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The history of rice breeding: IRRI's contribution

G.S. Khush , W.R. Coffman , and H.M. Beachell

Robert F. Chandler, Jr., early on assembled a team at IRRI that began to conceptualize a semidwarf rice plant. The main constraint to yield increases seemed to be the architecture of the tropical rice plant. Typical farmer varieties were tall, with long, weak stems. When a farmer added fertilizer, the tall plant would lodge (fall over). Photosynthesis would cease, and grain would be lost to the water, or eaten by rodents. To increase yields, a shorter, nonlodging rice plant was clearly needed.

The concept of dwarfism was already established in other crops. Dwarf sorghum was already available. S.C. Salmon, a geneticist with General Douglas MacArthur's Occupation Army in Japan, had sent seeds of Norin 10, a dwarf wheat variety that he found in a Japanese agricultural experiment station, to Orville Vogel at Washington State University. Within a few years, Vogel had developed Gaines, a semidwarf wheat variety that spread rapidly across the U.S. Pacific Northwest. Vogel sent seeds to Norman Borlaug of the Rockefeller Foundation wheat program in Mexico. He used those seeds to breed the Mexican semidwarf wheat varieties that made Mexico self-sufficient in wheat by the mid-1960s.

In 1949, the Food and Agriculture Organization of the United Nations (FAO) established the International Rice Commission (IRC), based in Rome, Italy. It sponsored an indica-japonica hybridization program at Cuttack, India, during the 1950s. Its mission was to cross the shorter japonica (temperate climate rices) with the taller indica (tropical climate rices) to obtain progenies with higher yield potential. ADT27 and Mahsuri, selected in that program, were planted on significant areas during the 1960s. Meanwhile, hoping to induce a short-statured mutant, U.S. breeders such as Nelson Jodan and Hank

Beachell irradiated populations of the tall U.S. varieties. High levels of sterility plagued all the selections from those early efforts.

In 1957, the Rockefeller Foundation sent Peter Jennings to Arkansas, Texas, and Louisiana to become acquainted with rice for the purpose of developing new cultivars for Latin America. The Foundation then sent Jennings to Mexico and Colombia. Jennings and Sterling Wortman, later to become IRRI's associate director, traveled across Asia in 1960 looking at rice varieties, meeting rice scientists, and interviewing prospective trainees and staff. In India, they encountered Taichung Native 1 (TN1), a Taiwanese variety that was probably the first widely grown semidwarf variety in the tropics outside of mainland China. But TN1 was highly susceptible to major disease and insect pests. At that time, the inheritance of the short stature was unknown.

Jennings joined IRRI as head of the Varietal Improvement Department in 1961. Among the germplasm that had been assembled at IRRI when he arrived was Dee-geo-woo-gen, a parent of TN1, and clearly its source of dwarfism.

Jennings and Akira Tanaka, hired from Japan as IRRI's first plant physiologist, conceptualized the semidwarf rice plant and systematically studied the causes, and effects, of lodging during IRRI's first 3 years. Chandler wrote about lodging research in his history of IRRI (Chandler 1982).

By supporting tall varieties such as Peta and MTU-15 with bamboo sticks, Jennings found that tall varieties yielded essentially as well as did lodging-resistant varieties. Moreover, the lodging-susceptible varieties, when supported, responded well to nitrogen applications, whereas the unsupported plants showed a decided negative response . . . . This proved beyond doubt that lodging *per se* was the primary cause of low yields when traditional tropical varieties were subjected to modern management methods.

Chandler made several references to IRRI's breeding objectives in the first IRRI Annual Report (1962), the section on Varietal Improvement almost presents a blueprint for IR8:

> It would seem that the following plant type might be useful in the near future throughout much of the tropics—a combination of short, stiff culms bearing erect, moderately sized, dark-green leaves; responsiveness to fertilizer; mid-season maturity and, in most cases, photoperiod insensitivity to permit double cropping practices. These objectives are being pursued with both indica by indica, and indica by japonica hybridization.

Jennings made 38 crosses in late 1962; 11 of them included a short-statured parent: Dee-geo-woo-gen (DGWG), TN1, or I-geo-tse (another dwarf from Taiwan). The eighth IRRI cross was between Peta, a tall, vigorous variety from Indonesia, and DGWG. From that cross, 130 seeds were formed. Those seeds were planted in pots in the screenhouse and produced the first generation (F_1) of plants. All were tall.

Seeds from the F_1 plants were sown in the field and produced about 10,000 F_2 plants, which segregated by height in the Mendelian ratio of 3 tall: 1 dwarf. That meant that dwarfism in DGWG was recessive and simply inherited.

Jennings brought Chandler and Wortman to the field to see the segregating plants. He then cabled the news to Beachell in Texas. "That's when we knew we had it [meaning that DGWG could be used to breed an improved semidwarf variety]," Beachell recalled years later.

With this discovery, Jennings persuaded Chandler and Wortman to exchange a cytogenetics position in the Varietal Improvement program for a second rice breeder to help with the increase in fieldwork that would obviously come. They agreed, and Jennings suggested Beachell, who arrived in 1963.

Tall, late-maturing plants were discarded, and only short, early maturing plants saved. Their seeds were bulked and planted in the rice blast nursery to screen out susceptible rices. In 1963, Jennings departed IRRI for study leave, leaving the material in the hands of newly arrived Beachell. From the F_3 generation, Beachell selected 298 of the best individual plants (Fig. 1). Seed from each plant were sown as individual pedigree rows—the F_4 generation. From row 288, a single plant (the 3rd one) was selected and designated IR8-288-3. Its seeds (F_5 generation) were grown to produce the basic IR8-288-3 seed stock (F_6 generation), with no further selection at the time.

IR8-288-3 was a semidwarf rice, about 120 cm tall, with strong stems that held the plant upright, even when heavily fertilized. It was also insensitive to photoperiod, which meant it could be grown in many latitudes, at any time of the year.

"The seed [of IR8-288-3] was uniform enough for trials in other countries, but a couple of years later Beachell devoted considerable effort to producing an extremely pure strain that would serve as a uniform seed source of IR8 for the future," Chandler wrote.

Meanwhile, seeds of IR8-288-3 and other promising lines were being sent for testing by national rice programs across Asia. IRRI's policy was free access to all of our genetic material. It was made available to the world.

1. Henry M. Beachell shows IRRI director Robert F. Chandler, Jr. (standing), breeding lines in the IRRI nursery (mid-1960s).

In the 1966 dry season, S.K. De Datta, a young Indian agronomist who had joined IRRI in early 1964, planted IR8-288-3, along with other rices, in variety × nitrogen response trials. He was amazed when he harvested the trials in May. IR8-288-3 averaged 9.4 t ha^{-1}, and yielded 10.3 t ha^{-1} in one trial. Average yields in the Philippines then were about 1 t ha^{-1}. De Datta took his yield data to Jennings, then to Beachell. "Let's go see Bob [Chandler]," Beachell said.

Chandler was chairing IRRI's Thursday afternoon seminar, so Beachell and De Datta had to wait until 5 p.m. to see him. De Datta showed his data. "The whole world will hear about this. We're going to make history!" Chandler said, as he congratulated Beachell for helping develop IR8-288-3, and De Datta for showing what it could do. "It was the most exciting thing that ever happened to me," De Datta later recalled.

Soon, similar reports of dramatic yield increases were coming in from across Asia, including 11 t ha^{-1} harvests in Pakistan. De Datta prepared his widely published yield response graph, showing how yields of IR8-288-3 rose with increased fertilization, while those of traditional varieties stagnated.

Philippine President Ferdinand Marcos heard about the new rice, and flew to IRRI by helicopter on 3 Jun 1966. Jennings and others briefed the President by a plot of IR8-288-3 next to Peta, a tall, traditional variety. De Datta recalls Marcos' reaction:

"Do you mean that little rice can outproduce our vigorous Philippine varieties?" the President asked. De Datta assured him that it could. "No kidding?" Marcos responded.

Marcos soon ordered the multiplication of IR8-288-3 seeds as rapidly as possible. The goal was to make the Philippines self-sufficient in rice production during his first term of office. And it was. During the last half of 1966 alone, 2,359 Filipino farmers came to IRRI by bus, bicycle, and on foot (from 48 of the country's 56 provinces) to get seeds.

Meanwhile, the IRRI seed committee deliberated over whether to name IR8-288-3 as a variety, because it had major disadvantages. Foremost was its bold, chalky grain, which distracted from the market appearance of polished rice. The grain also had high breakage during milling. And it had high amylose content, which meant that cooked rice would harden when cool. Beachell recalls a young Filipina saying, "I don't like it because it scratches my throat."

Beachell recalls the consensus: "We needed to move as fast as possible. There was not enough rice to go around. We had to have something to alleviate the rice shortage. Having rice was more important than grain quality.

"So, would we release the line as a variety, or wait to improve it? That was the question. We knew its limitations, but also knew we had the plant type. IR8 would be the prototype for future varieties. We decided to spread it."

The seed committee decided to name IR8-288-3 as IR8 on 14 November 1966. The news was released on 28 November. Chandler later wrote, "He [Beachell], Jennings, and Chang made a fine team. When I was asked, some years later, who, among the three senior scientists in the Varietal Improvement Department, should receive the coveted John Scott Award for the creation of IR8, I replied that the prize should be split among the three: Jennings for selecting the parents and making the cross, Beachell for identifying IR8-288-3 from among the multitude of segregating lines, and Chang for having brought to the immediate attention of IRRI breeders at the start the value of the short-statured varieties from Taiwan such as Dee-geo-woo-gen, I-geo-tse, and Taichung Native 1 (Fig. 2).

The quest for improved grain quality

IR8 broke yield records but critics pointed out its poor grain quality. Immediate attention was therefore directed to select breeding materials with slender and translucent grains. One of the main considerations in deciding to release IR532-E576 as IR20 and IR579-160-2 as IR22 in 1969 was their

2. IRRI breeders crossed short-statured Dee-geo-woo-gen and the tall rice Peta to create IR8-288-3 and ultimately produce IR8.

attractive and translucent grains with high milling recovery. A survey of rice germplasm from various countries in Asia by IRRI cereal chemist Ben Juliano had shown that consumers in Southeast Asia preferred rices with intermediate amylose content, soft gel consistency, and intermediate gelatinization temperature. However, preference in South Asia was for rice with high amylose content.

The main emphasis in the IRRI breeding program in the 1970s was on incorporation of disease and insect resistance. Most of the donors came from the Indian subcontinent and had high amylose content. As a result, the vast majority of improved germplasm developed in the 1970s had high amylose content—IR26, IR28, IR30, IR32, IR34, IR36, IR38, IR40, IR42, IR44, IR46, IR50, IR52, IR54, IR56, IR58, IR60, and IR62. IR48, released in 1979, was the first IR variety with intermediate amylose content. However, it had low gelatinization temperature and long growth duration and was not widely accepted. IR24 and IR43 had low amylose content and low gelatinization temperature and were also not widely accepted because of the stickiness of cooked rice.

The first variety with a desirable combination of intermediate amylose content, soft gel consistency, and intermediate gelatinization temperature, as well as long slender and translucent grains was IR64, released in 1985. It became the world's most widely grown rice variety, grown on about 8 million hectare of rice land in Asia. A descendant of 20 land races from eight countries, it inherited its superior grain quality from a popular pre-green revolution Philippine variety BPI 76. Several IRRI breeding lines released by the Philippine Seed Industry Council under the designation of PSBRc during the 1990s, such as PSBRc 4, PSBRc 18, PSBRc 28, PSBRc 30, PSBRc 52, PSBRc

54, and PSBRc 64, have intermediate amylose content, soft gel consistency, and intermediate gelatinization temperature. Of these, PSBRc 18, PSBRc 28, and PSBRc 52 are being adopted rapidly in the Philippines and in Indonesia.

Many of the high-quality preferred varieties are aromatic. Examples are Basmati rices of India and Pakistan, Sadri rices of Iran, Bahra rices of Afghanistan, Khao Dawk Mali (Jasmine rice) of Thailand, Azucena and Milagrosa of the Philippines, and Rojolele of Indonesia. An early cross involving Khao Dawk Mali at IRRI was IR841. Several aromatic lines from this cross were selected but were not named as varieties in the Philippines because they lacked disease and insect resistance. However, several lines were released as varieties in other countries—IR841-85 was released in the United States as Jasmine 85, in China as Zhong Yin 85, in Indonesia as Bengawan Solo, and in Brunei as BR1. IR841-63-5 was released as IR841 in Argentina and IR841-67-1-2 as Empasc 104 in Brazil.

Breeding work to develop high-yielding Basmati rices was initiated in the early 1970s, but progress has been extremely slow. Basmati rices are genetically differentiated from improved indica varieties and belong to a distinct group (Glaszmann 1987). Crosses between Basmati and improved indicas are partially sterile and this trait is passed on to their progenies. Moreover, such crosses do not produce a full spectrum of recombinants. Instead of 3:1 segregation, short-statured plants are rarely observed. Perhaps a gamete eliminator located close to the *Sd1* locus for short stature is responsible for such distortion.

Aroma and grain elongation are quantitative traits and difficult to transfer from one varietal background to another. After several cycles of hybridization and selection, lines with short stature that match the grain quality characteristics of Basmati have been selected. These have been shared with national program scientists in India and Pakistan and some are in pre-release stages.

Breeding for disease and insect resistance

The tropical and subtropical climate in which rice is grown is conducive for the buildup of diseases and insects. Improved cultural practices, such as fertilizer application and increased plant population, led to increased disease and insect problems. Therefore, IRRI's rice improvement program placed major emphasis on developing germplasm with multiple resistance (Table 1). Many national programs have also given priority to developing varieties with multiple resistance to diseases and insects.

Five diseases (blast, bacterial blight, sheath blight, tungro, and grassy stunt) and four insects (brown planthopper, green leafhopper, stem borer, and

Table 1. Disease and insect resistance of varieties named by IRRI (IR5 to IR34) and of IRRI lines named as varieties by the Philippine Government (IR36-IR65).

IR variety	Reaction[a]									
	Blast	Bacterial blight	Grassy stunt	Tungro	GLH	BPH biotype 1	BPH biotype 2	BPH biotype 3	Stem borer	Gall midge
IR5	MR	S	S	S	R	S	S	S	MS	S
IR8	S	S	S	S	R	S	S	S	S	S
IR20	MR	R	S	MR	R	S	S	S	MR	S
IR22	S	R	S	S	S	S	S	S	S	S
IR24	S	S	S	S	W	S	S	S	S	S
IR26	MR	R	MR	MR	R	R	S	R	MR	S
IR28	R	R	R	R	R	R	S	R	MR	S
IR29	R	R	R	R	R	R	S	R	MR	S
IR30	MS	R	R	MR	R	R	S	R	MR	S
IR32	MR	R	R	MR	R	R	R	S	MR	R
IR34	R	R	R	R	R	R	S	R	MR	S
IR36	R	R	R	R	R	R	R	S	MR	R
IR38	R	R	R	R	R	R	R	S	MR	R
IR40	R	R	R	R	R	R	R	S	MR	R
IR42	R	R	R	R	R	R	R	S	MR	R
IR44	R	R	S	R		R	R	S	MR	S
IR46	R	R	S	MR	MR	R	S	R	MR	S
IR48	R	R	R	R	R	R	R	S	MR	–
IR50	MS	R	R	R	R	R	R	S	MR	–
IR52	MR	R	R	R	R	R	R	S	MR	–
IR54	MR	R	R	R	R	R	R	S	MR	–
IR56	R	R	R	R	R	R	R	R	MR	–
IR58	R	R	R	R	R	R	R	S	MR	–
IR60	R	R	R	R	R	R	R	R	MR	–
IR62	MR	R	R	R	R	R	R	R	MS	–
IR64	MR	R	R	R	R	R	MR	R	MR	–
IR65	R	R	R	R	R	R	R	S	MS	–
IR66	MR	R	R	R	R	R	R	R	MR	–
IR68	MR	R	R	R	R	R	R	R	MR	–
IR70	R	S	R	R	R	R	R	R	MS	–
IR72	MR	R	R	R	R	R	R	R	MR	–
IR74	R	S	R	R	R	R	R	R	MR	–

[a]S = susceptible, MS = moderately susceptible, MR = moderately resistant, R = resistant. Reactions were based on tests conducted in the Philippines, for all diseases and insects except gall midge, which were conducted in India. GLH = green leahopper, BPH = brown planthopper.

gall midge) are of major importance in most countries in tropical and subtropical Asia. Prior to 1962, no rice varieties had been bred to be resistant to insect pests, although differences in field susceptibility to certain insect pests were known. In 1962, IRRI research was primarily on resistance to yellow stem borer and striped borer. About 15,000 germplasm accessions were screened in the field for their resistance to stem borers, with some 30 accessions found to be resistant. One of those was TKM6, a tall, leafy, narrow-stemmed indica with early maturity and good grain quality. TKM6 was crossed with a heavy tillering semidwarf line—IR262-24-2 (Peta/3/Taichung Native1). This cross was assigned the number IR532E. Intensive evaluation of the progeny up to F_6 in field and greenhouse experiments identified the line IR532E-576, which had moderate level of resistance to yellow stem borer and several other important diseases and insect pests. IRRI formally named it IR20 (Pathak et al 1973) in 1969 and it received wide acceptance in many countries, especially Bangladesh, India, Philippines, Vietnam, and Cambodia.

Large germplasm collections were screened at IRRI (Chang et al 1973) and donors for most of the diseases (except sheath blight) and insects identified. Utilizing those donors, improved varieties with resistance for as many as four diseases and four insects have been developed. IR20, released in 1969, was resistant to bacterial blight, blast, and green leafhopper. IR26, released in 1973, was resistant to bacterial blight, blast, green leafhopper, and brown planthopper. IR36 was the first IRRI improved variety with multiple resistance and other desirable features, such as early growth duration, excellent grain quality, and tolerance for abiotic stresses. It became the most widely planted rice variety in the 1980s, grown on about 11 million hectares of rice land annually between 1980 and 1989. IR36 was gradually replaced by IR64 but is still planted to substantial hectarage in Indonesia, India, and the Philippines.

Twelve varieties and one wild species from six countries were used for developing IR36. Early crosses that resulted in its development were made in 1969. An early maturing selection with bacterial blight resistance from IR8/Tadukan was crossed with another early maturing line from TKM6/TN1, bred for brown planthopper and stem borer resistance. Many progenies of this cross (IR1561) were resistant to bacterial blight, blast, stem borer, and brown planthopper but were susceptible to green leafhopper and grassy stunt.

Also in 1969, *Oryza nivara*, a wild rice from India with resistance to grassy stunt, was crossed with IR24, then backcrossed three times with IR24. Progenies with resistance to grassy stunt, good grain quality, and excellent plant type were obtained. In 1971, an IR1561 F_5 progeny was crossed with a grassy stunt-resistant plant from the *Oryza nivara*/IR24 backcross. This F_1 was topcrossed with a third parent (CR94-13) from India. It was resistant to gall midge and green leafhopper and field resistant to tungro. In 1972, F_2 seeds of the topcross were grown without insecticide protection at the Maligaya Rice Research and Training Center (now PhilRice) in Central Luzon, Philippines, where tungro and stem borer incidence was high. At maturity, 937 plants resistant to stem borer and tungro were harvested. These were grown in a pedigree nursery as F_3 rows at IRRI without insecticide protection in December 1972. The brown planthopper incidence at IRRI farm was high and susceptible rows were killed. The progenies were also tested for resistance to bacterial blight, blast, and green leafhopper and evaluated for grain quality. In March 1973, lines with multiple resistance were harvested. During 1973 and 1974, F_4 and F_5 progenies were evaluated for resistance to various diseases and insects at IRRI, at Laurang (Indonesia) for resistance to tungro, and at CRRI, Cuttack (India) for resistance to gall midge.

On the basis of those tests, IR2071-625-1-252 was selected as having multiple resistance for bacterial blight, blast, tungro, grassy stunt, brown planthopper, green leafhopper, stem borer, and gall midge. It had early maturity (110 days) and long, slender, and translucent grains. It was evaluated for yield potential at IRRI, in seedboard trials conducted at 10 sites in the Philippines and in International Rice Testing Program (IRTP) nurseries. It outyielded the IR30 check during both the dry and wet seasons and the Philippine Seed Board named IR2071-625-1-252 as IR36. A sister line from the same cross, IR2071-586-5-6-3, but with medium growth duration (130 days) and slightly taller stature was named IR42. It also had multiple resistance for diseases and insects.

Subsequent varieties were also bred with multiple resistance to diseases and insects but with different genes for resistance incorporated. Most of those IR varieties are resistant to green leafhopper, which vectors the tungro virus. However, after several years of wide-scale cultivation, the green leafhopper populations adapt to such varieties and varieties become susceptible to tungro.

A program to incorporate resistance to the tungro virus itself was initiated in the mid-1980s. Several donors for resistance such as Utri Merah, Utri Rajapan, Habiganj DW8, *Oryza longistaminata,* and *O. rufipogon* were crossed with IR1561-228-3, which is susceptible to green leafhopper. Segregating progenies were screened in the field with severe incidence of tungro. Resistant plants were selected. Those were susceptible to green leafhopper but resistant to tungro. Several promising lines with resistance to tungro and other diseases and insects were selected and evaluated for resistance at tungro hot spots in the Philippines and several other countries. A few of those lines are being multiplied as pre-release varieties in the Philippines and Indonesia.

As mentioned earlier, sources of resistance to sheath blight are not available in the rice germplasm and the levels of resistance to stem borer are only moderate. To develop rice germplasm with a high level of resistance to stem borers, the *Bt* gene from *Bacillus thuringiensis* was introduced into elite rice varieties, and transgenic lines obtained that have a high level of stem borer resistance. Similarly, a chitinase gene was introduced into rice and transgenic lines that are moderately resistant to sheath blight were obtained.

Short growth duration

Most traditional rice varieties in tropical and subtropical Asia mature in 160-170 days and many are photoperiod-sensitive. They were suitable for growing one crop of rice a year during the wet season but not for multiple cropping systems. IR8 and subsequent varieties such as IR5, IR20, and IR26 matured in 130-135 days and were photoperiod-insensitive. However, if the farmers grew those varieties, it was not possible to grow another crop after rice or a second crop of rice. Therefore, major emphasis was placed on developing improved varieties with shorter growth duration. IR28 and IR30 released in 1974, and IR36 released in 1976, mature in 110 days. The growth duration was further reduced to 105 days in IR50 and IR58.

During the selection process, only those short-duration lines with yield potential that matched that of medium-duration varieties were selected. The key to the success of this program was the selection of genotypes with good vegetative vigor. With high growth rates at earlier growth stages, the short-duration varieties such as IR36, IR64, and IR72 were able to produce about the same biomass in 110-115 days as the medium-duration varieties do in 130-135 days. Moreover, the harvest index of short-duration varieties was slightly better than that of the medium-duration varieties. Under most situations, yields of early and medium-duration varieties are similar and because the short-duration varieties produce the same amount of grain as medium-duration varieties in fewer days, their per-day productivity is much higher.

Because the short-duration varieties grow rapidly during the vegetative phase, they are competitive with weeds and weed control costs are reduced. They also use less irrigation water, thus lowering the production costs (Khush 1987). The availability of short-duration varieties led to major increases in cropping intensity, greater on-farm employment, increased food supplies, and higher food security in Asian countries.

Meeting the diverse needs of national programs

The Genetic Evaluation and Utilization Program

The IRRI Genetic Evaluation and Utilization (GEU) Program, initiated in the early 1970s, was the first effort to use an interdisciplinary team approach to develop improved rice varieties. Problem-area scientists such as plant pathologists, entomologists, soil scientists, and cereal chemists developed screening techniques, evaluated germplasm entries to identify the donor parents, and worked closely with plant breeders in evaluating the breeding materials for specific traits in their area of specialization.

The plant breeders provided leadership in developing breeding strategies, in the hybridization program, in managing the breeding nurseries, in selecting the breeding lines, and in managing the seed materials. Various traits were integrated into improved varieties through such cooperative endeavors.

Eighteen scientists from nine departments and eight disciplines worked together in the GEU program. Each plant breeder worked with more than one team and each problem area team was responsible for providing leadership for work in its particular area. Each team planned the research jointly, selected the parents for hybridization, screened the progenies, and selected the lines to be included in the various international screening nurseries.

The ultimate goal of the GEU program was to develop superior germplasm of rice with increased yield potential, good grain quality, resistance to economically important diseases and insect pests, and suitability for unique growing conditions. Varieties were produced with tolerance for certain stresses, such as high or low temperatures, adverse soils, drought, and excess water.

National GEU programs were assisted through the training of young scientists in the interdisciplinary approach. Strong linkages developed between IRRI and national programs facilitated transfer and exchange of ideas, techniques, materials, and personnel. This international network of cooperating scientists, trained in different disciplines, worked toward a mutual goal on an equal basis for exploiting the vast reservoir of genetic variability of rice.

The International Rice Testing Program

The International Rice Testing Program (IRTP), later named the International Network for Genetic Evaluation of Rice (INGER), was established in the mid-1970s to facilitate the worldwide distribution and testing of improved rice germplasm. About 1,000 rice scientists from the national agricultural research systems in countries of Asia, Africa, and Latin America now participate in this program. More than 20,000 lines and varieties have been evaluated, resulting in the release of 349 breeding lines as 525 varieties in 62 countries around the world. Economists have computed the annual net worth of each released variety to be about $2.5 million, resulting in an annual net impact of more than $1 billion for INGER and the breeding programs that contribute to it.

New plant type for increased yield potential

In 1988, IRRI prepared its strategy document entitled *IRRI toward 2020 and beyond* (1989). Several high-priority research areas were identified and one of them was the development of germplasm with higher yield potential.

3. The new plant type (right), as conceived at IRRI in 1989, compared with the semidwarf plant (center) and the traditional tall plant (left).

Agronomists, plant physiologists, and breeders met under the leadership of Director General Klaus Lampe and conceptualized a new plant type (NPT) of rice (Fig. 3) to increase the yield potential by 20%.

Yield is a function of total dry matter or biomass and the harvest index (HI) (grain-to-straw ratio). Therefore, enhancing either the total biomass production or the HI, or both, can increase yield. The HI of modern high-yielding varieties is around 0.5 and with optimum conditions, they produce 18–19 t ha^{-1} biomass. Thus they can yield 9–9.5 t ha^{-1} under best management. To increase the yield potential further, the NPT was conceptualized to increase the biomass as well as HI.

The HI can be increased by increasing the proportion of energy that is stored in the grain (the sink size) by, for example, raising the number of grains per panicle and reducing the allocation of dry matter to unnecessary plant parts such as unproductive tillers. Developing plants with sturdier stems so that there is no lodging when higher rates of nutrients are applied to them can increase biomass. Following were the attributes of the proposed NPT.

- Low tillering capacity (3–4 tillers when direct seeded, 8–10 tillers when transplanted)
- No unproductive tillers
- 200–250 grains per panicle
- Very sturdy stems

- Dark green thick and erect leaves
- Vigorous root system
- 100–130-day growth duration
- Multiple disease and insect resistance
- Acceptable grain quality

Breeding work on the NPT started in 1990 when about 2,000 entries from the IRRI germplasm bank were grown during the dry and wet seasons to identify donors for various traits. These germplasm entries came primarily from Indonesia, popularly called *bulus* and sometimes referred to as javanicas. This germplasm is known for low tillering, large panicles, and sturdy stems. The bulu varieties are genetically related to temperate japonicas and are now referred to as tropical japonicas. Crossing work was initiated in 1990. Many bulu varieties were crossed with a semidwarf japonica from China. The progress in obtaining the breeding lines with the proposed ideotype was quite rapid and numerous NPT breeding lines were selected by 1994. Many of these lines were found to have poor grain filling and the yield potential was not realized. The parents used in the initial crosses also had poor grain filling. New crosses were made with parents having good grain filling and breeding lines with optimum grain filling were obtained. Some of these lines have outyielded IR72 check by 15–20%.

Because these lines are based on the tropical japonica germplasm, they have short grains. But the preference in the tropics and subtropics is for long slender grains. Moreover, these lines lack resistance to brown planthopper, green leafhopper, and tungro. Sources of resistance to these insects and diseases are not available within the tropical japonica germplasm. To improve the grain quality and disease and insect resistance, crosses between the NPT lines and indica varieties and breeding lines with multiple resistance were made. Early generation progenies from these crosses are being evaluated for disease and insect resistance and yield potential.

Hybrid rice research

Hybrid rice research at IRRI aims to exploit the phenomenon of hybrid vigor for increasing rice yields beyond the level of semidwarf varieties and to develop associated seed production technology. Initial studies were made in 1970 by S.S. Virmani, under the supervision D.S. Athwal, for developing cytoplasmic male sterility system in indica rices. These resulted in the identification of TN1 cytoplasm that induces male sterility by interacting with Pankhari 203 nucleus (Athwal and Virmani 1972). However, further research on the subject was discontinued for lack of confidence in the economic feasibility of the technology.

The successful development and commercialization of hybrid rice in China in 1976 (Lin and Yuan 1980) encouraged IRRI to revive interest in the subject. G.S. Khush introduced a few commercial rice hybrids (Shan You 2, Shan You 6, and Wei You 6) and their cytoplasmic male sterile (CMS) parents (V20A and Zhen Shan 97A) from China in 1979 for evaluation at IRRI. Although these were found unadapted in the tropics because of their susceptibility to major tropical rice diseases and insects, it was decided to explore potentials and problems of hybrid rice in the tropics under the leadership of S.S. Virmani.

By 1982, significant standard heterosis was established in selected intervarietal indica/indica crosses (Virmani et al 1982). By 1988, about 40 CMS lines, including two commercially usable ones (IR58025A and IR62829A), and hundreds of restorer lines were developed to breed tropical rice hybrids. Numerous experimental hybrid combinations were subsequently made from those parental lines and critically evaluated in yield trials. Hybrid rice seed production technology for the tropics was concurrently developed. It used the Chinese seed production model and seeds of promising rice hybrids were produced for collaborative testing in the national programs, which were also provided with parental lines.

The first set of tropical rice hybrids developed at IRRI was released in 1993 for regional testing in Vietnam. In subsequent years, more hybrid rices were released for commercial cultivation in India and the Philippines. To date, numerous genetically diverse CMS, maintainer and restorer lines, and heterotic hybrids have been developed and shared with national programs. IRRI also supplied some CMS and restorer lines to RiceTec, Inc., Pearland, Texas. RiceTec has worked closely with Chinese scientists for the past 10 years to develop hybrid rice technology for the United States. RiceTec released their first product for commercialization in about 12,000 hectares in 2000.

Over the years, technology for production of hybrid rice seeds as well as nucleus, breeder, and foundation seeds of CMS, maintainer, and restorer lines has also been developed. Seed growers in India, Philippines, and Vietnam are able to obtain 2 t ha^{-1} hybrid seed yields. These developments have encouraged private seed industries to invest in hybrid rice technology generation, or seed production and marketing, or both. IRRI has also helped national programs and private companies in developing their human resources for generating and using hybrid rice technology.

Major challenges to large-scale adoption of hybrid rice technology in the tropics are

- high expectations of farmers,

- inconsistent performance of the first set of the released hybrids,
- inadequate understanding of agronomic management of hybrids,
- inadequate availability of pure seeds of parental lines and hybrids,
- poor grain quality of hybrids in comparison with the premier-quality rices,
- inadequate level of disease and insect resistance in the released hybrids,
- inconsistent seed yields,
- high cost of hybrid seeds, and
- the habit of rice farmers to use their own seed.

Inadequate linkage and understanding among research and seed production agencies and inadequate coordination among research, seed production, and technology transfer agencies also add to the list of the constraints. Future opportunities exist in

- indica/tropical japonica hybrids and selective use of heterotic groups and gene blocks;
- developing better agronomic, nutrient- and pest-management practices;
- improving grain quality and disease and insect resistance of hybrids; and
- developing hybrids for stress-prone environments and for direct seeding.

Prospects of further increasing seed yields and reducing input cost in hybrid seed production plots are also real.

IRRI is currently working in collaboration with the Food and Agriculture Organization, the Asia Pacific Seed Association, and China to expedite the development and use of hybrid rice in six Asian countries—Bangladesh, India, Indonesia, Philippines, Sri Lanka, and Vietnam.

Hybrid rice in China is planted to about 15 million hectares. Outside China, about 400,000 hectares are currently covered with hybrid rices. About 2 million hectares may be covered with hybrid rices during the next 5–8 years. This would significantly contribute toward global food security and environment protection.

Molecular marker-aided selection

Numerous genes of economic importance such as those for disease and insect resistance are transferred from one varietal background to another through conventional breeding approaches. Most of these genes behave in a dominant and recessive manner and require time-consuming efforts to transfer. Sometimes, screening procedures are cumbersome and expensive, and require a large field area. If such genes can be tagged by tight linkage with molecular markers, time and money can be saved in transferring genes from one varietal background to another. The presence or absence of the associated molecular marker would indicate, at the early stage, the presence or absence of the desired target gene.

Codominance of the associated molecular marker allows all the possible genotypes to be identified in any breeding scheme, even if the gene for economic trait cannot be scored directly. A molecular marker closely linked to the target gene can act as a tag, which can be used for indirect selection of the gene in a breeding program.

Numerous genes of economic importance have been tagged with molecular markers in rice as shown in Table 2 (Khush and Brar 1998). This allowed molecular marker-aided selection and integration of molecular marker technology into the breeding program. For example, NPT lines mentioned in a later section are susceptible to bacterial blight. Three genes for resistance to bacterial blight—e.g., *xa5, xa13,* and *Xa21*—were successfully transferred to NPT lines via molecular-assisted backcrossing. BC_3F_3 near-isogenic lines having more than one resistance gene showed a wider resistance spectrum and increased level of resistance to races of bacterial blight as compared with those having single genes (Sanchez et al 2000).

The next challenge: improved nutrition

While improved human nutrition has always been one of IRRI's goals, it has been addressed mostly, if not exclusively, through increased production, resulting in a reduced real price and increased availability to consumers. Now on the horizon is the prospect to manipulate the nutritional characteristics of rice. Rice has been successfully transformed to induce the production of vitamin A precursors. If this technology can be moved to the production stage, it could represent an enormous contribution to improved human nutrition. IRRI is actively pursuing this opportunity with the support of the international community.

Table 2. Examples of mapping genes of agronomic importance mapped with molecular markers in rice.

Gene	Trait	Chromosome	Linked marker
Pi-1	Blast resistance	11	Npb181
Pi-2	Blast resistance	6	RG64
Pi-4	Blast resistance	12	RG869
Pi-ta	Blast resistance	12	RZ397
Pi-5	Blast resistance	4	RG498, RG788
Pi-6	Blast resistance	12	RG869
Pi-7	Blast resistance	11	RG103
Pi-9	Blast resistance	6	RG16
Pi-10	Blast resistance	5	RRF6, RRH18
Pi-11	Blast resistance	8	BP127
Pi-b	Blast resistance	2	RZ123
Xa-1	Bacterial blight resistance	4	Npb235, Npb197
Xa-2	Bacterial blight resistance	4	Npb235, Npb197
Xa-3	Bacterial blight resistance	11	Npb181, Npb78
Xa-4	Bacterial blight resistance	11	Npb181, Npb78
xa-5	Bacterial blight resistance	5	RG556
Xa-10	Bacterial blight resistance	11	$OP07_{2000}$
xa-13	Bacterial blight resistance	8	RZ390, RG136
Xa-21	Bacterial blight resistance	11	pTA818, pTA248, RG103
RTSV	Rice tungro spherical virus resistance	4	RZ262
Bph-1	Brown planthopper resistance	12	XNpb 248
Bph-10	Brown planthopper resistance	12	RG457
ef	Early flowering	10	CD098
fgr	Fragrance	8	RG28
Gm-2	Gall midge resistance	4	RG329, RG476
Rf-3	Fertility restorer	1	RG532
S-5	Wide compatibility	6	RG213
Se-1	Photoperiod sensitivity	6	RG64
Se-3	Photoperiod sensitivity	6	A19
sdg	Semidwarf	5	RZ182
sd-1	Semidwarf	1	RG109
tms-3	Thermosensitive male sterility	6	$OPAC3_{640}$
PMS 1	Photoperiod sensitive male sterility	7	RG477
PMS 2	Photoperiod sensitive male sterility	3	RG191
Sub-1	Submergence tolerance	9	RZ698

References

Athwal DS, Virmani SS. 1972. Cytoplasmic male sterility and hybrid breeding in rice. In: Rice breeding. Manila (Philippines): International Rice Research Institute. p 615-620.

Chandler Jr., RF. 1982. An adventure in applied science: a history of the International Rice Research Institute. Manila (Philippines): IRRI. 233 p.

Chang TT, Ou SH, Kauffman HE, Pathak MD. 1975. The search for disease and insect resistance in rice. In: Frankel OH, Hawkes JG, editors. Crop genetic resources for today and tomorrow. Cambridge (United Kingdom): Cambridge University Press.

Chaudhary RC, Seshu DV, Alluri K, Cuevas-Perez F, Lopez VC, Khush GS. 1998. INGER-derived rice varieties directly released in various countries. Manila (Philippines): International Rice Research Institute. 37 p.

Glaszmann JC. 1987. Isozymes and classification of Asian rice varieties. Theor. Appl. Genet. 74:21-30.

IRRI (International Rice Research Institute). 1962. Annual report, 1961-1962. Manila (Philippines): IRRI.

IRRI (International Rice Research Institute). 1989. IRRI toward 2000 and beyond. Manila (Philippines): IRRI.

Khush GS. 1987. Development of rice varieties suitable for double cropping. In: Tropical Agriculture Research Series 20. Japan: Tropical Agricultural Research Center, Ministry of Agriculture, Forestry and Fisheries. p 235-246.

Khush GS, Brar DS. 1998. The application of biotechnology to rice. In: Eves CL, Bedford BM, editors. Agricultural biotechnology in international development. Wallingford (United Kingdom): CAB International. p 21-121.

Khush GS, Coffman WR. 1977. Genetic evaluation and utilization (GEU) program: the rice improvement program of the International Rice Research Institute. Theor. Appl. Genet. 51:97-110.

Lin SC, Yuan LP. 1980. Hybrid rice breeding in China. In: Innovative approaches to rice breeding. Manila (Philippines): International Rice Research Institute. p 35-51.

Pathak MD, Beachell HM, Andres F. 1973. IR20, a pest- and disease-resistant high-yielding rice variety. Int. Rice Comm. Newsl. (22):3.

Sanchez AC, Brar DS, Huang N, Li Z, Khush GS. 2001. STS marker-assisted selection for three bacterial blight resistance genes in rice. Crop Sci. 40. (in press)

Virmani SS, Aquino RC, Khush GS. 1982. Heterosis breeding in rice (*Oryza sativa* L.). Theor. Appl. Genet. 63:373-380.

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Oryza glaberrima × *Oryza sativa* interspecifics for Africa

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The wide range of ecological conditions in which rice grows in West Africa is evidence of the equally wide genetic variability found among cultivars of *O. sativa* and *O. glaberrima*. One of the primary objectives of today's rice breeders in West Africa is to use this variability to develop new rice varieties with high and stable ability to resist, or tolerate, adverse environmental and biological conditions. But the state of the science in West Africa varies significantly from country to country, from program to program, and from institution to institution.

Crop improvement scientists at the West Africa Rice Development Association (WARDA) systematically evaluate germplasm from both within and outside Africa, generate breeding materials, select superior lines, and test early and advanced breeding materials on-station and on-farm. WARDA's strategy for rice improvement is to combine specific agroecological adaptations of local rice varieties with the yield potential of introduced varieties.

Conventional breeding programs targeting the numerous constraints that limit rice yields of rice—drought, weeds, blast, and low-input cultural practices—have worked for more than three decades to improve the performance of rice varieties in West Africa. The gains from this research were limited, in part because *O. sativa*, the most widely cultivated rice species in West Africa, has limited resistance to many of the stresses that affect rice in the region. Although advanced selections from intraspecific breeding mostly outperform farmers' traditional varieties at the experiment station, they perform poorly when grown in the low-input systems that dominate rainfed rice farming in West Africa.

WARDA, in an effort to break this pattern, initiated an interspecific hybridization program in 1991 to introgress important traits between *O. sativa* and *O. glaberrima,* and thereby increase the genetic variability within each type.

Among eight other species indigenous to Africa, *O. glaberrima* is known to have been cultivated in parts of West Africa more than 3,500 years ago. During that time, it developed adaptive or protective mechanisms for resisting major biotic and abiotic stresses. It represents a rich reservoir of useful genes for resistance to diseases and insect pests as well as tolerance for acid soils, iron toxicity, drought, unfavorable temperatures, and excess water.

Production systems and biophysical constraints to rice production

Rice production systems in West Africa are extremely diverse. A total of 4.1 million hectares of rice is grown, of which 40% is grown as upland rice and 38% as rainfed lowland rice. Only 12% of the rice area is irrigated.

Biophysical constraints to rice production that cut across countries in West Africa include periodic drought; weeds; diseases such as blast, rice yellow mottle virus (RYMV), glum discoloration, leaf scald, brown spot, sheath rot, and sheath blight; insect pests such as stem borers, the African rice gall midge (AfGRM), defoliators, grain-sucking bugs, and nematodes; and acidic soils deficient in N and P and with toxic levels of Fe, Al, and Mn.

Weeds pose a double constraint. The ability to remove weeds before seeding largely determines the area that can be grown by family labor, and weeding after sowing greatly adversely affects grain yield.

Emphasis has been on high-yielding and well-adapted rice varieties by almost all national agricultural research systems (NARS) in West Africa (Jones et al 1978, Jacquot 1978). However, yield of a given variety on a given site is the combination of three factors—yield potential, environment (abiotic and biotic pressures), and land management by the farmer.

The yield potential of improved varieties grown in West Africa is frequently expressed by environmentally difficult conditions such as drought, diseases, and weeds. Increasing yield means essentially increasing the level of tolerance for those constraints. We, therefore, believe that an area where West African breeding can make a substantial contribution to varietal improvement is in developing resistance to, or tolerance for, the present and potential biotic and abiotic stresses of the region.

O. glaberrima, a reservoir of useful genes

Although rice cultivation in sub-Saharan Africa is mainly based on *O. sativa*, land races of indigenous *O. glaberrima* are still widely grown in traditional production systems in rainfed and deepwater ecosystems. Those land races are highly weed-competitive and resistant to local biotic and abiotic stresses, but have a low yield potential due to 1) limited number of spikelets per panicle, caused by the lack of secondary branches; 2) grain shattering; and 3) poor resistance to lodging (Jones 1999).

Efforts to use *O. glaberrima* genes to improve *O. sativa* cultivars intensified recently following a breakthrough in interspecific hybridization that yielded genetically stable and fully fertile progenies for the first time (Jones et al 1997).

Interspecific hybridization studies were initiated at WARDA to develop new low-management plant types for the labor-limited, weed- and drought-prone rice production systems of West Africa. The goal was to combine the superior weed competitiveness and resistance to other stresses of *O. glaberrima* with the higher yield potential of improved *O. sativa* tropical-japonica and indica rices (Dingkuhn et al 1996, Jones and Singh 1999).

Role of anther culture in interspecific breeding

Bridging materials (*O. sativa*/*O. glaberrima* fertile progenies) were used as females and crossed with either of the *O. glaberrima* and *O. sativa* parents as donors to improve drought tolerance, blast resistance, and multiple resistance to RYMV and AfRGM, and to improve tillering. Anther culture (AC) techniques were used to overcome genetic incompatibility and some general constraints to wide crosses such as 1) slow fixation of the lines, 2) frequent partial sterility of the progenies, and 3) low recovery of useful recombinants.

A number of double-haploid interspecific progenies with high fertility from the first (BC_1F_1) and second (BC_2F_1) backcross generations of interspecific hybrids are routinely generated through AC. Anther culture, therefore, helps at early generations to introgress and transfer important traits from *O. glaberrima* to improve *O. sativa*, thereby allowing rapid fixation. High rate of callus induction of the different genotypes was obtained from the liquid or semisolid N6 medium with additives and coconut milk, and incubation in the dark at 25 °C ± 1 °C. Green plantlets were obtained in an MS medium supplemented with biochemical additives under 2,500 lux and photoperiod of 16 h d^{-1}.

The green-plantlet-regenerating capacities of microspore calli increased slightly at 5 and 6 wk after inoculation of anthers, then decreased gradually. Plantlets transferred to the field fell into three distinct groups:

1. 50–76% of plantlets were haploid with 12 chromosomes.
2. 23–46% of the plantlets were spontaneous doubled-haploid with 24 chromosomes.
3. 0–17% of the plantlets in the second generation were polyploids.

A tillering medium, which gives 6–22 tillers from a single plantlet, was also developed. This improves the efficiency of the AC method because more plants can be obtained from a given cross without fear of losses.

Seventeen percent of the spontaneous doubled-haploid lines displayed only partial fertility, which was generally stable over successive selfing generations, suggesting abnormal chromosome combinations. However, several genetically stable anther explants had 96–100% seed fertility. Most of the AC-derived lines were homogeneous.

New rices for African rainfed systems

Development of low-management plant types

A systems approach is used to refine and test plant type concepts that would make optimal, environment-specific use of the morphological, physiological, and phenological traits available for recombination in the two species. On the basis of the potential-yield model ORYZA_1 (Kropff et al 1994), the hydrological model SAWAH (Ten Berge 1992), and additional model components, a comprehensive physiological model is being developed.

The successful introgression of genes from *O. glaberrima* into *O. sativa* has not only resulted in a significant broadening of the genetic base of cultivated rice, it has also produced new plant prototypes with extremely interesting agronomic traits. The low-management rice type combines weed suppression traits that *O. glaberrima* shows at early growth stage with high yield potential and input responsiveness traits from *O. sativa* at the reproductive stage.

Weed-competitive rice varieties

In tests during 1996 and 1999, seedling vigor ratings ranged between 1 (extra vigorous) in the *O. glaberrima* and 5 (normal seedlings) in the *O. sativa* parents. Ten interspecific progenies scored 1 or 2 while 110 scored 2.5. Early vegetative vigor showed the ability of the new plant types to rapidly establish ground cover filling the space between plants and rows.

The phenological patterns of growth, tillering, leaf area index (LAI), and specific leaf area (SLA) were characterized under different N inputs for an *O. sativa* and an *O. glaberrima* parent and some interspecific progeny. Compared with the *O. sativa* cultivar WAB56-104, the *O. glaberrima* land race CG14 had extremely high LAI, SLA, and tillering rates in all treatments and seasons, but had superior dry matter accumulation only when N was applied to the crop. The interspecific progeny had intermediate LAI, growth rates, leaf chlorophyll content, and SLA. Their tillering rates, however, were lower than CG14 but higher than those of WAB56-104, which was possibly a result of the increased assimilate demand of their sturdy, lodging-resistant stems.

We found SLA to be a major determinant of early growth vigor and LAI. We conclude that high-yielding, weed-competitive rice should have a high initial SLA to accelerate leaf area development, followed by a rapid decrease in SLA during the reproductive growth period to ensure high leaf photosynthetic rates. Breeding for such a plant type is now possible on the basis of *O. sativa*/*O. glaberrima* crosses, specific selection for the desired dynamics of SLA, and de-selection of lodging and shattering types.

High yields were observed in the interspecific progenies, resulting in part from panicles with secondary branches inherited from the *O. sativa* parent. This gives them the ability to respond to added inputs by producing a greater number of spikelets yielding up to 400 or more grains per panicle. In addition, most progenies showed transgressive segregation with substantially larger panicles and number of spikelets per panicle than either of their parents. For example, some progenies had more secondary branches than either parent.

Rices for mildly acidic and phosphorus-deficient uplands

More than 70% of upland rice grown in West and Central Africa is in the humid forest zone where annual rainfall is 2,000 mm or more. Upland rice in that zone is often grown on acid soils with low P status. Fertilizers are needed to improve yield, but the farmers are mostly resource-poor women. Past work with *O. sativa* materials showed significant response to P application in acidic soils at Man in the forest zone of Côte d'Ivoire. Interspecific progenies also responded well to P application there in 1999.

With the advent of the new interspecific rices, the farmers' need for higher yielding rice varieties with increased tolerance for acidic and low-P soil is realized. The interspecific progenies, WAB450-I-B-P91-HB and WAB450-I-B-P38-HB, outperformed both parents with yields of more than 3 t ha^{-1} in yield trials in nonamended soils at Man in 1999. In mildly acidic soils, the interspecific progenies behaved similarly to the *O. sativa* parent. These high-yielding interspecific varieties are generally of short duration.

Rices for drought-prone areas

Drought is a major constraint to increased upland rice production in West and Central Africa. Highly variable rainfall in the forest and savanna zones can induce drought stress at any stage of the crop development. Field screening nurseries in representative locations and soil types, different planting dates, and controlled irrigation are used to capture the different timings and intensities of drought stress encountered in West Africa. Dry- or wet-season rainout shelter evaluations are used in screening rice lines for two distinct types of drought prior to panicle initiation or prior to flowering.

Drought stress generally delays flowering and maturity. The most promising resistant entries at both the vegetative and reproductive stages of rice growth were four newly fixed interspecific lines, WAB450-I-B-P20, WAB450-12-2-BL1-DV5, WAB450-12-2-BL1-DR1, and WAB450-34-BL1-DR1 and three *O. glaberrima* land races, TOG5505, TOG5980, and TOG5486. All of those remained green and continued to tiller during and after the imposition of drought-stress treatments. Several promising lines were also selected from segregating populations, particularly from within the *O. sativa/O. glaberrima* (WAB56-104/CG14) cross, which showed profuse tillering and good vegetative growth with low spikelet sterility under drought stress.

Lines resistant to major diseases and insect pests

The two major rice disease problems in West and Central Africa are blast and RYMV. Blast is an especially serious problem in upland rice and, to lesser extent, in rainfed lowland ecosystems with inadequate water control. RYMV is a major production constraint in irrigated and rainfed lowland ecosystems, especially in valley bottoms where volunteer cultivated and wild rices, and other alternate hosts are plentiful. AfRGM is also a major pest of irrigated and lowland rice in sub-Saharan Africa.

Control of blast and RYMV is hampered by the fact that they are highly variable and requires the use of host resistance in combination with cultural and biological control measures. Chemical control is not economical in subsistence farming systems of West and Central Africa and, if used, gives rise to environmental considerations.

Blast. Enlargement of the genetic base of highly productive rice varieties is the prerequisite for obtaining commercial cultivars with good level of horizontal or durable resistance for blast. However, breeding for this type of resistance is more difficult because it is polygenic, compared with major-gene resistance, which is easy to identify. Unfortunately, the effectiveness of major genes is lost after a few years, or even sometimes just before the release of new cultivars. It is, therefore, better to look for varieties with horizontal, or partial, resistance that seems to be stable and durable. Hence, it is important to have an accelerated program of evaluation of a great number of lines under artificial disease pressure in order to identify entries with suitable resistance at key sites in West and Central Africa.

More than 500 entries, including 344 interspecific progenies, were screened under natural blast pressure with pre-sown spreader rows of susceptible varieties IR5, OB677, and Usen in the African Rice Blast Nursery at M'bé and Man in Cotê d'Ivoire. A high level of N (urea) was applied to induce disease development, which was scored from seedling to the reproductive stages of rice growth to

- identify resistant lines and cultivars under induced blast pressure in the field,
- characterize the nature of the resistance of best entries in order to select donors with stable resistance, and
- analyze the molecular basis of the resistance using molecular markers in order to provide the principle of applied breeding using lineage exclusion methods.

The blast reaction of interspecific populations was generally better than that of the other entries. The interspecific progenies WAB450-I-B-P149-3-1-HB, WAB450-I-B-P39-HB, and WAB450-4-11-1-1-P48-2-1-HB had stability in their reaction in three nurseries, which may indicate stable resistance to blast. However, there is a need to further characterize such varieties by their disease infection rates under sufficient blast pressure to ascertain whether their reaction is due to dominant genes (vertical resistance) or minor genes (partial or horizontal resistance).

Rice yellow mottle virus. All rice ecosystems affected by RYMV in West Africa, and elsewhere in Africa, are characterized by poor diversity of released varieties or commercial cultivars. The occurrence of biotypes or strains of RYMV has been reported, which makes varieties resistant in one place not necessarily resistant at another. There is a need to identify donors with stable resistance to RYMV and develop varieties with good resistance to the disease.

RYMV screening in 1998-99 was done in a screenhouse in a lowland polder at M'bé in Cotê d'Ivoire. Interspecific hybrid progenies and some resistant varieties within *O. sativa* subsp. indica were screened using a finger-rub technique with an infective expressed cell sap. The reaction was scored using the standard evaluation system (SES) for rice developed at IITA, Ibadan, Nigeria. The plants were infected with RYMV at the seedling stage and observed for virus development and effects right through to maturity. Moroberekan, IR47686-31-1-1, and Gigante were used as resistant-tolerant checks, and Bouake 189, BG90-2, and IR1529-680-3, as susceptible checks.

The first set screened showed 78% of the interspecific progenies resistant, while only 13% of the other varieties were resistant. Some of the promising entries with low scores were WAB450-I-B-P32-HB, WAB450-4-1-1-P18-1-11, WAB450-15-2-BL1-DR5, WAB450-24-2-3-P33-HB, all with a score of 1; and WAB450-I-B-P39-HB, WAB450-11-1-P28-4-HP, WAB450-24-3-P38-1-HB and WAB450-5-1-BL1-DR2, with a score of 3. These will have to be re-tested in hot-spot locations to determine stability and other agronomic characters such as yield and grain quality.

African rice gall midge. Preliminary screening for AfRGM resistance was done in a tunnel screenhouse on an irrigated rice field at IITA, Ibadan, Nigeria. Of 274 accessions screened, including 102 interspecific progenies, WAB450-I-B-P181-22-1-HB (with damage level of 8.8%) appeared to have strongest resistance to AfRGM. All the rest of the interspecific progenies scored higher for gall midge damage than the resistant check NATHA 8 (12.1% damage level). Promising non-interspecific entries that performed better than the resistant check were TOS14519 (0.95%) followed by TI477 (7.06%).

Enhancing nutrition through rice bred for high protein

Oryza glaberrima cultivars usually have not only higher protein content (2–5% more than the *O. sativa* but also larger variation in this trait. They can be a useful breeding source for high-protein rice, and the interspecific hybrids offer much promise in this respect. However, high-protein rices are often reported to have poor grain quality and low grain yields.

Fifty lines were selected in 1998 for yields in excess of 5 t ha^{-1} and good grain quality from 200 interspecific hybrid progenies. The 17 most promising selections were grown in 1998-99 at WARDA using standard agronomic practices. The selections had high head-rice ratio, low chalkiness, high translucency, medium-hard texture (about 200 or less setback values in Brabender viscograph), and good aroma. Protein content was more than 9% in milled rice. These results show that there is a strong possibility to select lines with good texture, high milling characteristics, and high market value as well as high protein content. Such rices would greatly enhance nutrition in poor rural and urban homes that depend mostly on rice for their daily food.

Farmer selection of rice varieties

The conventional top-down approach to technology transfer has given way in WARDA to applied and adaptive research, which favors farmers playing active roles in product development and spread. The approaches to farmers are 1) the task force (TF) mechanisms, and 2) farmer participatory varietal selection (PVS) studies. These assisted in early and broad dissemination and adoption of interspecific progenies.

Participatory varietal selection research in West Africa

WARDA started participatory research in West Africa through a small project in Boundiali, Côte d'Ivoire, in 1996. Farmers liked sharing responsibilities for rice research and being able to select varieties that met their needs. In 1998, WARDA scientists took the participatory approach to all the WARDA member countries. An 8-day training workshop in early 1998 taught PVS to cooperators who took the concept, and varieties, to Burkina Faso, Gambia, Guinea-Bissau, Nigeria, and Sierra Leone. PVS in Côte d'Ivoire, Guinea, Ghana, and Togo was initiated in 1997.

A team of a plant breeder or agronomist and a social scientist or extension specialist represented each country. Each team established local PVS trials to

- shorten the time required to move varieties onto farmers' fields,
- determine what varieties farmers want to grow on their own,
- learn what traits farmers value in varieties (for use in planning the release of varieties and breeding objectives for future varieties), and
- determine gender differences in varietal selection.

Almost 2,000 farmers in seven countries selected new rice varieties in 1998 through participatory research, and that includes about 1,300 farmers in Guinea alone.

Farmer participatory varietal selection

In addition to yields superior to those from traditional local cultivars, farmers often cited duration as an advantage of the improved varieties over the local cultivars. Most improved varieties, including the interspecifics, matured 40–45 days earlier than local varieties (150–155 days). Top in demand were interspecific progenies—e.g., WAB450-I-B-P28-HB, WAB450-I-B-P38-HB and LAC23, a traditional upland cultivar of widespread use in West Africa.

Farmer seed production. Most West African rice farmers use farm-saved seeds of local cultivars. The conventional seed multiplication system currently operating in Côte d'Ivoire is typical of most developing countries. Once a variety is released, the breeder provides breeder seed from which three classes of seed are obtained: foundation, registered, and certified. The system requires 6 years from release of a variety until a sufficient quantity is reached for distribution to a large number of farmers.

Community-based seed production system. A high level of adoption of the interspecific progenies in Côte d'Ivoire, Guinea, Ghana, and other countries in the region will create a need for a better and easy-to-handle and cost-effective approach to seed production.

A community-based seed production system (CBSPS), using farmers' practices and indigenous knowledge, was proposed as an alternative seed supply mechanism for smallholder farmers. For CBSPS, the National Seed Service (NSS) certifies only the foundation seed. The extension services make small quantities of that seed available to various informal seed growers—farmers' cooperatives, private seed producers, and NGOs. Those produce noncertified basic seeds for their regions, from which seeds of acceptable quality are produced by trained farmers for communities to use in their normal cultivation practices. In this way, seed is provided to at least some farmers within 4 years of a variety's release—3 years earlier than under the conventional system. At the same time, NSS resources are not stretched trying to meet the whole country's seed requirements. The seed production and distribution is done according to farmers' practices and capabilities, with some simple guidance given to help farmers maintain the seed purity during a 3–5 year period.

CBSPS was successfully tested in 1998 in Côte d'Ivoire in Man, Danané, Odienne, Korhogo, and Boundiali. Several on-field workshops were organized with farmers on seed purification, drying, germination testing, storage, and conservation of land races. Similar activities were ongoing in Guinea with the new interspecific varieties and other promising rices, including farmers' local cultivars.

CBSPS is simple to run because it operates on simply selecting the best grains at harvest to save seed. It offers an opportunity for the rapid spread of the interspecific progenies derived from *O. sativa/O. glaberrima* into existing low-input, subsistence crop production systems in West and Central Africa. It also helps farmers to become more self-sufficient in seeds and to handle local crop diversity better.

Impact of interspecific progenies

The need for improved technologies to assist West and Central African farmers to increase rice production in an economically and environmentally sustainable manner has never been greater. The preconditions for success are now in place.

The wide crossing program involving hybridization between *O. sativa* and *O. glaberrima* offers particularly exciting prospects for increasing and stabilizing upland and rainfed lowland rice yields in low- and high-input systems. The major impact of the interspecific progenies, in comparison with traditionally grown rice, includes a higher yield ceiling, weed suppression, shorter growth duration, increased level of resistance to or tolerance for major stresses, and higher protein content.

Higher yield ceiling

The interspecific progenies have raised the yield ceiling of upland rice by 50%. The maximum potential production for upland rice was previously estimated at 4 t ha^{-1}. The new rices can, in the best of conditions, produce 6 t ha^{-1}. In farmers' fields in Guinea, the interspecifics yield as high as 2.5 t ha^{-1} with few inputs. Some farmers are harvesting 5 t ha^{-1} or more with an increase in fertilizer use. Recent estimates are that 10% adoption of the interspecific progenies in three countries—Guinea, Cotê d'Ivoire, and Sierra Leone—will return an extra US$8 million per year. Adoption by 25% of farmers will return $20 million.

Weed suppression

Weeding accounts for 30–40% of labor invested in a traditional upland rice crop. The interspecific progenies have wide, droopy leaves, inherited from the *O. glaberrima,* that smother weeds in early growth and reduce weeding labor. When the interspecific progenies enter the reproductive stage, the droopy leaves grow erect, like leaves of *O. sativa.*

Growth duration

The interspecific progenies change the growth duration standards in upland rice. They mature in 90–100 days. Typical upland rice varieties mature in 150–170 days. Improved semidwarf varieties in Africa mature in 120–140 days.

The interspecific's shorter growth duration allows farmers to grow two crops during one rainy season. Double cropping with a legume is a recommended system for upland rice. Profuse growth of the legumes helps smother weeds. Incorporation of the legume into the soil can add 60 kg N ha^{-1}. Yields of rice grown after legumes are 30% higher than yields of rice grown after a natural weedy fallow. Best of all, farmers remain on the same land rather than leave their weed-choked, nutrient-depleted fields to clear more land. Each hectare of a well-managed rice-legume rotation can keep 4 hectares from coming under bush fallow.

Increased levels of stress resistance and tolerance

The interspecific progenies have shown increased levels of resistance to or tolerance for stresses such as weeds, blast, RYMV, drought, and acidity. Use of acidity- or drought-tolerant materials has potential to increase regional rice production by 229,000 t y^{-1} as sustainable rice production is intensified in systems prone to insect and disease outbreaks.

Higher protein content

More than 70% of the interspecific progenies evaluated had higher protein content than their African or Asian parents. Almost 40% had from 9–10.5% protein, and 43% had 8.5% protein. The extra protein can vastly improve the nutrition of poor families that depend mostly on rice for their daily food.

A rice green revolution in Africa

The interspecific progenies are expected to be at the base of a rice green revolution in sub-Saharan Africa.

Rice is grown in a range of agroclimatic conditions in sub-Saharan Africa but yields are constrained by unfavorable weather and soils, a number of diseases, and major insect pests. Variability in resistance to drought, soil acidity, rice blast, RYMV, stem borers, and AfRGM is limited in the widely cultivated species of *O. sativa.*

Breeding research programs have targeted these yield-limiting constraints to *O. sativa* rice varieties for more than three decades. While the products of this research outperformed farmers' traditional varieties in systems receiving a relatively high level of inputs, their performance under low-input conditions, which dominate rice farming in West and Central Africa, was poor.

We have confirmed the effectiveness of transfer and use of genes from indigenous African rice species, but we realize that the current fixed interspecific progeny are only prototypes of the new rice type. They can, and will, be improved. Studies have already begun to determine the physiology of the low-management and high-yield-potential rice types. We are developing crop models to optimize plant components for different management systems and ecologies.

WARDA's concept of low-management technologies, although evolved from upland-rice-based research, is now applicable to

- labor-limited upland rice-based systems, particularly where shortened fallow periods have led to increased weed pressure;
- systems in lowlands in inland valleys and floodplains, where the classical technology package of irrigation and transplanted rice may be

impractical for socioeconomic or hydrological reasons; and

- intensified, high-input systems prone to insect pests and diseases, where the use of resistance genes from *O. glaberrima* might prevent major pest outbreaks.

WARDA believes that a green revolution in rice production is now in the making in West and Central Africa. To sustain the momentum will require strong continued support from national partners.

References

Dingkuhn M, Jones MP, Fofana B, Sow A. 1997. New high-yielding, weed-competitive rice plant types drawing from *O. sativa* and *O. glaberrima* genepools. In: Kropff MJ, Teng PJ, Aggarwal PK, Bouma J, Bouman BAM, Jones JW, Van Laar HH, editors. Application of systems approaches at the field. Vol. 2. Dordrecht/Boston/London: Kluwer Academic Publications. p 37-52.

Dingkuhn M, Sow A, Samb A, Diack S, Asch F. 1995. Climatic determinants of irrigated rice performance in the Sahel. I. Photothermal and microclimatic response at flowering. Agric. Syst. 48:385-410.

Jacquot M. 1978. Varietal improvement program for pluvial rice in francophone Africa. In: Buddenhagen IW, Persley GJ, editors. Rice in Africa. London: Academic Press. p 17-129.

Jones MP. 1999. Food security and major technological challenges: the case of rice in sub-Saharan Africa. In: Proceedings of the International Symposium on World Food Security, Kyoto. p 57-64.

Jones MP, Singh BN. 1999. Basic breeding strategies for high-yielding rice varieties at WARDA. In: Proceedings of the International Symposium on World Food Security, Kyoto. p 133-136.

Jones MP, Dingkuhn M, Aluko GK, Semon M. 1997. Interspecific *O. sativa* L. × *O. glaberrima* Steud. progenies in upland rice improvement. Euphytica 92:237-246.

Jones RAD, Mahapatra IE, Raymundo SA. 1978. Rice research in Sierra Leone. In: Buddenhagen IW, Persley GJ, editors. Rice in Africa. London: Academic Press. p 223-231.

Kropff MJ, Van Laar HH, Matthews RB, editors. 1994. ORYZA_1: An ecophysiological model for irrigated rice production. SARP Research Proceedings. Manila (Philippines): International Rice Research Institute. 110 p.

Ten Berge HFM, Jensen DM, Rappoldt K, Stol W. 1992. The soil water balance module SAWAH: description and users guide. Simulation Reports CABO-II, No. 22. Wageningen (Netherlands): NL DCO-Centre for Agrobiological Research (CABO-DLO). 78 p.

Notes

Authors' address: West Africa Rice Development Associaiton, Bouaké, Côte d'Ivoire.

Citation: Rockwood WG, editor. 2001. Rice research and production in the 21st century: symposium honoring Robert F. Chandler, Jr. Los Baños (Philippines): International Rice Research Institute. 224 p.

Wild QTLs for rice improvement

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Over the course of thousands of years, human beings domesticated plant species by selecting desirable individuals from populations of wild plants. Seeds from the selected individuals formed the basis of subsequent populations, eventually giving rise to today's crop species. Domestication over the course of time brought about profound genetic changes in the ancestral species. New strains and subspecies were developed that were better suited to human needs and preferences than were the wild ancestors from which they were derived.

Genetic variation in domesticated crop plants

It is believed that the majority of genetic changes that distinguish domesticated from wild accessions involve selection and recombination of old (ancestral) genes rather than selection based on recent mutations, or the evolution of new genes. This view is supported by evidence from phenotypic and molecular studies showing that wild species contain a wider array of allelic variation than do domesticated varieties in almost every crop species, an observation that is especially evident in inbreeding species (Simmons 1976, Debouck 1991). Intensive, scientific breeding of crop varieties by modern plant breeders over the last 60–70 years has further narrowed the gene pool in many crops (Hargrove et al 1980, Dilday 1990, Yang et al 1994). A narrow genetic base in modern crop varieties makes them more susceptible to disease epidemics (Ullstrop 1978) and to environmental fluctuations (Harlan 1972). Over the long term, a low level of genetic variation in breeding material also has a more subtle effect; it reduces the possibilities for sustained genetic improvement by plant breeders. Although transgressive segregation occurs in crosses between closely related, "elite" prental lines, offspring generally have much in common with their parents and, thus, the likelihood of making major advances in breeding is diminished. This problem is especially critical as it relates to complexly inherited traits such as yield, where slow genetic gains have been achieved using crosses among adapted elite lines.

While this situation exists in breeding programs for domestic crops, there is abundant genetic variation in wild germplasm. Many wild ancestors of modern crop plants can still be found in their natural habitats and seeds or propagules from those wild relatives have been collected and maintained in national and international germplasm collections.

The International Rice Germplasm Collection (IRGC) at IRRI is the largest single species collection in the world (Jackson and Huggan 1993). The wild and nonadapted plant material maintained in the IRGC is freely available for use in crop plant improvement efforts. However, the genetic potential housed in this and other germplasm repositories has hardly been tapped.

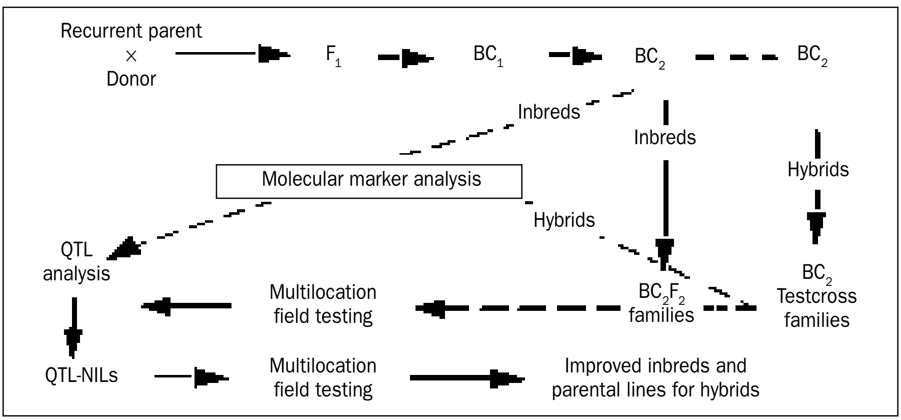
Most wild species yield less and are less well adapted to commercial agriculture than are their domestic counterparts. Though valuable insect and disease resistance, cytoplasmic male sterility, and nuclear restorer genes have been targeted for transfer from wild relatives to cultivated rice for many years (Chang 1984), there was no reliable strategy for transferring genes to improve complex traits, such as yield and quality. Because wild species are likely to contain more genes that reduce yield and quality than genes that could improve these traits, breeders have been reluctant to lose the yield advantages of existing cultivated germplasm in efforts to identify rare, new genes that might ultimately help exceed existing yield plateaus. In addition, the phenomenon known as linkage drag makes it difficult to transfer favorable genes from nonadapted sources because deleterious genes frequently hitchhike along with the desirable genes. Thus, intensive modern breeding efforts have concentrated on obtaining genetic improvements simply by reshuffling the genes (alleles) already present in elite breeding material (Debouck 1991, Ladizinsky 1985, Simmons 1976).

A recently developed breeding strategy demonstrates how one can identify valuable yield and quality genes in wild germplasm, even when they are largely masked by the many negative, or undesirable, genes (Tanksley and Nelson 1996, Tanksley and McCouch 1997). This approach addresses some of the challenges and opportunities recognized by Frey et al (1981) regarding the breeding value of nonadapted germplasm, and points the way toward a more efficient and effective use of natural forms of genetic diversity. Using molecular maps and markers as powerful indicators of useful genes, our method simultaneously paves the way for a broadening of the genetic base of cultivated crop species and provides new rationale for the conservation, characterization, and use of wild and unimproved germplasm in crop improvement.

The molecular linkage map of rice contains more than 4,000 closely linked, codominant loci (http://rgp.dna.affrc.go.jp/, www.gramene.org, Temnykh et al 2000 and unpublished) that can be monitored for linkage to genes controlling virtually any character important to crop plants (Tanksley et al 1989, Paterson 1995). These maps, when used in conjunction with traditional breeding techniques, allow researchers to locate and selectively transfer genes (QTLs) for pest resistance, yield, quality, and adaptability to different production conditions (Yano and Sasaki 1997, Yano 2001, RiceGenes database: http://ars-genome.cornell.edu/rice/). If previously untapped sources of genetic variation are used in crossing, molecular marker analysis offers an effective way of identifying and selectively bringing valuable new genes into the gene pool, while selecting against the deleterious loci implicated in linkage drag.

Population development

Collaborators in China, Indonesia, Korea, Colombia, Brazil, Côte d'Ivoire, and the United States undertook an extensive rice hybridization program. One or more elite, widely grown varieties with good yield, grain quality, and adaptability were selected by breeders and used as recurrent parents in an interspecific-backcross breeding scheme (Fig. 1). Locally adapted cultivars for



1. Diagram of the population development strategy for advanced backcross QTL analysis in rice.

each country reflected the diversity of cultural and climatic conditions under which rice is grown.

The genus *Oryza* includes about 20 wild species, in addition to the two cultivated species, *Oryza sativa* L. of Asian origin, and *O. glaberrima* of African origin (Vaughan 1989). Six of the wild species share the AA genome with cultivated rice and can be hybridized through sexual crossing. To identify accessions among the AA genome species that cross readily with *O. sativa*, 40 AA genome accessions were obtained from the IRGC at IRRI and used as males in crosses with a subset of diverse indica and japonica cultivars. The objective was to identify accessions that could be most reliably used to develop fertile interspecific populations. Thirty-four of the 40 accessions were also screened with 25 restriction fragment length polymorphism (RFLP) markers distributed on the 12 chromosomes of rice to determine the degree of genetic distance between the wild and the cultivated gene pools (Xiao et al 1998). Based on success in crossing experiments, and on estimates of genetic distance derived from molecular marker evaluation (but not any phenotypic criteria), wild or exotic *Oryza* species were selected for use in population development in all locations.

O. rufipogon (IRGC 105491), *O. glaberrima* (IRGC 103544), and *O. barthii* (IRGC 104119) were the wild or exotic *Oryza* species used as donors in crosses with the different locally adapted recurrent parents in each breeding program. Populations of about 300 individual BC_2 (testcross) lines (in China) or BC_2F_2 families (all other locations) were developed in parallel (Table 1). This aspect of the breeding scheme provided the basis for future comparisons to determine the phenotypic impact of specific donor introgressions in a range of genetic backgrounds (G × G). Our ability to evaluate the same populations in different years and locations within the zone of adaptation provided the basis for examining the impact of the donor introgressions in different environments (G × E).

Molecular marker evaluation

Some 150-200 RFLP and microsatellite (or simple sequence repeat [SSR]) markers from rice molecular linkage maps developed at Cornell University (Causse et al 1994, Temnykh et al 2000, 2001) were selected at 10–20-cM intervals throughout the genome and used to assay the BC_2F_2 families or BC_2TC lines derived from each cross combination. Markers were preferentially selected for RFLP analysis from the set of cDNA anchor probes used in comparative mapping studies (Van Deynze et al 1998, Wilson et al 1999, www.gramene.org). Those provided the basis for future comparisons of quantitative trait locus (QTL) locations identified in rice with studies in a wide

Table 1. Plant materials used in advanced backcross QTL studies in rice.

Parent	Population structure	Origin	Source	Collaborator	Comments
V20A	BC_2TC	China	HHRRC	L.P. Yuan	Subtropical indica, widely used CMS line for hybrid seed production in China
Ce64	BC_2TC	China	HHRRC	L.P. Yuan	Indica, widely used restoration line for hybrid seed production in China
IR64	BC_2F_2	Philippines	IRRI	S. Moelpojawiro	Indica, semidwarf, widely grown in irrigated lowlands throughout the tropics, excellent grain quality
Caiapo	BC_2F_2	Brazil	EMBRAPA	C. Martinez E. Guimaraes J. Tohme	Tropical japonica, tall variety, widely grown on upland soils in Brazil
BG-90	BC_2F_2	Sri Lanka	CIAT	C. Martinez J. Tohme	Tropical japonica/indica variety, semidwarf, widely grown in rainfed lowland areas throughout the world
WAB56-104	BC_2F_2	Cotê d'Ivoire	WARDA	M. Jones	Tropical japonica, grown on upland soils in West Africa areas throughout the world
Jefferson	BC_2F_2	USA	USDA	A. McClung C. Martinez	Tropical japonica, semidwarf, grown in high- input irrigated areas of the Southern USA
Milyang 23	BC_2F_2	Korea	RDA, Korea	S.N. Ahn H.P. Moon	Indica/ japonica, "tongil" variety, semidwarf, grown in in irrigated temperate areas in Korea
Gihobyeo	BC_2F_2	Korea	RDA, Korea	S.N. Ahn H.P. Moon	Temperate japonica, semidwarf, grown in irrigated areas of Korea
Donor					
O. rufipogon		Malaysia	IRRI, Acc. #105491		Ancestor of *O. sativa*
O. glaberrima		Mali	IRRI, Acc. #103544		Cultivated in Africa
O. barthii		Chad	IRRI, Acc. #104119		Ancestor of *O. glaberrima*

range of grass relatives. Polymorphism survey filters were prepared using the restriction enzymes, *Eco*RI, *Eco*RV, *Hin*dIII, and *Dra*I, and segregation analysis was undertaken for each population. For microsatellite marker analysis, polymerase chain reaction (PCR) conditions were as described in Chen et al (1997) and Temnykh et al (2000), and detection using either silver-stained polyacrylamide gels (Panaud et al 1996), or fluorescently labeled markers on an ABI373 automated sequencer (Coburn et al 2001) were used. Codominant segregation patterns were observed for both RFLP and microsatellite markers and genetic maps were constructed for each cross combination using the Mapmaker software package (Lander et al 1987).

Phenotypic evaluation

About 300 BC_2F_2 families or BC_2 testcross lines were evaluated in replicated field trials by collaborators at each location. All collaborators conducted field trials independently, but a systematic approach to the evaluation of 12 common agronomic traits (Table 2) provided the foundation for comparison

Table 2. Descriptions of the 12 agronomic traits measured in wild QTL populations.

Trait	Unit	Description
Days to heading	Day	Days from sowing in field (greenhouse) to 10% panicles heading averaged from the whole plot
Days to maturity	Day	Days from sowing in field (greenhouse) to 80% grains reaching golden yellow averaged from the whole plot
Plant height	cm	Averaged from 10 plants measured from ground to the tip of the tallest panicle (excluding awn)
Panicle length	cm	Averaged from all panicles of the 10 plants measured from panicle neck to panicle tip (excluding awn)
Panicles plant^{-1}	No. plant^{-1}	Averaged panicle number as counted from 10 plants (panicles having less than five seeds are not counted)
Spikelets panicle^{-1}	No. panicle^{-1}	(Number of spikelets from the 10 plants)/(number of panicles from the 10 plants)
Grains panicle^{-1}	No. panicle^{-1}	(Number of filled spikelets from the 10 plants)/(number of panicles from the 10 plants).
Seed set rate	%	(Number of grains panicle^{-1})/(Number of spikelets panicle^{-1})
Spikelets plant^{-1}	No. plant^{-1}	Averaged spikelet number as counted from the 10 plants
Grains plant^{-1}	No. plant^{-1}	Averaged grain number as counted from the 10 plants
1000-grain weight	g	Averaged from three samples of 1,000 fully filled grains
Yield plant^{-1}	g plant^{-1}	(Weight of bulked grains from the 10 plants)/10

of QTLs identified in each population. In addition, several groups evaluated grain quality and disease resistance characters that were of particular interest to them. The coordinated approach to population development and genotypic and phenotypic evaluation was designed to provide an underlying data set that would support comparisons of QTL locations across genetic backgrounds and environments. This strategy offers a powerful platform for identifying donor introgressions likely to be useful in a range of breeding contexts. Details of each field evaluation can be found in publications from individual studies—Xiao et al (1998), Moncada et al (2001), Martinez et al (2000), Thomson et al (1999), Ahn et al (pers. commun.),[1] and Septiningsih et al (pers. commun.).[2]

QTL analysis

An aliquot of seed from the BC_2F_2 families or the BC_2F_1 testcross progeny (from each of the populations that was planted in the field) was sent to researchers at Cornell University and planted in the Guterman Greenhouse in Ithaca, NY. DNA from a bulked sample of 20 individuals per BC_2F_2 or BC_2F_1 testcross family was used for molecular marker analysis. Significance thresholds were calculated for each trait in each population based on permutation tests at an experiment-wise significance level of $p \geq 0.01$ (Churchill and Doerge 1994) as described by Moncada et al (2001). Single point, interval, and composite interval analyses were performed using MapMakerQTL (Lincoln et al 1992), Qgene (Nelson 2000), and QTL Cartographer (Basten et al 1994, 1997) to determine the most likely location of QTLs associated with each of the traits evaluated in the field trials.

Phenotypic distribution

The distributions of grain yield (t ha^{-1}) and grain number and grain weight are illustrated from studies by Xiao et al (1998) and Moncada et al (2001) (Fig. 2). Transgressive segregation can be observed in both studies for all three traits, with several lines showing significantly increased grain weight, grain number, and yield compared with the original V20A/Ce64 hybrid combination (evaluated in an irrigated, high-input system in China) or the original Caiapo variety (evaluated in a low-input, upland system characterized by drought and

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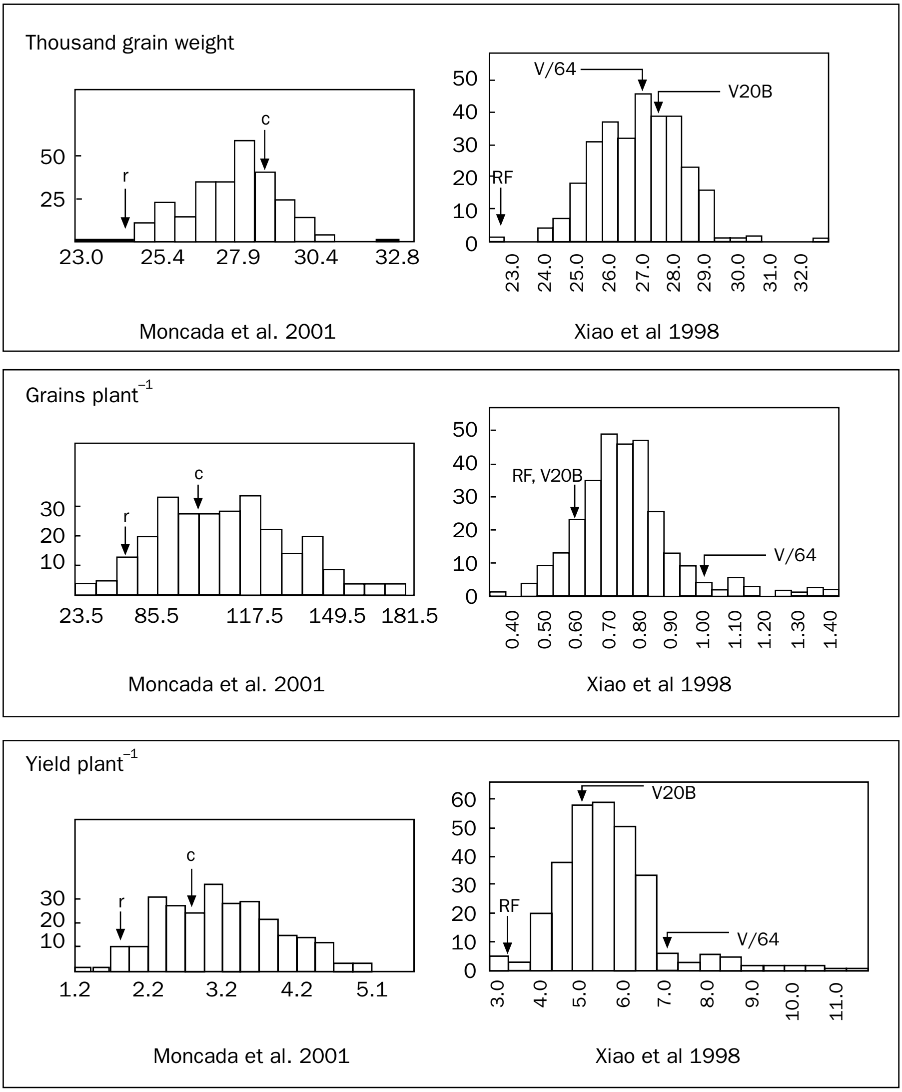


2. Frequency distributions of grain yield (t ha^{-1}) and its two components, grains per plant and grain weight, from the BC$_2$ populations for two wild QTL studies (Xiao et al 1998, Moncada et al 2001). Transgressive segregation can be observed in both studies for all three traits (r = *O. rufipogon* donor parent, c = Caiapo recurrent parent, V20B = V20B recurrent parent, V/64 = V20A/Ce64 hybrid combination, RF = *O. rufipogon* donor parent).

acid soils in Colombia). These data suggest that DNA introgressed from *O. rufipogon* contributes positively to yield and its components in elite rice varieties. Further, these histograms suggest that this may be a general phenomenon in interspecific crosses because similar results are observed in different genetic backgrounds grown in diverse ecosystems.

QTL analysis

Putative QTLs were identified for all of the traits examined in Xiao et al (1998) and for all but one of the traits examined in Moncada et al (2001). Of particular interest for this paper is the opportunity to compare these studies and to ask what proportion of QTLs introgressed from *O. rufipogon* are positive with respect to yield and other aspects of agronomic performance in elite rice varieties. In the two backcross populations examined here, 51% of all *O. rufipogon*-derived QTLs identified in the BC_2TC lines in China and 56% of those identified in the BC_2F_2 families in Colombia were associated with improved performance. Furthermore, as summarized by Xiao et al (1998) and Moncada et al (2001), 54% and 68% of the positive wild QTLs respectively had no deleterious effect on any other character evaluated. These data support the hypothesis that when evaluated in advanced backcross populations, these favorable wild QTL alleles occur at frequencies that are likely to be of practical interest to plant breeders.

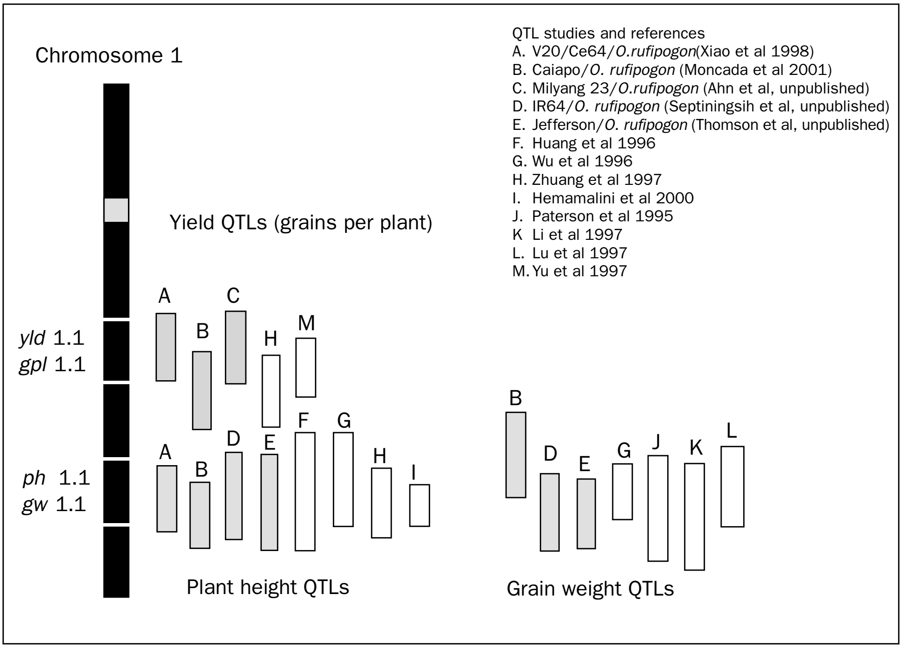
This information provides the basis for marker-assisted development of near-isogenic lines (NILs), each containing a single or few putative trait-enhancing QTLs from *O. rufipogon*. These NILs provide the basis for the development of new varieties as well as for fine mapping and gene discovery. The scheme we propose here avoids many problems associated with epistasis (G × G) and genotype by environment interaction (G × E) that commonly plague efforts to transfer QTLs across genetic backgrounds (Tanksley and Hewitt 1988) because the genetic background of interest for variety development is targeted from the beginning. By using elite lines adapted to different rice-growing environments as recurrent parents, our approach ensures that the QTLs identified are immediately useful for breeding.

The design of this study allows us to immediately compare the positions of QTLs identified in different populations to determine whether any of the same introgressions from *O. rufipogon* have a positive effect in the different recurrent parent backgrounds and different environments. We aim to compare the positions and effect of wild QTLs identified for the same traits across populations.

When five studies, all of which involve *O. rufipogon* as the donor parent, are compared, an introgression on the long arm of chromosome 1 is associated with an increase in the number of grains per plant (*gpl)*, and with an increase in yield (*yld*) for three of the studies (Fig. 3). Substitution of the recurrent parent DNA for *O. rufipogon* DNA in this region confers a phenotypic advantage in a hybrid variety grown with high inputs in tropical China (Xiao et al 1998), in an inbred japonica-indica (tongil) variety grown with high inputs in the temperate zone in Korea (Ahn et al, pers. commun.), and in an inbred tropical japonica variety grown as upland rice with low inputs in Colombia (Moncada et al 2001). The effect is not observed in Jefferson, the tropical japonica background grown with high inputs and irrigation in the southern United States, nor in IR64, the tropical indica background, grown with high inputs and irrigation in Indonesia. However, a QTL associated with yield or with number of filled grains per plant (*nfg)* and located in a similar position on chromosome 1 has been reported in other studies involving intraspecific crosses, as reported by Yu et al (1997) and Zhuang et al (1997). Together, these studies strongly support the hypothesis that genes in this region have a significant impact on yield, but our data are the first to provide evidence of an allelic advantage from a specific donor source (*O. rufipogon*) that is consistent in diverse genetic backgrounds and environments.

Stability of QTL effect is an important criterion when evaluating which regions of the genome are likely to be interesting for targeted gene introgression in a plant improvement program. While overlapping QTL regions is not a guarantee that the same sets of genes govern a trait, positional consistency across studies lends support to the hypothesis of a QTL. On the other hand, lack of previous reports may alert researchers to the possibility that a novel locus in a complex biochemical pathway may have been identified for the first time (McMullen et al 1998, Swarup et al 1999).

A second QTL-containing region, associated with effects on both plant height and grain weight in multiple studies, was detected just distal to the *yld-gpl* QTL on the long arm of chromosome 1 (Fig. 3). This region is of particular interest because it is believed to include the semidwarf (*sd-1*) gene. It has long been observed that the *sd-1* gene not only dwarfs plant stature (a qualitative trait), but it is also associated with increased harvest index and yield (quantitative characters). We are interested to understand the relationship between the genes governing these agronomically important characteristics. Our strategy is to identify the gene or genes that condition each of these three phenotypes as the basis for further investigations regarding gene structure and function. Our ultimate goal is to understand how

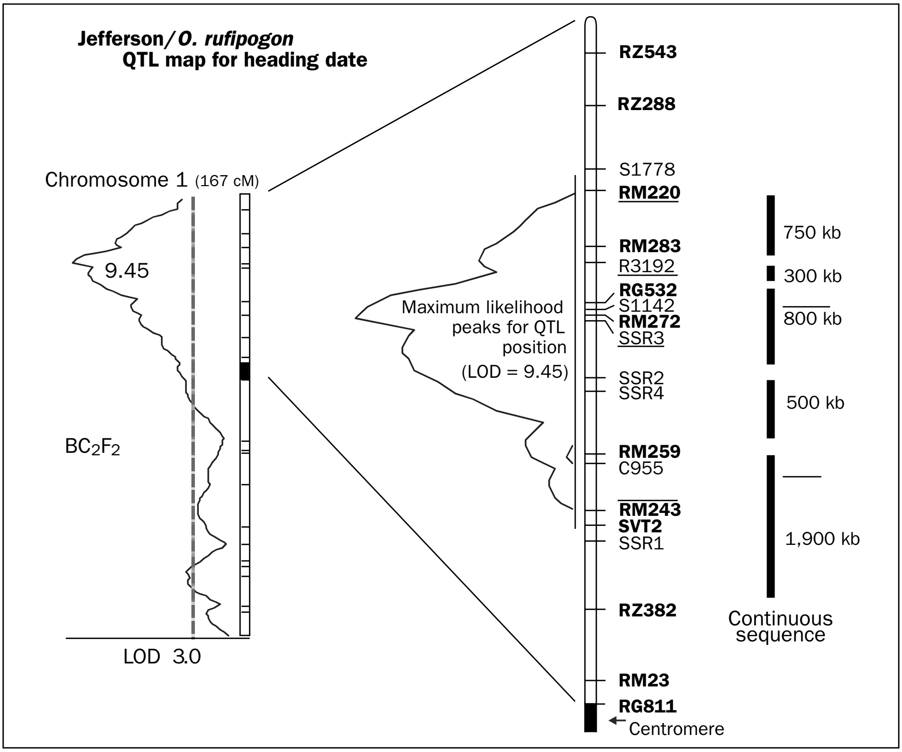


3. Comparison of QTLs identified using *O. rufipogon* as the donor parent (solid boxes, Xiao et al 1998, Moncada et al 2001, Ahn et al, unpublished,[4] Septiningsih et al, unpublished,[5] Thomson et al, unpublished,[5] with other published QTLs for yield (grains per plant), plant height, and grain weight for the long arm of rice chromosome 1 (empty boxes). The semidwarf locus *sd-1* (Cho et al 1996) has also been mapped to the bottom of chromosome 1.

the *O. rufipogon*-derived alleles interact with the recurrent parent alleles to generate useful transgressive variation in the progeny.

Lines containing one or a few well-defined introgressions from *O. rufipogon* are valuable as genetic stocks that provide appropriate material for studies involving gene isolation and characterization. These lines are also valuable as potential precursors of new varieties. A line containing a single, defined introgression, or introgressions, of interest may be inbred to fixation, and if the genetic background is homogeneous for the recurrent parent, it is considered an NIL. Near-isogenic lines can be tested by breeders for a wide variety of performance characteristics in multilocation trials and can simultaneously be used to further basic genetic studies.

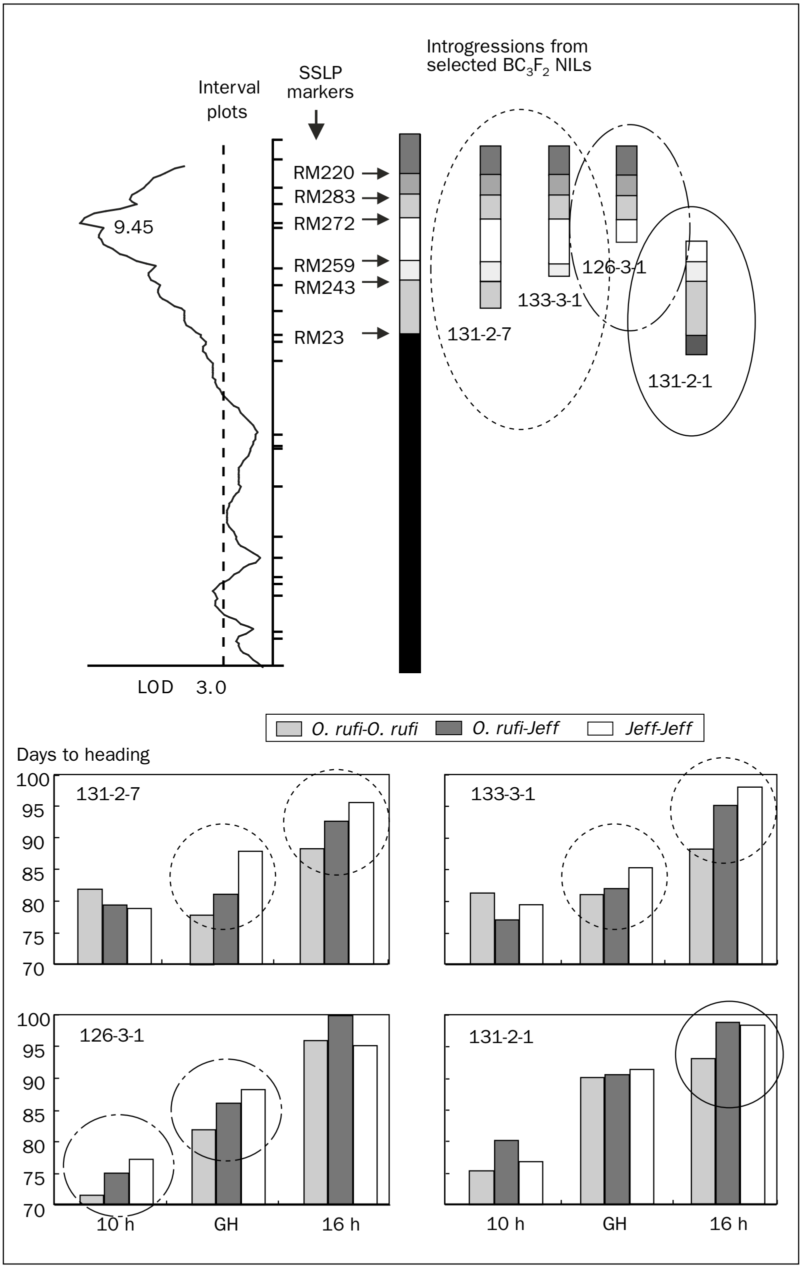
The resolution of primary QTL studies is generally quite low, making it necessary to undertake additional crossing and backcrossing of NILs to generate enough recombination events to adequately subdivide a target region. Fine mapping populations and sets of "substitution lines" containing an array of subdivided *O. rufipogon* introgressions in the background of each



4. QTL map of the short arm of chromosome 1 for heading date, anchored to recently published rice genomic sequence. Primary QTL peak with LOD 9.45 shown at left, oriented to the genetic map showing microsatellite marker positions in middle, and aligned with continuous sequence at far right.

recurrent parent are to be ultimately generated for each target QTL. Molecular marker analysis makes it possible to determine the exact size and location of the new, smaller introgressions (Fig. 4). Additional markers, necessary for monitoring the size of these small introgressions, are easily obtained if the QTL falls in a region of the rice genome that has been fully sequenced, or for which partial sequence (in the form of draft sequence, BAC ends or densely mapped ESTs) is available.

To clarify how specific sub-introgressions affect the performance of the plants, the high-resolution NILs, or substitution lines, are carefully analyzed for phenotype. An example of this is illustrated in Figure 5. A QTL for heading date was identified on the short arm of chromosome 1. Substitution lines containing overlapping introgressions from *O. rufipogon* in the target region were obtained and these lines were evaluated for heading date under



5. BC_3F_2 NILs with overlapping *O. rufipogon* introgressions provide the basis for substitution mapping and progeny contrasts for the heading date QTL on chromosome 1. Heading date measurements under different daylengths (growth chambers at 10 h and 16 h, greenhouse (GH) at 12-13 h) from segregating progeny reveal earlier flowering time from the *O. rufipogon* introgressions for three BC_3F_2 families. The effect of family 126-3-1 is greater for short days, while the effects of 131-2-7 and 133-3-1 are clearer for long days, possibly suggesting multiple flowering time genes underlying the QTL in this region.

different daylengths (10-, 13-, and 16-h days) and in different environments (greenhouse and growth chamber).

The differential phenotypic response for four of these substitution lines is summarized in Figure 5. *O. rufipogon* alleles at loci in the lower half of the introgressed region confer earliness under 16-h days, while *O. rufipogon* alleles at loci on the upper half of the introgression confer earliness under 10-h days. This suggests that some of the genes in this region are responsive to photoperiod. The critical region determining the time to heading is defined by the interval falling under the peak of the QTL curve, but the complexity of the phenotypic response suggests that more than one gene is involved in mediating early or late heading at this QTL. These results are similar to those obtained for other heading date QTLs in rice and *Arabidopsis* (Yano et al 1997, Yamamoto et al 2000, Swarup et al 1999).

The next steps are to a) rigorously characterize the effect of each sub-introgression on heading date and b) look for candidate genes residing in each region. Clues about gene function can often be obtained by comparing the sequences of various candidate genes with their homologous counterparts from other species or genera (McCouch 2001). Use of genomics approaches that compare structure-function relationships of genes across biological boundaries offer powerful insights that can often shorten the process of gene discovery and lead more quickly to the development of hypotheses regarding the genetic mechanisms that govern quantitatively inherited traits or that regulate complex biochemical pathways.

Information about the structure and function of genes or alleles associated with phenotypic variation is of interest to plant breeders for many reasons. As more is known about critical biochemical pathways that are involved in the expression of specific phenotypes, breeders will be able to select for, or against, specific allelic variants that affect the amount, timing, or volume of gene expression at critical points along those pathways. With additional information about the individual genes and signaling molecules that regulate those pathways, the presence of specific genetic characteristics can be targeted when selecting parents or progeny in a plant improvement program. Basic information about the relationship between genotype and phenotype and about the numerous ways that plant cells communicate with the environment will enhance understanding of how biological variation has evolved. All of this knowledge will help us mold new opportunities and expand the repertoire of genetic possibilities available to plant breeders and geneticists in the future.

Siphoning out positive alleles

Crop improvement involves a funneling process in which favorable alleles are siphoned out of germplasm that is compromised in some way and then concentrated in elite backgrounds resulting in improved cultivars. However, this tends to be a unidirectional process and few breeders choose to reenter the predomesticated gene pool in search of new sources of genetic variation once a certain level of performance has been achieved. By targeting wild and nonadapted germplasm for use in population development, alleles that were left behind during the domestication process, or those that are unique to specific gene pools, are selectively introduced into elite germplasm resources. These alleles often represent ancient forms of biological diversity, but they offer new sources of genetic variation to plant breeders. Of particular importance here is the demonstration that some of the novel genetic variation observed in the progeny of these interspecific crosses involves positive transgressive variation (plants that outperform the better parent). That the "positive" alleles come from the agronomically unacceptable wild parent underscores the fact that overall phenotypic performance of a genome may mask "genetic islands" that can be very useful in breeding. The use of molecular marker technology, coupled with the advanced backcross breeding strategy, presents an opportunity to identify and track the individual genetic components (QTLs) that contribute to the positive transgressive phenotype.

Based on evidence we outline in this paper, it can be concluded that some of the wild QTLs are associated with positive effects in a variety of different genetic backgrounds and different environments. More than half of the QTLs from *O. rufipogon* identified in published results from this project conferred a positive advantage in elite varietal backgrounds and would appear to merit further evaluation by plant breeders. These QTLs appear to be useful in both hybrid and inbred rice varieties.

At present, we have presented data regarding the identification of wild QTLs only from *O. rufipogon*; but our study is designed to allow us to determine whether any QTLs from more distantly related species, such as *O. glaberrima* and *O. barthii,* are also likely to provide valuable genetic opportunities for plant breeders working primarily with *O. sativa.*

As part of this project, we have established an international network of plant breeders who are working together to implement a new approach to rice improvement. Rather than a centralized approach, this collaborative project emphasizes local initiative and provides training in laboratory and analytical techniques aimed at bridging the gap between classical and biotechnological approaches to plant improvement. The active involvement of all participating scientists has been a key ingredient since the conceptualization of the project. New collaborations among and between participants have enriched the experience of all and helped to create new opportunities for young scientists entering the field. By taking advantage of complementary expertise in a variety of rice research programs around the world, this network serves to enhance collaboration and communication among people interested in the application of new tools and approaches to plant improvement.

The long-term benefit of successfully employing the strategy outlined in this project would be to simultaneously develop improved varieties and to broaden the gene pool of cultivated rice. The effort can help to reverse the trend toward a narrowing of the genetic base of our crop species and is likely to increase interest in and utilization of valuable collections of wild and unadapted germplasm. Such a strategy can contribute to improved sustainability of agricultural systems by helping to minimize the vulnerability of crops to pest populations and changes in environment. It also offers a sound basis for increasing the potential rate of genetic improvement by increasing the level of genetic variation available to breeders. Molecular markers can aid in the discovery of potentially valuable QTLs from wild germplasm and can reduce the difficult problem of linkage drag associated with transfer of genes from wild species.

Whether a plant breeder relies primarily on classical phenotypic selection or enlists the aid of new technologies and sources of information, the greatest asset that he or she can bring to the practice of plant improvement is an open mind. This approach will continuously reward those who embark on a wild QTL program for cultivar enhancement.

References

Basten CJ, Weir BS, Zeng ZB. 1997. QTL cartographer: a reference manual and tutorial for QTL mapping. Raleigh (NC): Department of Statistics, North Carolina State University.

Basten CJ, Weir BS, Zeng ZB. 1994. Zmap-a QTL cartographer. Proceedings of the 5th Congress on GTenetics Applied to Livestock Production: Computing strategies and software. Guelph, Ontario.

Causse M, Fulton TM, Cho YG, Ahn SN, Wu K, Xiao J, Chunwongse J, Yu Z, Ronald PC, Harrington SB, Second GA, McCouch SR, Tanksley SD. 1994. Saturated molecular map of the rice genome based on an interspecific backcross population. Genetics 138:1251-1274.

Chang TT. 1984. Conservation of rice genetic resources: luxury or necessity? Science 224:251-256.

Chen X, Temnykh S, Xu Y, Cho YG, McCouch SR. 1997. Development of a microsatellite framework map providing genome-wide coverage in rice (*Oryza sativa* L.). Theor. Appl. Genet. 95:553-567.

Cho YG, Eun MY, McCouch SR, Cae YA. 1994. The semidwarf gene, *sd-1*, of rice (*Oryza sativa* L.): molecular mapping and marker-assisted selection. Theor. Appl. Genet. 89:54-59.

Coburn J, McCouch SR. 2001. Chromosome-specific panels of microsatellite markers for semi-automated genotyping of rice (*Oryza sativa* L.). (in prep)

Churchill G, Doerge R. 1994. Empirical threshold values for quantitative trait mapping. Genetics 138:963-971.

Debouck DG.1991. Genetic variation in crop species and their wild relatives: a viewpoint for their conservation. In: Genetic diversity and crop strategies for roots and tubers. Bonn (Germany): Arbeitsgemeinschaft Tropische und Subtropische Agrarforschung e.V. and International Board for Plant Genetic Resources. p 41-51.

Dilday RH.1990. Contribution of ancestral lines in the development of new cultivars of rice. Crop Sci. 30(4):905-911.

Frey KJ, Cox TS, Rodgers DM, Bramel-Cox P. 1981. Increasing cereal yields with genes from wild and weedy species. Journal Paper No. J-11254. Iowa Agric. Home Econ. Exp. Stn. Ames, Iowa, USA. p 51-68.

Hargrove TR, Coffman WR, Cabanilla VL. 1980. Ancestry of improved cultivars of Asian rice *Oryza sativa.* Crop Sci. 20(6):721-727.

Harlan J. 1972. The genetics of disaster. J. Environ. Qual. 1(3):212-215.

Hemamalini GS, Shashidhar HE, Hittalmani S. 2000. Molecular marker-assisted tagging of morphological and physiological traits under two contrasting moisture regimes at peak vegetative stage in rice (*Oryza sativa* L.). Euphytica 112:69-78.

Huang N, Courtois B, Khush GS, Lin H, Wang G, Wu P, Zheng K. 1996. Association of quantitative trait loci for plant height with major dwarfing genes in rice. Heredity 77:130-137.

Jackson M, Huggan R. 1993. Sharing the diversity of rice to feed the world. Diversity 9(3):22-25.

Lander R, Green P, Abrahamson L, Barlow A, Daley M, Lincoln S, Newburg L. 1987. Mapmaker: an interactive computer package for constructing primary genetic linkage maps of experimental and natural populations. Genomics 1:174-181.

Ladizinsky G. 1985. Founder effect in crop-plant evolution. Econ. Bot. 39(2):191-199.

Li Z, Pinson SRM, Park WD, Paterson AH, Stansel JW. 1997. Epistasis for three grain yield components in rice (*Oryza sativa* L.). Genetics 145:453-465.

Lincoln S, Daly M, Lander E. 1993. Mapping genes controlling quantitative traits using Mapmaker/QTL version 1.1: a tutorial and reference manual. Whitehead Institute Technical Report, 2nd edition. Cambridge, MA (USA): Whitehead Institute.

Lu C, Shen L, Tan Z, Xu Y, He P, Chen Y, Zhu L. 1997. Comparative mapping of QTLs for agronomic traits of rice across environments by using a doubled-haploid population. Theor. Appl. Genet. 94:145-150.

Martínez CP, Moncada P, Lopez J, Almeida A, Gallego G, Borrero J, Duque MC, Roca W, McCouch SR, Bruzzone C, Tohme J. 2000. Utilization of new alleles from the wild rice *Oryza rufipogon* to improve cultivated rice (*Oryza sativa*) in Latin America. Abstracts of the 4th International Rice Genetics Symposium, 22-27 Oct 2000, Los Baños, Philippines.

McCouch SR. 2001. Genomics and synteny. Plant Physiol. 125:152-155.

McMullen MD, Byrne PF, Snook ME, Wiseman BR, Lee EA, Widstrom NW, Coe EH. 1998. Quantitative trait loci and metabolic pathways. Proc. Natl. Acad. Sci. USA 95:1996-2000.

Moncada MP, Martínez CP, Tohme J, Guimaraes E, Chatel M, Borrero J, Gauch Jr H, McCouch SR. 2001. Quantitative trait loci for yield and yield components in an *Oryza sativa* × *Oryza rufipogon* BC_2F_2 population evaluated in an upland environment. Theor. Appl. Genet. 102:41-52.

Nelson JC. 2000. QGENE: software for marker-based genomic analysis and breeding. Mol. Breed. 3:239-245.
Panaud O, Chen X, McCouch SR. 1996. Development of microsatellite markers and characterization of simple sequence length polymorphism (SSLP) in rice (*Oryza sativa* L.). Mol. Gen. Genet. 252:597-607.
Paterson AH, Lin YR, Li Z, Schertz KF, Doebley JF, Pinson SRM, Liu SC, Stansel JW, Irvine JE. 1995. Convergent domestication of cereal crops by independent mutations at corresponding genetic loci. Science 269:1714-1718.
Simmons NW. 1976. Evolution of crop plants. London and New York: Longman.
Swarup K, Alonso-Blanco C, Lynn JR, Michaels SD, Amasino RM, Korneef M, Millar AJ. 1999. Natural allelic variation identifies new genes in the *Arabidopsis* circadian system. Plant J. 20:67-77.
Tanksley SD, Hewitt J. 1988. Use of molecular markers in breeding for soluble solids content in tomato—a reexamination. Theor. Appl. Genet. 75:811-823.
Tanksley SD, McCouch SR. 1997. Seed banks and molecular maps: unlocking genetic potential from the wild. Science 277:1063-1066.
Tanksley SD, Nelson JC. 1996. Advanced backcross QTL analysis: a method for the simultaneous discovery and transfer of valuable QTLs from unadapted germplasm into elite breeding lines. Theor. Appl. Genet. 92:191-203.
Tanksley SD, Young SD, Paterson AH, Bonierbale MW. 1989. RFLP mapping in plant breeding: new tools for an old science. Biotechnology 7:257-264.
Temnykh S, De Clerck G, Lukashova A, Lipovich L, Cartinhour S, McCouch SR. 2001. Computational and experimental analysis of microsatellites in rice *(Oryza sativa* L.): frequency, length variation, transposon associations, and genetic marker potential. Genome Res. (submitted)
Temnykh S, Park WD, Ayres N, Cartinhour S, Hauck N, Lipovich L, Cho YG, Ishii T, McCouch SR. 2000. Mapping and genome organization of microsatellite sequences in rice (*Oryza sativa.* L). Theor. Appl. Genet. 100:697-712.
Thomson MJ, Tai TH, Li J, Moncada MP, McClung AM, Marchetti MA, Heatley ME, Mann J, Ahn SN, Cho YG, Martinez C, Tohme J, McCouch SR. 1999. Marker-assisted discovery and transfer of beneficial quantitative trait loci alleles from the wild rice relative *Oryza rufipogon.* In: Rutger JN, Robinson JF, Dilday RH, editors. Proceedings of the International Symposium on Rice Germplasm Evaluation and Enhancement, 30 Aug-2 Sep 1998. Stuttgart, Arkansas (USA): Agricultural Experiment Station, University of Arkansas. p 108-114.
Ullstrup AJ. 1978. Corn diseases in the United States and their control. United States Department of Agriculture (USDA), Agricultural Handbook 199. Washington, D.C.: USDA Agricultural Research Service.
Van Deynze AE, Sorrells ME, Park WD, Ayres NM, Fu HY, Cartinhour SW, Paul E, McCouch SR. 1998. Anchor probes for comparative mapping of grass genera. Theor. Appl. Genet. 97:356-369.
Vaughan DA. 1994. The relationship between the genus *Oryza* and other grasses. In: The wild relatives of rice: a genetic resources handbook. Manila (Philippines): International Rice Research Institute. p 3-5.
Wilson WA, Harrington SE, Woodman WL, Lee M, Sorrells ME, McCouch SR. 1999. Inferences on the genome structure of progenitor maize through comparative analysis of rice, maize, and the domesticated panicoids. Genetics 153:453-473.

Wu P, Zhang G, Huang N. 1996. Identification of QTLs controlling quantitative characters in rice using RFLP markers. Euphytica 89(3):349-354.
Xiao J, Li J, Grandillo S, Ahn SN, Yuan LP, Tanksley SD, McCouch SR. 1998. Identification of trait-improving QTL alleles from a wild rice relative, *Oryza rufipogon*. Genetics 150:899-909.
Yamamoto T, Lin HX, Sasaki T, Yano M. 2000. Identification of heading date quantitative trai locus *Hd-6* and characterization of its epistatic interactions with *Hd-2* in rice using advanced backcross progeny. Genetics 154:885-891.
Yang GP, Saghai Maroof MA, Xu CG, Zhang Q, Biyashev RM. 1994. Comparative analysis of microsatellite DNA polymorphism in landraces and cultivars of rice. Mol. Gen. Genet. 245:187-194.
Yano M, Sasaki T. 1997. Genetic and molecular dissection of quantitative traits in rice. Plant Mol. Biol. 35:145-153.
Yano M, Harushima Y, Nagamura Y, Kurata N, Minobe Y, Sasaki T. 1997. Identification of quantitative trait loci controlling heading date in rice using a high-density linkage map. Theor. Appl. Genet. 95(7):1025-1032.
Yano M. 2001. Genetic and molecular dissection of naturally occurring variation. Curr. Opin. Plant Biol. 4:130-135.
Yu SB, Li JX, Xu CG, Tan YF, Gao YJ, Li XH, Zhang Q, Saghai Maroof MA. 1997. Importance of epistasis as the genetic basis of heterosis in an elite rice hybrid. Proc. Natl. Acad. Sci. 94:9226-9231.
Zhuang JY, Lin HX, Lu J, Qian HR, Hittalmani S, Huang N, Zheng KL. 1997. Analysis of QTL × times environment interaction for yield components and plant height in rice. Theor. Appl. Genet. 95(5-6):799-808.

Notes

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The evolving relationship between the CGIAR and national agricultural research systems

R.P. Cantrell and G.P. Hettel

It is most appropriate that this prestigious symposium is being held to honor Robert F. Chandler, Jr.—a scientist of vision, conviction, and wisdom, whose impact on international agricultural research is still widely felt today, particularly in Asia and especially in rice research. Our topic, *The evolving relationship between the CGIAR and NARS*, is very appropriate for this symposium. Without visionaries such as Bob Chandler, there may not have been a CGIAR—and the makeup and strength of the national agricultural research systems we see today in Asia and other regions of the world would be quite different.

Although the symposium organizers have not made a direct connection to IRRI's 40th birthday in 2000, we would like to tie our anniversary to this week's event—alongside the International Rice Research Conference that we hosted in April and the International Rice Genetics Symposium set for late October in Los Baños. IRRI's 40th birthday is an auspicious and appropriate time for reflecting briefly on some past achievements in rice research and for contemplating, perhaps a bit longer, how IRRI's evolving relationship with the NARS—which we are using to represent similar relationships between other IARCs and their NARS—will contribute to our continued success well into the 21st century.

CGIAR's focus on its relationship with the NARS

Something extremely attractive about the CGIAR has been its focus on the NARS with a real, profound dedication to assist them. When we use the term NARS, we refer to the full range of institutions in a developing country that play different but complementary roles in the process of generating, adapting, disseminating, and using technology to improve the quality of sustainable livelihoods in the rural sector. In the early days of the development of the CGIAR, the NARS umbrella encompassed mostly public-sector institutions involved in agricultural research. What has happened over time, especially in Latin America, is that private-sector groups have arrived on the scene. So now when we talk about the NARS in Guatemala, for example, we include all those little seed companies too! Also now, we have expanded the term to include the technology-extension organizations involved in adaptive research. Some use the term NARES with an E to add the extension activities.

So the national system now includes government institutions, private institutions and companies, extension technology organizations, and nongovernment organizations (NGOs). Our use of the term NARS in this paper includes all these entities.

We believe some critics do not truly understand how crucial the relationships between these NARS and IARCs—even predating the CGIAR itself—have been to the success of the international agricultural research system over the last four decades. Thanks to the ever-strengthening relationships between the IARCs and the NARS—some of which have evolved into true partnerships—the developing world has made many scientific advances in food crop production.

The NARS' contribution to those advances has been so great that IRRI's third director general, Nyle C. Brady, has said that many of IRRI's and other IARC's accomplishments are truly successes of Third World science (Spurgeon 1995).

Much credit goes to the NARS

The earliest and perhaps best-known accomplishments were the parallel development of the high-yielding varieties of wheat and rice that, together with a package of production practices, led to the green revolution.

Norman Borlaug gave major credit to NARS scientists in India and Pakistan during his acceptance speech for the Nobel Peace Prize in 1970. He said that the All-India Coordinated Wheat Improvement Program was "largely responsible for the wheat revolution in India" that eventually led to self-sufficiency in the country's wheat production (Spurgeon 1995). Dr. Borlaug also singled out Indian plant geneticist, Dr. M.S. Swaminathan—and IRRI's fourth director general—for first recognizing the potential value of the Mexican dwarf wheat varieties without which it is quite possible that there would have been no green revolution in Asia.

Dr. Brady has noted that most of the successful varieties in IRRI's international testing program originated in developing-country NARS, rather than IRRI (Spurgeon 1995). He was talking about what is today's incredibly successful International Network for the Genetic Evaluation of Rice (INGER).

How we got where we are today

In taking a look at how we got to where we are today, we immediately see Dr. Chandler's major role in what took place in the 1960s and 1970s. As early as the 1930s, food shortages were already confronting Asian countries such as India, Indonesia, Pakistan, Thailand, and the Philippines.

As rice farmers struggled to grow enough food, malnutrition became a serious problem in some regions. In the 1950s, food supply projections appeared glum—even as advanced research institutes in Japan, China, and Korea were exploring new applications of agricultural technology. The major obstacle then was that most of their research involved temperate rice.

An international center for tropical rice research

Until the mid-1950s, there had been no significant efforts to make any advances with tropical rice. The Rockefeller Foundation's J. George Harrar and the Ford Foundation's Forrest F. Hill, looking particularly to alleviate hunger in tropical Asia, took the lead in proposing a novel research approach for the times. They proposed creating an international institute for tropical rice research that would tackle the challenge of increasing rice production in the poor countries of Asia with centralized laboratories, experimental plots, and a high-powered international team of experts. As negotiations between the Rockefeller and Ford foundations began in earnest, it was decided that an Asian country should be the strategic location for such a research institute (Chandler 1982).

It was this turn of events that brought the fledgling International Rice Research Institute to the Philippines and the arrival of Dr. Robert Chandler to start setting things up in September 1959 (Chandler 1982). A Rockefeller Foundation official who shared the vision and drive of Drs. Harrar and Hill, Bob Chandler moved into the Manila Hotel with his wife Sunny to establish IRRI's first presence in the Philippines. Dr. Chandler legitimately has a place alongside Drs. Harrar and Hill in forming the triumvirate that was responsible for IRRI's creation—and in retrospect the CGIAR itself some 11 years later.

Founding of the CGIAR

IRRI was so successful under Bob Chandler's 12-year leadership as director that it was the major stimulus to the development of a worldwide network of international agricultural research centers (IARCs)—today's Consultative Group on International Agricultural Research (CGIAR).

By the late 1960s, three additional IARCs—CIMMYT in Mexico, IITA in Nigeria, and CIAT in Colombia—were in operation and contributing to increased agricultural production in their regions of the world and beyond. Unprecedented harvests, particularly in Asia from new varieties of rice and wheat based on international research, raised hopes and optimism that the scope of agricultural transformation could be extended worldwide.

The successes of IRRI and its three sister centers led to a series of four meetings in Italy (Bellagio I, II, III, IV) over the 1969-71 period (Chandler 1982). In those meetings, representatives of the major foreign assistance organizations explored how best the international community could protect and strengthen IRRI, CIMMYT, CIAT, and IITA, which had demonstrated their enormous potential contribution to development. Bob Chandler participated in those historic meetings, and contributed to all of the discussions.

At that time, the ability of developing countries' research institutions to generate needed technology, except for maize, wheat, and rice was weak (Chandler 1982). This led to exploring the feasibility of new international efforts, based on the IRRI and CIMMYT models, for dryland crops, animal production, water management, and agricultural policy. The Bellagio participants invited the World Bank, which had already established consultative groups for individual countries, to establish a consultative group on international agricultural research. Hence, the CGIAR system was born just in May 1971. By 1972, the first year of funding, the CGIAR supported five international centers. By 1976, the network of centers and programs financed through the system numbered 11.

Today, there are 16 centers. Surely, Bob Chandler and his fellow CGIAR cofounders could not have envisioned an international system that would have such magnitude and success.

CGIAR successes

What have some of the CGIAR successes been? Globally, CGIAR centers have provided training to 50,000 researchers, educators, and extension agents from the developing world since 1971. At present, eminent developing-country agricultural scientists chair a number of key CGIAR systemwide committees and sit on boards of research centers (Pinstrup-Andersen and Cohen 2000). Pinstrup-Anderson and Cohen point out that CGIAR research has borne considerable fruit, including

- the adoption of new plant varieties, agricultural know-how, and technologies developed at CGIAR research centers—all crucial in the doubling of developing-country grain harvests in a few decades;

- between 80 and 100% of the rice land in major rice-producing countries in Asia and Latin America planted to high-yielding varieties developed at CGIAR centers;
- a decline in Latin America of unit costs and prices by 50% over the past 30 years, saving consumers some $500 million, while increasing incomes of small farmers;
- eighty percent of the wheat varieties planted in developing countries coming from CGIAR centers, with the additional output due to high yield worth nearly $2 billion a year;
- great increases in Asian freshwater fish production;
- the crossing of African and Asian rice varieties using tissue culture techniques to develop a strain that is both hardy and has exceptionally broad leaves, thereby providing biological weed suppression and thus reducing the time women rice farmers have to spend weeding; and
- a threefold increase in African maize production between 1981 and 1996—enough to feed an additional 40 million people each year, at a value of $1.2 billion.

We would add only one caveat to this litany of CG accomplishments. Like Drs. Brady and Borlaug, we believe that ample credit must be given to the NARS researchers, who have worked, and continue to work, with the CGIAR center researchers as true side-by-side partners—often as young trainees or visiting scientists first and then continuing their collaboration later by playing key roles in their home country.

One last point on the recognition given to the CGIAR: the report of the Third External Review of the CGIAR (CGIAR 1998) stated, "investment in the CGIAR has been the single most effective use of official development assistance (ODA), bar none. There can be no long-term agenda for eradicating poverty, ending hunger, and ensuring sustainable food security without the CGIAR."

Parallel appearance of the NARS

It is interesting to note the parallel appearance on the scene of the NARS during the same period that saw the rise of the first IARCs and their CGIAR umbrella. Also during the early 1960s, developing countries facing the acute shortages of food grains that Drs. Harrar, Hill, and Chandler were so concerned about were not, to their credit, going to wait around for handouts. They realized that the systems of agricultural research and extension that they had inherited from the colonial powers were ineffective and inadequate for providing the required technologies for increasing food production.

Developing nations in the tropics—India, Pakistan, the Philippines, and Upper Volta (now Burkina Faso), and Brazil among others—started making efforts to invest and build their agricultural research infrastructure into the NARS that we are familiar with today. In a manner of speaking, the early IARCs (and subsequently the CGIAR) and the NARS matured together during the 1960s and 1970s. They were uniquely poised to move boldly forward hand in hand into uncharted territory.

Structure of the NARS

The core of most NARS consists of the organizations and institutions created and funded by their respective governments. According to APAARI (2000), three models for the organization of NARS have evolved over the past 40 years: 1) the agricultural research council (ARC), 2) the national research institute (NRI), and the agricultural university (AU).

The agricultural research council model. The ARC model represents a variant of an autonomous research organization, playing the role of policymaking, managing or administering, coordinating, and funding. The distinguishing feature of this model is the full managerial responsibility and freedom from bureaucracy given to scientists. Examples are the Indian Council of Agricultural Research (ICAR) and the Pakistan Agricultural Research Council (PARC), in which a loose association of independent regional or provincial institutes, although autonomous, is coordinated and funded centrally.

The national research institute model. Agricultural research in Latin American countries is, in general, nationally organized and provincial governments have no role. Autonomous and semiautonomous institutions organized on the pattern of private enterprises have become the instruments of conducting research. This may be one reason that some NARS in Latin America appear to be more open to dealing with the private sector when compared with resistance to doing so on the part of most Asian NARS. Examples of these models are the National Institute of Agriculture in both Argentina and Chile. The Brazilian Agricultural Research Corporation (EMBRAPA) combines some of the good features of the Asian ARCs and the Latin American autonomous NRIs.

The agricultural university model. The AU model is seen especially in Asia, where education and training are organized under an autonomous agricultural university established on the pattern of the U.S. Land Grant universities. The state agricultural universities of India, Pakistan, and the Philippines are based on this model.

A critical link often missing in the AU is the fact that the universities—where much of the training is done—do not necessarily receive funding for research. Another missing link is a lack of integration at the national level of the three major functions of research, extension, and education. For example, if Pakistan's PARC and its agricultural universities had better linkages, more might be accomplished faster and more efficiently.

IRRI consortia are working to bring the universities into the research picture because, if the universities are going to be good trainers of new scientists, they need to be involved in research activities. For example, our Irrigated Rice Research Consortium in India brings together ICAR's Directorate of Rice Research, Punjab Agricultural University, Tamil Nadu Agricultural University, and G.B. Pant University.

NARS secretariat, GFAR, global fora

By the end of the century, the NARS had evolved to such a degree that they established their own secretariat in mid-1998 at FAO headquarters in Rome, also home of the CGIAR's TAC secretariat. Through their secretariat, the NARS are playing a key role in assuring development impact from the efforts in international agricultural research.

Since October 1996, another evolutionary step in globalization came into being—the Global Forum on Agricultural Research (GFAR). IARCs inside and outside the CGIAR system, NARS, ARIs of developed countries, NGOs in both developed and developing countries, local and national governments, the private sector, farmers' organizations, and donors are taking part in GFAR. All of these members of what we might call an emerging global agricultural research system are now working together to explore, establish, and implement collaborative programs for sustainable food security.

GFAR 2000 met most recently (21-23 May 2000), and most logically, in Dresden, Germany, in conjunction with the CGIAR's mid-term meeting. The overall theme was s*trengthening partnership in agricultural research for development in the context of globalization.*

To facilitate cooperation among all these players at the regional and even the subregional level, GFAR 1999 points out that the NARS have established an impressive set of fora including APAARI (for Asia and the Pacific), which will be mentioned again later in connection with INGER, FORAGRO (for Latin America and the Caribbean), FARA (for sub-Saharan Africa), AARINENA (for West Asia and North Africa), and CEE/CAC (for Central and Eastern Europe and Central Asia and the Caucasus).

So, the communication structure is there. We have no excuses for not talking to each other. With all these mechanisms in place to facilitate communication and brainstorming among the players in this emerging global system, the health of international agricultural research, in general, is as good as it has ever been.

Successful CGIAR-NARS relationships using IRRI as an example

Networks and consortia

Networks were early means to link NARS with IRRI by using participatory planning, execution, and evaluation. Some began as information exchange or material exchange efforts but, with time, gradually evolved into research consultation or collaborative research networks. However, networks have the difficulty that peer and nonpeer institutions are often linked together, thereby creating situations where the work pace is set by the slowest member.

Within the CGIAR, IRRI took the lead using the consortium concept to link NARS research capacity with that of IRRI to solve important problems through multicountry collaboration. By general definition, a consortium is a group of individuals or institutions or companies, or both, formed to undertake an activity that would be beyond the capabilities of the individual members or difficult for them to perform effectively. IRRI uses consortia to provide ways to conduct primarily strategic research by sharing research responsibilities according to each partner's interests and capabilities. The key to success here is that we have truly peer relationships among the NARS and IRRI for strategic research on significant issues with substantial commitment of staff and resources.

Over the past 40 years, the various NARS have advanced at different paces. Some NARS have sophisticated laboratories and facilities rivaling those of ARIs in developed countries. Others—because of war, economic crises, etc.—do not have the capacity to do even applied research. We work with all NARS across this spectrum, from networks with the weaker partners to consortia with the stronger partners capable of contributing to strategic research.

IRRI currently has three consortia in operation—the Rainfed Lowland Rice Research Consortium (RLRRC), the Upland Rice Research Consortium (URRC), and the Irrigated Rice Research Consortium (IRRC). The special feature of collaboration in these consortia is that IRRI scientists put substantive components of their own strategic research with NARS partners at the consortia sites.

The RLRRC and the URRC (both established in 1991) have established good models for the consortium concept. In the RLRRC, NARS from Bangladesh, India, Indonesia, the Philippines, and Thailand are collaborating with IRRI to identify issues and work on strategic research with main goals of contributing 1) alleviation of rural poverty and social and gender inequities and 2) increasing agricultural productivity.

The URRC has provided a collaborative mechanism for India, Indonesia, Thailand, the Philippines, and IRRI to work together on major constraints to the productivity and sustainability of upland rice-based cropping systems. The main efforts have been drought in India, soil fertility in Indonesia, soil management in Thailand, weeds in the Philippines, and blast at IRRI—all respective strengths of the consortium members.

The IRRC, composed of NARS from China, India, Indonesia, Lao PDR, Malaysia, the Philippines, Thailand, and Vietnam, is working to create regionwide multidisciplinary and integrated research projects to look at the interaction of crop production with the resource base and the assessment of the impact of these interactions on local, regional, and global scales.

In an interesting twist, these NARS and IRRI are working with a set of component networks and workgroups, namely, the Integrated Pest Management Network (IPMNET), the Integrated Nutrient Management Network (INMNET), and the newly established Hybrid Rice Network. While each of these groups retains its integrity wherein internal operations are guided and monitored by its respective steering committee, each group is contributing to a multidisciplinary and international research effort governed by the IRRC steering committee. This is an exciting concept and we will be closely watching the output of this effort.

The International Network for Genetic Evaluation of Rice

There is no bigger success story about CGIAR-NARS partnerships than the International Network for the Genetic Evaluation of Rice (INGER). This network involves NARS collaboration with four CGIAR centers. Over a 25-year history, INGER and its predecessor, the International Rice Testing Program (IRTP), have shown clearly how CGIAR centers—in conjunction with the NARS—can benefit by cooperating and sharing. The network has also provided thousands of examples of what can be achieved through such collaboration.

INGER has allowed some of the world's poorest farmers to reap the benefits of CGIAR center-NARS collaboration and also provides ample evidence of the importance of a long-term commitment to the fight against poverty. Since IRTP was launched in 1975, about 1,500 rice scientists from the

NARS of 95 countries in Asia, Africa, and Latin America have shared genetic resources and collaborated as part of the INGER process (Chaudhary et al 1998).

But INGER is not just a network involved simply in the sharing of genetic resources, or rice seed. It achieves far more than this simple process, and it should be noted that the work of the network is quite distinct from the usual germplasm distribution systems that operate elsewhere. Since the network was launched in 1975 with funding from the UNDP, it has resulted in the successful collaboration of IRRI, CIAT, IITA, WARDA, and the NARS in their respective regions.

In each of the regions where INGER now operates, the basic exchange mechanism has remained the same. Scientists and researchers in all the countries involved in the network are asked each year to nominate their best varieties and breeding lines for testing in INGER's 110 nurseries around the world. The four CG centers then serve as hubs for the exchange of the rice germplasm supplied by the scientists.

The best breeding lines and varieties developed by the NARS and IARCs are included in INGER's observational, yield, and screening nurseries, where they are evaluated by NARS scientists all over the world. In all, 21 different types of INGER nurseries target irrigated, rainfed lowland, upland, and flood-prone ecosystems. Some stress-oriented nurseries also focus on major biotic and abiotic stresses. NARS scientists select promising material from the nurseries for release as varieties, or use it in their own breeding programs.

The results of INGER's different evaluations are supplied to all participating scientists. The network has also traditionally ensured that the best-performing rice germplasm can be freely shared and used. However, considering the present situation concerning plant variety rights and patents, the network will obviously face some challenges in this area.

INGER also facilitates the distribution of germplasm to collaborators while strictly adhering to safety and quarantine procedures that have allowed it to maintain an unblemished record since the network was established.

The roles of each of the CGIAR centers have changed over the years. The Latin American Fund for Irrigated Rice (FLAR) has become involved in the funding and operation of INGER in that region, while CIAT has retained an important role. FLAR has, interestingly, introduced a private-sector dimension to INGER. In Africa, WARDA took over the operations of INGER in 1997 and has worked hard since to ensure that the benefits of the network are as widely disseminated as possible on that continent. In the Asia Pacific, APAARI, the regional forum mentioned earlier, has begun working to become more involved in the network.

The impact of INGER. Over the past 20 years, more than 21,000 breeding lines and varieties of rice developed in countries around the world have been exchanged and evaluated through INGER, crossing all political, religious, cultural, and philosophical boundaries. By the late 1990s, more than 350 breeding lines had been released as more than 530 varieties in some 62 countries. Just to give some idea of the global nature of the cooperation, varieties made available in countries as dispersed as Brazil, Burkina Faso, China, Côte d'Ivoire, Myanmar, Sierra Leone, and Vietnam were bred in nine or more other countries and organizations, an incredible success story indeed!

Yale economist Robert Evenson has calculated the annual net worth of each variety released via INGER to be about US$2.5 million (Chaudhary et al 1998). Thus, the 290 modern varieties released through INGER and selected for his study are estimated to generate $725 million a year. This is a very large impact indeed, especially in the developing countries that are the key cooperators and main supporters of the network. It is clear that the genetic material made available through INGER has contributed significantly to increased rice production in many countries and, therefore, greater food security (Evenson 1998).

Over the years, INGER has led to less and less reliance on IARC varieties and the release of more and more NARS varieties as the research capacities of the developing nations involved have quickly developed. In many cases, the poorest countries have benefited most from the varieties introduced by INGER. If the program looks back on its outstanding performance, the financial value of such sharing and collaboration is clear. Networks like INGER are one of the keys to the continued success of the CGIAR.

Asian Rice Biotechnology Network

Another network of note is the Asian Rice Biotechnology Network (ARBN) established at IRRI in 1993 to provide a vehicle for collaborative research with universities and rice breeding institutes of the Asian NARS. ARBN, through its training and collaborative research activities, is providing a unique mechanism for NARS to gain access to relevant knowledge and biotechnology tools. The ultimate goal is to assist the NARS in applying biotechnology to meet their own national needs in rice varietal improvement. Many opportunities exist for rice scientists from Asian countries to train abroad in advanced laboratories, but the network is unique in providing

- participation in research activities that match the priorities and capabilities of the home institute,
- opportunities for repeated exchange of personnel between the home institute and IRRI,

- team training on relevant techniques at IRRI and in-country,
- shuttle research at IRRI for the more advanced steps of a particular biotechnology procedure, and
- help with infrastructure development and technical troubleshooting.

Networks such as INGER and ARBN are keys to the continued success of the CGIAR and its relationship with the NARS. Research cannot be done in isolation. It is only by sharing the results of our research and collaborating with each other that we can hope to achieve the vitally important goals we have set for ourselves and to experience continued growth together.

Future intermediary roles between the public and private sectors

Consortia and networks such as INGER and ARBN are examples of our current "bread and butter" relationships and joint ventures with the NARS. But what is in the future? The current mechanisms will undoubtedly continue to be important, but what new roles might the IARCs need to play, particularly in the light of new areas of research and methodologies emerging on the horizon that encompass functional genomics, bioinformatics, and information and communication technologies (ICT)?

As the NARS continue to grow in strength, our intermediary role, as in the ARBN example, between the various public institutions and, increasingly, between the public and private sectors will become very important. For instance, IRRI could serve as the hub for the gene sequencer in an advanced laboratory in Japan and the breeder in Bangladesh identifying traits. Some specific examples already in motion illustrate our potential as an intermediary.

Functional genomics

One exciting new area of great interest to many NARS and ARIs is IRRI's initiative in the area of functional genomics, the identification of the functions of gene sequences in order to analyze when and how and which genes work together to generate a trait.

Rice genes are the denominators of all rice improvement programs. Thus, knowing the identity and location of each gene in the rice genome is of immense value in all aspects of rice science. The complete sequencing of the rice genome will lead to even more efficient identification and manipulation of traits.

Rice, having one of the smallest genomes among the food crops, has been a target for basic research in many countries and will be the first food crop to be completely sequenced (Fischer et al 2000). Many are aware that an

International Rice Genome Sequencing Project (IRGSP) was launched in February 1998 with coordination provided by the Rice Genome Research Program of Japan. This has now expanded to a consortium of 10 countries.

Private companies such as Monsanto and Syngenta are also developing working drafts of the rice genome map (Pollack 2001). We are encouraged about their apparent willingness to make their research available at no cost to subsistence farmers. This is a promising trend by the corporate sector we hope to see continue. This large infusion of data will enable the international community to complete the genome sooner and at a lower cost than we ever dreamed. With this commitment and collaboration from the public and private sector, a completely decoded rice genome should soon be publicly available.[1]

Because of the conservation of gene sequences in plants, rice sequence information is widely viewed as a gold mine for developing products and technologies in both rice and nonrice crops.

What will IRRI's role be in all of this? Essentially, we have three main goals:

- Generate genetic resources for applications of genomic databases to discover new genes and traits.
- Enhance ecosystem-based varietal improvement programs with new genes and bioinformatics tools.
- Promote accessibility of the genomic databases and genetic resources to our NARS partners.

Functional genomics requires diverse expertise in agronomy, physiology, pathology, genetics, breeding, biochemistry, and bioinformatics. Therefore, a multidisciplinary approach is essential to the success of the research, and to maintain relevance for solving practical problems. For this reason, IRRI formed a working group in 1999 to build a public resource platform to obtain international collaboration (Fischer 2000). Through the working group, broad participation from the NARS and ARIs will be sought to accelerate the applications of genomics in rice—and to provide NARS with free access to those. It is through this participatory process that we can best capture the large investments in genome sequencing.

The working group met during the Plant and Animal Genome Meeting at San Diego in early January 2000. There we continued our initiative to develop a specific collaborative agenda. Interest was high, attracting NARS and ARIs from China, France, India, Japan, Korea, the Philippines, UK, and USA. The major rice sequencing groups (Institute for Genome Research, the collaborative Rice Genome Program of Clemson University, Cold Spring

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[1]Syngenta, Basel, Switzerland, and Myriad Genetics, Utah, USA, announced the first complete sequencing of the rice genome in January 2001.

Harbor, Washington University, Japan, and France-Genoplant) were also there.

IRRI coordinates a web site (*www.irri.org/genomics*) as an information node to deposit and disseminate information relevant to functional genomics. The web site serves as the entry point for finding and sharing information and provide a link to individual laboratories and organizations. IRRI is also facilitating activities to promote the sharing of genetic stocks and DNA resources for microarray analysis.

There is interest in having a grow-out field day in future meetings of the functional genomics working group. This might consist of a mutant garden displaying known mutants and novel variation.

Golden rice

Also exciting is the intermediary role we plan to play involving work on improving the vitamin A content of rice by engineering the plant to produce beta-carotene in the grain. According to the World Health Organization, about 250 million people worldwide are deficient in vitamin A, putting them at risk to contracting various serious ailments. The situation is worst in countries where the population is overly dependent on rice as a staple food. Normal rice contains no beta-carotene, the precursor of vitamin A. Vitamin A deficiency causes more than 1 million childhood deaths each year and is the single leading cause of blindness among children in developing countries.

Rice plants do produce carotenoid compounds, but only in the green parts of the plant. Researchers from the Swiss Federal Institute of Technology (ETH) inserted the genes from a daffodil and a bacterium into temperate rice plants to produce a modified grain, which has sufficient beta-carotene to meet total vitamin A requirements in a typical Asian diet.

Lately, this story has been a hot item in both the popular and scientific press (Guerinot 2000, Nash 2000, Ye et al 2000), especially since the announcement of the agreement between the Swiss inventors of the genetically modified rice plant and the biotech companies Zeneca and Greenovation to distribute seed for the crop at no extra cost to farmers in developing countries.

IRRI is well positioned to play an important role as an intermediary between the biotech companies and interested NARS to transfer the genes required for beta-carotene biosynthesis into popular tropical indica rice varieties. In May 2000, the U.S. Senate's Appropriations Subcommittee on Foreign Operations proposed a significant direct allocation to IRRI so that we can explore further development of this new golden rice. The proposed funding would support a strategy that truly will make a real difference in the lives of millions.

Global knowledge system for rice

IRRI can also play an intermediary role in the area of improving the future flow of vital information within the international agricultural research system. The NARS secretariat is on record stating that the CGIAR, in collaboration with the NARS secretariat and the respective regional and subregional fora mentioned earlier, needs to aggressively support collaborative relationships for improving information flows within and among NARS, and between them and the IARCs and other stakeholders and partners.

This issue is one of GFAR's major thrusts. At a 1999 GFAR consultation in Rome on *Information initiatives in agricultural research: enhancing global cooperation*, the statement was made that "Knowledge, and equitable access to it, is essential to achieve food security and sustainable development" (GFAR 1999). We could not agree more. With this in mind, a task force was formed at IRRI in February 2000 to explore what needs to be done for rice in the context of a global knowledge system being discussed and promoted by GFAR. A few key aspects of that task force's deliberations follow (McLaren et al 2000).

The explosive development of ICTs will enable many components of a *Global Knowledge System for Rice* to be integrated and made accessible from anywhere at any time. IRRI must make use of these new technologies to continue to develop its role in the discovery, integration, and dissemination of knowledge on rice. New ICTs, however, still deal with electronic data only and much of the old knowledge system is in non-electronic form, including human experience. The challenge to making a knowledge system work is to capture all kinds of data, information, and knowledge in electronic form and integrate them into a global network in an accessible and understandable way. This may not change what we do, but it will dramatically change the way we do it.

New ICTs make information systems dynamic and flexible; they are not controlled or directed by organizations or institutes, but rather by demand and users. IRRI, however, has 40 years of experience in accumulating and disseminating knowledge on rice and it should continue to focus on its mandate to provide a conduit for information exchange between rice science and rice scientists, producers, and consumers.

As we have already pointed out, IRRI's successful collaborative consortia and networks are founded on the principles of partnership, sharing, and exchange. A global knowledge system for rice would offer tremendous opportunities to improve the efficiency and effectiveness of our consortia and networks. It would reduce transaction costs by allowing effective remote collaboration and it would improve efficiency by ensuring that knowledge is exchanged. The knowledge system would likewise speed up and target feedback from users of technology to researchers. It would allow real dialogue in real time.

New ICTs are also changing research—both what research can be done and how we do it. A global knowledge system for rice would deal with research data by providing management systems for their collection and documentation and linking data from different sources so that integrated analyses and broad understanding of scientific results will be possible. This system would contain massive databases of genomic data, which must be linked to scattered islands of phenotypic information through the new science of bioinformatics to facilitate the discovery of useful genes that will improve the productivity, sustainability, and quality of rice.

ICT development is revolutionizing human interaction. Access to global communications and powerful computing will be as affordable and widespread as radio and television are today. The concern for CGIAR centers like IRRI is not whether our clients have access, but rather whether we will be ready with the expertise and leadership to help our partners integrate into a global knowledge system.

To accomplish this, our task force suggested that IRRI take the following steps:

- Develop an institutional information strategy that clearly defines IRRI's role in a global knowledge system for rice, sets out how to achieve that role, and identifies the resources required.
- Collaborate actively with international organizations to develop infrastructure, human resources, and standards that will lead to effective global information systems for agriculture and development.
- Participate in the regional bodies developing regional information networks to ensure access to and participation in global information systems for our NARS partners.
- Develop an information awareness culture at IRRI so that our human resources and infrastructure can be updated and ready to meet the challenge of creating a global knowledge system for rice and making it function efficiently for those who would use it.

By taking advantage of the opportunities afforded by new ICTs, we can integrate our research and information activities with those of our partners through an enhanced global knowledge system for rice. In this way, we can achieve the vision of a true science partnership from the rice fields of Asian farmers to the molecular laboratories and super computers of the developed world.

In a recent development tied to the global system, IRRI has joined the Asia-Pacific Advanced Network (APAN—Asia's version of Internet2). This high-bandwidth network has been used for video conferencing and for course presentations in the Ministry of Agriculture in Thailand.

International symposia

Another role of IRRI—if it is to maintain its flagship position in rice research—will be to continue to organize international symposia on cutting-edge science that perhaps no one else would initiate. Such a symposium that readily comes to mind is the one sponsored in December 1999 on redesigning rice photosynthesis to increase yield (Sheehy et al 2000). IRRI hosted a gathering of world experts so that they could look at the intriguing possibility of transferring to rice the more efficient C_4 photosynthetic pathway found in maize, sorghum, millet, and sugarcane. Other features of the C_4 pathway might include enhanced efficiency of water and nitrogen use as well. Who knows what this nudge of the scientific community might have fomented?

In October 2000, we hosted the 4th International Rice Genetics Symposium (Khush et al 2001)—a major event for rice geneticists that IRRI has sponsored and hosted every 5 years since 1985. In 2002, we will work with the Chinese to call scientists together for a world conference in Beijing to participate in discussing a wide array of issues critical to rice agriculture.

Rice researchers—indeed all agricultural researchers—are in for an exciting time in the 21st century. The CGIAR centers, the NARS, the ARIs, and all the other players in what has developed into a truly dynamic international agricultural research system are all positioned to really make things happen in a united effort.

Unbiased brokering of information and germplasm

So, as our NARS partners increase their research capacities, as the private sector gets more involved in developing-country agriculture, and as IRRI and other IARCs take on more intermediary responsibilities, let us not lose sight of one important concept. The tremendous successes of international agricultural research over the past four decades can be traced to one overriding factor—the IARCs' role as unbiased brokers of scientific information and germplasm for the benefit of the NARS. This circumstance is truly unique in the international research arena, and it is something we must preserve at all costs.

The IARCs must be vigilant of becoming too much like their ARI counterparts when dealing with the private sector, particularly in Asia. We certainly do not want to strain our relationship with the NARS just to become players with the private sector. We can leave that niche to the ARIs since the tradeoff for us, and the NARS, may not be worth it in the long run.

Conclusion

It is sad that George Harrar, Frosty Hill, and other early visionaries who orchestrated what would one day become the CGIAR are no longer with us. Fortunately, Bob Chandler lived to the ripe old age of 91 and did see what all his early efforts brought forth. Although his well-known modesty would never have allowed him to personally acknowledge the seminal role he played in this monumental effort to improve the plight of the world's poor, deep down he must have truly been proud.

The world owes a debt of gratitude to Bob Chandler for his vision, conviction, leadership, and wisdom.

References

APAARI (Asia Pacific Association of Agricultural Research Institutions). 2000. National agricultural research systems in the Asia-Pacific Region—a perspective. Bangkok (Thailand): APAARI. 37 p.

CGIAR (Consultative Group on International Agricultural Research). 1998. The international partnership for food security and sustainable agriculture. Third System Review of the CGIAR. Washington (D.C.): CGIAR Secretariat.

Chandler Jr. RF. 1982. An adventure in applied science: a history of the International Rice Research Institute. Manila (Philippines): International Rice Research Institute. 233 p.

Chaudhary RC, Seshu DV, Alluri K, Cuevas-Perez F, Lopez VC, Khush GS. 1998. INGER-derived varieties directly released in various countries. Manila (Philippines): International Rice Research Institute. 37 p.

Evenson RE. 1998. Rice varietal improvement and international exchange of rice germplasm. In: Pingali PL, Hossain M, editors. Impact of rice research. Proceedings of the International Conference on the Impact of Rice Research, 3-5 Jun 1996, Bangkok, Thailand. Bangkok (Thailand): Development Research Institute and Manila (Philippines): International Rice Research Institute. p 51-82.

Fischer KS, Barton J, Khush GS, Leung H, Cantrell R. 2000. Collaborations in rice. Science 290(5490):279-280.

GFAR (Global Forum on Agricultural Research). 1999. Towards a global agricultural research system: activities of the NARS Secretariat—1999-2000. Rome (Italy): NARS Secretariat. 32 p.

Guerinot ML. 2000. The green revolution strikes gold. Science 287(5451):241-243.

Khush GS, Brar DS, Hardy B, editors. 2001. Rice genetics IV. Proceedings of the Fourth International Rice Genetics Symposium, 22-27 Oct 2000, Los Baños, Philippines. New Delhi (India): Science Publishers, Inc., and Manila (Philippines): International Rice Research Institute. 488 p.

McLaren G, Hettel GP, Jackson M, Kam SP, O'Nolan P. 2000. IRRI's role in a global knowledge system for rice. Unpublished internal document. Manila (Philippines): International Rice Research Institute. 3 p.
Nash JM. 2000. Grains of hope. Time 156(5):38-46.
Pinstrup-Andersen P, Cohen NJ. 2000. Biotechnology and the CGIAR. Paper presented at the International Conference on Sustainable Agriculture in the Next Millennium—The Impact of Modern Biotechnology on Developing Countries, 28-31 May 2000, Brussels, Belgium.
Pollack A. 2001. Companies unravel rice genome, providing model for grains. New York Times, 26 January.
Sheehy JE, Mitchell PL, Hardy B, editors. 2000. Redesigning rice photosynthesis to increase yield. Proceedings of the workshop on the Quest to Reduce Hunger: Redesigning Rice Photosynthesis, 30 Nov-3 Dec 1999, Los Baños, Philippines. Manila (Philippines): International Rice Research Institute and Elsevier Science B.V. 293 p.
Spurgeon D. 1995. Southern lights: celebrating the scientific achievement of the developing world. Ottawa (Canada): International Development Research Centre. 137 p.
Ye X, Al-Babili S, Kloti A, Zhang J, Lucca P, Beyer P, Potrykus I. 2000. Engineering the provitamin A (b-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 287(5451):303-305.

Notes

Authors' address: International Rice Research Institute, DAPO 7777, Metro Manila, Philippines.
Citation: Rockwood WG, editor. 2001. Rice research and production in the 21st century: symposium honoring Robert F. Chandler, Jr. Los Baños (Philippines): International Rice Research Institute. 224 p.

The evolution of plant breeding in the private sector: field crops in the United States

D.N. Duvick

Plant breeding, broadly defined, started with plant domestication about 10,000 years ago when our ancestors began to nurture favorite species and eventually developed domesticated crops from some of them. We have no record of what procedures were used, but suppose that these first plant breeders selected favored phenotypes from successive generations of segregating populations. Those populations would have resulted from chance hybridization or mutation.

The concept of deliberately planned plant breeding is much younger. It arose in the late 18th and early 19th centuries at about the time that botanists first described sexuality in plants. This new knowledge provided a firm technical foundation for individuals who wished to make planned crosses to provide new segregating populations for selection (Evans 1998, Harlan 1992, Smith 1995, Smith 1966).

The concept of science-based plant breeding is even younger. It arose in the early decades of the 20th century, simultaneously with the development of theoretical and practical aspects of genetics and statistics (Smith 1966).

Starting in the early 1900s, government and academic institutions established full-time professional positions in plant breeding with expectation that the professionals would develop superior new varieties more efficiently than ever before. The professionals were expected to excel in plant breeding because of the application of genetics and other kinds of science to their work. But they were more importantly charged with developing improved plant varieties, using any methods that worked. These plant breeders were not funded by their customers, the farmers; they were supported by public funds—by tax revenues. They were the public plant breeders.

Commercial plant breeding also got its start at or just before the beginning of the 20th century, more or less in step with public plant breeding. It, too, was based on the expectation that full-time professional plant breeders could produce superior products. But there was a further expectation (or hope) that seed of their superior varieties could be sold for a profit. The breeders in the commercial sector, like those in the public sector, intended to serve farmers but they differed in that they expected to be supported by payments from the farmers, rather than by payments from the public purse (Duvick 1993). These were private plant breeders.

Although interest in commercial plant breeding arose at about the same time as that for public plant breeding, commercial breeding of field crops did not become widespread until several decades after public plant breeding was well established. Survival of a commercial seed industry required the development of practical ways for the seed companies to maintain ownership—and thereby control the reuse and sale—of their products. Maintaining ownership was not easy, and often impossible. One of the early commercial breeders, the horticulturist Luther Burbank, was frustrated by his inability to prevent others from reproducing and selling varieties developed by him (Encyclopaedia Britannica 1983, Toth 1998). He tried, without success in his lifetime (he died in 1926) to bring about passage of legislation that would give patent-like protection to creators of new crop varieties.

In absence of legal protection, commercial breeders had two alternatives:

- They could introduce a new variety in large amounts for an initial offering, with the expectation that virtually all of their sales would take place in the first 2 or 3 years after release. After that time, farmers would have sufficient seed from their own plantings, or other seed companies would be providing seed of the new variety at cut-rate prices. Prices and volume of sales in the breeder's initial offering had to be high enough to ensure repayment of research expense plus a reasonable profit in a 2-year period. If not, the gamble was lost. Despite the risks, commercial plant breeders in Europe used this method during the first half of the 20th century although they were not satisfied with it for the reasons already stated. They, like Burbank, wanted more protection for the products of their research.
- Crops that could not be reproduced from initial plantings could be bred and sold commercially. Each variety in theory could be sold for many years or at least for as long as it was popular with farmers. First-generation hybrids fit this definition because succeeding generations usually yield much less than the initial hybrid, or they lack required uniformity for important quality characteristics, or both. But in the

early years of the 20th century, no one knew how to make hybrid seed of field crops on a large scale.

Hybrids and the private sector

Hybrid maize

The increased vigor and yield (heterosis) of maize (*Zea mays* L.) hybrids compared with their inbred parents had been known since the first decade of the 20th century (Shull 1909, 1952). Maize could be hybridized on a large scale because male and female organs were borne on separately on the tassel and the ear. Removal of the tassel by hand was relatively easy, and so large blocks of emasculated female plants could be produced. They then could be hybridized via wind pollination to a suitable nondetasseled male parent planted in contiguous blocks. But the inbred maizes of that time were weak and low-yielding. If they were used as seed parents, one could not produce hybrid seed at economically acceptable prices.

In 1918, D. F. Jones suggested that one could make hybrid maize as a double cross (Crabb 1993, Jones 1918). Two first-generation hybrids (single crosses) could be crossed and the resulting double-cross hybrid would be nearly as good as single-cross hybrids and definitely superior to the best open-pollinated varieties. This news stimulated several individuals and seed companies to institute research programs to develop hybrid maize for sale on a commercial scale (Duvick 1998). Henry Wallace formed the Hi-Bred Corn Company (later Pioneer Hi-Bred International, Inc.) in 1926 to capitalize on breeding he had started several years earlier. The DeKalb Agricultural Association set up a hybrid maize breeding program in 1925 and sold their first hybrid in 1934. A farmer, Lester Pfister, instituted a personal breeding program in 1925 and eventually founded the Pfister Hybrid Corn Company. Funk Brothers Seed Company, already in business to develop open-pollinated varieties of maize, instituted a hybrid maize breeding program in 1927. By the mid-1930s, all of these companies, and many others as well, were supplying maize hybrids to American farmers, principally in the Corn Belt states. By the end of the 1930s, the preponderance of Corn Belt maize was hybrid. Iowa led the way; 97% of its 1941 maize crop was planted to hybrid seed. Farmers in all parts of the country abandoned their open-pollinated varieties in favor of hybrids. By 1960, maize production in the United States was essentially 100% hybrid.

Although private companies or individuals were among the pioneers in producing and selling maize hybrids, it is important to note that the public sector did most of the original breeding and developed virtually all of the theory that supports hybrid development (Frey 2000, Huffman and Evenson 1993, Wallace 1955). Furthermore, breeding in the public sector accompanied that in the private sector for many years after the private sector developed its own research capacity (Duvick 1998). Public inbred lines developed by breeders employed by the USDA or state land grant colleges provided nearly all of the inbred parents used in the first hybrids produced and sold by the commercial seed companies. For example, a private company might produce a hybrid with three public lines and one private (in-house) line. This allowed the company to claim its hybrid had a unique pedigree, but nevertheless the hybrid's performance also owed much to public inbred lines (such as Hy or Wf9) that were widely used by most of the other seed companies.

In time, the larger research programs in the private sector developed a full line of their own inbred parents, and their need for public inbreds decreased (Frey 2000). However, as recently as the 1980s, public inbred lines such as Mo17 (University of Missouri) and B73 (Iowa State University) were widely used although not specifically credited by commercial companies.

Smaller seed companies usually were unable to develop a full line of their own inbred parents. Public breeding programs supplied their needs at first but gradually public maize breeding programs shifted from applied to basic research and their output of inbred lines declined. As the public programs reduced inbred line output, the small companies gradually came to depend on foundation seed companies. Foundation seed companies were specialists in developing inbred lines that could be leased and used for production of private-label hybrid seed. The foundation seed firms produced and tested inbred lines and the production-sales firms produced, tested, and eventually sold hybrids made with those lines.

Cytoplasmic male sterility and hybrid seed production

Onion and sugar beet. Maize is unique among field crops, and many horticultural crops as well, because it can be emasculated on a large scale. Most crop species bear perfect flowers—male and female organs borne in the same structure—and therefore emasculation is difficult, slow, and expensive. A genetic method of emasculation—male sterility—eliminates the need for hand emasculation. However, when nuclear genes control male sterility, the rules of genetics (unaided by biotechnology) dictate that one cannot produce blocks containing only male sterile plants.

One cannot propagate male sterile plants by self- or sib-pollination; the sterility genes must be maintained in heterozygous condition. This problem can be eliminated by use of cytoplasmic male sterility, in which an interaction between recessive nuclear genes for male sterility and a genetically distinct cytoplasm (typically with altered mitochondrial genes) allows production of progeny that are entirely male sterile. The nuclear male sterility genes are without effect in normal cytoplasm and so lines that are homozygous for those genes (maintainer lines) can be reproduced via normal self- or sib-pollination.

Plant breeders, private and public, recognized the potential utility of cytoplasmic male sterility (actually, cytoplasmic-nuclear male sterility) to effect large-scale hybridization for seed production of maize as early as the 1920s. The first attempts to use the method were abandoned, however, because plants were not reliably male sterile (Duvick 1959).

An onion (*Allium cepa* L.) breeder in the public sector developed the first successful program to use cytoplasmic-nuclear male sterility for making hybrids (Jones and Clark 1943). The commercial seed sector soon adopted the method and used it for much of its seed production. At almost the same time, a public-sector breeder developed a cytoplasmic-nuclear male sterile system for sugar beet (*Beta vulgaris* L.) (Owen 1945). Once again, commercial seed producers adopted the method, although progress was slower because of difficulties in finding nuclear genotypes that gave reliable male sterility when in combination with the sterility-inducing cytoplasm.

Maize. Next in line was a new attempt, successful this time, to use cytoplasmic-nuclear male sterility for production of maize hybrids (Jones and Everett 1949). D.F. Jones, the private-sector breeder who developed the new procedure, was the same person who had proposed the highly successful double-cross system for producing hybrid maize. A new cytoplasmic-nuclear combination produced a more reliable kind of male sterility. A further innovation was that use of the dominant allele (the fertility restorer allele) of the nuclear male sterility gene in the pollinator parent produced hybrids that shed pollen in the farmers' fields. This meant that 100% of the plants in the seed field could be male sterile. Detasseling was eliminated in production of fertility-restorer hybrids (Jones and Mangelsdorf 1951).

Seed companies adopted the new system as fast as inbreds could be re-bred to carry either sterile cytoplasm or restorer genes (Duvick 1965). By the 1960s, most of the hybrids in the United States carried sterility-inducing cytoplasm. Some hybrids carried only sterile cytoplasm and some were blends of normal and sterile cytoplasm, depending on whether or not the male parent contained restorer nuclear genes. Two kinds of sterility-inducing cytoplasm were used—S and T. T cytoplasm was used most widely because its cytoplasmic-nuclear interactions were more reliably male sterile.

In 1970, a new variant of an old disease, southern corn leaf blight (*Cochliobolus heterostrophus* (Drechs.)) appeared, and was specifically virulent on plants with T cytoplasm (Tatum 1971). The variant was called southern corn leaf blight race T. In some parts of the country (especially the south and east), many hybrids were so severely damaged that no grain was produced. In the southern portions of the central and eastern Corn Belt, damage was less severe but still disastrous. Southern corn leaf blight caused an estimated 10-15% reduction countrywide in the yield of the 1970 maize crop. As a result, seed companies immediately stopped use of T cytoplasm and many also stopped use of S cytoplasm out of concern that it could be the next target of a new cytoplasm-specific disease. Only now are some companies again beginning to use cytoplasmic sterility. They use S cytoplasm, and also a third kind called C.

Grain sorghum. In 1954, Stephens and Holland (1954) described a cytoplasmic-nuclear interaction for male sterility in sorghum (*Sorghum bicolor* (L.) Moench). Plants of kafir nuclear genotype were sterile when backcrossed into plants with milo cytoplasm. Milo types also provided restorer genes. Stephens and Holland suggested that the system they described could be used to produce hybrid sorghum. They were right. Commercial seed companies took advantage of the opportunity and within 5 years, 50% of the grain sorghum acreage in the United States was planted to hybrids, and in a few more years, essentially 100% of the plantings were hybrid (Duvick 1959).

Sorghum farmers adopted hybrids even faster than maize farmers had adopted hybrid maize. And, for the first time, a field grain crop other than maize was produced as hybrid on a large scale.

Wheat. Cytoplasmic-nuclear systems causing male sterility in common bread wheat (*Triticum aestivum* L.) were first described in 1951. More useful systems were described by public-sector researchers in the 1960s (see Knudson and Ruttan 1988). Wild species contributed sterile cytoplasm and fertility-restoring genes. Seed companies set to work to take advantage of this commercial opportunity, but success did not come as easily as with sorghum.

Yield advantage of wheat hybrids, compared with pure line varieties (i.e., heterosis), was less than for grain sorghum. Seed production was more costly because wheat sheds less pollen than sorghum—the ratio of male to female rows had to be increased and seed set often was poor. The net result was that seed yields per unit area were low. Perhaps, the most important, rapid advances in yield and performance of pure line varieties happened to be occurring at just the time breeders were starting to breed wheat hybrids. Hybrids typically used pure line varieties or their close relatives as parents, and the time spent in backcrossing varieties into sterile cytoplasm or converting them to restorer genotype meant that hybrids nearly always were made with outdated parents. Consequently, the small advantage from heterosis was not enough to match the performance of the newest pure line varieties.

The unfortunate consequence of all of these factors was that hybrid seed was expensive and hybrids gave little advantage over the pure line varieties. Not surprisingly, farmers showed little interest in them. Hybrid wheat production was never great and has declined to small amounts at the present time.

Nevertheless, some companies continue to experiment with hybrid wheat. They believe that advances in technology will allow successful production of hybrid wheat (Duvick 1999). For example, chemical-hybridizing agents can be used for emasculation, eliminating the need to use a cytoplasmic-nuclear system.

Sunflower. In the early 1970s, public-sector researchers in France and the United States described cytoplasmic-nuclear systems that would allow production of hybrid sunflower (*Helianthus annuus* L.) (Miller 1987). Sterile cytoplasm and nuclear genes for fertility restoration came from wild species. Seed companies immediately began production and breeding of hybrids in the United States and other countries. The first hybrids were introduced in 1972 and, 4 years later, 80% of the oilseed sunflower production area in the United States was planted to hybrids. Essentially all production today is with hybrids. Sunflower hybrids yield about 50% more than their pure line parents do, and so can easily outcompete their inbred parents in the farmers' fields. Also, because they are naturally cross-pollinated (with aid of insects), hybridization is not pollen-limited as is the case with wheat, a self-pollinated species.

Rice. Putative cytoplasmic male sterility in rice (*Oryza sativa* L.) was described in 1954 (Sampath and Mohanty 1954) but use of cytoplasmic male sterility to produce hybrids did not get under way until about 20 years later, when satisfactory cytoplasmic-nuclear systems were identified (Virmani 1994). China adopted hybrid rice production on a large scale starting in 1975, and hybrids are making progress in other Asian nations as well. But hybrid rice is not yet widely commercialized in the United Sttaes for many of the same reasons that prevented the success of hybrid wheat (Mackill and Rutger 1994). Seeding costs are too great in relation to the gain in yield contributed by heterosis. Private-sector interest continues, however, in hopes that advancements in technology can allow economical production and sale of rice hybrids. Prospects for hybrid rice look somewhat better in the southeastern rice-growing regions of the United States primarily because the breeding materials adapted to the southeast provide greater opportunities for increased heterosis.

Other crops. Seed companies in various countries around the world breed and sell hybrid seed of several crops in addition to those covered above (see Coors and Pandey 1999). The list includes cotton (*Gossypium hirsutum* L.), pearl millet (*Pennisetum glaucum* R. Br.), and rye (*Secale cereale* L.). Hybrid cotton is not grown in the United States (Meredith 1999). Current hybridizing technology for cotton (e.g,. hand pollination as used in India) is too expensive in relation to potential yield gains from heterosis. Rye is a minor crop in the United States and is not yet attractive to commercial breeding interests. Pearl millet production (for forage) in the United States is 100% hybrid (Hanna 2000). Pearl millet hybrids succeeded for many of the same reasons that prompted farmers to choose hybrids of other crops—added income from hybrids comfortably exceeded the added expense for seed.

Consistencies and lessons

This brief review of development and commercialization of hybrid seed production in the United States points up two consistencies:

1. Public-sector breeders performed the initial research and breeding, with very few exceptions. In particular, they were responsible for development of the theory that preceded and stimulated investigative breeding.
2. Private-sector seed companies efficiently utilized the products of public-sector breeding to produce hybrid seed and deliver it to farmers. The pace of adoption of hybrids for several crops was amazingly fast. It could not have happened if seed companies had failed to produce sufficient amounts of good-quality hybrid seed, properly labeled and delivered to farmers at the right time for planting.

Two more lessons can be learned from these short histories of private-sector plant breeding:

1. Although they initially depended on public-sector plant breeding, private-sector seed companies soon developed their own breeding programs to supplement and, in many cases, replace the work of the public-sector breeders. Hybrid maize is the most striking example but success in producing and selling publicly developed varieties of other crops stimulated seed companies to develop their own proprietary hybrids. They intended to make unique and valuable improvements that eventually would increase their company's hybrid sales, market share, and profitability.
2. The ability to breed, produce, and sell hybrids does not guarantee that seed companies can build a market for hybrid seed for every crop in every region where it is grown. Hybrid wheat, rice, and cotton have

not yet succeeded in the United States. The primary reason for their failure is that companies were unable to deliver a product that increased farmers' profits. A typical problem was that costs of seed production were too high in relation to the value of yield added by heterosis. The seed companies could not afford to sell the hybrids to farmers at prices the farmers could afford to pay.

Intellectual property rights and the private sector

As noted earlier, European commercial plant breeders were not satisfied with a system that required them to gamble on success of a large initial offering of seed of new varieties. Their major field crops were not amenable to hybrid production like maize in the United States. They looked, therefore, for some kind of legal protection—some kind of intellectual property rights (IPR)—that would let them control sales of the varieties they had bred. The quest for IPR for plant varieties culminated in the 1961 International Convention for the Protection of New Varieties of Plants (UPOV) (see UPOV 1982). It gave breeders in countries that subscribed to the Convention and passed appropriate laws the right to control sales of seed of their varieties within certain limits. With this example before them, seed companies in the United States brought about passage of the U.S. Plant Variety Protection Act in 1970 (USDA/AMS 1970). Commercial breeders now, in theory, could breed varieties of self-pollinated crops with assurance that they would be able to control sales of those varieties. Commercial breeding would no longer need to be restricted to hybrids.

Seed companies promptly started breeding and sales of the self-pollinated field crops, particularly soybean and wheat. Although hybrid wheat breeding was already under way, breeding pure line varieties would be an alternative way to develop varieties in shorter time periods and with less expense. Private-sector investments were much smaller for breeding of minor self-pollinated crops such as oats or barley, presumably because market size did not warrant major expenditures. The current private-sector breeding effort, expressed as scientist-years, for some of the major self-pollinated crops is: soybean 101, wheat 54, barley 14, oats 5 (Frey 1996).

As with the hybrid crops, possession of IPR for a crop variety does not guarantee that it can be bred and sold profitably. A major hurdle in commercialization of crop breeding under auspices of the 1970 U.S. PVPA has been a provision that allows farmers to save seed for replanting and also to sell it to neighbors in small, noncommercial amounts. With some crops in some parts of the country, this exemption has been legally, and perhaps illegally, stretched to its limits. The practical result of such practices has been that, in some cases, a commercial variety has been widely planted but the developer and owner of the variety has sold seed for only a minor portion of the total planted area. One company calculated that its own sales accounted for only 9% of the total area planted to one of its popular hard red winter wheat varieties (Newlin 1990). The net result was that sales did not pay for the cost of research. The hard red winter wheat breeding program was dropped and the company withdrew from the market. Similar results caused the same company to discontinue its hard red spring wheat breeding program. Other companies have followed suit, and commercial breeding now is minimal for the two major bread wheat production areas of the United States, despite the large planting area and despite the high need for improved varieties.

In contrast, the same company's repeat sales were satisfactory in the soft red winter wheat area located in the eastern part of the United States. That program continues to serve farmers' needs in competition with other commercial breeding programs. But the greatest competitor for all seed companies, even in this region, is saved seed. Although commercial varieties are popular, nearly one-half of the soft wheat production is from saved seed—seed not purchased from the company that bred the variety.

Although private-sector cotton breeding is active overall, commercial cotton breeding programs (nonhybrid) in some cotton-growing areas have been discontinued for the same reasons that stopped commercial breeding of bread wheat. Repeat sales were so low that income did not match expenses for research.

The original UPOV and PVPA have been amended, strengthening the rights of breeders to control replanting as well as resale of their varieties (Anonymous 1994). For example, U.S. farmers can still replant for their own needs but they cannot sell seed to their neighbors. Time will tell whether or not these changes encourage more commercial breeding and seed sales.

More recently, application of utility patent laws to all kinds of products and processes of genetic manipulation has broadened the protections of IPR applied to plant breeding. One now can obtain IPR for plant varieties and their components all the way down to the DNA level (Eberhart et al 1998). Patents also are granted for inventive methods for manipulation of the germplasm. Some seed companies use utility patents to add extra protection to maize inbreds and hybrids. These valuable properties thus can have three kinds of protection—trade secret, PVP, and utility patent.

Status of private-sector plant breeding in the United States

Commercial plant breeding now dominates breeding of many field crops in the United States. In 1994, 71% of all plant breeders (not including those in biotechnology) worked for private industry (Frey 1996). Table 1 shows plant breeding activity in private and public sectors for several of the most widely planted field crops. Private-sector breeders outnumbered those from the public sector in all but one of the eight crops listed.

Biotechnology and the private sector

About 20 years ago, plant breeders in public and private sectors recognized the potential for applying the rapidly accruing new knowledge in molecular biology to plant breeding. After some hesitation, both sectors began to invest in biotechnology applied to plants and plant breeding.

In the private sector, entrepreneurial companies led the way. They intended to base their plant breeding primarily on biotechnology, especially genetic engineering. Classical breeding would play a greatly reduced role. Founders of these companies rarely had practical plant breeding experience and so they soon sought alliances and also funding from established plant breeding firms. As time went on and their product development and sales continued to recede into the future, many of the entrepreneurial companies disappeared as individual entities. In some cases, they merged with other companies and, in other instances, larger firms—often agribusiness or pharmaceutical firms that were not primarily (or not at all) in the seed business—purchased them.

Table 1. Scientist person-years (SY) devoted to breeding selected crops in United States, 1994.

Crop	Private sector	Public sector	Total
Maize	510 (94%)	35 (6%)	545
Canola	28 (80%)	7 (20%)	35
Cotton	103 (77%)	31 (23%)	134
Sorghum	41 (75%)	14 (25%)	55
Soybean	101 (65%)	55 (35%)	156
Alfalfa	41 (60%)	27 (40%)	68
Rice	22 (52%)	20 (48%)	42
Wheat	54 (42%)	76 (58%)	130

Source: Frey 1996. SYs include plant breeding research, germplasm enhancement, and cultivar development. They do not include biotechnology in aid of breeding.

At about the time that the first wave of entrepreneurs was receding, the larger seed companies began to set up their own biotechnology research and development teams, using various methods such as in-house departments or collaboration with outside firms. In at least one case, a firm first built its biotechnology arm and then purchased numerous plant breeding companies. In all cases, the goal was to build a plant breeding organization that was well based in classical breeding but also capable of using advances in biotechnology to the fullest extent possible.

To this end, the seed industry collectively made large investments in biotechnology research. The need for funds in turn prompted further reorganizations (mergers, acquisitions) to increase funding potential to a size that could support an efficient biotechnology operation (Miller et al 1996). As Frey noted, "The cost of adopting biotechnology to cultivar development probably has been a factor in the restructuring of much of the U.S. plant breeding industry into just a handful of large companies, all of which operate internationally" (Frey 2000).

Restructuring still proceeds. Even the largest seed companies are no longer independent. Larger firms, often based in agricultural chemicals, have purchased them. On the other hand, scores of small seed companies still exist as independent entities. They continue to find ways to obtain varieties, inbred lines, and other genetic stocks that enable them to present a line of products that farmers will buy.

A further consequence of the private sector's heavy investment in biotechnology is that, contrary to earlier practice with classical plant breeding, the private sector now conducts considerable amounts of basic research (e.g., in genomics) and in some research fields, it leads the public sector. There is an important difference, however. A large portion of the results of basic research conducted by the private sector is patented or kept as trade secrets (Miller et al 1996, van Wijk 1995). This means that the plant breeding industry as a whole (public and private sectors combined) cannot utilize the private sector's fundamental knowledge to develop new products, new plant varieties, or other kinds of improved germplasm unless they get the owner's permission in the form of licenses or other instruments. Permission may or may not be granted, depending on the owner's judgment about the comparative advantage of release vs nonrelease.

Geneticists and plant breeders, public and private, are wrestling with this problem. It is clear to all that plant breeding assisted by biotechnology can move forward best if it does so on a broad front with all researchers being able to use a common pool of fundamental knowledge to devise specific practical applications. The practical applications could be privately owned.

But it also seems obvious to private-sector breeders that they need to hold back any fundamental information that could give competitive advantage to other commercial firms, their rivals in the marketplace. Time will tell how or if this puzzle can be solved.

Commercial applications of biotechnology are now on the market in the form of improved varieties as products of genetic transformation. Although the number of improvements is not large, farmers in the United States have accepted transgenic varieties enthusiastically and plant them widely (James 1998).

But at the moment, the future of biotechnology in aid of plant breeding is not clear, at least in regard to transgenic varieties (popularly known as genetically modified organisms or GMOs). Influential environmental organizations have campaigned against their use with great success in many countries of the world, and are now turning their attention to the United States. The outcome is uncertain. The body of basic biological knowledge now being developed by research in plant molecular biology is so fundamental and empowering that it seems certain that eventually it will be used to further plant breeding. But it may not be used as soon as was expected or in the ways expected.

Two themes stand out in the campaign against use of biotechnology in plant breeding. One often-stated dictum is that genetic engineering is qualitatively different from all other kinds of biological manipulation and as such is inherently dangerous to human health and to the environment. The other is that use of biotechnology in plant breeding is intended to benefit for-profit industry and for this reason cannot be expected to alleviate sociological problems. In fact, it will make them worse. As stated in two advertisements in The New York Times,

"The genetic structures of living beings are the last of Nature's creations to be invaded and altered for commerce. Now they're being seized for corporate ownership. Nothing will ever be the same, and we approach the gravest moral, social, and ecological crises in history." (Turning Point Project 1999b).

"The biotechnology industry promotes itself as the solution to world hunger. In reality, the industry's practices may drive self-sufficient farmers off their land and undermine their food security—increasing poverty and hunger." (Turning Point Project 1999a).

One can conclude from these statements that the signatory nongovernment organizations (NGOs) intend to prevent use of biotechnology in plant breeding, or at least prevent its use by industry. The outcome of their campaign will determine the nature of private-sector plant breeding. Various alternatives present themselves:

- Genetic engineering will be outlawed for all plant breeding, public or private.
- Public-sector plant breeders will be allowed to use genetic engineering, but the private sector will be restricted to use of classical methods.
- Private-sector plant breeding will be forbidden.
- Private-sector plant breeding will be permitted but only if practiced by small companies with no international ties.
- Strict governmental rules to ensure biosafety of transgenic varieties will be applied impartially to public- and private-sector plant breeding.

Further speculation on this topic is not warranted, but one must realize that the future course of plant breeding, public and private, rests in the balance. Furthermore, the issue is global.

Global plant breeding and the private sector

Private-sector plant breeding in the United States is neither isolated nor necessarily different from that in the rest of the world. Commercial breeding operations in the United States and Europe have followed more or less parallel paths during the past century, although with some differences. For example, Europe has led the way in development of breeders' rights (plant variety protection) for plant varieties, whereas the United States has led the way in application of utility patents to plant germplasm (Pistorius and Wijk 1999). Commercial plant breeding in other industrial countries such as Australia and Canada has stayed in step with Europe and the United States, although again, not in all details.

In all of the industrialized countries, private-sector breeding arose first as small local companies. Some of them grew to national importance and dominated the seed market. The larger companies began to look abroad for new markets. American hybrid maize companies set up operations in Europe as maize became a more important crop on that continent, and at the same time European companies invested in and purchased American companies. Mergers and acquisitions were not restricted by national boundaries.

The net result has been that global corporations conduct and control the preponderance of commercial plant breeding for the industrialized nations. But, at the same time, one should recognize that scores or hundreds of small seed companies still exist and that they control a significant share (even though a minority) of the seed market (Duvick 1998).

Commercial plant breeding in the developing world by and large has followed a different path. Developing countries until recent years have placed the main responsibility for plant breeding on the public sector. Private-sector breeding has developed at a much slower pace than in the industrialized countries. Additionally, public-sector plant breeding research has been severely under-financed in most of the developing countries and therefore has been unable to offer technical and scientific assistance to private-sector seed firms on the same scale as has been true in industrialized countries.

Another factor, perhaps more important than government policies toward research support, has been the inability of large segments of the developing world's farming class to support commercial plant breeding. Many farmers (a strong majority in some countries) could not afford to buy seed at prices high enough to sustain commercial seed companies. In other cases (or sometimes at the same time), market prices for farm produce have been so low or so unpredictable that farmers had no incentive to risk scarce cash on inputs of any kind, including improved seed.

Nevertheless, as economic conditions improve in some of the developing countries, or in some parts of those countries, farmers have shown greater inclination to buy improved seeds and the private sector has responded. International seed companies based in industrialized countries have set up operations in developing countries, usually operating much as they do in the industrialized countries. Indigenous seed companies have grown in size, and numerous small new companies have been formed. Thus some (but not all) of the developing countries are following the path trodden by the industrialized countries in the first and middle parts of the 20th century.

There are important differences, however. The industrialized countries did not receive infusions of capital from foreign seed companies and they did not have to worry about market domination by those foreign corporations. The industrialized countries probably provided more technical and scientific support for start-ups of small local seed firms than is the case with today's developing countries. And most important, the unsettling effects of today's anti-biotechnology and anti-seed company activism were not a factor 50 years ago. For these reasons, one hesitates to predict the outcomes of commercial plant breeding in developing countries during the next 50 years, other than to say that it will not exactly duplicate the development path in the industrialized countries.

Future prospects for plant breeding in the private sector

Before speculating on the future prospects for plant breeding in the private sector, it will be instructive to examine its global prevalence at the present time. Table 2 presents an estimate of the area planted globally to private-sector varieties of the four major field crops. It shows that commercial plant breeding plays an insignificant role in global rice production, a minor role in global wheat production, and a significant although not predominant role in global production of maize and soybean. The relatively large proportion of private-sector varieties in the area planted to maize and soybean globally is due in large part to the predominance of the private sector in seed production of these two crops in the United States. Table 2 also points out that the private sector plays a much greater role in production of feed than in food, i.e., maize is a feed grain in the industrialized countries, and soybean meal is also an important ingredient in animal feeds in the industrialized countries. Of course, all of the production is indirectly used for food.

It seems likely that the private sector's role in plant breeding will increase in years to come, in both developing and industrialized countries. As noted earlier, the demand for products of private-sector plant breeding relates directly to economic health and stability of a country's agriculture and this in turn is tied to the social and economic well-being of the nation. If the trend is for improvement in economic and social well-being of farmers in developing countries, the chances seem good that there will be a larger role for commercial plant breeding in those countries. In industrialized countries, the trend toward larger and highly specialized crop production units may result in a greater demand for purchased seed of known quality and performance potential to allow producers to concentrate on efficient crop production per se.

Two factors, at least, can affect this prediction.

1. Political policies in developing countries can hold back development of commercial plant breeding in favor of public-sector research and

Table 2. Estimates of proportionate area (%) planted to private-sector crop varieties.

Region	Wheat	Rice	Maize	Soybean
Industrialized	25–30	?	99	70–90
Eastern Europe	<1	<1	<5	<1
Developing countries	4	<1	15	30–60
World	10	<1	35	45–75

Source: Paul Heisey (USDA/ERS, pers. commun., 6 Mar 2000).

development, or of farmer- or community-based plant breeding. Such policies are advocated for developing countries as a class by some organizations.

2. As noted earlier, anti-GMO advocacy groups may prevail in their campaigns to inhibit or eradicate use of genetic engineering for plant breeding, especially in the hands of commercial seed firms. Commercial plant breeding can continue to produce improved varieties without use of biotechnology (as it has for the past 100 years), but it is conceivable that large and unsettling changes would take place in the industry if companies were forced to forgo the use of biotechnology as a breeding tool. The net result would be reduced productivity for commercial plant breeding—fewer good new varieties—at least until a new balance is achieved.

If I were required to make an unqualified prediction for the future of private-sector plant breeding, I would say the prospects are good that many developing countries will improve their economic and social well-being and therefore, their farmers will demand and profit from commercial plant breeding as a supplement to public-sector plant breeding. But the pace of improvement in the developing world will be slow and uneven. In the developing countries, the private sector primarily will breed hybrid crops or high-value crops with relatively low seeding costs. In industrialized countries or in industrial agriculture sectors of developing countries, the seed companies will breed and sell self-pollinated crops as well as hybrid crops, but not all crops in all regions. Biotechnology eventually will be used worldwide by both private and public sectors as a tool of plant breeding but its value to farmers will be reduced for many years to come because of the costs and delays involved in providing tests for safety. Finally, economic rather than political pressures will cause large corporations to divest themselves of plant breeding operations because commercial plant breeding for commodity crops inherently cannot produce the high profit margin expected of the major corporations. Exceptions to this trend will be instances where genetic engineering is used to develop high-value (and high-profit) specialty crops for production of plant-produced pharmaceuticals, plastics, etc. Regardless of their ownership, a relatively small number of seed companies will dominate the market globally but significant anti-monopoly pressure will persist in the form of many small indigenous companies that collectively control a significant share of the market for commercial seeds in their country.

References

Anonymous. 1994. Congressional passage of new PVP law: a triumph for seed industry. Diversity 10(3):34-35.

Coors JG,Pandey S. 1999. Genetics and exploitation of heterosis in crops. Madison, WI (USA): American Society of Agronomy, Inc., Crop Science Society of America, Inc. 524 p.

Crabb R. 1993. The hybrid corn-makers. West Chicago, IL (USA): West Chicago Publishing Company. 414 p.

Duvick DN. 1999. Commercial strategies for exploitation of heterosis. In: Coors JG, Pandey S, editors. Genetics and exploitation of heterosis in crops. Madison, WI (USA): American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc. p 295-304.

Duvick DN. 1998. Country case studies: the United States. In: Morris ML, editor. Maize seed industries in developing countries. Boulder, CO (USA): Lynne Rienner Publishers, Inc. and México, D.F. (Mexico): CIMMYT. p 103-211.

Duvick DN. 1965. Cytoplasmic pollen sterility in corn. In: Caspari EW, editor. Advances in genetics. New York and London: Academic Press. p 1-56.

Duvick DN. 1993. Funding agricultural research: an assessment of current innovation. In: Weaver RD, editor. U.S. agricultural research: strategic challenges and options. Bethesda, MD (USA): Agricultural Research Institute. p 69-87.

Duvick DN. 1959. The use of cytoplasmic male-sterility in hybrid seed production. Econ. Bot. 13:167-195.

Eberhart SA, Shands HL, Collins W, Lower RL. 1998. Intellectual property rights III. Global genetic resources: access and property rights. Madison, WI (USA): Crop Science Society of America and American Society of Agronomy. 176 p.

Encyclopaedia Britannica. 1983. Luther Burbank. In: The New Encyclopaedia Britannica. 15th edition. Chicago (USA): Encyclopaedia Britannica, Inc. p 374.

Evans LT. 1998. Feeding the ten billion: plants and population growth. Cambridge (UK): Cambridge University Press. 247 p.

Frey KJ. 1996. National plant breeding study. I. Human and financial resources devoted to plant breeding research and development in the United States in 1994. Iowa Agric. Home Econ. Exp. Stn. Rep. 98.

Frey KJ. 2000. National plant breeding study. IV. Future priorities for plant breeding. Iowa Agric. Home Econ. Exp. Stn. Rep. 102.

Frey KJ. 1966. Plant breeding. Ames, IA (USA): Iowa State University Press. 430 p.

Harlan JR. 1992. Crops and man. Madison, WI (USA): American Society of Agronomy, Inc., and Crop Science Society of America, Inc. 284 p.

Huffman WE, Evenson RE. 1993. Science for agriculture: a long-term perspective. Ames, IA (USA): Iowa State University Press. 268 p.

James C. 1998. Global review of commercialized transgenic crops: 1998. ISAAA Briefs Rep. 8.

Jones DF. 1918. The effects of inbreeding and cross-breeding upon development. Conn. Agric. Exp. Stn. Bull. 207.

Jones DF, Everett HL. 1949. Hybrid field corn. Conn. Agric. Exp. Stn. Bull. 532.

Jones DF, Mangelsdorf PC. 1951. The production of hybrid corn seed without detasseling. Conn. Agric. Exp. Stn. Bull. 550.

Jones HA, Clark AE. 1943. Inheritance of male sterility in the onion and the production of hybrid seed. Proc. Am. Soc. Hortic. Sci. 43:189-194.

Knudson MK, Ruttan VW. 1988. The R&D of a biological innovation: the case of hybrid wheat. Food Res. Inst. Stud. 21:45-67.

Mackill DJ, Rutger JN.1994. Public sector research on hybrid rice in the United States. In: Virmani SS, editor. Hybrid rice technology: new developments and future prospects. Manila (Philippines): International Rice Research Institute. p 235-239.

Meredith Jr. WR. 1999. Cotton and heterosis. In: Coors JG, Pandey S, editors. Genetics and exploitation of heterosis in crops. Madison, WI (USA): American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc. p 451-462.

Miller D, Deterling D, Keller D. 1996. Seeds of change. Progressive Farmer. June-July. p 18-20.

Miller JF. 1987. Sunflower. In: Fehr WR, editor. Principles of cultivar development. New York: MacMillan Publishing Company. p 626-668.

Newlin OJ. 1990. Testimony before the Department of Operations, Research and Foreign Agriculture Subcommittee of the House Agriculture Committee (U.S. Congress) Regarding Amendments to Strengthen the Plant Variety Protection Act. May 1, 1990, Des Moines, IA, Pioneer Hi-Bred International, Inc. 6 p.

Owen FV. 1945. Cytoplasmically inherited male-sterility in sugar beets. J. Agric. Res. 71:423-440.

Pistorius R, Wijk Jv. 1999. The exploitation of plant genetic information: political strategies in crop development. New York: CABI Publishing. 248 p.

Sampath S, Mohanty HK. 1954. Cytology of semisterile rice hybrids. Curr. Sci. 23:182-183.

Shull GH. 1952. Beginnings of the heterosis concept. In: Gowen GW, editor. Heterosis. Ames, IA (USA): Iowa State University Press. p 14-48.

Shull GH. 1909. A pure-line method of corn breeding. Am. Breeders' Assoc. Rep. 5:51-59.

Smith BD. 1995. The emergence of agriculture. New York: Scientific American Library, distributed by W.H. Freeman and Company, New York. 232 p.

Smith DC. 1966. Plant breeding—development and success. In: Frey KJ, editor. Plant breeding: a symposium held at Iowa State University. Ames, IA (USA): Iowa State University Press. p 3-54.

Stephens JC, Holland RF. 1954. Cytoplasmic male-sterility for hybrid sorghum seed production. Agron. J. 46:20-23.

Tatum LA. 1971. The southern corn leaf blight epidemic. Science 171:1113-1116.

Toth SA. 1998. The father of invention: Luther Burbank, plant wizard. Garden Design 1998:59-65.

Turning Point Project. 1999a. Biotechnology = Hunger (Paid advertisement by *Turning Point Project* on behalf of 22 non-governmental organizations). The New York Times. New York. November 8, 1999. p A5.

Turning Point Project. 1999b. Who plays God in the 21st century? (Paid advertisement by *Turning Point Project* on behalf of 19 non-governmental organizations). The New York Times. New York. October 11, 1999. p A11.

UPOV (International Union for the Protection of New Varieties of Plants). 1982. International Convention for the Protection of New Varieties of Plants of December 2, 1961 and Additional Act of November 10, 1972 and Revised Text of October 23, 1978. Geneva: UPOV. 64 p.

USDA (United States Department of Agriculture)/AMS. 1970. United States Plant Variety Protection Act of December 24, 1970 (84 Stat. 1542) (7 U.S.C. 2321 Et Seq.). Plant Variety Protection Office, AMS, USDA. 19 p.

van Wijk J. 1995. Plant breeders' rights create winners and losers. Biotechnol. Dev. Monit. 23:15-19.
Virmani SS, editor. 1994. Hybrid rice technology: new developments and future prospects. Selected papers from the International Rice Research Conference. Manila (Philippines): International Rice Research Institute. 296 p.
Wallace HA. 1955. Public and private contributions to hybrid corn—past and future. In: Heckendorn W, Gregory J, editors. 10th Hybrid Corn Industry Research Conference, Chicago, Illinois. American Seed Trade Association. p 107-115.

Notes

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Sustaining global agricultural research and development

R.W. Herdt

In the aftermath of World War II, with its widespread hunger, and the evident food shortages of India, China, and other poor countries of Asia, there was broad concern that food shortages might emerge as major problems. The rationale for establishing the International Rice Research Institute (IRRI) was to increase food production to ensure food security for Asian developing countries.

Since 1960, partly as a result of the work of the IRRI and other CGIAR centers, the number of poor and malnourished people in the developing world has declined—while population more than doubled. A number of Asian countries have emerged from the threat of famine, and several have demonstrated vigorous rates of economic growth (Barker and Dawe 2000).

Rigorous analysis of the changes in child malnutrition in 63 developing countries between 1970 and 1998 shows that the decline was driven by increased national food availability, improvements in the status of women relative to men, increases in women's education, and improvements in the quality of the health environment (Smith and Haddad 2000). Where malnutrition has declined, these determinants are closely associated with national economic growth and effective democracy.

However, the world still has nearly 800 million hungry people concentrated in sub-Saharan Africa and South Asia. Poor, hungry people are the primary concern of the food security programs of the Rockefeller Foundation, just as they were the primary concern of Bob Chandler. IRRI and the other organizations that make up the global agricultural research system exist to help those people.

Agricultural research is but one part of the larger development context. People have nonmaterial as well as material needs. Democracy, self-determination, women's rights, creativity, voice, and participation are some of the nonmaterial needs. They are important for personal and national development, but people must also have at least a minimal level of the material needs—food, health, education, water, and a livable environment. It is here that the global agricultural research system makes its contribution. This paper explores some of the issues associated with sustaining that international system into the future.

Challenges and opportunities

Innovations developed through research have contributed to food production increases, as demonstrated by Hayami and Kikuchi (2000), Hazell and Ramasamy (1991), Lipton and Longhurst (1989), and many others. Gains in agricultural productivity, higher incomes, and better lives are associated with agricultural innovations, and the research centers supported by the Consultative Group on International Agricultural Research (CGIAR) have provided many of those innovations. As a result, many developing-country farmers have higher incomes and many consumers have more adequate diets at lower costs. But a substantial number of people have been left behind—people who need innovations in technology, services, policy, and institutions to climb out of poverty. Many of them live in countries where the national agricultural research and extension organizations are simply not up to the job alone. The international agricultural research system is still needed to work together with people from those countries.

Today's world is very different from the world in 1957-59 when IRRI was designed and very different from the world of 1975 when the CGIAR was designed. Scientific advances in biology and new information technology have transformed the globe. Agricultural research capacity in many countries, especially in Asia and Latin America, improved dramatically. But research funding in some countries, after rapid expansion in the 1970s, slowed or reversed in the 1990s. Many African countries have never achieved well-functioning, robust research systems. The global agricultural research system has not proactively provided lagging national systems with access to the new information and biological technologies, nor has it vigorously addressed the challenges arising from the extension of intellectual property rights driven by international agreements.

Scientific advancements are generating huge amounts of genomic information and new biotechnology tools. These are being used to change the genetics of crops and animals and further raise food productivity. A few CGIAR centers have the capability to use these tools, but many have not maintained a capability to lead in the development of scientific techniques.

Along with the scientific advances have come changes in intellectual property rights as well as new international conventions affecting plant and seeds. While private companies are seeking to capitalize on publicly held germplasm and knowledge at the CGIAR centers, each of the centers is dealing independently with companies about very similar matters.

Information infrastructure being created by the private sector is cheap and can be used by everyone who has access. However, access is restricted by lags in connectivity, and although that will be solved by wireless innovations, many outside the primary cities and in some lagging countries are asking, when and at what cost? On the other hand, global communications from most capital cities and for wealthy institutions is a reality. Managing programs globally is as cheap and nearly as easy as managing research on a single campus. Research discoveries can be shared almost instantly on a global basis.

Populations have doubled in many countries, but public physical infrastructure—roads, social infrastructure such as schools, and services such as extension—designed to serve the public have changed little, and in some countries have deteriorated. Investments in roads, schools, market regulations, and contract law are needed to encourage agricultural innovations.

Challenges to the international community

The two most important areas in this changed world in which the international community can assist developing countries to increase food availability through agricultural production are

- protecting and using, in the public interest, the germplasm collections held by the CGIAR centers, and
- developing and applying innovations that promote higher incomes through sustainable agriculture for the poorest farmers and consumers.

Germplasm matters are complex and require competence in a range of disciplines, some not traditionally associated with agriculture. A recent paper by Petit et al (2000) provides an excellent review of many of these issues. Every country needs its own capacity to understand plant intellectual property matters and must have some people who understand biosafety and environmental issues. In addition, some countries may wish to have the capacity to undertake plant biotechnology research. The international system should be assisting countries to acquire these capabilities.

Private companies are not providing the new seeds needed by poor farmers in poor countries but are driving the global plant germplasm system in directions companies can exploit. It is in the vital public interest of many developing countries to have an effective, global, all-commodity public effort that protects and exploits existing publicly owned crop germplasm collections to benefit poor farmers and consumers and to use biotechnology to generate innovations that the private sector will not produce. This work must include the capacity to deal with agricultural intellectual property on behalf of developing-country public interest.

The poorest countries, where national resources are scarcest and poverty is increasing, also need assistance in identifying and implementing sustainable agriculture policies, institutions, and technologies that raise poor farmers' incomes and are tailored to their circumstances. Most international agricultural research centers currently confine themselves to research and stop short of engaging proactively with national research and national extension authorities. Many countries have research and extension systems that can take the products of the centers and apply them. But in countries with the least capability, the CGIAR donors and national authorities are ready for centers to take a fuller role in developing, testing, and disseminating sustainable agricultural practices to farmers.

The special capabilities and limitations of the CGIAR

The CGIAR centers meet the demand of development assistance agencies (donors) for high-quality organizations that are effective, financially well managed, and that can operate "on the ground" in rural areas of the developing world. Support for nongovernment organizations (NGOs) also demonstrates that demand. But most NGOs have limited technical agricultural knowledge and are unable to deliver solutions to farmers that improve their livelihoods through increased farm productivity. The CGIAR centers have the technical knowledge and can deliver such solutions. The CGIAR's Technical Advisory Committee (TAC) and Secretariat provide assurance of quality, while the participation of increasing numbers of developing countries as donors gives evidence of the value countries place on the centers' work.

The CGIAR centers continue to play a major role in the development and delivery of varieties of the food crops important in the developing world. The rice and wheat stories are familiar. Less well-recognized are the contributions made in the breeding of improved varieties of crops grown under rainfed and even dry conditions—maize, sorghum, millet, barley, lentils, beans, and cassava. It is estimated that about half the maize, sorghum, and millet varieties released in the 1990s in Africa were either crosses made at a CGIAR center or crosses made by national plant breeders using CGIAR center materials; a similar situation holds for barley varieties in the Mideast, and a majority of cassava varieties released in both Latin American and African countries are from CGIAR-center crosses (Evenson 2000).

The current organization of the CGIAR is, however, showing significant strains. Some of these constrain what individual centers can accomplish; others make the operations of the CGIAR unwieldy and less efficient than it should be. All constrain the system from making its most efficient contribution to developing-world needs. Funding has gradually declined over the past 5 years; formal and informal links between center scientists and national scientists are fragmented and duplicative so that to gain the full range of benefits, national authorities must deal individually with each of the centers.

The centers, individually and collectively, cannot efficiently exploit advances in modern molecular biology (based in the common function of genes across organisms) because their genetics work is crop-focused and researchers work independently of those in other centers. None of the centers are large enough to afford an effective capacity to deal with intellectual property rights, and centers have limited capacity to help countries understand and deal with the provisions of the World Trade Organization–Trade Related Intellectual Property Rights (WTO-TRIPS), the FAO-International Undertaking, and the Convention on Biodiversity, which bear on agricultural germplasm movement. From many viewpoints, the current system simply does not deliver much of what donors and developing countries need—and are demanding.

Within the CGIAR, some centers have operating styles that differ from others. WARDA, for example, has reached beyond the usual research limits to work directly with national research and extension authorities in delivery of technology to farmers. ICRAF has created a Development Division that is mandated to put technology in the hands of farmers, and other centers have done some work of this kind. But the CGIAR as an organization does not recognize the legitimacy of such activities—they are considered "special projects."

Some global agricultural research centers provide alternatives to the CGIAR centers. A number of international centers operate outside the CGIAR with support from many of the same donors who are CGIAR members. The International Center for Insect Pest Ecology (ICIPE), the Tropical Soil Biology and Fertility Program (TSBF), the International Board for Soils Research and Management (IBSRAM), and the International Fertilizer Development Center (IFDC) are examples. More recently, the International Network for Bamboo and Rattan (INBAR) has been established as an international organization whose members are sovereign states who sign the INBAR treaty.

One need that has become evident to us in the Rockefeller Foundation is for some kind of an entity to take responsibility for moving the golden rice from its current status of an exciting scientific discovery to the point where it is on the plates of poor people in the developing world. An impressive scientific discovery has been made that must be taken through to application. It is a huge job, including

- negotiating agreements with holders of more than 30 pieces of intellectual property; breeding well-adapted, high-beta-carotene, tropical rices;
- conducting the necessary food safety and environmental safety evaluations;
- conducting the laboratory and clinical work needed to test the nutritional efficacy of the new rices;
- achieving varietal release of rice lines following the procedures of a number of different countries; and
- multiplying seeds and promoting their use by farmers and their consumption by consumers.

IRRI is working to address these needs, but a new corporate entity may be needed—entrepreneurial and international, dedicated to delivering high-beta-carotene rice seed to farmers at minimal cost in cooperation with national seed organizations.

Options for the CGIAR

Without a decisive change of some kind, I am convinced that the CGIAR will continue to lose its effectiveness. Some individual centers may thrive, but many will continue to slowly drift away, as several have over the past 5 or more years. The meetings of the CGIAR Group will become increasingly irrelevant. Donors who wish to fund particular activities will continue to seek out centers able to carry out those activities and give them the funds, whether or not the TAC and the Group has agreed. Those few donors who have continued to provide unrestricted core funds in accord with the TAC's priorities will switch more and more of their funding to restricted purposes.

Some directions are less evident, and the system may take one of several possible directions in the future. The most radical, mentioned by a recent external review of the system, is complete centralization of all functions under a corporate model. In this model, TAC, the Secretariat, donors, clients, and existing centers would all designate members to a corporate board, which would make all the decisions that are currently made independently by the various units. But it would also require the donors to contribute money to a fund controlled by the corporate board and would thus ignore what most observers believe has been the essential genius of the CGIAR—the independence of donors to contribute funds for the activities they wish to support.

A second option would be to retain the independence of TAC, the Secretariat, and the donors, but completely merge the centers with all their functions into a single entity with a single board with responsibility for management of all functions—budget, staffing, intellectual property, relations with national authorities, etc. Donors could contribute funds for specified activities if the single center chose to accept them. An independent TAC, financed by the donors, would continue to conduct assessments of the quality of operations. The single center could phase-down less productive activities; it would speak globally with one voice on agricultural germplasm-related matters on behalf of the public interest.

A third option would be for the centers to create a federation. Each board would give up certain of its powers and responsibilities to the federated board. Chief among those would be responsibility for the germplasm held in trust for the developing world and the responsibility to use intellectual property rights to protect that germplasm on behalf of the developing world. Each board would have to turn over certain budgetary responsibility to the federated board to fund the germplasm and intellectual property work. The federated board might also be designated to take on other joint responsibilities such as Future Harvest, public education, fund raising, and perhaps even personnel management. Donors could continue to contribute funds for specific activities and for an independent TAC.

A fourth option would be for an Intellectual Properties Council, in which the centers give responsibility for intellectual property negotiations to a designated set of individuals and agree to follow the procedures established by the Council. All other operating features of the present system would remain unchanged.

A fifth option is to continue as the system currently operates.

A sixth option is for centers to "secede" from the CGIAR and do it alone, raising their own funds and conducting whatever program they might decide on, without reference to others, except of course subject to the availability of funds. A variant of this option is for two or more centers to secede and then merge, outside the CGIAR.

Identifying these options (and there are many more variants that might be imagined) clarifies two necessary conditions for change:

- The boards of the existing centers must agree to the chosen option.

- Donors that provide the bulk of the funds to the centers must agree to the chosen option.

Whether any of these options is likely to be effective is impossible to say. How radical a restructuring is needed in order to recreate an organization suitable to the tasks at hand has yet to be defined, but increasingly I believe a single management for all the research units may be the way to go—either the unified center or the federated center. This might be achieved immediately by adopting option 2 or somewhat more gradually by adopting option 3. With financial management the responsibility of the single management, the CGIAR Secretariat could be much smaller. The unified management would have responsibility for financial negotiations directly with donors and for intellectual property management. It would inherit the operating responsibility for germplasm conservation and utilization.

TAC would continue to be independent, and, of course, the donors would continue to be independent and retain their ability to interact directly with the research center. Other constraints would arise, depending on the management system put in place. We should anticipate those, gauge their seriousness, and plan effective ways to address those that can be anticipated.

The new federated center would continue to display some cherished features of the old:

- Each donor would be able to identify the particular program it funded, if desired, through direct negotiation of the center with donors.
- The CGIAR Secretariat would have a greatly reduced role in financial coordination.
- The TAC would be retained with its primary roles of evaluating quality of efforts and advising donors.
- The center would be autonomous.
- The center would deal directly with private companies and entities like GFAR and the regional forums.

The 16 centers supported by the donor members of the CGIAR provide the world with a valuable source of innovation and common action. They have played a pivotal role in the food production increases of the past 40 years and contributions to the development of new crop varieties continue at a significant rate. However, the centers are lagging in their ability to use the latest scientific tools of genetic improvement and in their ability to deal with the private companies who are claiming intellectual property on seed varieties. Financial support for the centers has weakened over the past 10 years and no evident solution is at hand. Without significant structural reform and consolidation to increase their productivity, it seems to me that the system will continue to slowly slide downward.

But it is not clear how such a reform is to be achieved.

References

Barker R, Dawe D. 2001. The Asian rice economy in transition. In: Rice research and production in the 21st century. Manila (Philippines): International Rice Research Institute.

David C, Otsuka K. 1994. Modern rice technology and income distribution in Asia. Boulder, CO (USA): Lynne Rienner Publishers and Manila (Philippines): International Rice Research Institute.

Evenson R. 2000. Crop genetic improvement and agricultural development. Paper prepared for the Impact Assessment Evaluation Group of the Technical Advisory Committee for the CGIAR May 2000 meeting, Dresden, Germany.

Hayami Y, Kikuchi M. 2000. A rice village saga: three decades of green revolution in the Philippines. New York (USA): Barnes & Noble and Manila (Philippines): International Rice Research Institute. 274 p.

Hazell P, Ramasamy C. 1991. The green revolution reconsidered. Baltimore, MD (USA): The Johns Hopkins University Press.

Lipton M, Longhurst R. 1989. New seeds and poor people. Baltimore, Maryland (USA): The Johns Hopkins University Press.

Petit M, Fowler C, Collins W, Correa C, Thornstrom C. 2000. Why governments can't make policy: the case study of plant genetic resources in the international arena. Washington, D.C.: The World Bank.

Smith LC, Haddad L. 2000. Overcoming child malnutrition in developing countries: past achievements and future choices. Washington, D.C.: International Food Policy Research Institute.

Notes

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Closing remarks

R. Havener

Colleagues, ladies and gentlemen, and friends of Robert F. Chandler; it is a singular pleasure for me to provide closing remarks for this symposium which was organized, in part, to honor Bob Chandler's memory and his lifetime contributions. During his tenure as the first director of IRRI, and in the days which were to follow, it was my great pleasure to spend many hours, indeed days, with him on issues of improving agricultural research and researcher performance in the service of mankind. He was truly a remarkable individual.

A number of our presenters spoke of regretting not having had a chance to work with, or really get to know, Bob Chandler. That certainly was their loss. Those who did know him gave us a glimpse of his personality through key words used to describe him—pioneer, extraordinary leader, team builder, task master, perfectionist, scientist, vigorous, enthusiastic, courageous, intellectual honesty, integrity, fairness, visionary.

All are true. But I return to the last one—visionary. As mentioned earlier, Bob was awarded the World Food Prize in 1988. The prize was in recognition of his service as the founding director of the International Rice Research Institute, which was to set the mold for the creation of the CGIAR system and the 15 research centers that followed.

Yesterday, Klaus Lampe said that he doubted that Bob was aware when he set out to create IRRI that eventually the world would have to produce enough food for 10 billion people. In fact, Bob was very much aware of the imperative nature of the population explosion. Even in 1960, the trends were known and it was a part of his mission to speak clearly of the challenges it posed.

In his World Food Prize acceptance speech he wrote, "In my view, the greatest threat to the well-being of mankind is overpopulation—neither the optimists nor the peasants can deny the fact that the land area on this planet is a constant and that our species cannot continue to increase its number indefinitely. In 1996, Herman Kilpper, executive director of the World Food Prize, wrote Bob asking him to make a presentation on Agricultural Science and the Food Balance on the occasion of the 10th anniversary of the prize. Bob wrote back that he would prefer to make a presentation on Population Dynamics and Food Security. He was also an advocate of education in general and particularly for females.

I turn now to this symposium, which honors Bob Chandler. In my view the insights and challenges posed by Randy Barker, Prabhu Pingali, Jim Hill, and Ken Cassman are real and very sobering. I particularly think that the policy change and bureaucratic commitment needed to facilitate new information exchange for knowledge-based production systems is indeed formidable. I believe we will all need to put more thought and effort into that endeavor. But I also agree with Bob Herdt that farmers do learn rather quickly to adjust new information and recommendations to their production circumstances.

We were all encouraged by the new scientific discoveries and insights described in the presentations of Ronnie Coffman, Stephen Tanksley, Monty Jones, and Susan McCouch. They gave us hope for new and broader adaptation, or tolerance, of the rice plant, for conditions of biotic and abiotic stress. They even provide a glimmer of hope that the yield barrier might be broken or at least raised.

The contributions of Drs. Cantrell, Duvick, Jefferson, and Herdt each encouraged us to think more deeply about the biological and bureaucratic determinants of development. They urge us forward to create the conditions favorable to change.

I have no doubt the papers presented at this symposium would meet the high standards that would have been set by Bob Chandler. I am confident he would be very pleased. My great regret is that Sunny Chandler's accident prevented her from being with us personally. I trust that the video camera has captured a bit of the affection we all feel for her and for the great impact she and Bob had on the succeeding generations who continue to wage war on hunger.

Please join me in expressing thanks to the organizing committee and support staff for this excellent symposium. Please give them your applause.

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