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Closing the rice yield gap for food security

Dat Van Tran
International Rice Commission, Food and Agricultural Organization (Italy)

Abstract: The Green Revolution has enabled rice production to meet the demands of the growing population. Since 1990, however, rice production has increased at a lower rate than the population. This deceleration in the growth of rice production is a cause for concern in terms of world food security. It has been the topic of numerous reviews and several rice scientists have alerted those concerned of the risk of a pending food crisis. Yield gaps can still be observed in several countries, while evidence of a productivity decline in intensive rice production has been increasingly noticed both on research stations and in farmers' fields. An increase in rice yield can lead to improved farmers' income and food security. Because of the complexity of this problem, different points of view exist regarding the possibility of narrowing yield gaps as a tool for increasing rice production. Several experts believe that yield gaps in favorable rice ecosystems are not significant for improving rice yield potential. Others believe that large and exploitable rice yield gaps still exist. In 1998, the average rice yields in 81 countries were less than the world average yield of 3.8 t ha^{-1}, indicating the existence of yield gaps. Also, progressive farmers usually obtain higher yields and more profits than ordinary farmers, indicating the presence of knowledge gaps. The yield gap in rainfed rice, which is usually larger than in irrigated rice, suggests the potential for increasing rice production.

Closing the rice yield gap aims not only to increase rice yield and production but also to improve the efficiency of land and labor use, reduce production costs, and increase food security. Various factors cause exploitable yield gaps in rice, such as physical, biological, socioeconomic, and institutional constraints, which can be effectively improved through participatory research and government attention. In practice, yield gaps are classified into agronomic gaps, socioeconomic gaps, institutional gaps, and mixed gaps according to constraints in improvement programs. The narrowing of the yield gap is not static but dynamic with technological development in rice production, as the gap tends to enlarge with the improvement of the yield potential of rice varieties. This requires integrated and holistic approaches, including appropriate concepts, policy interventions, understanding of farmers' actual constraints to high yield, deploying new proven technologies for production and postproduction in an integrated approach, and adequate institutional support to farmers.

Rice is the staple food for three billion people. The crop plays an important role in the national economy in many developing countries, but many rice farmers live under the poverty line. Most resource-poor farmers are forced to use their limited resources to produce adequate food for their family, leading to the degradation and reduction in potential of these resources. To achieve national food security, many countries have strived to increase rice production to reach self-sufficiency. Rapid population growth, which has made rice self-sufficiency disappear fast in a few countries, has also encouraged agricultural expansion into fragile ecosystems and intensive rice-based production systems, causing environmental degradation and pollution.

Land and water resources will become scarce for rice production in Asia in the next 30 years or so, mainly because of urbanization, industrialization, and increased population. Most land faces more constraints such as a high degree of slope, adverse soil type, and unfavourable climate. Water sources will be competitive between agriculture and industrialization and urbanization, especially in water-scarce countries in the dry season. The Green Revolution, which took place from the late 1960s to the 1980s, provided enough food to meet the world's demand and helped several countries escape from starvation, as had been predicted earlier. However, concerns have been raised about sustainable rice production, yield stagnation, a decline in productivity, large yield gaps, pest infestation, soil mining, environmental pollution, and social inequity. New technologies should be more carefully selected and deployed for sustainable increased food production and to avoid a negative effect on the environment. Particular attention should be given to the appropriate management of natural resources, increased efficiency and productivity, agricultural diversity, and minimization of risk to ensure sustainable production.

High-yielding varieties have reached the ceiling of their yield potential since the release of IR8 in 1966. Increasing efforts are therefore being made to develop varieties with higher yield potentials. FAO, IRRI, and several national institutions outside China are now promoting the development and use of hybrid rice, following the successful Chinese example.

Future increased rice production therefore requires improvements in productivity and efficiency. Innovative technologies such as hybrid rice, new plant types, and possibly transgenic rice can play an important role in raising the yield ceiling in rice production, thus increasing productivity, while widening the existing rice yield gaps between farmers and research stations. Narrowing of these gaps could not only improve the productivity and efficiency of rice production but also increase food security worldwide. In fact, increased rice yield could lead to lower prices on the market, thus facilitating access to food for many low-income citizens. High rice productivity could offset rice growers' losses caused by low prices. The ultimate objective of food security is to ensure that all people at all times have both physical and economic access to the basic food they need. According to this concept, food security should satisfy three conditions: availability of adequate food supplies, stability in food supplies, and economic access to food supplies. The closing of rice yield gaps could meet these three goals, as mentioned earlier. However, the problems in bridging the yield gap under the limitations of social, biological, cultural, environmental, and abiotic constraints still need close scrutiny.

I – Global rice yield and production

Table 1 shows the annual growth rates of the world's population and rice production, harvested area, and yield. The year 1961 was selected as the base year for the analysis of the evolution of rice production since it is the earliest year when statistics on rice production were available in the FAO databases (FAO 1998).

Table 1 shows that world rice production has continuously increased since 1961, but at varying growth rates. The annual growth rate was about 3.5% during the 1960s, 2.7% in the 1970s, 3.1% in the 1980s, and 1.3% in the first half of the 1990s. A comparison between the growth rates of rice production and those of population since 1961 shows that, for the first time since 1990, rice production has grown slower than population. The reversal of this trend and the bridging of yield gaps require urgent concerted efforts of all concerned parties and political support from both national and international authorities.

Asia accounts for more than 90% of world rice production and consumption. Therefore, the evolution of rice production, area, and yield in Asia is similar to that observed at the global level, but more pronounced. The increase in rice production has been due mainly to improved productivity per hectare. Harvested rice area has increased at a decreasing rate since 1961: from about 1.3% per year during the 1960s to only 0.3% in the 1980s and 0.1% since 1990. On the other hand, the annual growth rate of rice yield was 2.7% during the 1960s, 1.9% in the 1970s, 2.8% in the 1980s, and only 1.1% since 1990 (Table 2). The increase in the annual growth rate of rice yield from 1.9% during the 1970s to about 2.8% during the 1980s could be attributable to the wide adoption of a new generation of rice varieties, the improvement of farmers' crop management practices, and the increased use of irrigation, fertilizer, and other agrochemicals in rice production. It may also be due to the adoption of policies that are favorable to rice production in several countries. Vietnam, for example, became a major rice exporter only in the late 1980s after favorable policies were adopted.

II – Rice yield gaps: different views

The Expert Consultation on Bridging the Rice Yield Gap in the Asia-Pacific Region, which took place in Bangkok in 1999, recognized the existence of a sizable yield gap between attainable and farm-level yields across ecologies, regions within ecologies, and crop seasons in all rice-growing countries in the Asia-Pacific Region (RAP 1999). The yield gap ranges from 10% to 60% between attainable and economically exploitable yields. Rainfed, flood-prone, and problem soil ecologies have the highest yield gaps. The practical yield gap that can be addressed is the difference between the maximum attainable yield and the farm-level yield as defined below:

- ❑ *Maximum attainable yield* is the rice yield of experimental/on-farm plots with no physical, biological, and economic constraints and with the best-known management practices at a given time and in a given ecology.

- ❑ *Farm-level yield* is the average farmers' yield in a given target area at a given time and in a given ecology.

Rice is cultivated under a wide range of agroecologies. Irrigated rice yields improved substantially during the Green Revolution, whereas, in other ecologies, with the possible exception of the favorable rainfed lowland ecology, rice yields have not improved substantially because of several biotic and abiotic stresses. However, yields of irrigated rice in many developing countries are only around 4–5 t ha^{-1}. Substantial and exploitable yield gaps are therefore generally found only in irrigated and, to a lesser extent, in favorable rainfed ecologies. In the Philippines, it was reported that water control, seasonal factors (solar radiation), and economic factors are the yield constraints that account for the difference between actual and potential yields of 35%, 20%, and 15%, respectively (De Datta 1981).

Yield gaps have at least two components. The first component is mainly due to factors that are generally not transferable such as environmental conditions and some built-in component technologies available at research stations. This component of the gaps (or gap I in Fig. 1) therefore cannot be narrowed or is not exploitable.

The second component of yield gaps, or gap II in Figure 1, however, is mainly due to differences in management practices. This gap II exists because farmers use suboptimal doses of inputs and cultural practices. Herdt (1996) provided a similar description of yield gaps and their components. Gap II is manageable and can be narrowed by deploying more efforts in research and extension services as well as appropriate government intervention, particularly in institutional issues. In practice, yield gaps are also classified according to constraints:

- ❑ *Agronomic gaps:* due mainly to biological and partly physical constraints
- ❑ *Socioeconomic gaps:* due mainly to socioeconomic constraints
- ❑ *Institutional gaps:* due mainly to institutional constraints
- ❑ *Mixed gaps*: due to the above constraints. In this case and for the 2nd and 3rd bullet points, the socioeconomic and institutional constraints should be solved before the agronomic gaps can be narrowed using improved technological packages.

Because of this complexity, different views exist on the possibility of narrowing yield gaps as tools for increasing rice production. Pingali et al (1997) argued that the yield gaps in favorable rice ecologies are not significant for exploiting to increase rice yield and production. Under this situation, a further increase in yield is possible only with the deployment of new technologies, such as hybrid rice. Agronomic yield potential determined on experimental stations is the maximum achievable yield with no physical, biological, and economic constraints to rice production (gap I). Once these constraints are accounted for, the exploitable gap of rice is small and, in many cases, nonexistent. Therefore, narrowing of the exploitable yield gap in Asia is of little profit, particularly in irrigated rice. Pingali et al (1997) reported a reduction in the yield gaps on farms with favorable conditions in Nueva Ecija and Laguna, Philippines, from nearly 2 t ha^{-1} to less than half a ton after a decade. They also reported that yield gaps in the remaining two-thirds of the same rice areas remained around 2 t ha^{-1} and were even widening. Thus, the narrowing of yield gaps is not profitable for farmers in these environments.

Authors of the other school of thought believe that large rice yield gaps still exist in both favorable and less favorable conditions in many countries and that they could still be exploitable for further improvement in productivity. This is due to poor crop management and problems of institutional support, especially inputs and farm credit supplies, in many developing countries. Table 3 shows that the estimated yield gaps in irrigated rice production vary from 0.8 t ha^{-1} in Bangladesh to 2.3 t ha^{-1} in India.

The national rice yield is an average of yields of rice planted across agroecologies and locations in a country. Therefore, the exploitable yield gap cannot be defined as the difference between the national yield and that of research stations. National yields may be used as indicators to monitor the evolution of rice productivity in a country. In general, the analysis of the evolution of rice yield in the world shows that national average yields have increased, suggesting that yield gaps have narrowed, although at a slow rate. National average yields of rice in many developing countries in 1998 were still low—national yields in 81 countries were less than the world average yield of 3.8 t ha^{-1}—hence, yield gaps obviously exist in many countries.

However, yield gaps at a specific location in each growing season still need further studies. Yield differences among farmers in the same area are frequently observed because of their different levels of crop management and environmental variation. Progressive farmers usually obtain higher yields and more profits than ordinary farmers, indicating the presence of knowledge gaps. In India, the yield gap varies from 15.5% to 60%, with the national average yield gap of 52.3% in the irrigated ecosystem (Siddiq 2000).

III – Factors causing yield gaps

Several factors can cause yield gaps. These need to be classified according to their nature and degree by which they contribute to yield gaps. In general, the factors causing yield gaps (RAP 1999) could be classified as

1. Biophysical: climate/weather, soils, water, pest pressure, weeds.
2. Technical/management: tillage, variety/seed selection, water, nutrients, weeds, pests, and postharvest management.
3. Socioeconomic: social/economic status, farmers' traditions and knowledge, family size, household income/expenses/investment.
4. Institutional/policy: government policy, rice price, credit, input supply, land tenure, market, research, development, and extension.
5. Technology transfer and linkages: competence and equipment of extension staff, research, development and extension integration, farmers' resistance to new technology, knowledge and skills, weak linkage among public, private, and nongovernmental extension staff.

According to a survey made with the participation of nine Asian countries during the Expert Consultation on Bridging of the Rice Yield Gap in the Asia-Pacific Region, specific constraints affecting rice productivity in different ecosystems of selected Asian countries were identified. In the irrigated rice ecosystem, the major factors were (1) declining soil productivity and inappropriate/unbalanced nutrient use, (2) increasing pest and disease pressure, (3) poor water management resulting in low water-use efficiency and soil salinity/alkalinity problems, (4) declining profit, and (5) inadequate research and extension support to farmers.

In the rainfed lowland ecosystem, the major factors accounting for yield gaps were:

1. low soil fertility and fertilizer use,
2. poor weed management,
3. low profit,
4. inadequate and ineffective extension support to farmers (slow adoption of recommended technologies).

In the upland rice ecosystem, the main constraints were:

1. drought,
2. weed infestation,
3. inadequate research and extension support service,
4. low profit. In general, low profit is common in all ecologies, indicating that rice is not attractive.

The constraints of soil fertility, water availability and management, and inadequate research and extension are also the major causes of yield gaps in this survey.

Based on the data from experiments on yield constraints, fertilizer application rate and timing are the strongest constraints to high yields in the dry season. In the wet season, insect control and fertilizer management are about equal in importance in contributing to high rice yields (IRRI 1979). At the farmer level, the management of inputs—fertilizer, insect control, weed control, and seedling age—contributed little to explaining the difference between low- and high-yielding crops. However, the environmental parameters and a combination of weather-related factors and insects and diseases accounted for some 80% of the yield difference. In the dry season, the level of managed inputs used and their interaction with environmental factors accounted for 50–60% of the yield differences among farmers (Herdt and Mandac 1980). Observations at the farmer level suggest that potentially exploitable yield gaps are more prevalent under favorable environmental conditions.

Yield gaps may be caused by technical deficiencies but also by economic considerations. For example, farmers who seek maximum profit may not apply fertilizer doses to obtain maximum production. The effort to narrow the yield gap without considering economic aspects may have a counter-productive effect. Closing the yield gap may actually decrease farmers' income, particularly if rice prices are low. The ratio between the price of rice and price of fertilizer could influence the rate of fertilizer applied by farmers and thus rice yield. Consequently, institutional factors that increase the price of rice or fertilizer could positively contribute to gap narrowing (De Datta 1981).

IV – Strategies for closing rice yield gaps

Narrowing yield gaps aims not only to increase rice yield and production but also to improve the efficiency of land and labor use, to reduce production costs, and to increase sustainability. Exploitable yield gaps of rice are often caused by various factors, such as physical, biological, socioeconomic, and institutional constraints, which can be effectively improved through participatory and holistic approaches in action and government attention. An integrated program approach is essential. The narrowing of the yield gap is not static but dynamic with technological developments in rice production, as the gaps tend to enlarge with improvement of the yield potential of rice varieties (Tran 1997, Duwayri et al 1999).

1. Policy support

Rice policy should be well defined and formulated in a country, especially where major structural reforms have been introduced. Most sub-Saharan African and several Asian countries have experience with these reforms. Governments should address and find solutions for socioeconomic and political questions before narrowing the agronomic gap between farmers' fields and the research station (Hanson et al 1982). The goodwill of governments is also essential to initiate a yield-gap-narrowing program and to achieve effective coordination and intervention, with the aim of providing appropriate solutions to actual problems. Policymakers and government officers should be sensitive to these problems, which is a very important activity in bridging yield gaps. The pilot approach should be considered when selecting a zone(s) for intervention.

2. Identifying and classifying yield gaps

The first step in narrowing the yield gap is to identify and analyze actual and potential constraints to rice production in a particular area. The major constraints to high yield vary from one place to another and should be well understood. A group of agronomists and socioeconomists should carry out this preliminary survey. Based on the survey results, for practical purposes, yield gaps should be classified into:

Case 1—unexploitable: gaps due mainly to nontransferable factors (or gap I in Fig. 1).

***Case 2—less exploitable gaps**:* these gaps can be closed, but with less economic gains due to the yield ceiling and law of diminishing returns in a production function. This type of gap can be found when rice yields are equal to or more than 6 t ha^{-1} under tropical climate and 8 t ha^{-1} or more under Mediterranean climate.

***Case 3—exploitable gaps**:* gaps are due mainly to suboptimal crop management practices (or gap II in Fig. 1). This type of yield gap occurs when
For irrigated rice under tropical climate, yields are below 6 t ha^{-1}.
For irrigated rice under Mediterranean climate, yields are less than 8 t ha^{-1}.
For favorable rainfed lowland rice, yields are less than 4 t ha^{-1}.
The introduction of emerging technologies, such as hybrid rice and the new plant type, is needed to increase yield ceilings in the first *two cases*, while the promotion of integrated crop management along with the improvement of socioeconomic and institutional issues are relevant for narrowing of the *exploitable gaps* in *case 3*. In case 3, the yield gaps can be further classified into agronomic, socioeconomic, institutional, and mixed gaps for practical purposes.

3. Promotion of integrated crop management

Integrated crop management, including varieties of higher yield stability, can narrow agronomic yield gaps and at the same time help farmers to reduce wasteful resource use—due to poor management of inputs, natural resources, and other cultural practices—and increase rice yield and farmers' income at a particular location. Precision crop management practices can be realized with the use of advanced technologies. Precise application of fertilizers, for example, can be done by using computer-aided systems and costly equipment. However, most resource-poor farmers cannot afford such systems. The technique of the chlorophyll meter and leaf color chart for field-specific N management, which has been tested by IRRI and several national agricultural research centers, could be suitable for these farmers. It was reported that the only time-bound crop management activities in timely planting, irrigation, weeding, plant protection, and harvesting account for more than 20% of harvestable yield (Siddiq 2000).

Narrowing yield gaps by improving crop management practices of small farmers in developing countries is often not an easy task. Although several improved crop management practices exist, their dissemination has proven to be more complicated than that of seed-based technologies. Crop management practices are seldom static and often must be adjusted to environmental factors, knowledge, and market forces. Interactions among crop varieties, environmental conditions, and crop management practices are well known. Also, factors such as input and output prices and employment opportunities affect farmers' decisions on the level of inputs to be applied and time spent in crop management. The influence of market factors on farmers' decisions on crop management practices will increase as markets become more and more open under the General Agreement on Tariffs and Trade (GATT).

It is therefore essential that crop management practices not be applied in isolation but be holistically incorporated into integrated crop management packages (ICMPs) with flexibility for adjustment to fit prevailing environmental, socioeconomic, and market factors. The development of ICMPs, which are similar to the Australian Ricecheck package (Lacy 1994), and their transfer through the farmer field school approach could effectively help farmers in many countries to narrow yield gaps as well as reduce rural poverty. The ideal ICMP, however, must aim to improve farmers' knowledge not only on crop production and protection but also on the conservation of natural resources and market dynamics. This requires substantial improvement in the collection and dissemination of information on rice, its production factors, and its technologies as well as modification of extension systems in many countries.

4. Deployment of new technologies

Yield can be raised either by lifting actual yield closer to the ceiling by improving crop management or by raising the ceiling itself. The theoretical maximum rice yield is probably not much different from the maximum yield of wheat of 20 t ha^{-1} per crop (Hanson et al 1982). The highest yields obtained with research are about 17 t ha^{-1} per crop for hybrid rice, 15 t ha^{-1} for high-yielding japonica varieties planted under subtropical climate, and 10 t ha^{-1} for high-yielding indica varieties planted under tropical climate. Hybrid rice is now available for increasing the yield ceiling by 15–20%. The new plant type of rice, which has been developed by IRRI, could raise current yield potential by 25–30% (Khush 1995). Rice biotechnology, which has recently made considerable progress, may also provide an opportunity to increase rice yield in a more effective and sustainable manner.

5. Adequate input and farm credit supplies

Fertilizers, especially nitrogen, play an important role in rice production and productivity. Farmers need adequate amounts of fertilizer at the right time to obtain high yields in rice cultivation. The supply of fertilizers needs to be decentralized to village markets and fertilizer quality should be assured. Small farmers are usually unable to buy sufficient quantities on time for application; hence, the provision of village credit could greatly help them. The Bangladesh Grameen Bank is an interesting example of providing rural credit to landless and resource-poor farmers in developing countries. The bank receives loan proposals only on a group basis (at least five persons), focusing on technology loans, housing loans, joint loans, and general loans (Dadhich 1995).

6. Postproduction

Yield losses can be caused during pre- and postproduction. Postproduction losses range from 10% to 30% of the harvestable yield. Losses are more serious in the wet-season havests due to the lack of drying facilities. Resource-poor farmers tend to deploy labor-intensive practices in hand harvesting, sun drying, manual threshing, wind winnowing, and inappropriate storage, thus contributing greatly to grain losses. Training of farmers and access to credit to introduce more efficient technologies to handle threshing, drying, storage, and milling at the village level are important for reducing postproduction losses.

7. Linkage of research and extension

The support of research and extension ensures the effective bridging of rice yield gaps. Farmers' adoption of the abovementioned improved technologies depends on the capability of national agricultural research centers and extension services, which need more government resources and training.
This research should understand well farmers' constraints to high rice productivity and provide farmers with appropriate technological packages for specific locations to bridge the gaps under participatory approaches. The extension service should ensure that farmers use correctly and systematically recommended technological packages (ICMPs) in rice fields through effective training and demonstrations. For example, only the relevant application of nitrogen fertilizers from seeding to heading, in terms of quantity and timing, will significantly contribute to narrowing the rice yield gap while avoiding unnecessary losses of nitrogen, which increase production costs and pollute the environment.

V – Achievements in closing the rice yield gap in selected countries

In China, rice production has steadily increased even though the rice area harvested has declined. This was possible due to substantial increases in rice yield that could be attributed to both the development and use of hybrid rice since 1976 (Yuan 1996) and the improvement in crop management including increased fertilizer use (Singh 1992). Hybrid rice area expanded rapidly in China after 1976, reaching about 15 million ha in the late 1980s. During 1950-79, crop management improved with the transfer of integrated crop management packages such as the "Seven Techniques," which encompass improved varieties, growing strong/healthy seedlings, intensive cultivation, proper plant populations, balanced fertilizer application, rational irrigation, and control of pests and diseases. After 1980, the crop management package was improved, with emphasis on improved land development, fertilization, cultivation, and cropping systems and the use of improved seeds as well as integration of socioeconomic factors such as prices. The annual growth rates for rice yield were only 1.8% during 1967-77 but increased to 4.9% during 1977-87. Stagnation of the yield of 3-line hybrid rice varieties may be responsible for the decline in yield growth to about 1.7% in 1987-97 (Table 4).

In Indonesia, national rice yield increased considerably by about 4.9% per year during 1967-77 and 4.3% during 1977-87. This increase in rice production enabled the country to attain self-sufficiency in rice. Indonesia benefited from the Green Revolution from 1977 to 1987 and the government's INSUS/SUPRA INSUS Rice Intensification Programs have been effectively implemented since 1975. A successful integrated pest management program has also contributed to this high yield (Dudung 1990).

Vietnam had been a rice-importing country; it started exporting rice only in the late 1980s thanks to its adoption of new agricultural policies. National rice yield grew only about 1.0% per year from 1967 to 1977, although about 850,000 ha of IRRI's high-yielding varieties were grown in South Vietnam in 1974. This was probably due to inadequate fertilizer use and the large area grown with traditional varieties under rainfed conditions in this period. The annual growth rates of rice yield increased to about 4.2% annually during 1977-87 and about 3.6% annually during 1987-97. Increased fertilizer application has played an important role in these increases in rice yields and narrowing of yield gaps. The use of fertilizers, especially urea, increased from 45 kg ha^{-1} in 1988 to 200 kg ha^{-1} in 1997 (Le 1998).

In Egypt, rice yield increased from 5.8 t ha^{-1} in 1987 to 8.5 t ha^{-1} in 1997, one of the highest yields in the world. The adoption of new high-yielding varieties (such as Giza 175, 176, 181, 177, and 178 and Sakha 101 and 102), intensive demonstrations and training on crop management, and monitoring of production constraints carried out under national coordinated programs, such as Markbouk 4 and others (Badawi 1998), have led to the successful narrowing of yield gaps.

In Australia, rice yield declined about 2.4% per year during 1967-77, moderately increased during 1977-87, but then grew rapidly during 1987-97. The integrated rice crop management package called Ricecheck was developed in the mid-1980s and transferred to farmers in 1986 (Lacy 1994). Cropping systems using legume-based pastures (*Trifolium subterraneum*) in rotation with rice were another factor responsible for the impressive increase in rice yield. This increase has made rice production in Australia a profitable business for farmers and enabled the country to earn substantial foreign exchange from exports.

In the United States, the annual growth rate of rice yield was high (2.3%) in 1977-87 but rather low (0.9%) in the past decade. Among the rice-growing states, California has made considerable progress in increasing yield, reaching around 9 t ha^{-1} thanks to improvements in weed control, laser-based land preparation, and modern rice varieties.

It is worthwhile to note that yields in some Mediterranean countries, such as Italy, Spain, France, and Turkey, stagnated at around 6 t ha^{-1} for many years, whereas rice yield in Egypt reached 8.5 t ha^{-1} in 1997 (FAO 1998). The difference in yield between these countries and Egypt in the Mediterranean region is difficult to explain. Greece has also made great progress in narrowing yield gaps, with its yield reaching 8 t ha^{-1} in 1998.

Conclusions

The use of innovative genetic improvements including hybrid rice, the new plant type, and possibly transgenic rice can increase the yield ceiling where yield gaps are almost closed. These increases in rice productivity and efficiency in production systems result in high economic outputs as well as high income for farmers. On the other hand, in many countries, the gaps between yields at research stations and in farmers' fields are still substantially large due to a combination of lack of initiatives, knowledge, resources, and goodwill to narrow them. It is essential to expedite the bridging of yield gaps, which are caused by pre- and postproduction operations, thus improving the productivity and efficiency of rice production and eventually food security.

It is therefore necessary to promote close collaboration among research, extension, local authorities, nongovernmental organizations, and the private sector to identify specific constraints to high yield and appropriate location-specific technologies and solutions, and take concerted actions to bridge rice yield gaps through participatory approaches. Moreover, institutional and policy support to farmers is crucial for ensuring agricultural input supplies, farm credit, price guarantees, and adequate marketing systems in a holistic approach for sustainable increased production.

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TABLES

Fig. 1. Components of yield gaps. (Adapted from De Datta 1981)

Table 1. Annual growth rate (%) of world population, rice production, harvested area, and yield

Period	Population	Rice production	Rice harvested area	Rice yield
1960s (starting 1961)	2.17	3.48	1.54	2.51
1970s (1970-79)	2.03	2.71	0.80	1.76
1980s (1981-89)	1.86	3.14	0.23	2.80
1990s (ending 1996)	1.55	1.31	0.23	1.10

Note: Data on population, rice production, harvested area, and yield in FAOSTAT (1998) were transformed into 3-year-moving-average (3YMA) values. Growth rate was calculated based on the following formula:
GR (%) = ((B – A)/A) × 100)/N
where: GR = annual growth rate, A = 3YMA value of the starting year of a period, B = 3YMA value of the ending year of a period, N = number of years in a period.

Table 2. Annual growth rate (%) of population, rice production, harvested area, and yield in Asia[a]

Period	Population	Rice production	Rice harvested area	Rice yield
1960s (starting 1961)	2.64	4.35	1.34	2.70
1970s	2.28	2.59	0.60	1.88
1980s	2.05	3.24	0.31	2.86
1990s (ending 1996)	2.05	1.25	0.10	1.06

[a] Please refer to note in Table 1 for formula for calculating the growth rate.

Table 3. Comparative national average rice yields, irrigated rice yields, and experimental station rice yields in Asia, 1991

Country	National average rice yield (t ha^{-1})	Irrigated rice yield (t ha^{-1})	Average potential rice yield (t ha^{-1})
Bangladesh	2.6	4.6	5.4
China	5.7	5.9	7.6
India	2.6	3.6	5.9
Indonesia	4.4	5.3	6.4
Nepal	2.5	4.2	5.0
Myanmar	2.7	4.2	5.1
Philippines	2.8	3.4	6.3
Thailand	2.0	4.0	5.3
Vietnam	3.1	4.3	6.1

Sources: IRRI (1993). Average potential yield data cited from Dey and Hossain (1995).

Table 4. Yield and yield growth rate in selected countries, 1966-97

Country	**Growth rate of rice yield (%)**[a]			**Average yield ($t\ ha^{-1}$)**[b]		**Estimated N rate ($kg\ ha^{-1}$)**[c]	
	1967-77	1977-87	1987-97	1966-68	1995-97	1980	After 1990
China	1.81	4.47	1.72	3.12	6.17	–	145 (1994)
Indonesia	4.91	4.32	1.03	1.89	4.42	68	90 (1993)
Vietnam	0.97	4.22	3.56	1.81	3.73	–	90 (1997)
Egypt	0.54	1.26	4.46	4.95	8.25	83	120 (1997)
United States	0.20	2.32	0.92	4.96	6.74	–	–
Australia	–2.41	1.69	3.06	7.33	8.23	–	32 (1996)

[a] Please refer to Table 1 for information on formula for calculating the growth rate.
[b] Source: FAOSTAT (1998).
[c] Estimated based on FAO/IFA/IFDC (1999) database on fertilizer use by crop. For Vietnam, based on Le (1998).