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CIMMYT
International Maize and Wheat Improvement Center

IRRI

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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today, IRRI is one of the 15 nonprofit international research centers supported in part by more than 40 donors: members of the Consultative Group on International Agricultural Research (CGIAR – www.cgiar.org), other government funding agencies, foundations, the private sector, and nongovernment organizations.

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Content

Foreword

Rice-maize (R-M) cropping systems have emerged in recent years on 3.5 million hectares in Asia in response to the increasing demand from a rapidly expanding human population for rice and livestock products. They are rapidly spreading in southern and northeastern India and Bangladesh, driven by the rising demand for maize by the poultry and fish sectors and the tightening world export-import markets. The recent development of short-duration rice varieties and maize hybrids with improved drought tolerance is also providing opportunities for the expansion of R-M systems into areas of South Asia with insufficient irrigation or rain for continuous rice cultivation. Agroecologically, R-M systems have the potential to expand into broad climatic zones across Asia. Because strong economic multipliers exist between food production and feed and livestock production, more diversified cropping systems are also likely to become a key engine for economic growth in rural areas of Asia. This will contribute to more diversified diets, improved human nutrition, reduced poverty, and greater investment in other aspects of quality of life such as education and health care. R-M systems will also provide new business opportunities for the local agribusiness sector, including hybrid seed production and marketing, the fertilizer sector, the agricultural machinery sector, and the grain marketing and livestock feed-processing sector.

Recognizing the importance of diversifying cropping systems in Asia and the need for system-level research to support new opportunities for agricultural development, IRRI and CIMMYT scientists, in collaboration with NARES partners, have recently begun work on R-M systems in many countries of Asia. This report contains information on a strategic assessment of R-M systems for 29 selected sites representing diverse soils, climate, and agroecosystems across nine countries in Asia (Bangladesh, China, India, Indonesia, Nepal, Pakistan, the Philippines, Thailand, and Vietnam). Conducted jointly by IRRI and CIMMYT, the process involves regional and site-level biophysical assessment, supported by socioeconomic evaluation using economic data at the regional level and some microeconomic data. Biophysical assessment includes agroecosystem characterization of R-M systems, analysis of historical daily climatic data, and regional-level prediction of yield potential for the 29 sites. The study then provides a detailed analysis of 10 selected sites to understand existing cropping systems, identify alternative potential systems, and explore measures to optimize these.

The Cereal Systems Initiative for South Asia (CSISA), a project funded by the Gates Foundation and USAID in Bangladesh, India, Nepal, and Pakistan, was launched in early 2009. It now provides an overall strategy and a new umbrella for contributing new science and technologies to accelerate short- and long-term cereal production growth in South Asia's most important grain baskets. It builds on technologies developed and lessons learned from the Rice-Wheat Consortium (RWC) and many other investments in agricultural R&D by both the public and private sector. Through creating and facilitating innovative and effective public-/private-sector partnerships in key “hubs” in South Asia, CSISA will boost the deployment of existing varieties, hybrids, crop- and aquaculture-related management technologies, and market information. The results from the strategic assessment of R-M systems are already being used in several CSISA hubs, and we hope that they will find wider usage in other countries as well.

We would like to thank the authors and their partners who took on the task of putting together this important book, which we are sure cereal systems researchers, donors, policymakers, and other stakeholders interested in cereal systems research and policy will find insightful.

Robert S. Zeigler
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Executive summary

I. Rice, maize, and wheat are major cereals that contribute to food security and income in Asia. These crops are grown either as a monoculture or in rotations in tropical, subtropical, and warm temperate regions of Asia. In the irrigated and favorable rainfed lowland areas, rice-rice (R-R), rice-wheat (R-W), and rice-maize (R-M) are the predominant cropping systems. R-R is common in tropical climates with distinct dry and wet seasons such as those in the Philippines, Indonesia, Vietnam, and southern India, and in subtropical areas with mild cool winter such as those in Bangladesh, eastern India, and eastern Nepal. R-W is common in subtropical areas of South Asia and in the southern, central, and southeastern parts of China with cool winter climate. The R-M system is practiced in many tropical and subtropical areas but not as extensively as R-R or R-W. All these double-cropped systems often include an additional crop, which could be potato, lentil, chickpea, or mustard during rabi and jute, aus or spring rice, mungbean, or cowpea during kharif I (premonsoon season).

II. This study reports various macro data on long-term trends in (i) area, production, yield, consumption, and trade of rice, wheat, and maize; (ii) production and consumption of N, P, and K fertilizers; and (iii) population, consumption, and trade of cattle, swine, poultry, and their meat for Bangladesh, China, India, Indonesia, Nepal, Pakistan, the Philippines, Thailand, and Vietnam. Likewise, food and nutrition and economic indicators, current and projected human population and rural and urban poverty levels, and current and projected cereal requirements and demand, livestock population and demand, and prices of cereals are reported in detail for these countries.

III. Based on long-term NASA-derived (and, in some cases, in combination with actual ground-measured) data and on climatic trends and patterns, the study analyzed and established the variability in daily rainfall, solar radiation, and maximum and minimum temperatures for all those sites. Climate at 29 sites ranged from humid tropical monsoon in the Philippines to subtropical cold winter in northern India, Nepal, Bangladesh, and northern Vietnam, and to subtropical to warm temperate with severe cold winter in China. Total annual rainfall across locations ranged from as low as 707 mm (Punjab, India) to as high as 3,134 mm (Medan, Indonesia). Annual mean minimum temperature ranged from as low as 11.1 °C (Yangzhou, Jiangsu, China) to as high as 25.7 °C (Thanjavur, Tamil Nadu, India), while annual mean maximum temperature ranged from 20 °C (Yangzhou, China) to 31.4 °C (Nalgonda, Andhra Pradesh, India). Annual daily mean incident solar radiation ranged from 12.6 MJ m^{-2} d^{-1} (Changsha, Hunan, China) to 19 MJ m^{-2} d^{-1} (Punjab, India). There were large differences in climate variables between seasons and among locations.

IV. Soil at the 29 sites ranged from sandy and silty loam in Bangladesh, Nepal, and the Indian Punjab to light-to-heavy clay in other countries.

V. Four main R-M agroecosystems with four broad climates were identified. The first agroecosystem (tropical, warm, humid and subhumid, no winter) includes locations in Indonesia, the Philippines, and southern Vietnam with high rainfall with distinct dry- and wet-season patterns. The second agroecosystem (tropical, warm, semiarid, no winter) includes locations in southern India with tropical monsoon and a longer dry season. In both agroecosystems, both rice and maize are not limited by low temperature and can be grown year-round. The third agroecosystem (subtropical, subhumid, warm summer, mild cool winter) includes locations in Bangladesh, Nepal, northern India, and northern Vietnam. In this agroecosystem, winter is mildly cool and so rice may be limited by the low temperature. Maize, however, has a long grain-filling period and performs well due to the mild cool winter. The fourth agroecosystem (subtropical to warm temperate, subhumid, warm summer, mild to severe cold winter) has been divided into three subclasses. The first subclass is subtropical monsoon with cold winter and summer rainfall, such as that found in northern and northwestern India and in the Terai and hills of Nepal. The second subclass has a subtropical to warm temperate climate with severe cold winter such as that found in locations in China. In this agroecosystem, both rice and maize are limited by low temperature and cannot be grown for some time in winter. The third subclass has a subtropical to warm temperate, semiarid, hot summer and cool to cold winter with very low rainfall as is found in the Punjab and Sindh provinces in Pakistan.

VI. NASA data have been validated against field-measured data for all weather parameters and variables globally and in the U.S. All studies show good agreement between NASA-derived data and ground-measured data for solar radiation and temperatures but not satisfactory agreement for rainfall, especially for the mountainous and coastal areas. In this study, the maximum temperature for the NASA/POWER data ranged from –3.0 to 46.1 °C, while the measured temperature ranged from –2.1 to 50.1 °C. The corresponding NASA-derived and measured minimum temperature ranged from –12.0 to 34.9 °C and –10.3 to 38.2 °C. Daily average NASA-derived solar radiation ranged from 0.5 to 32.2 MJ m^{-2}, while measured solar radiation ranged from 0 to 35.8 MJ m^{-2}. The overall mean maximum temperature for the NASA/POWER data was 1.6 °C cooler than the measured data, while values of mean minimum temperature were exactly the same for both sources of data. For mean solar radiation, NASA/POWER data were 0.3 MJ m^{-2} d^{-1} higher than measured data. Although mean daily rainfall was similar (4.8 vs 4.2 mm for NASA and measured data), there were large variations in individual daily rainfall (ranging from 0 to 177 mm for NASA and 0 to 382 mm for measured data).

VII. Comparisons of potential yield and growth duration of maize and rice as simulated by Hybrid Maize and ORYZA2000 using NASA/POWER and measured data showed that maize yields using NASA-derived data matched reasonably well with those using measured data (R^2 = 0.62) when all locations were combined. Likewise, simulated growth duration using the two data sources matched very well (R^2 = 0.88). Except for some cooler environments of Vin

Phuc in northern Vietnam and for some sites in Bangladesh, potential yields of rice simulated by ORYZA2000 using NASA-derived data also matched well with those simulated using measured data ($R^2 = 0.57$). Simulated growth duration using the two sources matched extremely well with least discrepancy ($R^2 = 0.95$).

VIII. Based on satellite-derived NASA data, the yield potential (Yp) of rice and maize for the R-M systems for all sites in the nine countries was estimated using ORYZA2000 and Hybrid Maize, and, for selected sites, Yp of wheat and soybean was estimated using CERES-Wheat and CROPGRO-Soybean. This study reports a detailed assessment of the R-M system at 10 sites representing different R-M agroecosystems in Asia. Four generic rice varieties differing in maturity and four maize hybrids differing in growing degree days (GDD) were used. The mean Yp of extra short, short, intermediate, and long-duration rice varieties across R-M agroecosystems ranged from 1.6 to 9.0, 0.4 to 10.6, 1.9 to 13.0, and 1.2 to 17.6 t ha^{-1}, respectively. There were large differences in Yp among sites within a country or among the countries as well as differences among planting dates at each site. For each site, the long-duration varieties had the highest Yp and the extra short-duration ones had the lowest. The large ranges in Yp for different varieties were associated with large variations in growth duration, total intercepted solar radiation, and growing-season temperature, leading to differences in grain-filling period.

IX. Yp of rice varieties in the tropical warm climate ranged from 3.9 to 8.9, 4.7 to 10.6, 5.3 to 13.0, and 7.4 to 15.1 t ha^{-1}, respectively. Yp was highest for Chiang Rai in northern Thailand and lowest for Los Baños in the Philippines. Yp values for sites in Indonesia, central and southern India, and the Mekong Delta in Vietnam were in the middle range. The high Yp in Chiang Rai was associated with longer growth duration, greater solar radiation, and slightly cooler environment, while the low Yp in Los Baños was attributed to shorter duration and smaller amount of solar radiation received. Yp of rice varieties in the subtropical climate ranged from 2.9 to 9.0, 3.4 to 10.2, 4.7 to 12.3, and 5.5 to 14.5 t ha^{-1}, respectively. Yp was highest for Dinajpur in Bangladesh and Begusarai in Bihar, followed by Bogra in Bangladesh; it was lowest at the Red River Delta (RRD) sites in Vietnam. At the two RRD sites, all varieties took much longer to mature when transplanted in October and January because of low temperatures during the growing season. The Yp of four varieties in subtropical to warm temperate climate ranged from 1.5 to 8.8, 0.4 to 9.3, 1.9 to 12.8, and 1.2 to 17.6 t ha^{-1}, respectively. Yp was highest in Punjab in India followed by Chitwan in Nepal, and comparatively lower at the four Chinese sites. In the Punjab, extra short-duration varieties planted from November to January suffered from cold injury throughout the season and the plants died. Short-, intermediate-, and long-duration varieties, however, also experienced cold injury and plants also died when planted in October. Likewise, in Chitwan, transplanting extra short-, short-, and intermediate-duration varieties from October to January resulted in cold injury and subsequent death. The long-duration variety was also exposed to cold and did not produce any yield when planted in September. At all sites in China, transplanting extra short and short varieties from October to February resulted in cold injury and subsequent death; intermediate- and long-duration varieties also suffered from cold injury when transplanted in September.

X. The mean Yp of different hybrid maize maturity groups across tropical, subtropical, and warm temperate agroecosystems ranged from 7.7 to 23.0, 6.4 to 20.4, and 5.6 to 27.4 t ha^{-1}, respectively. In the tropics and subtropics, Yp was always higher in terms of GDD, but no such trend was observed in warm temperate areas. The growth duration in the respective agroecosystem ranged from 67 to 127, 76 to 154, and 63 to 271 d. Unrealistically longer growth duration in warm temperate areas resulted in greater interception of solar radiation. Unexpectedly, the mean temperature during grain filling was higher in warm temperate places than in the tropics and subtropics. This indicates extreme temperatures during parts of the year in temperate regions and fairly even temperatures throughout the year in the tropics. At all Chinese sites, except for Wuhan, cold injury during germination and seedling emergence was noted in crops planted between 1 September and 1 March. This resulted in crops dying and no yield. For the 1 October- and 1 November-planted crops, even if the plants survived, growth duration was excessively long, with a very large amount of solar radiation received. Results suggest that, for all Chinese sites, maize should be planted between March and August to avoid cold injury. For South Asia, planting from August to November gave exceptionally high yields because of low temperature during grain filling, long growth duration, and a large amount of solar radiation. For rabi planting of maize after rice in South Asia, the October and November crop would have high Yp, while ensuring successful intensification and diversification of the rice-based systems. Likewise, for kharif I or the premonsoon season, a late March to early May planting of maize would result in a reasonably high Yp and the maize crops fitting easily into the rice-based systems.

XI. ORYZA2000 has been validated against data from many experiments in many locations in Asia. The model has performed satisfactorily in most cases in irrigated and favorable rainfed environments, especially in tropical and subtropical Asia. However, under drought conditions, with less than 2–3 t ha^{-1} yield, the model did not perform adequately. Based on current simulations across locations in Asia, simulations of leaf area index development, tiller dynamics, and spikelet fertility under drought are the key processes that need further improvement in ORYZA2000. Hybrid Maize has also been evaluated in north-central U.S. and has been tested and used in Indonesia, the Philippines, and Thailand under an International Plant Nutrition Institute (IPNI) project. The model, however, has not yet been evaluated under conditions of water and/or nutrient stress. In the current work under default settings, Hybrid Maize predicted unrealistically high yields under low-rainfall and dry situations for many locations in Asia.

XII. Both models could not accurately predict yield under extreme cold and heat conditions. ORYZA2000 “killed” the plants under mild to severe cold conditions, while the plants seemed to grow longer and produce a reasonable amount of grain in actual field conditions. In contrast, Hybrid Maize “let” the plants grow unrealistically longer, allowing the interception of a large amount of solar radiation and the production of exceptionally high yields under mild to moderate cold conditions. Thus, the model processes relating to the effects of cold and heat injury in both ORYZA2000 and Hybrid Maize and the effects of drought and waterlogging in Hybrid Maize should be further refined to better estimate yields under varying conditions of moisture and temperature. ORYZA2000 can simulate reasonably well under N-limiting situations, but Hybrid Maize currently lacks the routines for simulations under nutrient-limiting situations.

XIII. Ten representative sites were selected for a detailed assessment of current and potential yields of the R-M systems. Five sites represent tropical climate—Pila, Laguna, in the Philippines; An Giang, Mekong Delta, in Vietnam; Phitsanulok in the Central Plain in Thailand; Central Lampung in Indonesia; and Thanjavur in Tamil Nadu in southern India. Four sites represent subtropical climate—Dinajpur in northwest Bangladesh; Begusarai in Bihar, India; Rampur in Chitwan, Nepal; and Vinh Phuc in the RRD in northern Vietnam. The 10th site is Changsa, China, representing warm temperate climate. Based on Yp of individual crops, total system productivity, long-term climate, and probability of occurrence of extreme rainfall and typhoon/cyclone events, various combinations of rice varieties and maize hybrids were examined and the R-M systems were optimized for each of those sites.

XIV. Of the 10 sites selected for detailed assessment, four sites (Pila in the Philippines, An Giang and Vin Phuc in Vietnam, and Dinajpur in Bangladesh) were treated in greater detail for R-M system optimization. Based on the simulated Yp of rice and maize, various combinations of rice varieties and maize hybrids were examined to obtain the maximum R-M and M-R system productivity. For Pila, Philippines, the “optimum R-M system” would comprise an intermediate rice variety planted in late June and a maize hybrid of 1,700 GDD planted in late December/early January with a total Yp of 20.5 t ha^{-1}. It would require less irrigation water for rice and would have less risk of typhoons in rice and of waterlogging in maize. For the M-R system, a maize hybrid of 1,700 GDD planted in late April to early May and IR72 planted in late November to early December would be “optimum” with the greatest Yp of 21.7 t ha^{-1}; this, however, would require more irrigation for rice. Thus, compared with the currently practiced R-fallow system with a Yp of 7 t ha^{-1} and the R-R system with a Yp of 15.7 t ha^{-1}, the optimized R-M system has a Yp of 20.5 t ha^{-1} and the M-R system has a Yp of 21.7 t ha^{-1}.

XV. For An Giang, Vietnam, various combinations of rice varieties and maize hybrids were examined to obtain maximum productivity from the R-M-R and M-R-R systems. In the R-M-R system, the key is avoidance of heavy typhoons during maturity and harvest of rice in October for late wet-season rice, during early growth for dry-season rice, and heavy rains and waterlogging damage during maturity and harvest for early wet-season maize. For M-R-R, it is critical to avoid typhoons during the maturity of late wet-season rice and avoid waterlogging during the establishment and early growth of dry-season maize. For maize in the R-M-R system, minimal irrigation would be required during the vegetative stage, but a lot of rainfall is needed for the reproductive stage. For maize in the M-R-R system, some irrigation may be necessary during the reproductive period of the crop. Based on Yp and considering all constraints, dry-season rice planted between 15 November and 1 December, early wet-season maize planted between 15 March and 1 April, and late wet-season rice planted between 15 June and 1 July would give a total system productivity of 25–26 t ha^{-1}. This would be the best option for the R-M-R system. For the M-R-R system, dry-season maize planted between early and mid-December, early wet-season rice planted between mid- and late March, and late wet-season rice planted between mid- and late July would give better results.

XVI. The current main systems in Dinajpur, Bangladesh, are R-R and R-W. The total system Yp of R-W is quite low (13.9 t ha^{-1}). Based on Yp, four alternative potential triple-cropping systems are proposed. The first involves the addition of a 1,600- GDD maize crop in kharif I to the existing R-R system (with both intermediate- duration rice), thus increasing total system Yp from 19.8 to 29.5 t ha^{-1}. The second involves growing one rice (intermediate) and two maize crops (1,600 GDD) in rabi and kharif I, with a total system Yp of 31.5 t ha^{-1}. The third and fourth systems involve growing intermediate-duration rice in kharif II, a potato or a pulse crop in rabi, and maize (1,600 GDD) in kharif I. The first two systems involving only rice and maize require high nutrient and water use by rice (especially for two rice crops in the R-R-M system). Some supplemental irrigation is needed for maize, but it is nominal and can be met with existing surface-water sources or shallow tube wells. Potato yields are very high and the crop needs lots of nutrients and water. Appropriate nutrient and water management and the use of best cultivars will ensure the sustainability of these systems.

XVII. Rice-rice, R-R-soybean, and R-R-sweet potato (or Irish potato) are the existing predominant cropping systems in Vin Phuc. The alternative systems proposed are R-R-M and M-R-M. For a successful R-R-M system, the key is avoidance of cold damage during emergence and seedling stage in spring rice and during flowering and grain filling in winter maize. Likewise, typhoons during the growing period of summer rice and waterlogging during establishment and seedling stage in maize must be avoided. In the M-R-M system, soil under spring maize could remain saturated from March to May and waterlogging could be an issue. As in the R-R-M system, typhoons, waterlogging, and cold damage need to be avoided. Based on the Yp and with all constraints considered, spring maize planted between 1 and 15 September, summer rice planted between 1 and 15 June, and winter maize planted between 15 September and 1 October would give a total system productivity of 22.6 t ha^{-1}. This would be the best option for the M-R-M system. For R-R-M, spring rice planted between 15 January and 1 February, summer rice planted between 15 May and 1 June, and winter maize planted between 1 and 15 September would be best, with a total system productivity of 20.7 t ha^{-1}.

XVIII. In addition to the main biophysical constraints such as soil waterlogging and typhoons/cyclones, some other soil-related constraints are acidity, alkalinity, sodicity, and salinity. To minimize their adverse effects, varieties with some tolerance should be used or appropriate management practices should be developed. Some of the conservation agriculture-based resource-conserving technologies (such as planting crops on raised beds) have the potential to reduce the adverse effects of waterlogging and sodicity or salinity, but they need to be tested under a range of soil and climatic environments.

XIX. Finally, socioeconomic factors such as family and hired (on-farm and off-farm) labor availability; farm size; availability of and accessibility to inputs such as quality seeds, fertilizers, and supplemental irrigation; availability of and accessibility to credit; seasonal market and prices of commodities; and the existence of marketing institutions need to be considered. All these factors influence the selection and adoption of "optimal" cropping calendars that include rice and maize in the cropping systems. Policy reforms in the individual countries will be required to enable small farmers to adopt the improved technologies. Availability of and accessibility to quality seeds, fertilizers, and irrigation water are extremely important because high Yp assumes the use of good-quality seed and optimum fertilization and irrigation. Proper marketing channels and institutions should be in place to ensure a smooth functioning of the supply and demand chains, especially that of maize, as demand for it in Asia is growing due to its increasing use in livestock and poultry.

General introduction

World population, poverty, and Millennium Development Goals

The world's population, based on projections by the UN, is expected to grow from 6.67 billion in 2008 to 7.25 billion in 2015 and to 9.19 billion in 2050 (Annex Table A1.1). These projections show alarming trends in population increase in all countries of Asia, especially in Bangladesh, India, Indonesia, Pakistan, and the Philippines (www.esa.un.org/unpp*)*. The data reveal that, globally, there is now a slightly higher population in rural areas, but that, over the projection period from 2005 to 2050, a large number of rural people will move to cities. From 2005 to 2015, there will be negative growth rates of rural populations in China, Indonesia, and Thailand but positive growth rates in other countries. The countries where the largest number of people will move to cities are China, Indonesia, and the Philippines, although the greatest growth rates of urbanization will occur in Bangladesh and Nepal. Nevertheless, even though a large number of people will move to cities in almost all Asian countries, there will still be quite a large proportion of the rural population in those countries because of high population growth rates. Thus, in four South Asian countries (Bangladesh, India, Nepal, and Pakistan) and in two Southeast Asian countries (Thailand and Vietnam), >40% of the people will still be living in rural areas by 2015. At that time, about 53% of the world population will live in urban areas compared with 49% in 2005; in 2050, the urban population will increase to 70% (Annex Tables A1.2 and A1.3) (www.esa.un.org/unpp).

Development, economic, and nutrition indicators, including poverty data, for the world and South Asia reveal striking differences in urban and rural poverty profiles among countries. For example, in 2002, with a poverty line of US$1 a day, there were about 1,165 million poor people in the world, of which 883 million lived in rural areas and 283 million lived in urban areas (Ravallion et al 2007). The urban share of the population was 42.3%, whereas the urban share of the poor was 24.2%. With a poverty line of $2 a day, there was a slightly higher share of the poor (26.2%) in urban areas compared with that with $1 a day (Tables A.2 and A.3). South Asia, particularly India, had the largest number of poor people (irrespective of poverty line) in both urban and rural areas, while China had a very small poor sector in urban areas. In India (and also in South Asia), about 28% of the population lived in urban areas, and, of the total urban population, 24–26% were poor, regardless of poverty rate. Poverty incidence was also high in East Asia and the Pacific, including China.

Thus, poverty is quite extensive in the world and in densely populated areas of South and Southeast Asia. Based on FAO (2008) records, in all the seven Asian countries, there were no or very minimal cereal stocks in 2007 and 2008. As a result of the lack of stocks and the increased population, all countries imported a large quantity of cereals (in the form of commercial purchases and food aid) in 2007 (Tables A.4 and A.5). Bangladesh, Indonesia, and the Philippines continued to be the largest importers in 2008 (FAO 2007; www.fao.org/docrep/010/ah881e/ah881e08.htm; http://devdata.worldbank.org).

Intensive agricultural systems are the primary source of food and income security for rural and urban households and are central to reducing poverty in South and Southeast Asia, where these systems supply 80–90% of the cereals for the region's food needs. Double- and triple-cropped rice-based systems in the lowlands of Asia provide the bulk of the food consumed by billions of Asians. The ability to produce a cereal surplus on intensively cultivated land has been a key factor for economic development and political stability in Asia. In recent years, increases in demand for food have been met by higher productivity through agricultural intensification, technological advance, mechanization, and irrigation. However, the continuing depletion and degradation of natural resources that constitute the agricultural sector's main inputs, water and land, have resulted in a slowdown of productivity growth, thereby undermining food security (World Bank 2007b) (Annex Figs. B.1-B.9).

Four of the eight targets of the Millennium Development Goals (MDGs) that can be addressed through sustainable agriculture are (1) eradicating poverty and hunger by halving extreme poverty by 2015, (2) reducing child mortality, (3) improving maternal health, and (4) ensuring environmental sustainability. These goals, particularly the first one, can be achieved by developing productive, profitable, and sustainable agriculture. Intensive cereal-based systems, particularly R-M systems, can contribute to meeting these goals.

The role of cereals in alleviating poverty and increasing income

Rice, wheat, and maize are the three most important cereals in the world and in Asia. In many countries in Asia, rice and wheat are used as staple crops, but in many poverty-stricken areas, especially those in the hills, maize is also a food crop. In sub-Saharan Africa, 80% of the maize grain is used for human food; in Asia, maize is mostly used as animal feed and some as human food. Maize is a potential food crop in tribal areas of India. Wheat accounted for 31% and rice for 21% of global cereal consumption in 1997-99. The contribution of these cereals to average calorie and protein intakes varies widely among Asian countries. The contribution of rice to average calorie intake from 1994 to 2003 ranged from 750 to 1,700 calories capita^{-1} day^{-1}, that of maize from 0 to 560, and that of wheat from 25 to 600. The share of calories and proteins from these cereals also varied widely (10–50%) among the countries (www.faostat.fao.org).

Long-term FAO data also reveal that the yield of rice, wheat, and maize in Asian countries has increased gradually in the past (www.faostat.fao.org). Average yields increased from 1994 to 2006. Average yield of rice ranged from 2.1 to 6.3 t ha^{-1}, that of maize from 1.5 to 5.9 t ha^{-1}, and that of wheat from 1.6 to 4.2 t ha^{-1} (Annex Figs. B.10-B.12). Areas under rice and wheat have increased little in most countries but those under maize increased recently in all countries, most strikingly in Bangladesh. However, limits have been reached in most countries (Annex Figs. B.13-B.36). Thus, further increases in area will either not occur or, if they occur, they will be at much lower rates than before. The total production of these cereals likewise increased. Continuing increases in yield and production of these cereals are necessary to increase farmers' income, ensure food security, and alleviate poverty in rural and urban areas of Asia. Rice is particularly important in many countries of Asia, being a staple crop, followed by wheat. Maize, however, is of particular importance because of multiple demand for it as human food, animal feed, and biofuel.

Fertilizer consumption

High and sustainable production of cereals requires appropriate management and optimum use of fertilizers. Nitrogen (N), phosphorus (P), and potassium (K) are the main fertilizers used widely for cereals. FAO data show that consumption of all N fertilizers in all Asian countries, except in Nepal and Pakistan, increased substantially from 1962 to 2005, whereas that of P and K fertilizers increased a little (www.fao.org/site/575/default.aspx) (Annex Figs. C.1-C.10). There has been a dramatic decrease in N fertilizer consumption since the mid-1980s in Pakistan and a decrease in N and P fertilizer use since early 2000 in Nepal. Consumption of all fertilizers was greatest in China, followed by India; it was smallest in Nepal. While the populations in China and India are similar, fertilizer consumption in China more than doubled that of India. Likewise, Indonesia has quite a large population, but fertilizer use was quite low. Except for Nepal, all countries produced some N and P fertilizers, but they also imported as well as exported some N fertilizers. Except for Bangladesh, India, and Nepal, all countries exported P fertilizers. Only China produced and exported K fertilizers; all countries, including China, imported K fertilizers (http://faostat.fao.org/site/575/default.aspx).

Changes in food consumption patterns

In many Asian countries, a change is occurring very rapidly in food consumption patterns. In most countries, the high rates of urbanization and rising incomes resulted in shifts in diet preferences from the traditional habit of consuming large amounts of cereals to having new cravings for vegetables, milk, and meat products. Rising incomes have led to two forms of change in dietary patterns. On the one hand, a substitution occurs in staples away from coarse grains such as maize to staples such as rice and wheat and vegetables, and, on the other hand, a move away from the consumption of staples toward eating high-value products such as beef, pork, poultry, and dairy products. What is happening in most rising economies in Asia is mostly the second form of change. For example, demand for poultry has increased in most Asian countries, but there has also been a significant increase in beef and pork consumption. In China, per capita meat consumption increased from 20 kg in 1980 to 50 kg in 2007. Such a change from cereals to meat is driving demand for maize as feed, which is expanding its niche, especially in irrigated and favorable crop-intensive regions. The increase in meat consumption demands a lot of feed because 7–8.5 kg grain is required to produce 1 kg of beef and 5–7 kg grain is needed to produce 1 kg of pork (Ravallion et al 2007, World Bank 2007b).

The role of livestock in improving nutrition and income

The demand for meat and milk in several Asian countries has resulted in a dramatic increase in livestock population, especially poultry, ushering in a "livestock revolution" (Delgado et al 1999). Long-term FAO data on livestock and livestock products for several Asian countries also reveal that consumption of beef is increasing very rapidly in China in contrast to India and the Philippines, where only a small increase occurs (Annex Figs. D.1-D.14). Consumption of pork has increased dramatically in China, the Philippines, and Vietnam. Consumption of poultry has likewise increased rapidly in China, Indonesia, and the Philippines and at a slower rate in Indonesia and Thailand. Countries with the livestock population remaining stable or decreasing import meat and milk products from neighboring countries or from developed countries such as Australia, the European Union, New Zealand, and the U.S. (www.fao.org/site/575/default.aspx).

Projections for cereal and livestock demand

The world population for 2030 and 2050 and the demand for cereals projected by FAO (2006) are presented in Figure 1. As for the UN projections aforementioned, these data indicate a faster rate of population growth from 2000 to 2030 compared with that from 2030 to 2050. The food requirements and other needs of the growing population underpin the strong demand for cereals. The demand for wheat, based on production and stock changes, is expected to increase from 621 million t in 2004-06 to 760 million t in 2020 (Rosegrant et al 2001), to around 813 million t in 2030, and to >900 million t in 2050 (FAO 2006, 2007; Rosegrant et al 2007). This implies growth rates of 1.6% in 2005-20, 1.2% in 2005-30, and 0.9% in 2005-50. For rice, it is 500 million t in 2030 and 520 million t in 2050. The projections suggest that demand for maize will grow faster than that for wheat particularly because of the strong demand for livestock and poultry feed and the increasing demand for food and biofuel. The rapid population growth in Asia, persistent poverty in areas where maize is an important staple (especially parts of South Asia, Indonesia, and the Philippines), and the rising prices of main staples such as rice and wheat will continue to exert upward pressure on maize demand. The latter is expected to be a main driver toward the shift in food consumption patterns, especially in poverty-stricken areas, since international and farm-gate prices of maize are comparatively lower than those of rice and wheat. Climate change—that is, occurrence of temperature extremes—would also produce a shift in area from wheat to maize. Demand for maize will increase by almost 50%, from 558 million t in 1995 to 837 million t in 2020. The increase in maize demand will be acute in Asia—an 87% rise from 162 million t in 1995 to 303 million t in 2020 (IFPRI 2000). As stated previously, rising incomes, population growth, urbanization, and changes in diet preferences will be responsible for much of the shift from rice and wheat to maize. Most of the extra 141 million t of maize that will be produced in Asia between 1995 and 2020 will be fed to livestock. Delgado et al (1999) report that developing countries of Asia are in the midst of a demand-driven "livestock revolution."

Livestock production and consumption of both meat and milk products are expected to grow about four times faster in developing countries than in developed countries up to 2020. By 2020, developing countries will produce 60% of the world's meat products, and Asia, led by China, will account for 43% (51 million t) of additional meat demand worldwide between 1997 and 2020 (Delgado et al 1999). The demand for wheat is expected to grow faster than that for rice and will follow very closely the growth in global population (Fig. 1). Demand for rice, wheat and maize based on IFRI and FAPRI projections for several Asian countries is presented in Annex Fig. E.1 and Annex Table E.1. Demand for livestock and meat based on FAPRI projections is given in Annex Table E.2.

Further maize demand in the future may come from the energy sector. Rising energy needs, especially in China and India, may put upward pressure on petroleum prices. This is likely to increase dependence on renewable sources of energy such as ethanol, which uses maize as an input. This is already occurring in the U.S. and, at current prices, can be expected to spread into Asia quickly (Wada et al 2008). OECD-FAO (2008) estimate that fuel ethanol production in China will grow steadily and reach some 3.8 billion liters by 2016, up from 1.5 billion liters in 2006. Most of the ethanol is expected to be based on maize, even though other feedstocks are being used or explored. Maize use for ethanol in China will exceed 9 million t in 2016 compared with 3.5 million t in 2006.

Projected increases in demand for maize, either to meet domestic food, feed, and energy requirements or to satisfy export demand, are expected to result in crop substitution, intensification, and diversification of both irrigated and rainfed lands

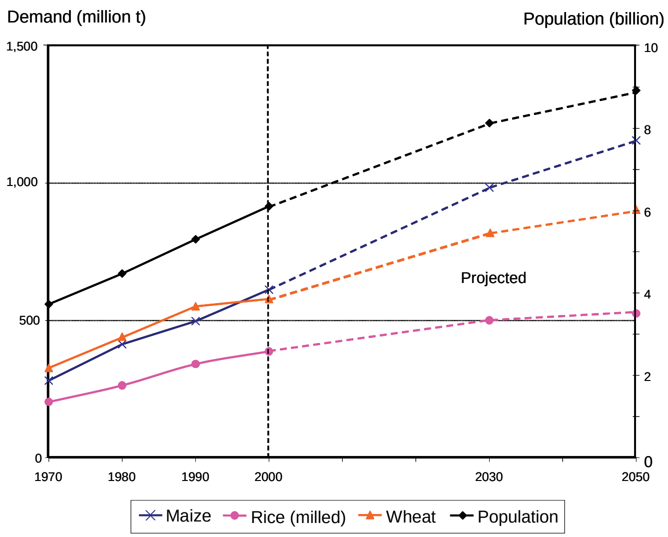


Fig. 1. World demand for wheat, maize, and rice, 1970-2050.
Sources: Dixon et al (2009); FAO (2006).

and expansion of maize cultivation into lands not currently farmed. The irrigated and favorable rainfed lowlands are of particular importance because of their high potential for sustainable intensification and diversification.

Historical and projected prices of cereals

Between 1970 and 2000, real international prices of wheat, rice, and maize declined by 47%, 59%, and 61%, respectively (Rosegrant et al 2002). FAO data on long-term international prices of rice, wheat, and maize showed these to be highest in the mid-1970s and early to mid-1990s. They started to decline in the mid-1990s and were lowest around 2000. The prices started to rise again in 2000 and were highest in 2007-08 (Annex Table F.1 and Annex Figs. F.1-F.4). Between 2001 and 2008, the international prices of rice, wheat, and maize rose by 143%, 209%, and 139%, respectively. The prices of all cereals rose drastically in the first quarter of 2008. The international price of rice decreased from around \$360 t^{-1} (1994) to around \$173 t^{-1} (2001), then again drastically increased to around \$1,000 t^{-1} in April 2008 (Normile 2008). Wheat and maize prices have fluctuated over the years, always remaining much lower (\$89–165 t^{-1} for maize and \$111–207 t^{-1} for wheat) than the price of rice (\$173–950 t^{-1}). Producer (or farm-gate) prices followed a similar trend but these were much lower than international prices. Producer prices of rice in all countries were highest in the mid-1990s and have decreased since then. Over the same period, the N price decreased from \$460 t^{-1} in 1995 to \$169 t^{-1} in 1999 but increased thereafter to \$760 t^{-1} in 2008.

Recent projections by FAPRI for 2017-18, based on 2007-08 prices, indicate a sharp decline in wheat price, a steady or small decline in maize price, and an increase in rice price (FAPRI 2008; www.fapri.iastate.edu/brfbk08). However, projections by OCED-FAO, also based on 2007-08 prices, indicate a steady decline in the prices of all cereals in 2016-17 (OECD/FAO 2007; www.oecd.org/dataoecd/6/10/38893266.pdf). These projections (Annex Table G.1) are based on assumptions regarding demand and supply of commodities, population growth, and other factors. Considering the recent dramatic increases in prices of these cereals, there is some doubt whether these projections will follow real-world prices in the future.

Drivers and issues for R-M systems

Currently, many intensively cultivated rice lands in South and Southeast Asia are undergoing a transition that involves diversification toward new cropping practices and rotations including R-M or intensification toward triple-cropping systems that include maize. The key drivers for this transition are new market opportunities for farmers due to rapidly rising demand for maize as livestock feed and biofuel; a decline in available irrigation water; pest outbreaks in intensive continuous rice systems; and a rapidly expanding agribusiness sector associated with maize seed markets, other production inputs, and processing and marketing of maize products (feed and biofuel).

There exist key cross-cutting issues on R-M systems in Asia. Two issues are of strategic importance and the other two relate to partnership and delivery of R-M technologies. One concern is the rapid expansion of R-M systems in some countries despite insufficient understanding of their biophysical and socioeconomic potential, constraints, and risks. Another issue is the uncertainty about long-term performance and sustainability of R-M systems, particularly with regard to their impact on soil quality, ecological resilience, and global warming potential from agriculture. In all Asian countries, the dominance of commodity-specific research, lack of R&D support for system-level research, and insufficient partnerships at the an international level and within countries are concerns that need to be addressed. Likewise, in all countries, the private sector and NGOs have a large role in the expansion of R-M systems and dissemination of knowledge and new technologies.

Current area under rice, maize, and R-M systems

R-M systems currently occupy more than 3 million ha in Asia (Table 1). They are, however, rapidly spreading, driven by the rising demand for maize and the tightening world export-import markets. The recent development of short-duration rice varieties and maize hybrids with improved drought tolerance is also giving rise to opportunities for the expansion of R-M systems into areas of South and Southeast Asia with insufficient irrigation or rain for continuous rice cultivation.

Agroecologically, R-M systems have the potential to expand into broad climatic zones across Asia. Because there are strong economic multipliers between food production and feed and livestock production, more diversified cropping systems are also likely to become a key engine for economic growth in rural areas. This will

Table 1. Areas currently under R-M systems in Asia.

Country	Area (million ha)		
	Rice	Maize	R-M
Philippines	4.2	2.6	0.12
Indonesia	11.8	3.5	1.55
Vietnam	7.3	1.1	0.32
China	29.1	26.4	Not available
Thailand	10.0	1.1	0.04
India	43.4	7.8	0.53
Bangladesh	10.5	0.4	0.35
Nepal	1.6	0.9	0.43
Total	117.9	43.8	3.34 (exc. China)

Sources: Government statistics and authors' personal observations.

contribute to more diversified diets, improved human nutrition, reduced poverty, and greater investment in other aspects related to quality of life such as education and health care. R-M systems will also provide new business opportunities for the local agribusiness sector, including hybrid seed production and marketing, the fertilizer sector, the agricultural machinery sector, and the grain marketing and livestock feed-processing sector. Thus, more productive and profitable R-M systems have the potential to meet the UN's MDG 1 (halving poverty by 2015) in many R-M-growing countries through R-M system-led economic growth and through improved nutrition. In low-income countries in Asia, economic growth results in increased employment and rising wages, enabling the poor to meet their needs satisfactorily. Such income growth through improved R-M systems can also contribute to other MDGs such as reduced child mortality (MDG 4) and improved maternal health (MDG 5).

IRRI-CIMMYT alliance on IPSA

Recognizing the importance of diversifying cropping systems in Asia and the need for system-level research to support new opportunities for agricultural development, IRRI and CIMMYT in 2005 formed a joint project on Intensive Production Systems in Asia (IPSA). Consultations with national agricultural research and extension system (NARES) partners from Asia during an IPSA workshop at IRRI in December 2006 led to a regional initiative with a focus on R-M systems and five mutually agreed-upon outputs: (1) strategic assessment of R-M systems; (2) improved germplasm for R-M systems; (3) local solutions for best management practices (BMPs) for R-M systems; (4) assessment of productivity, profitability, sustainability, and environmental impact of R-M systems; and (5) new models for information sharing and technology dissemination, including innovative public-/private-sector partnerships.

IPSA has established partnerships with NARES in South and Southeast Asia and is involved in regional public-/private-sector-supported initiatives for research and technology dissemination. Examples are the Irrigated Rice Research Consortium (IRRC) coordinated by IRRI; the Cereal Knowledge Bank jointly developed and managed by IRRI and CIMMYT; and a regional project on site-specific nutrient management (SSNM) for maize in Indonesia, the Philippines, and Vietnam coordinated by the Southeast Asia Program (SEAP) of the International Plant Nutrition Institute (IPNI) and the International Potash Institute (IPI) based previously in Singapore, and now in Penang, Malaysia. IRRI and CIMMYT scientists, in collaboration with NARES partners, have begun work on R-M systems in selected countries of Asia.

As a result of this alliance, IRRI and CIMMYT, along with NARES, the private sector, and NGO partners in South, Southeast, and East Asia, have begun implementing joint research and delivery activities on R-M systems. In the beginning, it was thought that IPSA would provide the regional umbrella framework for strategic research, technical support to national R-M projects, collaboration, and synthesis across the region (Fig. 2). It was also agreed that IRRI, CIMMYT, and other international partners would primarily focus their resources on research thrusts 1, 2, and 4 but would also provide technical assistance and support for all activities in national projects. It was

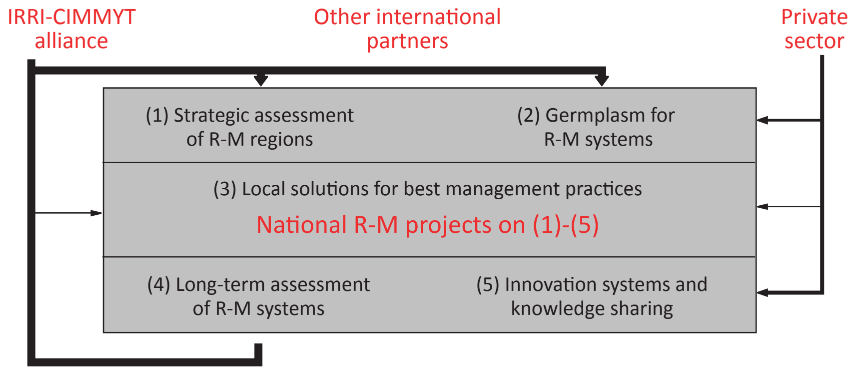


Fig. 2. Proposed research program structure for IPSA.

also conceived that the national R-M projects would primarily focus on local solutions for BMPs (3) and delivery of new information and technologies at the national level (5). Collaboration with the private sector would be sought to support research and extension activities on maize germplasm improvement (2), local solutions for BMPs (3), and dissemination of new technologies and knowledge (5). Collaboration with other advanced research institutions would concentrate on specific areas of technical expertise needed (e.g., remote sensing, agroecosystem modeling, and land-use analysis). However, 4 years after the formation of this alliance, IRRI, CIMMYT, and other international centers decided to form a larger initiative, the Cereal Systems Initiative for South Asia (CSISA) (see below). The CG centers realized that IPSA and other similar alliances or consortia should come under the overall umbrella of CSISA. As a result, beginning in 2009, R-M activities under IPSA were implemented under CSISA auspices.

CSISA: an initiative for intensive cereal systems in South Asia

Given the persistence of massive poverty in South Asia, IRRI, CIMMYT, IFPRI, and ILRI jointly developed and are currently implementing CSISA, a project funded by the Gates Foundation and USAID. The project provides an overall strategy and a new umbrella for contributing new science and technologies to accelerate short- and long-term cereal production growth in South Asia's most important grain baskets. It builds on technologies developed and lessons learned from the Rice-Wheat Consortium (RWC) implemented in Bangladesh, India, Nepal, and Pakistan, the IRRC, the IPSA, and many other investments in agricultural R&D by both the public and private sectors. Through creating and facilitating innovative and effective public-/private-sector partnerships in key "hubs," the project would enable the deployment of existing varieties, hybrids, crop management technologies, and market information. CSISA will initially concentrate on four geographical regions with intensive cereal systems: the western IGP (Haryana, Punjab, and western Uttar Pradesh (UP) in India, and Punjab and Sindh in Pakistan); the central Gangetic Plains (central and eastern UP and Bihar in India, and Terai in Nepal); the eastern Gangetic Plains (West Bengal and Bangladesh); and subtropical southern India (Karnataka, Tamil Nadu, and Andhra Pradesh). It would expand activities beyond the IGP as more resources become available and as public-private partnerships start to develop. The initial nine hubs selected from four South Asian countries for CSISA also include sites selected for strategic assessment of R-M systems under the IPSA project presented in this publication. There is thus an overlap of sites and activities between IPSA and CSISA. It is envisioned that the RWC will also come under the umbrella of CSISA.

Strategic assessment of R-M systems

A strategic assessment of R-M systems is one of the five agreed-upon outputs of the IPSA project. This publication contains information on the strategic assessment of R-M systems for selected environments across nine countries in Asia. The process primarily involves regional-and site-level biophysical assessment, supported by some socioeconomic assessment using macroeconomic data at the regional level and some microeconomic data at the site level. Biophysical assessment includes agroecosystem characterization of R-M systems; analysis of historical daily climatic data (rainfall, maximum and minimum temperature, and solar radiation); regional-level prediction of yield potential (Yp) for 29 sites across the nine countries; and a detailed analysis of a few selected sites to understand current cropping systems, identify alternative potential systems, and optimize these, considering Yp and prevailing biophysical constraints. Site-level socioeconomic information is also used for such assessment, whenever this information is available.

Methodology

Acquisition of climate data

Daily data for maximum and minimum temperature, solar radiation, and rainfall for 29 locations in nine countries of Asia were downloaded via the Internet from the National Aeronautics and Space Administration (NASA)/Prediction of Worldwide Energy Resource Radiation (POWER) site (http://earth-www.larc.nasa.gov/n Power/) (Stackhouse 2006). The NASA/POWER project at the NASA Langley Research Center provides daily data for main climate variables on 1° latitude by 1° longitude grid cells for the entire globe. For maximum and minimum temperature and solar radiation, NASA provides data from 1983; rainfall data are available from 1997 only. The POWER/Surface Meteorology and Solar Energy (SSE) ver. 6.0 (http://power.larc.nasa.gov) (SSE 6.0) contains more than 200 primary and derived solar-, meteorology-, and cloud-related parameters. All solar and meteorological values in POWER/SSE Release 6.0 represent the average over 1° grid cells from data spanning a 22-year period (1983 to 2005). The solar- and cloud-related data are derived from the Surface Radiation Budget (SRB) portion of NASA's Global Energy and Water Cycle Experiment (GEWEX). The current SRB archive is Release 3.0 (http://eosweb.larc.nasa.gov/PRODOCS/srb/table_srb.html). The temperature data are derived from NASA's Global Model and Assimilation Office (GMAO) Goddard Earth Observing System model ver. 4 (GEOS-4) (Bloom et al 2005). The precipitation parameters are derived from the Global Precipitation Climate Project (GPCP—http://precip.gsfc.nasa.gov) and the Tropical Rainfall Measurement Mission (TRMM). The wind data are based on the NASA/GMAO GEOS ver. 1 (GEOS-1). More detailed descriptions of SRB, GEOS-4, and GPCP/TRMM can be downloaded from NASA's online Web sites (http://eosweb.larc.nasa.gov/PRODOCS/srb/table_srb.html, http://gmao.gsfc.nasa.gov/index.php, http://precip.gsfc.nasa.gov, and http://disc.sci.gsfc.nasa.gov/precipitation). For all 29 locations, we downloaded the solar radiation and maximum and minimum temperature data from 1 July 1983 to 31 December 2004, whereas those for rainfall covered the period 1 July 1997 to 31 December 2004. For some locations, we also had long-range actual historical daily rainfall data and, for these, we used actual data as well as NASA-derived data to predict yield potential (Yp) of rice and maize. The long-range weather data provide better estimates of long-term trends of Yp than the short-range data.

Based on the downloaded NASA weather data, we prepared Box diagrams for weekly total rainfall and weekly average maximum and minimum temperature and solar radiation. For each location, we then prepared a combined climate figure showing the weekly variability in total rainfall, weekly mean minimum and maximum temperature, and weekly mean daily incident solar radiation. The Box diagrams show weekly variability in climate variables over the years, giving median values together with 10th, 25th, 75th, and 90th percentiles as vertical boxes with error bars and closed symbols as extreme values. The combined climate figures for each location were then used for regional-level analysis of Yp as well as for optimization of potential cropping systems at representative locations across Asia.

Characterization and classification of R-M agroecosystems

The 29 locations in the nine countries selected for strategic assessment of R-M systems were first characterized in terms of geographic location (latitude, longitude, and elevation), climate, soil, season, and current and emerging cropping systems. Then, the sites were put into major agroecosystem classes based on moisture regime and mean temperature during the growing season.

Evaluation of NASA weather data

NASA data have been validated against field-measured data for all weather parameters and variables (see http://power.larc.nasa.gov/common/MethodologySSE6/POWER_Methodology_Content.html for details; White et al 2008 and Bai et al 2010 for several sites in the U.S.). Solar radiation parameters in SRB Release 3.0 and subsequently in POWER/SSE ver. 6.0 have been validated against observations from the Baseline Surface Radiation Network (BSRN), while meteorological parameters have been compared against data from the National Climate Data Center (NCDC; www.ncdc.noaa.gov/oa/ncdc.html). The total (i.e., diffuse plus direct) surface insulation observed at ground sites in the BSRN network (above and below 60° latitude, north and south) has been compared with insulation values from the SRB Release 3.0 archive. In particular, the GEOS-4 temperature, relative humidity, and surface pressure have been explicitly compared against global data obtained from NCDC global "Summary of the Day" (gsod) files and against observations from other high-quality networks such as Surface Radiation (SURFRAD—www.srrb.noaa.gov/surfrad/index.html) and Atmospheric Radiation Measurement (ARM—www.arm.gov/), as well as observations from automated weather data networks such as the High Plains Regional Climate Center (HPRCC—www.hprcc.unl.edu/index.php). All air temperature validations have used ground observations at an elevation of 2 m above Earth's surface.

Daily precipitation values obtained from the SSE Release 6.0 archive for a 1° cell were compared with measurements made at ground sites within the same 1° cell globally and for average rainfall over the continental United States (CONUS); the rainfall values were compared against NCDC ground sites within the CONUS. In general, precipitation often tends to be a rather localized and short-duration event. Consequently, accurately capturing the amount of precipitation, even in terms of mean daily amounts from satellite observation, becomes challenging. The precipitation data in SSE 6.0 results are GPCP 1-degree daily mean values augmented with TRMM observations to fill in missing values in the GPCP data. Three ground sites in Louisiana, U.S., all within a 1° grid cell bounded by 32 N and 31 S latitudes and by 92 E and 93 W longitudes, were also used for daily mean precipitation data measurements over a 9-year period beginning in 1997, and they have been compared against daily mean values available from the POWER/SSE Release 6.0.

In this study, to demonstrate the usefulness of NASA-derived data, daily weather data for 1998 at Los Baños, Laguna, Philippines (tropical climate) and for 2000 at Ludhiana, Punjab, India (subtropical climate) were compared against NASA data for the same years. The daily historical measured and NASA-derived data for several locations and countries in Asia were also compared. The data ranged from hot and humid tropical Philippines and southern Vietnam to mild cool subtropical Bangladesh and to severe cold subtropical to warm temperate Changsa in China. Sites with maximum and minimum temperature and solar radiation data included Bogra (1984-2002), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Changsa (1990-2000) in China; Ludhiana (1984-2004) and Begusarai (1984-2004) in India; Central Lampung (2000-04) and Maros (1990-2004) in Indonesia; Los Baños (1984-2004) and Muñoz (1994-2001) in the Philippines; and An Giang (1999-2004) and Vin Phuc (1992-2002) in Vietnam. All sites were compared with NASA rainfall data from 1997 only. Following that, simulated potential grain yield and growth duration of maize and rice using NASA-derived and ground-measured data for several locations in South and Southeast Asia were compared. Weather data were used for simulations at selected sites: Bogra (1984-2004), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Maros (1990-2004) in Indonesia; Muñoz (1994-2001) and Los Baños (1984-2004) in the Philippines; and An Giang (1999-2004) and Vin Phuc (1992-2002) in Vietnam. For maize, the hybrid maturity group ranging from 1,400 to 1,800 GDD and, for rice, extra short, short, intermediate, and long maturity groups were simulated. The Weather Aid Utility in Hybrid Maize (Yang et al 2004) allows downloading the NASA weather data in Hybrid Maize format. For use by ORYZA 2000 (Bouman et al 2001), some processing was necessary. The observed weather data consisted of several missing data, so careful checking and appropriate interpolation techniques were necessary to fill in the missing data.

Evaluation of crop simulation models

Our study aimed to explore the Yp of rice and maize across many locations in Asia. To attain this objective, we chose four generic varieties of rice and four generic hybrids of maize. We wanted to parameterize the varieties and hybrids with as few parameters as possible and use simple simulation models to estimate the Yp of rice and maize. In some cases where wheat and soybean are grown in cropping systems, their Yp was also predicted using the DSSAT-wheat (Hoogenboom et al 2004) and CROPGRO-soybean (Boote et al 1997, 1998) models. Yield potentials assume no limitations of water, nutrients, and pests and diseases and no soil-related constraints. Yields are dictated by climatic and genetic factors only. Simulations for Yp used at least 20 years of solar radiation, and maximum and minimum temperature data. NASA weather data for rainfall are available from 1997 only; so, for sites where long-term historical rainfall data were not available, yield estimations under water-limited production were based on 10-year weather data only.

ORYZA2000

Calibration. To calibrate ORYZA2000, a variety under use in a particular location requires the determination of appropriate genetic coefficients. In this study, for each location, rice varieties of four growth durations based on the tropical climate of Los Baños, Philippines, were chosen: extra short (80–90 d), short (90–100 d), intermediate (105–115 d), and long (125–140 d). The extra short-, short-, and long-duration varieties were created by calibrating the development rate during the juvenile phase (DVRJ), development rate during the photoperiod-sensitive phase (DVRI), development rate during the panicle development phase (DVRP), and development rate during the reproductive phase (DVRR) coefficients used in the model. Coefficients for an intermediate maturity type (e.g., for IR72) were adapted from Bouman et al (2001). The values for these coefficients and chilling injury-related parameters (lower air temperature threshold for growth, °C—COLDMIN; consecutive number of days below COLDMIN when crop dies—COLDDEAD) determined for four varieties at different sites after calibration are given in Table 2. All other parameters and coefficients for all varieties remained the same as those used for IR72 in ORYZA2000. For predictions under water- and N-limited situations, more parameters would need to be calibrated (Bouman et al 2001).

Validation. Model processes, parameters, and coefficients used in ORYZA2000 have been well documented (Bouman et al 2001). The model has been validated widely in field experiments using modern high-yielding varieties in the tropics, subtropics, and temperate areas. Bouman and van Laar (2006), Kropff et al (1994a, b), Matthews et al (1995), and Jing et al (2007) have presented validation results for potential production. All these studies reported a good match between simulated yields predicted by ORYZA2000 and yields measured in well-managed experiments without any limitations of yield-limiting factors (water, N, and other nutrients) and with ample control of yield-reducing factors (insects, diseases, and weeds). Our study did not aim to further validate the model. Bouman et al (2001) conclude that, under a potential production situation, the model is expected to perform well for different varieties and under different environments if proper calibration is performed.

Hybrid Maize

Calibration. Processes, parameters, and coefficients used in Hybrid Maize are described in detail elsewhere (Yang et al 2004). Briefly stated, the model uses a growing degree day (GDD 10 °C) of 15 for germination and a GDD of 6 for emergence per centimeter depth. The maximum number of days for plants to emerge is set at 25. The lower temperature threshold (°C) at which assimilation stops is set at 8, while the lower and upper thresholds of the optimum temperature range for maximum photosynthesis are 18 and 30 °C, respectively. In our study, we chose four hybrid maturity groups ranging from 1,300 to 1,800 GDD at each site. A generic seed brand hybrid was chosen from within the Hybrid Maize software. No other modifications in the model processes were made, and all default parameters/coefficients were used. Simulations were carried out for maize planted with a plant population of 70,000 ha^{-1} sown at 3-cm depth. To estimate Yp, the model was run under the Potential Production Mode, while for yields

Table 2. Development rate coefficients and chilling injury parameters for four rice varieties used for running ORYZA2000 in different environments in Asia.[a]

Variety	DVRJ	DVRI	DVRP	DVRR	COLDMIN	COLDDEAD	Countries and sites
Extra short	0.000883	0.00758	0.0014	0.0026	12	5	All sites in Bangladesh, China, Indonesia, Philippines, Thailand, and Vietnam; India (Aduthurai, Bangalore, Nalgonda, Begusarai)
Short	0.000783	0.00758	0.0010	0.0023	12	5	
Intermediate	0.000683	0.00758	0.000749	0.0019	12	5	
Late	0.000583	0.00758	0.000549	0.0016	12	5	
Extra short	0.001283	0.00758	0.0014	0.0026	12	5	Nepal (Chitwan), India (Punjab) Pakistan (Larkana, Okara)
Short	0.001083	0.00758	0.0014	0.0026	12	5	
Intermediate	0.000983	0.00758	0.0010	0.0023	12	5	
Late	0.000883	0.00758	0.000749	0.0019	12	5	

[a]DVRJ = development rate in juvenile phase (°Cd), DVRI = development rate in photoperiod-sensitive phase (°Cd), DVRP = development rate in panicle development phase (°Cd), DVRR = development rate in reproductive phase (°Cd); COLDMIN = lower air temperature threshold for growth (°C); for Thanh Hoa and Vinh Phuc in Vietnam, the values are 10 and 8, respectively; for four sites in China, it is 8. COLDDEAD = consecutive number of days below COLDMIN when the crop dies; increased to 5 from the original value of 3 reported in ORYZA2000 (Bouman et al 2001).

under water-limited situations and for the calculation of irrigation water requirements, the Water-limited Production Mode was chosen. All simulations were conducted using Long-term Run Simulation Mode.

Validation. Hybrid Maize has been evaluated under Potential Production Mode using field experimental data from well-managed experiments in north-central U.S. (Yang et al 2004) and its applications have also been well demonstrated (Yang et al 2006). The model is being extensively used to estimate Yp and perform yield gap analyses at various locations in Indonesia, the Philippines, and Vietnam under the International Plant Nutrition Institute (IPNI) project on "Site-specific nutrient management for maize in Southeast Asia" (Witt et al 2008). Considering the satisfactory performance of the model across environments in the U.S. and Southeast Asia, we did not attempt to validate the model here.

CROPGRO and CERES-Wheat

For cropping systems involving soybean, the DSSAT-CSM-CROPGRO-Soybean V4.2 model (Boote et al 1998, Hoogenboom et al 2004) was used and, for those involving wheat, DSSAT-CSM-CERES-Wheat V4.2 (Hoogenboom et al 2004) was applied. For both soybean and wheat, the most commonly used cultivar (or cultivar group) in a given location was chosen, its genetic coefficients derived, and the models calibrated. These models have already been extensively evaluated and applied in many Asian field environments (Boote et al 1997, Timsina and Humphreys 2006a,b).

Regional-level analysis of yield potential

Successful intensification of cropping systems requires the selection of suitable crop varieties and hybrids of varying maturities with acceptable Yp. Depending on the local climate, soil, water resources, available technologies, and prevailing socioeconomic conditions, farmers may choose varieties and hybrids from a range of maturity types and sow them on optimum planting dates. Knowing the Yp over the entire year allows one to choose appropriate hybrids and varieties and suitable planting dates to fit into the local crop calendars. Rice Yp for four generic varieties and maize Yp for four hybrid maturities with seed sowing on the first day of each month were determined for each location in each country using the ORYZA2000 and Hybrid Maize models, respectively. Because of differences in climate, the range of GDDs for different hybrids varied from 1,300 to 1,800 across locations in the different R-M agroecosystems. For each location, we chose four hybrids with the four most appropriate GDDs, representing the best range of hybrids for a particular location. The choice of 29 locations allowed us to compare Yp across locations as well as to understand Yp variability across the different agroecosystems.

Detailed analysis of selected sites

Yield potential

In addition to estimating Yp for monthly planting dates needed for regional analysis, Yp for critical planting windows for current and potential key cropping systems was also assessed for detailed analysis of the selected sites. The Yp values of cropping systems involving soybean and/or wheat were also evaluated. One such detailed analysis was carried out for An Giang in southern Vietnam. For that site, Yp at fortnightly intervals for maize and rice crops to determine critical planting windows for key cropping systems such as rice-rice-rice (R-R-R) and rice-maize-rice (R-M-R) was also estimated. The additional planting dates for the three rice planting seasons for which simulations were conducted were 16 February, 16 March, 16 June, 16 July, 16 November, and 16 December. For maize, Yp for 16 November, 16 December, and 16 January for the first maize crop in the potential maize-rice-rice (M-R-R) and maize-maize-rice (M-M-R) systems, and Yp for 16 February and 16 March for the second maize crop for the R-M-R and M-M-R systems were also simulated. The Yp of an early-maturing soybean variety was simulated for six planting dates at monthly intervals (1 September to 1 April) for M-R-R and R-M-R systems using the CROPGRO-Soybean model (Boote et al 1998). After calibrating for various maturity groups of soybean, maturity group 10 was finally chosen but with some modifications for some coefficients. Critical short day length (CSDL) was increased from 11.78 to 12.33 h, time from emergence to flowering (R1) (EM-FL) from 23.5 to 29.5 photo thermal days (pd), time from R1 to first seed formation (R5) (FL-SD) from 16 to 17 pd, and time from R5 to physiological maturity (R7) (SD-PM) from 37.4 to 39.4 pd. These calibrations were essential to create varieties that fit into existing cropping systems.

Current and potential cropping systems and system optimization

In each selected location for detailed strategic assessment, the current main rice-based cropping systems and the main biophysical and socioeconomic constraints were first identified. Subsequently, based on this information, potential cropping systems involving maize in rice-based systems and biophysical and socioeconomic constraints were identified and proposed as interventions. Some of the potential systems are already well established, are emerging in many locations, or have great potential for successful intervention and expansion. In most locations, the main crop of rice is grown during the monsoon or wet season and the crop either normally receives enough rainfall or requires only some supplemental irrigation. Hence, we did not estimate the irrigation water requirement for rice; rather, we estimated this for maize using Hybrid Maize. An estimation of irrigation requirement for maize becomes necessary because it is grown either in the rabi season in South Asia or in the dry season in Southeast Asia, and it thus requires supplemental irrigation through surface-water or groundwater sources. Finally, cropping systems were optimized considering the growth duration of the crop cultivar, the irrigation potential, the probability of occurrence of seasonal rainfall and waterlogging, and temperature extremes. Information on typhoons and cyclones, if available, were also considered for system optimization.

Socioeconomic analysis

Village- or site-level socioeconomic information were used whenever they were available. Most of these information were obtained through a set of questionnaires sent to one or two research teams (with biophysical and socioeconomic expertise) in each location. Gathered were data on household- and village-level resources, farming systems, inputs and outputs together with prices or costs, socioeconomic and biophysical constraints to production, processing and marketing, and the current situation, as well as potential for expansion of R-M systems.

Analysis of macro data

Macro-level data reflecting economic and development indicators and historical trends in production, consumption, and trade of rice, maize, livestock, and livestock products, and prices of rice, maize, and wheat were obtained from various sources (FAO, UN, World Bank, IFPRI, FAPRI). The drivers for change in rice-based cropping systems are dependent on the dynamics of production, consumption, and trade of these three crops across South and Southeast Asian countries. Macro data for wheat were included, together with those for rice and maize, wherever wheat was regarded as an important crop.

Results

Characterization of R-M agroecosystems

The general characteristics of the 29 sites selected for strategic assessment of the R-M systems are presented in Table 3. The sites range in latitude from 7.8° south (Kediri, East Java) to 32.26° north (Yangzhou, Jiangsu), and in elevation from close to mean sea level (MSL) (An Giang, Vietnam; Aduthurai and Thanjavur, India; Maros, Indonesia) to 1,450 m (Dhankuta, Nepal) (Fig. 3). The climate ranges from humid tropical monsoon in Southeast Asia to subtropical cool winter in the Indo-Gangetic Plains of South Asia and Red River Delta in northern Vietnam, to subtropical to warm temperate with severe cold winter in China. Soils range from sandy and silty loam in Bangladesh, Nepal, and the Indian and Pakistan Punjab to light to heavy clay in other countries. Seasons are named differently in different countries. For example, in the Philippines, Thailand, and Indonesia, they are called wet and dry seasons; in Vietnam and China, they are referred to as spring, summer, and winter seasons. In South Asia, they are classified as prekharif or kharif I or premonsoon (spring), kharif or kharif II or monsoon (summer), and rabi (winter). Current annual rice-based cropping systems comprise one to three crops per year with either one or two crops of rice, maize, wheat, and other crops. In all locations, cropping systems involving maize are either expanding or emerging.

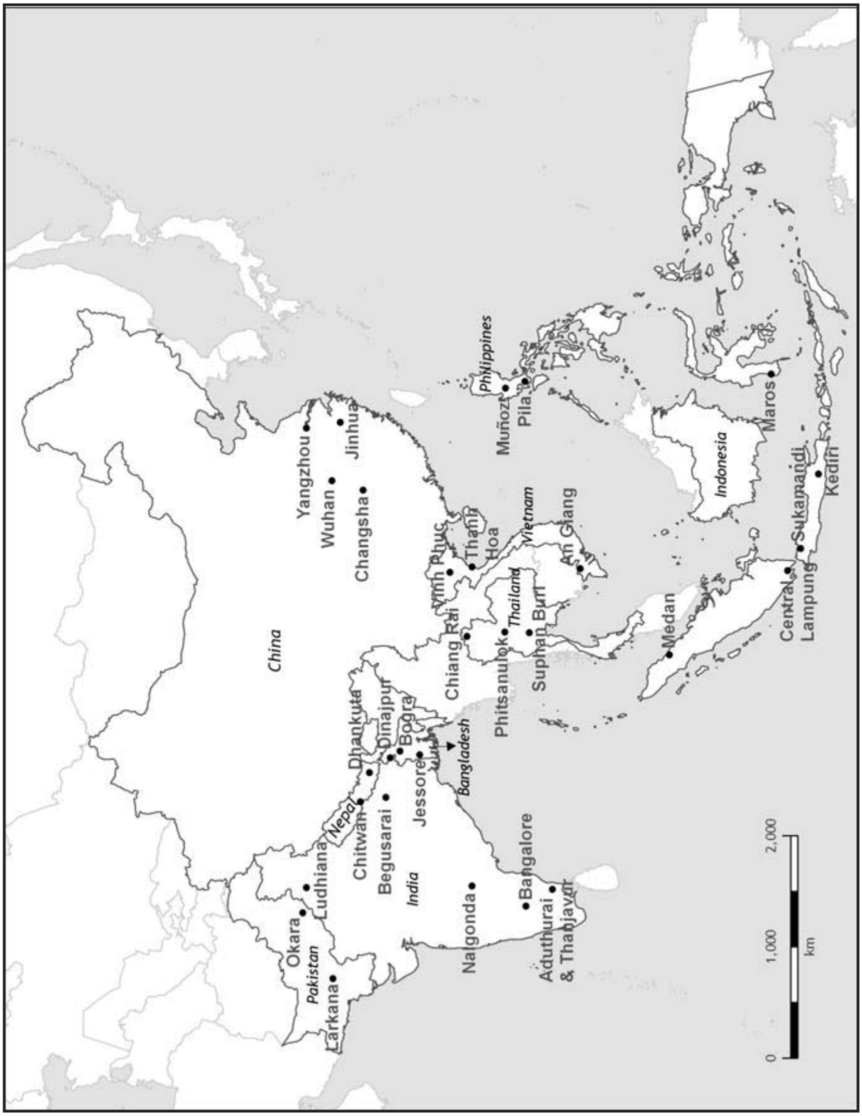


Fig. 3. Countries and sites selected for the strategic assessment of R-M systems in Asia.

Table 3. General characteristics of sites selected for strategic assessment of R-M systems.

Country	Location	Geography			Climate	Soil	Seasons	Current systems	Emerging systems
		Latitude	Longitude	Elevation (m)					
Philippines	Pila, Laguna	14.11°N	121.15°E	21	Humid tropical monsoonal	Heavy clay	Wet (Jun/Jul-Oct/ Nov); dry (Dec-Mar/Apr)	Rice-rice (R-R), rice-fallow (R-F), rice-vegetables (R-V), rice-watermelon (R-WM)	Rice-maize (R-M), rice-maize-rice (M-R)
	Muñoz, Nueva Ecija	15.75°N	120.8°E	66	Humid tropical monsoonal	Heavy clay	Wet (Jul-Oct); dry (Dec-Apr)	R-R, R-F, R-V, R-M	R-M, M-R
Indonesia	Sukamandi, West Java	6.3°S	106.67°E	41	Humid semi-hot equatorial	Clay	Wet (Nov-Mar); dry (May-Aug)	R-R, rice-secondary crops (R-SC)	R-M, R-R-M
	Kediri, East Java	7.8°S	112°E	290	Humid, semi-hot equatorial	Clay		Rice-rice-vegetables (R-R-V), rice-maize-maize (R-M-M), rice-rice-maize (R-R-M)	R-R-M, R-M-M
	Medan, North Sumatra	3.6°N	98.7°E	50	Humid semi-hot equatorial	Clay	Wet (Aug/Sep-Jan/ Feb); dry (Feb/Mar-Jun/ Jul)	R-R, R-M, rice-rice-mungbean (R-R-B), R-R-M, rice-rice-soybean (R-R-SB)	R-M, R-R-M
	Central Lampung	5.3°S	105.1°E	90	Humid semi-hot equatorial	Clay	Wet (Sep/ Oct-Apr/ May); dry (May/ Jun-Aug/Sep)	R-R, R-M, R-R-MB, R-R-M, R-R-SB	R-M, R-R-M

Country	Location	Geography			Climate	Soil	Seasons	Current systems	Emerging systems
		Latitude	Longitude	Elevation (m)					
	Maros, South Sulawesi	5.0°S	119.5°E	5	Humid, semi-hot equatorial	Clay	Wet (Oct-Mar); dry (Jun-Sep)	R-R, R-F, rice-mungbean (R-MB)	R-M
Vietnam	An Giang, South Vietnam	10.7°N	105.5°E	1.0	Tropical monsoonal	Sandy loam	Dry (Nov/Dec-Feb/ Mar); early wet (Mar/Apr-Jun); late wet (Jun-Sep)	R-R-R	
	Thanh Hoa, north-central Vietnam	19.5°N	105.8°E	7.0	Subtropical, cold winter, hot and humid summer	Sandy loam	Spring (Feb-Jun); summer (Jun-Sep); winter (Oct-Jan)	R-R	R-R-M
	Vinh Phuc, North Vietnam	21.32°N	105.36°E	9.9	Subtropical, cold winter, hot and humid summer	Clay loam (degraded)	Spring (Feb-Jun); summer (Jun-Sep); winter (Oct-Jan)	R-R, R-R-M, R-R-SB, R-R-V, rice-rice-sweet potato (R-R-SP)	R-R-M
China	Changsha, Hunan	28.12°N	113.05°E	44.9	Subtropical, cold winter	Clay loam to silty clay	Summer (Apr-Oct); winter (Nov-Mar); cooler winter	Early rice-late rice (ER-LR), late rice- fallow (LR-F)	R-M
	Wuhan, Hubei	30.6°N	114.1°E	23	Subtropical, cold winter	Clay loam to silty clay	Summer (Apr-Oct); winter (Nov-Mar); cooler winter	ER-LR, LR-F	R-M
	Yangzhou, Jiangsu	32.26°N	119.26°E	12	Subtropical to warm temperate, severe cold winter	Clay loam to silty clay	Summer (May-Aug); winter (Sep-Apr); cooler winter	ER-LR, late rice-winter crops (LR-WC)	R-M, M-R

Country	Location	Geography			Climate	Soil	Seasons	Current systems	Emerging systems
		Latitude	Longitude	Elevation (m)					
Thailand	Phitsanulok, Muang Dist.	16.8°N	100.24°E	44	Tropical	Loamy clay to clay	Early wet (Apr-Jun); wet (Jul-Oct); dry (Nov-Feb)	R-R	R-M
	Suphan Buri, Central Plain	14.8°N	100.2°E	9	Tropical, warm and humid	Clayey	Early wet (Apr-Jun); wet (Jul-Oct); dry (Nov-Mar)	R-R, R-R-R	R-M, R-R-M
	Chiang Rai, North	19.9°N	99.8°E	384	Tropical	Loamy clay to clay	Early wet (Apr-Jun); wet (Jul-Oct); dry (Nov-Mar)	R-R	R-M
India	Aduthurai and Thanjavur, Tamil Nadu	11.1°N	79.29°E	2	Humid tropical, northeast monsoon	Ad: clay loam to clay, Th: sandy loam to clay loam	Kuruvai or dry (Jun-Sep), thaladi or rainy (Oct-Feb), summer (Mar-May)	R-R, rice-rice-pulses (R-R-Pu), rice-rice-sesame (R-R-S), rice-rice-cotton (R-R-C)	R-M, R-R-M
	Nalgonda, Andhra Pradesh	17.6°N	78.5°E	489	Tropical, semiarid, southwest monsoon	Clay	Dry (Nov-Apr); wet (May-Oct)	R-R, R-M, rice-pulses (R-Pu), rice-mustard (R-Mu)	R-M
	Bangalore, Karnataka	12.98°N	77.58°E	913	Tropical, semi-arid, monsoon	Clay	Dry (Nov-Apr); wet (May-Oct)	R-R, R-M, R-Pu, R-V	R-M
	Begusarai , Bihar	25.6°N	85.1°E	49	Subtropical, monsoonal, cold winter	Clay	Hot summer (Mar-Oct); cool winter (Nov-Feb)	Rice-wheat (R-W), rice-boro rice, R-Pu, R-F	R-M

Country	Location	Geography			Climate	Soil	Seasons	Current systems	Emerging systems
		Latitude	Longitude	Elevation (m)					
	Ludhiana, Punjab	30.9°N	75.8°E	247	Subtropical monsoonal, cold winter	Sandy loam, loamy sand	Hot summer (Apr-Sept); cool winter (Oct-Mar)	R-W	Rice-potato-maize, rice-wheat-maize
Bangladesh	Bogra, central	24.85°N	89.37°E	23	Tropical, warm/cool winter	Sandy loam, silty loam	Hot summer (Mar-Oct), cool winter (Nov-Feb)	T. aman rice-boro rice (TR-BR), T. aman rice-wheat (TR-W), maize-T. aman rice (M-TR), potato-maize-T. aman (P-M-TR), maize-jute-T. aman (M-J-TR)	TR-M, M-TR, P-M-TR, M-J-TR
	Jessore, west-central	23.2°N	89.2°E	7	Tropical, warm/cool winter	Sandy loam, silty loam	Hot summer (Mar-Oct), cool winter (Nov-Feb)	TR-BR, TR-W, M-TR, P-M-TR, M-J-TR	TR-M, M-TR, P-M-TR, M-J-TR
	Dinajpur, northwest	25.6°N	88.7°E	37	Subtropical, cool winter	Sandy loam	Hot summer (Mar-Oct), cool winter (Nov-Feb)	TR-BR, TR-W, M-TR, P-M-TR, M-J-TR	TR-M, M-TR, P-M-TR, M-J-TR

Country	Location	Geography			Climate	Soil	Seasons	Current systems	Emerging systems
		Latitude	Longitude	Elevation (m)					
Nepal	Chitwan, south-central	27.62°N	84.42°E	228	Subtropical, cold winter	Sandy loam, silty loam	Hot summer (Apr-Sept), cool winter (Oct-Mar)	R-W, rice-wheat-maize (R-W-M), rice-potato-maize (R-P-M), rice-mustard-maize (R-Mu-M)	R-M, R-M-M
	Dhankuta, eastern hills	27.17°N	87.17°E	1,450	Subtropical to warm temper-ate, cold winter, cooler nights year-round	Sandy clay loam, silty clay loam	Summer (Apr-Sept), winter (Oct-Mar), cooler nights throughout the year	R-W-M, R-P-M, R-Mu-M	R-W-M, R-P-M, R-Mu-M
Pakistan	Okara, Punjab	30.8°N	73.4°E	180	Subtropical to warm temperate, cold winter	Coarse- to medium-textured calcareous soils	Hot summer (Apr-Aug), cold winter (Oct-Feb)	R-W, R-P-M	R-P-M, R-M-M
	Larkana, Sindh	27.4°N	68.1°E	85	Subtropical, cool winter	Fine- to medium-textured calcareous soils	Hot summer (Mar-Sept), cool winter (Nov-Feb)	R-W, sorghum-wheat, cotton-wheat	R-W, R-M, M-W

Table 4 shows four key R-M agroecosystems classified based on moisture (rainfall, irrigation) and temperature. The first agroecosystem (tropical, warm, humid and subhumid, no winter) includes locations in Indonesia, the Philippines, and southern Vietnam with high rainfall and distinct dry and wet seasons. The second agroecosystem (tropical, warm, semiarid, no winter) includes locations in southern India with tropical monsoon and a long dry season. In both agroecosystems, both rice and maize are not limited by low temperature and can be grown year-round. The third agroecosystem (subtropical, subhumid, warm summer, mild cool winter) includes locations in Bangladesh, Nepal, northern India, and northern Vietnam. In this agroecosystem, winter is cool and so rice may be limited by low temperature. Maize, however, will have a long grain-filling period and it will perform well. The fourth agroecosystem (subtropical to warm temperate, subhumid, semiarid, warm summer, mild to severe cold winter) has been divided into three subclasses. The first subclass is subtropical monsoon with cold winter and summer rainfall such as that found in northern and northwestern India and in the Terai and hills of Nepal. The second subclass has a subtropical to warm temperate climate with severe cold winter such as that found in locations in China. The third subclass has a subtropical to warm temperate semiarid type of climate with hot summer and cool to cold winter and very low rainfall. In the second and third subclasses, both rice and maize will be limited by low temperature and cannot be grown for some time in winter.

Table 4. Key R-M agroecosystems for Asia.

Key feature	Current systems	Emerging systems	Key examples
1. Tropical, warm, humid and subhumid, no winter			
Tropical, high rainfall; mostly in a dry-season–wet-season pattern; both rice and maize not limited by low temperatures and can be grown year-round	R-R, R-fallow	R-M, M-R	Laguna, Central Luzon, Philippines; West Java, Central Java, North Sumatra, South Sulawesi, Indonesia; Central and lower north plain, Thailand
	R-R-R, R-R-M, R-M-M	R-M-R, R-R-M, R-M-M	Mekong Delta, Vietnam; East Java, Central Lampung, Indonesia
2. Tropical, warm, semiarid, no winter			
Tropical monsoon with longer dry season; both rice and maize not limited by low temperatures and can be grown year-round	R-R, R-R-pulses	R-M	Cauvery Delta, Tamil Nadu, India; Karnataka, India; Andhra Pradesh, India
3. Subtropical, subhumid, warm summer, mild cool winter			
Subtropical monsoon with cool winter and summer rainfall; rice but not maize may be limited by low temperatures	R-W, R-boro rice	R-M, R-R-M	Central, western, and northwest Bangladesh; eastern Terai, Nepal; West Bengal, eastern Uttar Pradesh and Bihar, India; Red River Delta, Vietnam

Key feature	Current systems	Emerging systems	Key examples
4. Subtropical to warm temperate, subhumid, semiarid, warm summer, mild to severe cold winter			
4.1. Subtropical monsoon with cold winter and summer rainfall; both rice and maize limited by low temperatures and cannot be grown for some time in winter	R-W	R-M	Northern and northwest India; central and western Terai and mid-hills, Nepal
4.2. Subtropical to warm temperate, with severe cold winter; both rice and maize limited by low temperatures and cannot be grown for some time in winter	R-R, R-fallow	M-R, R-M	South-central China (Hunan, Hubei), southeast China (Jiangsu, Zhejiang)
4.3. Subtropical to warm temperate, semiarid, with hot summer and cool to cold winter; very low rainfall; both rice and maize limited by low temperatures and cannot be grown for some time in winter	R-W, cotton-wheat, sorghum-wheat	R-M, M-W, R-P-M	Punjab and Sindh, Pakistan

Analysis of historical climate

Total annual and seasonal rainfall, mean annual and seasonal minimum and maximum temperature, and mean annual and seasonal solar radiation are presented in Table 5. Total annual rainfall across sites ranges from as low as <200 mm (Larkana, Sindh, Pakistan) to as high as 3,134 mm (Medan, Indonesia). Annual mean minimum temperature ranges from as low as 11.1 °C in (Yangzhou, China) to as high as 25.7 °C (Thanjavur, India), while annual mean maximum temperature ranges from 20 °C (Yangzhou) to 31.4 °C (Nalgonda, India). Annual mean daily incident solar radiation ranges from 12.6 MJ m^{-2} d^{-1} (Changsha, China) to 19 MJ m^{-2} d^{-1} (Punjab, India). There are large differences in climatic patterns between seasons and among sites.

Tropical warm agroecosystem

For each of the sites below, weekly means for maximum and minimum temperature and solar radiation and the variability in weekly total rainfall are presented in the different figures.

Philippines. Pila, Laguna: Laguna Province, located in Southern Luzon, has two distinct seasons—a wet season from June/July to October/November and a dry season from December/January to March/April. Rainfall in Pila, a site near IRRI, Los Baños, is low and less variable during the dry season than during the wet season. The weekly median rainfall during the dry season is extremely low (<20 mm), though, in 1 out of 10 years (10th percentile), there could be up to 100–300 mm of rain in some weeks.

Table 5. Mean annual and seasonal minimum temperature, maximum temperature and solar radiation, and total and seasonal rainfall across sites in nine Asian countries.

Country	Site	Season	Rainfall (mm)	Minimum temperature (°C)	Maximum temperature (°C)	Solar radiation (MJ m^{-2} d^{-1})
Philippines	Pila	Annual	2,045.5	23.3	29.5	16.2
		Dry	478.5	23.0	29.7	17.2
		Wet	1,567.0	23.8	29.6	15.9
	Muñoz	Annual	2,120.5	22.8	29.4	17.3
		Dry	528.4	22.4	29.4	18.4
		Wet	1,592.2	23.2	29.2	26.2
Indonesia	Sukamandi	Annual	2,042.6	23.7	26.4	17.3
		Dry	566.0	23.7	26.4	17.4
		Wet	1,476.6	23.7	26.3	16.8
	Maros	Annual	2,559.2	24.1	28.1	20.0
		Dry	687.3	23.7	28.7	23.3
		Wet	1,872.0	24.4	28.2	18.7
	Medan	Annual	3,133.9	23.6	26.8	16.4
		Dry	1,522.6	23.7	27.4	16.7
		Wet	1,611.3	23.4	26.2	16.1
	Central Lampung	Annual	2,128.2	24.6	27.5	17.1
		Dry	683.9	24.7	27.6	16.6
		Wet	1,444.3	24.5	27.4	17.5
	Kediri	Annual	1,989.0	22.8	27.9	18.2
		Dry	457.7	22.4	27.8	18.2
		Wet	1,531.4	23.2	28.0	18.3
Vietnam	Vinh Phuc	Annual	1,352.5	19.5	25.6	14.3
		Spring	273.2	18.3	24.1	13.7
		Summer	838.2	24.5	30.8	17.4
		Winter	241.1	15.7	21.9	11.7
	Thanh Hoa	Annual	1,755.9	20.4	24.2	14.5
		Spring	385.6	19.0	23.1	15.1
		Summer	1,044.4	24.6	28.6	17.0
		Winter	325.9	17.3	20.9	11.5
	An Giang	Annual	1,698.5	23.6	30.3	17.9
		Dry	112.5	22.6	30.7	18.7
		Early wet	439.0	24.5	30.7	18.8
		Late wet	1,147.0	23.8	29.6	16.7

Country	Site	Season	Rainfall (mm)	Minimum tempera-ture (°C)	Maximum tempera-ture (°C)	Solar radiation (MJ m^{-2} d^{-1})
Thailand	Chiang Rai	Annual	1,376.3	18.8	26.2	17.2
		Early wet	401.3	22.3	28.8	19.3
		Wet	894.1	20.6	26.5	14.9
		Dry	81.0	15.3	24.5	17.8
	Suphan Buri	Annual	1,414.4	22.7	29.3	18.8
		Early wet	435.3	24.3	30.3	20.8
		Wet	864.1	23.3	28.9	17.4
		Dry	115.0	21.2	29.1	18.8
	Phitsanulok	Annual	1,250.4	22.1	28.8	18.7
		Early wet	392.1	24.3	30.2	20.9
		Wet	771.3	22.9	28.4	17.1
		Dry	87.0	20.0	28.2	18.6
India	Aduthurai	Annual	1,081.6	25.6	29.3	18.6
		Summer	74.2	25.8	29.8	22.0
		Dry	303.1	26.9	30.8	19.1
		Wet	704.4	24.4	27.9	16.2
	Thanjavur	Annual	1,104.3	25.7	29.3	18.8
		Summer	159.3	25.9	29.7	21.7
		Dry	284.1	26.7	30.6	19.7
		Wet	660.9	24.8	28.0	16.2
	Begusarai	Annual	972.6	20.4	29.5	18.7
		Prekharif	176.9	23.1	32.8	23.3
		Kharif	758.6	24.0	29.9	16.7
		Rabi	37.2	13.8	25.7	16.3
	Ludhiana	Annual	706.8	16.3	29.3	19.0
		Prekharif	107.6	18.8	30.1	23.1
		Kharif	526.1	22.4	30.2	20.1
		Rabi	73.1	7.0	27.6	13.3
	Nalgonda	Annual	888.3	22.9	31.4	18.8
		Wet	801.0	24.5	31.6	17.9
		Dry	87.3	21.2	31.1	19.5
	Bangalore	Annual	1,240.6	20.7	29.5	18.8
		Wet	1,030.5	21.7	29.2	17.8
		Dry	210.1	19.8	29.8	19.8

Country	Site	Season	Rainfall (mm)	Minimum tempera-ture (°C)	Maximum tempera-ture (°C)	Solar radiation (MJ m^{-2} d^{-1})
China	Changsha	Annual	1,490.9	12.9	21.4	12.6
		Spring-summer	1,235.5	15.5	23.9	14.0
		Winter	255.4	4.9	13.6	8.7
	Jinhua	Annual	1,614.6	11.8	20.1	13.2
		Spring-summer	1,336.0	15.9	24.1	14.9
		Winter	278.7	3.4	11.9	9.7
	Wuhan	Annual	1,274.0	12.3	21.3	13.7
		Spring-summer	1,080.1	16.3	25.4	15.7
		Winter	193.9	4.0	12.9	9.5
	Yangzhou	Annual	1,109.7	11.1	20.0	14.2
		Spring-summer	916.7	15.3	24.4	16.2
		Winter	193.1	2.4	10.8	10.1
Bangladesh	Dinajpur	Annual	1,905.1	20.2	28.5	17.7
		Kharif I	489.2	22.2	30.5	21.2
		Kharif II	1,357.2	23.7	29.3	15.6
		Rabi	58.6	14.4	25.5	16.3
	Bogra	Annual	1,908.6	21.2	29.3	17.3
		Kharif I	631.3	23.3	31.2	20.5
		Kharif II	1,222.0	24.4	30.0	15.5
		Rabi	55.3	15.5	26.5	16.0
	Jessore	Annual	1,314.2	21.6	29.7	17.3
		Kharif I	446.8	23.8	31.7	20.4
		Kharif II	790.8	24.6	30.1	15.6
		Rabi	76.7	16.3	27.1	15.9
Nepal						
	Chitwan	Annual	1,029.7	13.4	22.4	17.9
		Spring	224.8	15.7	24.9	22.3
		Summer	785.6	17.9	23.7	16.1
		Winter	19.2	6.1	18.5	15.3
Pakistan	Okara	Annual	385	17.9	31.0	18.1
		Kharif	284	22.6	33.7	19.1
		Rabi	101	13.3	28.3	17.2
	Larkana	Annual	160	19.9	33.6	19.4
		Kharif	122	24.0	36.1	20.2
		Rabi	38	15.8	31.0	18.6

In July, weekly median rainfall is on the order of 40–50 mm but is highly variable, with more than 400 mm of rain in some weeks in 1 out of 10 years. October has the greatest rainfall with weekly rain of about 100 mm in 75% of the years and between 100 and 500 mm in 25% of the years. November and December have weekly median rainfall of 25–50 mm with 100–250 mm rain in 25% of the years (Fig. 4). Weekly mean minimum temperature ranges from 22 to 24 °C, whereas mean maximum temperature ranges from 27 to 31 °C. Maximum temperatures are highest from March to June, but minimum temperatures are somewhat stable throughout the year. Solar radiation is highly variable, ranging from 12 to 22 MJ m^{-2} d^{-1}, and is higher from March to June.

Muñoz, Nueva Ecija: Like Pila, Muñoz, located in Central Luzon, also has distinct dry and wet seasons—a wet season from May to October and a dry season from November to April (Fig. 5). In the wet season, the weekly median rainfall ranges from 25 to 100 mm; in the dry season, except for a few weeks in November and April, rainfall is very low or almost nil for most months. In some weeks in 10% of the years, there could be as high as 200–300 mm of rain during the wet season. In the dry season too, rainfall becomes highly variable, with more than 100 mm of rain in about 10% of the years (Fig. 5). Minimum and maximum temperatures are stable, with 20 °C and 30 °C, respectively, throughout the year. Solar radiation, however, is variable, with a mean of 15–22 MJ m^{-2} d^{-1} during the dry season and 13–17 MJ m^{-2} d^{-1} during the wet season.

Indonesia. *Medan*: Medan, located in North Sumatra, has a wet season from August to December and a dry season from January to July (Fig. 6). Rainfall is low but highly variable during both the wet and dry seasons. In the wet season, weekly

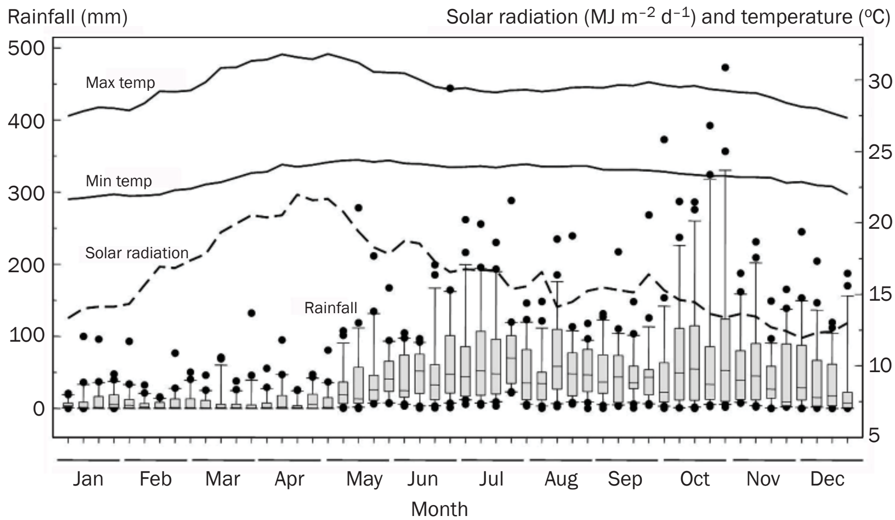


Fig. 4. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Pila, Laguna, Philippines, during the whole year.

median rainfall ranges from 20 to 120 mm, whereas, in the dry season, it ranges from 10 to 75 mm. The rainfall can support a rainfed crop of rice during the wet season and a nonrice crop during the dry season, if supplemental irrigation water is unavailable. Weekly maximum and minimum temperatures are fairly stable throughout the year, but solar radiation is slightly higher from February to June (Fig. 6).

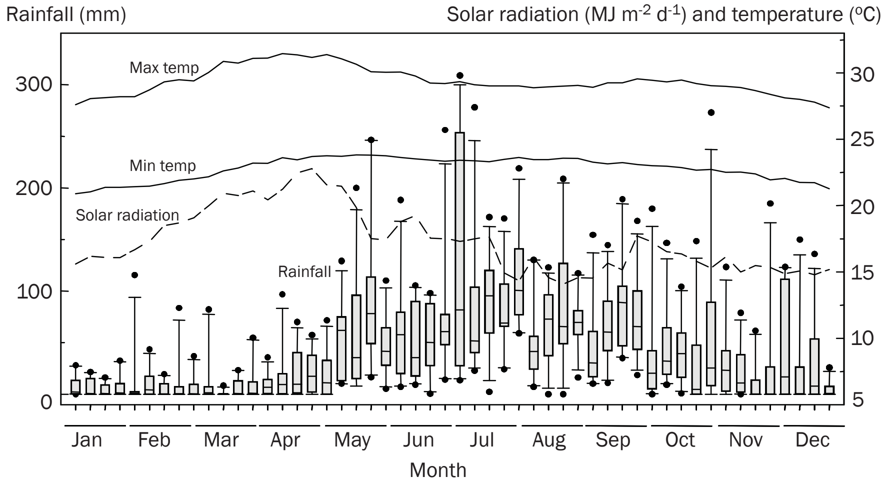


Fig. 5. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Muñoz, Nueva Ecija, Philippines, during the whole year.

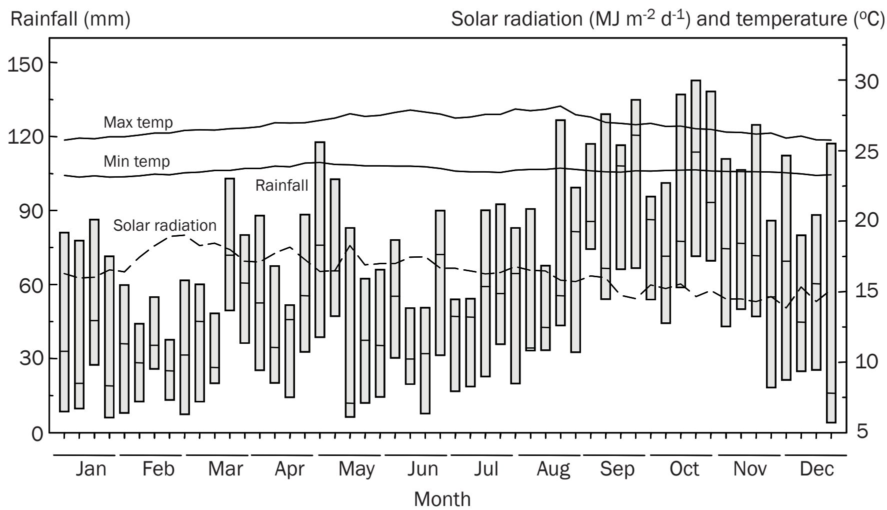


Fig. 6. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Medan, North Sumatra, Indonesia, during the whole year.

Kediri: Kediri, located in East Java, also has two distinct seasons—a wet season from November to April and a dry season from May to October (Fig. 7). The rainfall in the wet season is highly variable, with weekly median rainfall ranging from 20 to 115 mm. In contrast, in the dry season, it is less variable, with weekly rainfall ranging from 0 to 20 mm. Mean maximum and minimum temperatures are fairly stable throughout the year, with slightly lower temperatures during June-August. Solar radiation has a distinct pattern, much higher from August to December (18–22 MJ m^{-2} d^{-1}) but lower in the other months (15–17 MJ m^{-2} d^{-1}; Fig. 7).

Maros: Maros, located in South Sulawesi, also has two distinct seasons—a wet season from November to April and a dry season from May to October (Fig. 8). Rainfall in the wet season is highly variable but less so in the dry season. The weekly median rainfall in the wet season ranges from as low as 10 mm in early November to more than 100 mm in late January. It is so variable that, in some weeks in some years, there could be no rainfall while there is a 10% probability of weekly rainfall of 300 mm or more in some weeks in other years. In the dry season, weekly median rainfall is on the order of 0–20 mm, although some years have a 10% probability of weekly rainfall of about 100 mm. Weekly maximum temperature is more variable than minimum temperature, with the former reaching its peak from September to November. Solar radiation is highly variable, with the highest values noted from July to mid-November (mean 20–25 MJ m^{-2} d^{-1}) and lowest during December-February (15–18 MJ m^{-2} d^{-1}) (Fig. 8).

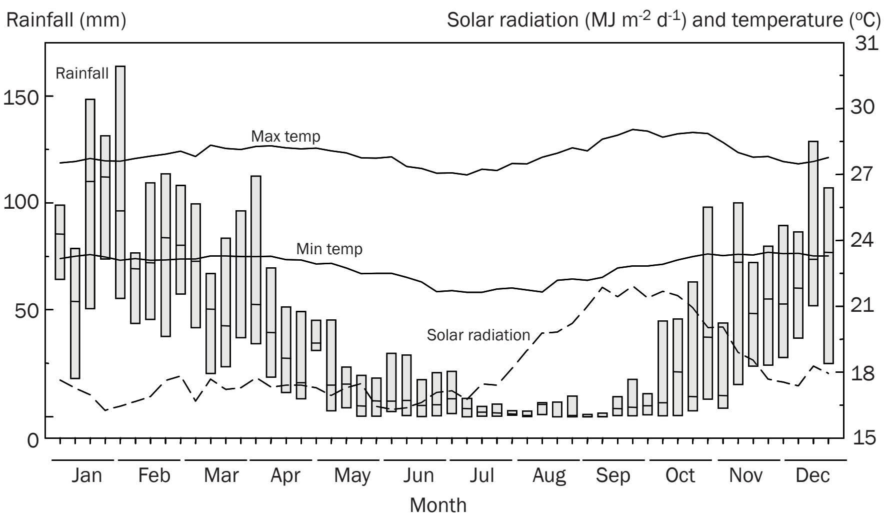


Fig. 7. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Kediri, East Java, Indonesia, during the whole year.

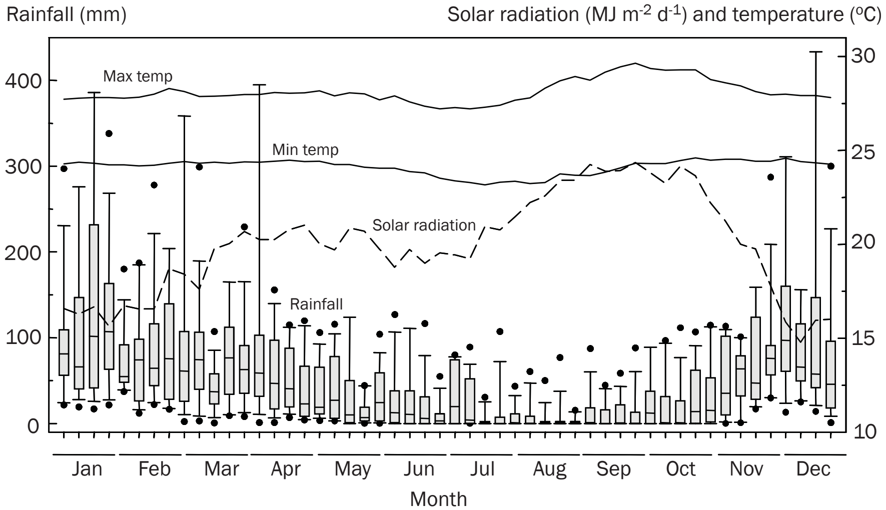


Fig. 8. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Maros, South Sulawesi, Indonesia, during the whole year.

<u>*Sukamandi*</u>: Sukamandi, located in West Java, also has two distinct seasons—a wet season from October/November to April/May and a dry season from June to September (Fig. 9). Weekly median rainfall in the wet season ranges from 10 to 100 mm, but, in many weeks, there is a 20% probability of extreme rainfall, that is, either no rain or more than 150 mm of rain. In the dry season, in most weeks, rainfall is quite minimal, although in some weeks there could be some rainfall events. Daily mean maximum temperatures are around 27–31 °C, with the highest noted during the wet season. Daily mean minimum temperatures are fairly stable, at 22–23 °C throughout the year. Daily solar radiation during the year is highly variable, with daily mean values ranging from 12 to 22 MJ m^{-2}. Daily mean solar radiation is higher during the latter part of the wet season (March to May) than in other months (Fig. 9).

<u>*Central Lampung*</u>: Central Lampung also has two distinct seasons—a wet season from October to May and a dry season from June to September (Fig. 10). Weekly median rainfall in the wet season ranges from 10 to 120 mm and in the dry season from nil to 70 mm. Daily mean maximum and minimum temperatures are stable throughout the year, at 27–28 °C and 24–25 °C, respectively. Daily solar radiation tends to be somewhat variable, with the mean ranging from 15 to 18 MJ m^{-2}. Solar radiation is less in the dry season than in the wet season (Fig. 10).

Thailand. <u>*Chiang Rai*</u>: Chiang Rai in northern Thailand is located at 384 m. It has two distinct seasons: a wet season from May to October and a dry season from November to April (Fig. 11). The weekly median rainfall in the wet season ranges from 20 to 80 mm, but the dry season has almost no rain. Weekly mean maximum and minimum temperatures are quite variable, with the maximum ranging from 20 to

32 °C and the minimum from 11 to 21 °C. Daily mean solar radiation is also highly variable, with higher radiation (13–21 MJ m^{-2} d^{-1}) during the latter part of the dry season (February to May) than in other months (12–16 MJ m^{-2} d^{-1}) (Fig. 11).

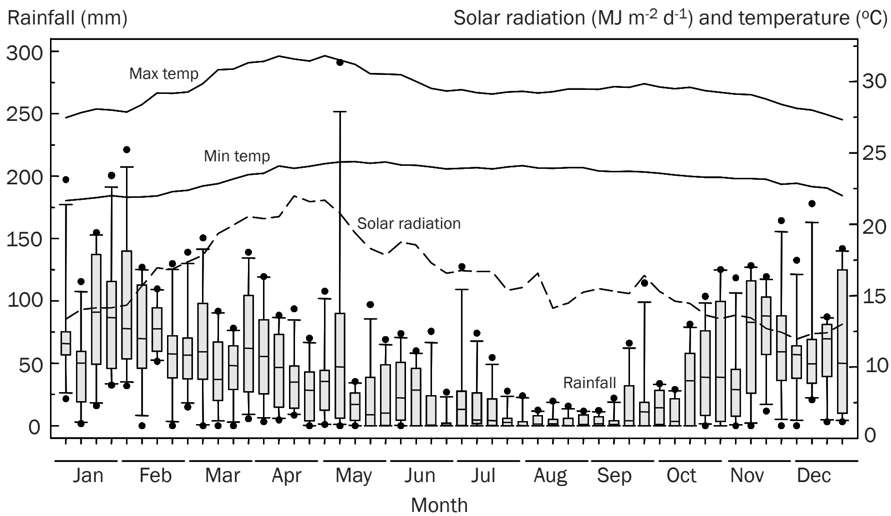


Fig. 9. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Sukamandi, West Java, Indonesia, during the whole year.

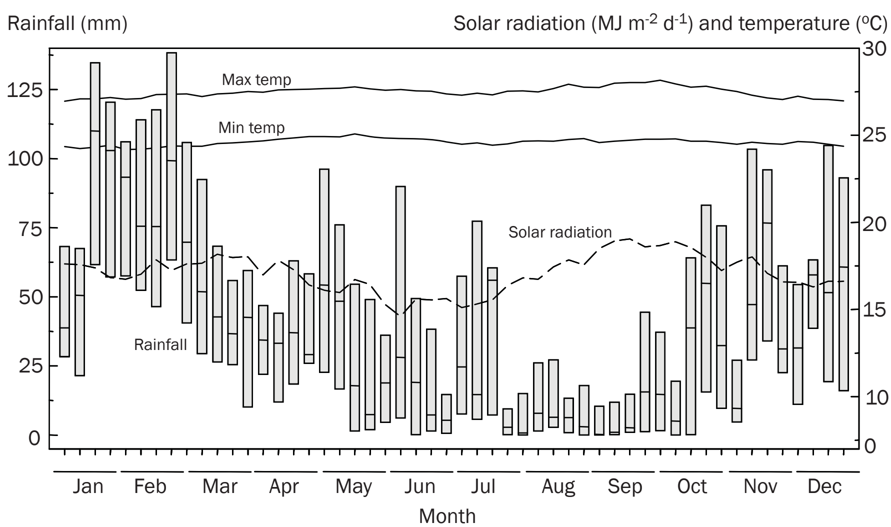


Fig. 10. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Central Lampung, Indonesia, during the whole year.

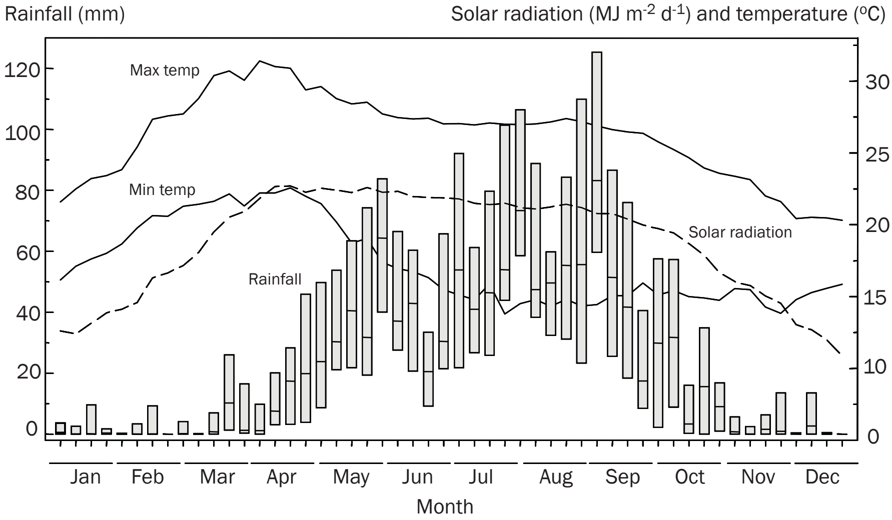


Fig. 11. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Chiang Rai, northern Thailand, during the whole year.

Suphan Buri: Suphan Buri is located in the Central Plain of Thailand. Like Chiang Rai, Suphan Buri also has two main seasons—a wet season from July to September/October and a dry season from November to March (Fig. 12). The median rainfall in the wet season ranges from 15 to 85 mm. During the preceding 3 months (April to June), there can be very little rain in some weeks but there can be as high as 60 mm of median rainfall in other weeks. There are slightly different patterns of weekly mean maximum and minimum temperatures. The weekly maximum temperatures are slightly higher from February to May, while the weekly minimum temperatures are higher from March to October. The weekly mean daily solar radiation is highly variable, with higher radiation observed from February to May than in other months. From June to January, solar radiation is fairly stable (Fig. 12).

Phitsanulok: Unlike in Chiang Rai and Suphan Buri, Phitsanulok has three distinct seasons—an early wet season from March to June, a regular wet season from July to October, and a dry (and winter) season from November to February (Fig. 13). The weekly median rainfall in the early wet season ranges from 0 to 50 mm, whereas, in the regular wet season, it ranges from 10 to 65 mm. The dry season has little or no rain in most weeks. Weekly mean maximum and minimum temperatures are quite variable with much lower temperatures during the dry season (November to January) and higher temperatures from February to April. During the other months, temperatures are quite stable. Weekly mean daily solar radiation is also highly variable, with higher radiation in February-May (18–22 MJ m^{-2} d^{-1}) than in other months (16–17 MJ m^{-2} d^{-1}) (Fig. 13).

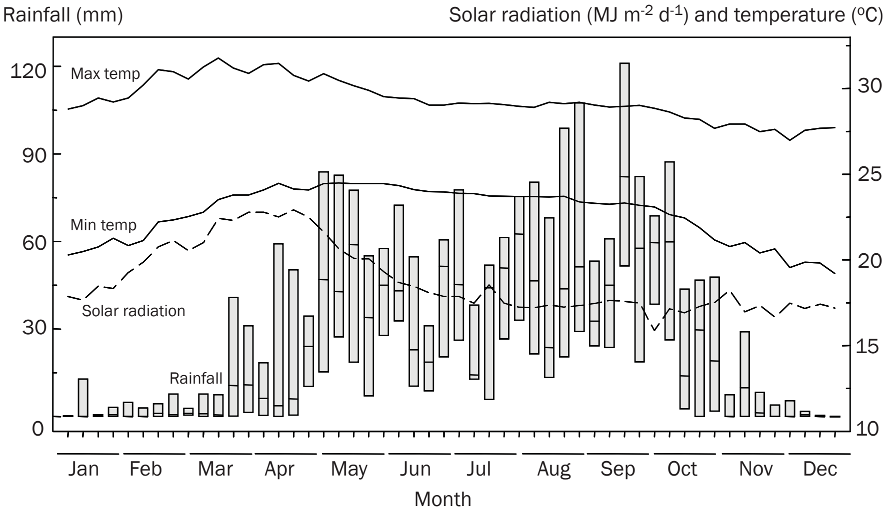


Fig. 12. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Suphan Buri, Central Plain, Thailand, during the whole year.

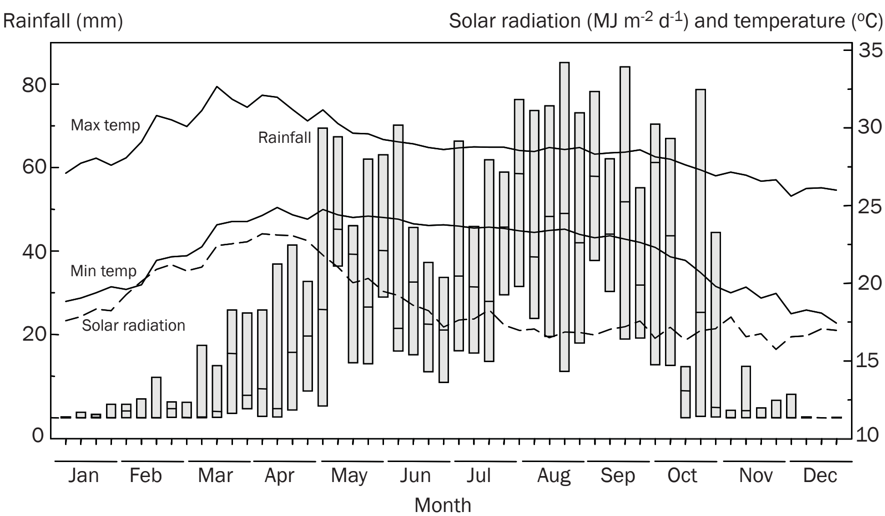


Fig. 13. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Phitsanulok, Thailand, during the whole year.

Vietnam. <u>*An Giang*</u>: An Giang is located in the upper part of the Mekong River Delta in southern Vietnam. It has three seasons: dry season, early wet season, and late wet season. The rainfall in An Giang is low and less variable during the dry season (November to April) than in the wet season (May to October). In the dry season, the weekly median rainfall is generally less than 20 mm, although, in 2 out of 20 years (10th percentile), there could be 50–100 mm of rain in some weeks (Fig. 14). In the wet season, rainfall is high, with a weekly median of 20–75 mm. October has the greatest rainfall, with a weekly median of 40–75 mm and between 100 and 230 mm in 10% of the years. The high rainfall in the wet season results in rice fields becoming submerged even in November, causing difficulties in planting the dry-season rice before December. The maize-growing season from March to July receives a good amount of rainfall. Weekly median rainfall in the season ranges from 0 to 50 mm, with more rain falling as the season progresses. This leads to some probability of flooding damage to the maize crops when they are in the grain-filling to maturity stage.

The weekly median solar radiation ranges from 15 to 21 MJ m^{-2} d^{-1}, with high radiation during February-April (>20 MJ m^{-2} d^{-1}), intermediate during December and January, and low during other months. Solar radiation is highly variable during the wet season (from late April to mid-September) but is less variable during the dry season. The weekly median daily minimum temperature ranges from 21.8 to 24.4 °C; it is higher (>24 °C) but less variable during the rainy season than in the dry season (22–24 °C). The weekly median daily maximum temperature ranges from 29 to 32 °C. Maximum temperatures are generally constant at 30 °C throughout the year, with slightly higher temperatures (31–32 °C) observed from January to April (Fig. 14).

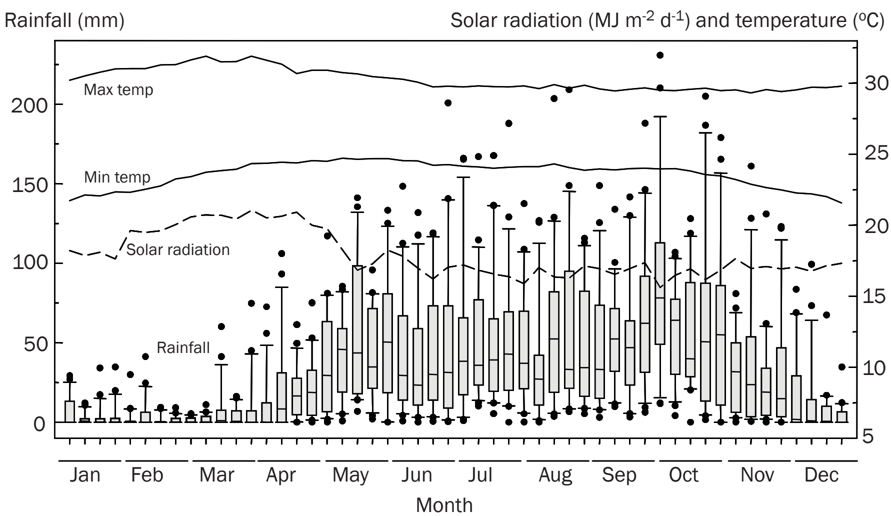


Fig. 14. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at An Giang, southern Vietnam, during the whole year.

India. Aduthurai and Thanjavur: Aduthurai is located in the old Cauvery River Delta (CRD) and Thanjavur is in the new CRD in Tamil Nadu. The two sites are located about 90 km away from each other. Rice in Tamil Nadu is mainly grown in the alluvial terrain of the CRD. The old delta has been under irrigated rice cultivation for centuries, whereas the new delta has been under irrigated rice for 50–55 years. Soils in the CRD are generally of alluvial origin, have low organic carbon and total N, and neutral to slightly alkaline pH; these values differ significantly between the two deltas (Nagarajan et al 2004). The long-term means for rainfall, maximum and minimum temperatures, and solar radiation for the two sites are presented in Figures 15 and 16, respectively. For Aduthurai, rainfall means also include historical daily data from 1980 to 1996 in addition to NASA-derived data from 1997 to 2005. For Thanjavur, rainfall data are from NASA only. There are three seasons in Aduthurai and Thanjavur—thaladi from October to January, kuruvai from June to September, and samba from September to February/March. Rainfall at both sites is highly variable throughout the year. Weekly median rainfall in the thaladi season at Aduthurai ranges from 0 to 60 mm, with 10% probability of having as much as 400 mm or more rain in some weeks. In November and December, however, there can be 200 mm or more rain in many weeks. All seasons can have many extreme events, with weekly rainfall ranging from 50 to 500 mm. However, in most weeks, especially from January to July, there is very little or no rain. Rainfall patterns and trends for Thanjavur are similar to those for Aduthurai, but because only 9-yr rainfall data are available, the mean and median values for rainfall are lower for Thanjavur than for Aduthurai. Long-term trends for weekly mean maximum and minimum temperature and weekly mean daily solar radiation are similar for Aduthurai and Thanjavur. Both sites have low mean minimum and maximum temperatures from November to February but fairly stable and high temperatures from April to September. Solar radiation is highly variable throughout the year, with higher radiation during summer and kuruvai (18–22 MJ m^{-2} d^{-1}) and lower radiation during thaladi (13–16 MJ m^{-2} d^{-1}) (Figs. 15 and 16).

Bangalore: Bangalore is located in Karnataka State in southern India. It has two distinct seasons—a wet season from May to October and a dry season from November to April (Fig. 17). Rainfall during the wet season is fairly stable, with weekly median rainfall ranging from 10 to 60 mm. The dry season has very little or no rain. Weekly mean maximum and minimum temperatures and solar radiation are highly variable during the year. Weekly mean maximum temperature ranges from 26 to 32 °C, while the mean minimum temperature ranges from 16 to 22 °C. Weekly mean daily solar radiation ranges from 15 to 22 MJ m^{-2}. Mean maximum and minimum temperatures and solar radiation are higher during the dry season than during the wet season (Fig. 17).

Nalgonda, A.P.: Nalgonda also has two distinct seasons—a short wet season from June to October and a long dry season from November to May (Fig. 18). As in Bangalore, the rainfall in the wet season is fairly stable, with weekly median rainfall ranging from just a few millimeters to about 75 mm. The dry season has very little or no rain. Weekly mean daily minimum temperature ranges from 17 to 28 °C, while the mean daily maximum temperature ranges from 27 to 37 °C. Mean maximum

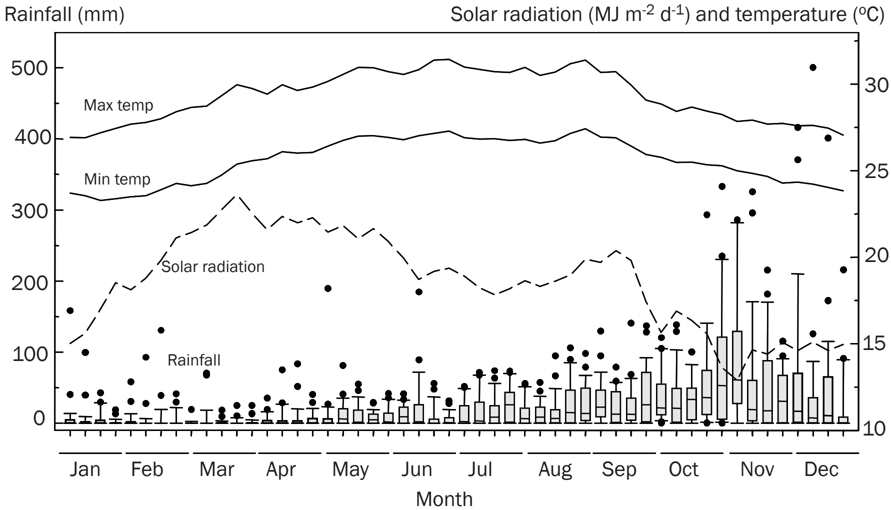


Fig. 15. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Aduthurai, Tamil Nadu, India, during the whole year.

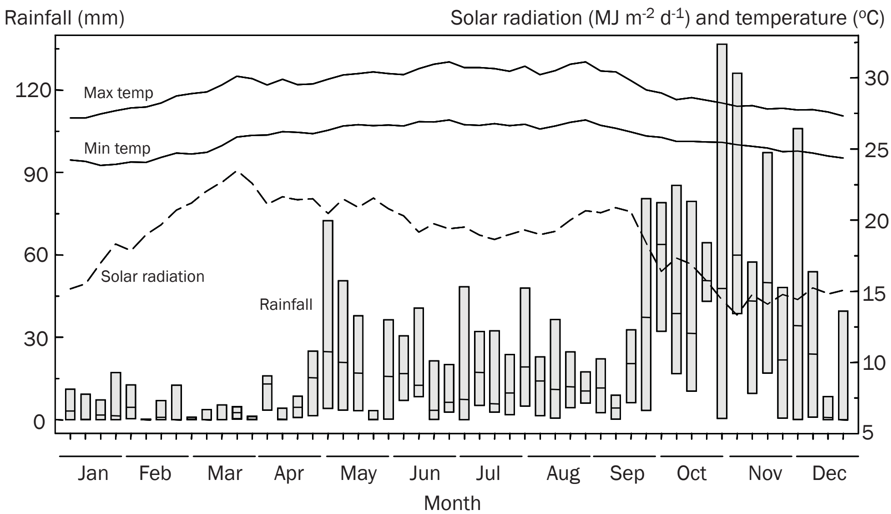


Fig. 16. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Thanjavur, Tamil Nadu, India, during the whole year.

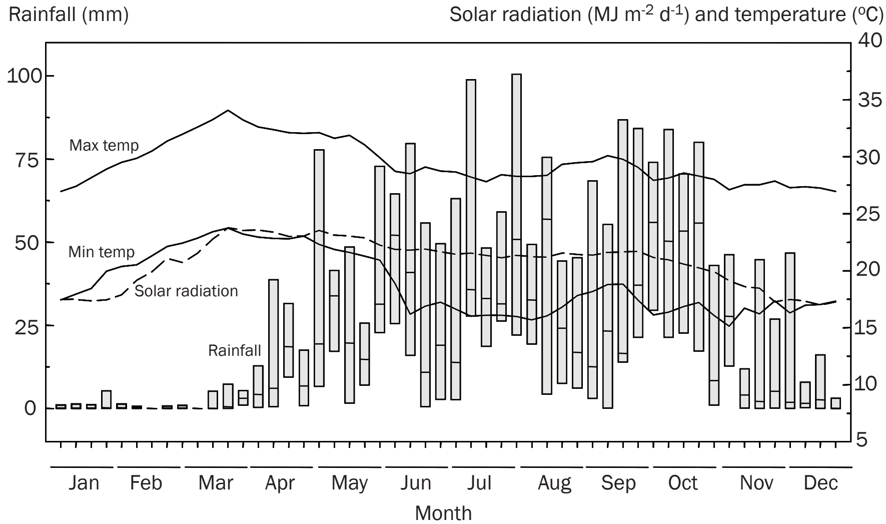


Fig. 17. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Bangalore, Karnataka, India, during the whole year.

temperatures are highest during mid-February to mid-June (30–37 °C), while mean minimum temperatures are highest during mid-March to mid-June (24–27 °C). Solar radiation is also highly variable, with mean radiation ranging from 15 to 24 MJ m^{-2} d^{-1}. Solar radiation is higher from February to May (20–24 MJ m^{-2} d^{-1}) than in other months (15–18 MJ m^{-2} d^{-1}) (Fig. 18).

Subtropical warm agroecosystem

Bangladesh. Bangladesh has three seasons—premonsoon or kharif I from March/April to May/June, monsoon or kharif II from June/July to October, and winter or rabi from November to March. Throughout Bangladesh, annual rainfall is very high, and it is much higher in the east than in the west. The rainfall in kharif I and kharif II is highly variable and erratic, sometimes causing both flooding and drought in the same weeks or months. Three sites in Bangladesh are discussed below.

Bogra: The weekly median rainfall in kharif I at Bogra in the north-central region ranges from a few mm to about 60 mm, though there is 10–20% probability of having more than 100 mm of rain in some weeks (Fig. 19). In some extreme cases, rainfall in some weeks in June alone could reach 500 mm or more. In kharif II, the weekly median rainfall ranges from 40 to 80 mm. Rainfall is so variable that, in many weeks, there is a 10–20% probability of greater than 200 mm of rain and, in most weeks, there is at least a 25% probability of having greater than 100 mm of rain. Both daily mean maximum and minimum temperatures and daily mean solar radiation are highly variable throughout the year. Mean maximum temperature ranges from 25 to 35 °C, while mean minimum temperature ranges from 12 to 24 °C. Maximum temperatures are highest in March and minimum temperatures are highest from May to October.

Daily mean solar radiation is highest during March to May in kharif I (19–22 MJ m^{-2} d^{-1}). In other months, mean solar radiation is 13–15 MJ m^{-2} d^{-1} (Fig. 19).

Dinajpur: The weekly median rainfall in kharif I in Dinajpur in northwest Bangladesh ranges from 0 to 80 mm; that in kharif II ranges from a few mm to about 140 mm (Fig. 20). In both seasons, rainfall is highly variable, with a 10–20% probability of having more than 100 mm of weekly rainfall in many weeks in kharif I and more

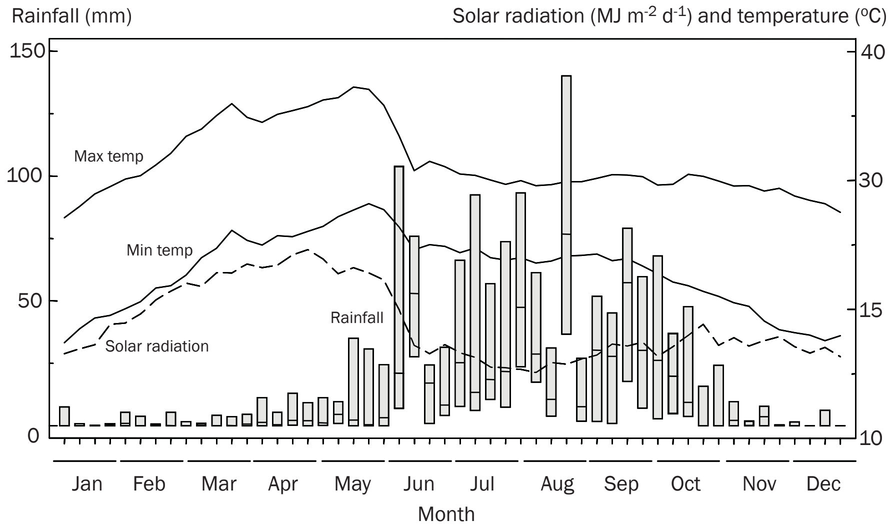


Fig. 18. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Nalgonda, A.P., India, during the whole year.

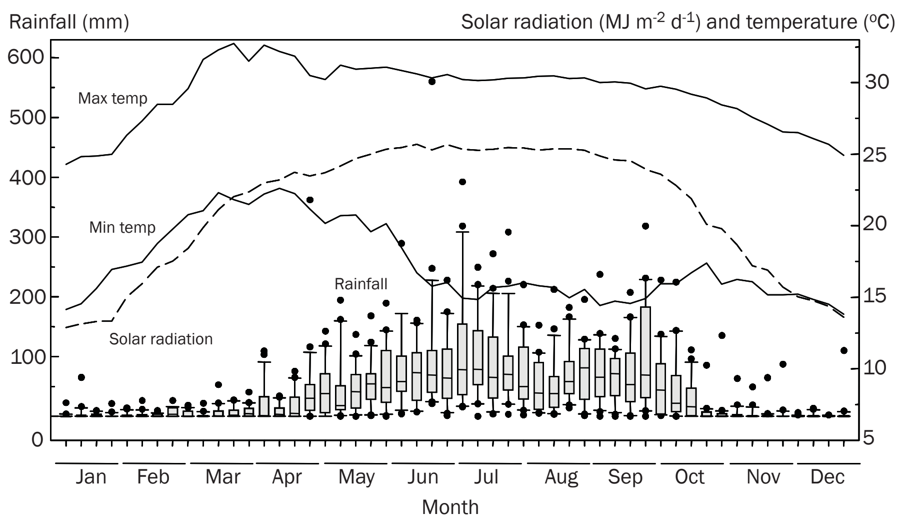


Fig. 19. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Bogra, north-central Bangladesh, during the whole year.

than 200 mm in many weeks in kharif II. Extreme rainfall events can occur in all seasons, including rabi. For example, in kharif I, there is a 10% probability of having a weekly rainfall of more than 250 mm in some weeks in May and even up to 350 mm in some weeks in June, whereas, in kharif II, there is a 10% probability of having 300–400 mm of rain in some weeks in July and August. Although the rabi season does not generally receive significant rainfall in most years, there is a 10–20% probability of having 10–50 mm of rain in most weeks. As in Bogra, mean minimum and maximum temperatures and mean solar radiation at this site are highly variable. Mean daily minimum temperature ranges from 12 to 23 °C, while maximum temperature ranges from 22 to 32 °C. Though the ranges for both minimum and maximum temperatures are large, the temperatures remain more or less stable during most parts of the year. Mean maximum temperatures peak during March and April and decrease in January. Likewise, minimum temperatures are lowest in December and January and highest from April to October. Mean daily solar radiation ranges from 13 to 22 MJ m^{-2}; it is highest during kharif I, followed by rabi, and then kharif II (Fig. 20).

Jessore: The weekly median rainfall at Jessore in southwest Bangladesh ranges from 0 to 50 mm in kharif I and from a few to about 60 mm in kharif II (Fig. 21). In both seasons, rainfall is highly variable but more so in kharif II. In kharif II, there is a 75% probability of having 50 mm or less rain in most weeks, but there is a probability of having 50–100 mm of rain only in a few weeks. There is also a 10–20% probability of having weekly rains of 250 mm or more in some weeks. The trends for mean minimum and maximum temperatures and solar radiation for Jessore are similar to those for Dinajpur and Bogra. More extreme rainfall events occur in Dinajpur, followed by Bogra and then Jessore (Fig. 21).

India. Begusarai, Bihar: At this site, most of the rain occurs during kharif season from June to September, with very minimum rainfall during rabi from October to May. The variability of weekly rainfall during kharif is also quite high, ranging from zero to as high as 300 mm or more in some weeks in August. Unexpectedly, solar radiation is also higher during the kharif season than during the rabi season (Fig. 22). Daily average maximum temperatures can be as high as 35 °C during March/April and above 23 °C throughout the year. Daily average minimum temperatures are also highest in March/April and lowest from July to September. The patterns of maximum and minimum temperatures and solar radiation are similar to those of Dinajpur in nothwest Bangladesh, but the rainfall pattern is different.

Vietnam. Vinh Phuc, northern Vietnam: Vinh Phuc is located in the Red River Delta (RRD) in northern Vietnam. It has three seasons: spring from February/March to May/June, summer from June/July to September, and winter from October to January/February. Rainfall during spring and winter is low and less variable than in summer (Fig. 23). The weekly median rainfall during the spring and winter seasons is extremely low (0–15 mm), although, in 1 out of 10 years, there could be 70–170 mm of rain in some weeks. Rainfall during the summer season from May to October is high, with a weekly median of 5–60 mm. July has the greatest rainfall, followed by June. In July, the weekly median rainfall is 10–60 mm, with 120–250 mm in 10% of the years, but also almost no rain in another 10%. In June, the weekly median rainfall

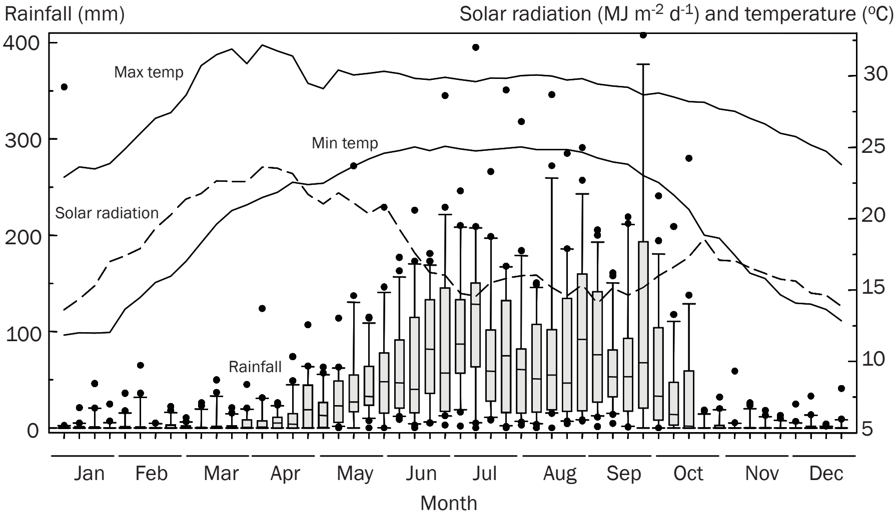


Fig. 20. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Dinajpur, northwest Bangladesh, during the whole year.

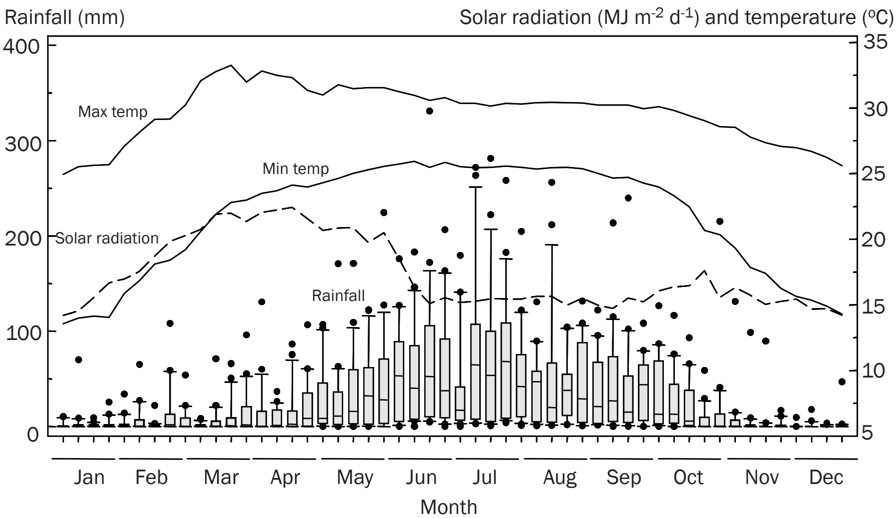


Fig. 21. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Jessore, southwest Bangladesh, during the whole year.

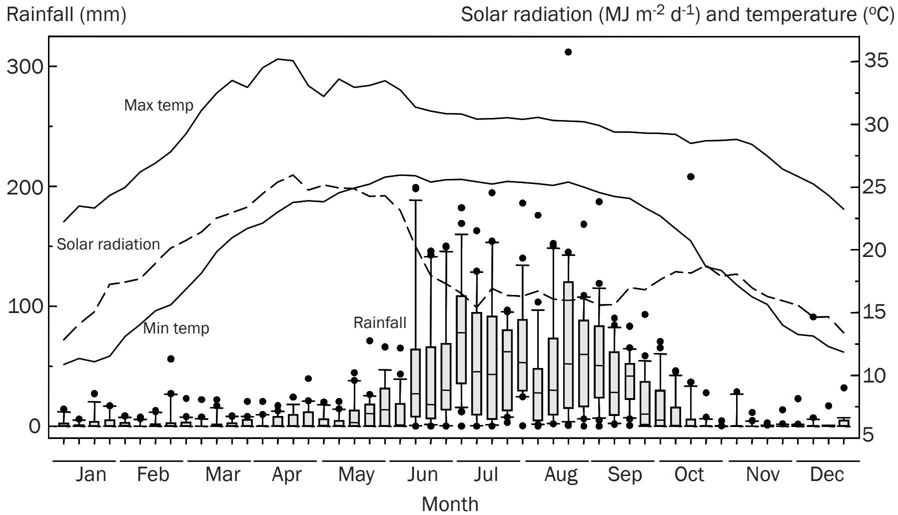


Fig. 22. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Begusarai, Bihar, India, during the whole year.

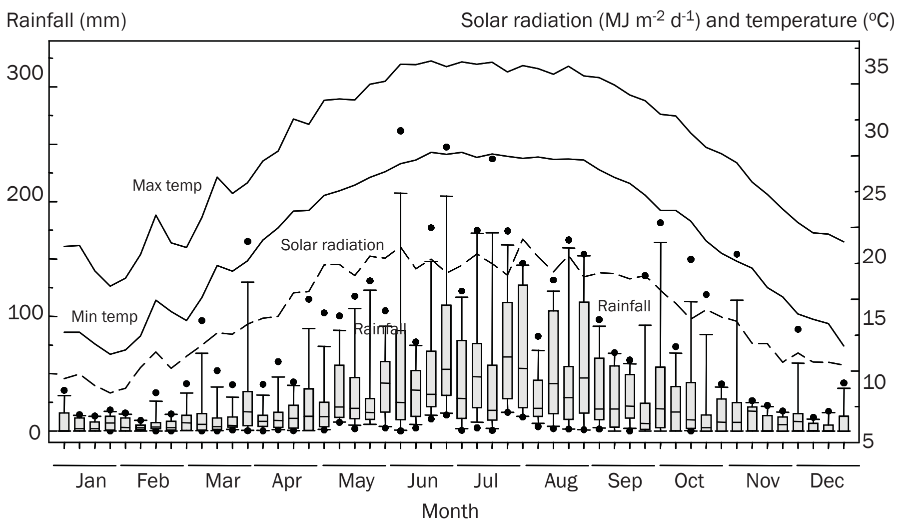


Fig. 23. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Vinh Phuc, northern Vietnam, during the whole year.

is lower than in July, but variability of rainfall could be quite high. In 10% of the years, there could be more than 250 mm of rain in a week and 80 to 180 mm in other weeks. In about 10% of the years, there could also be no rain in June. In September, weekly median rainfall could be 10–15 mm, varying from 50 to 150 mm in 10% of the years. The weekly median average daily solar radiation over the 20 years ranges from 8 to 19 MJ m^{-2}. Surprisingly, solar radiation is generally higher during the rainy months from May to September and lower during the dry or winter season from December to February. Rainfall in the form of continuous drizzles in January, February, and March contributes to low solar radiation near the surface during that period. The weekly median minimum and maximum temperatures range from 11 to 26 °C and from 16 to 32 °C, respectively, with higher temperatures during the summer or rainy season and lower during the winter or dry season. Both minimum and maximum temperatures are highly variable, ranging from 3 to 29 °C and from 8 to 37 °C, respectively. They are less variable in the rainy or summer season than in the dry season.

Thanh Hoa: Thanh Hoa is also located in the RRD in northern Vietnam. As in Vinh Phuc, there are also three distinct seasons in Thanh Hoa—spring from February/March to May/June, summer from June/July to September, and winter from October to January/February. The weekly median rainfall in summer ranges from a few to about 105 mm and, in spring and winter, from zero to about 45 mm (Fig. 24). Except during the early part, most weeks in winter have little or no rain, whereas, in spring, there is little rain during the early part and substantial rain during the latter part of the season. Mean maximum and minimum temperatures and mean daily solar radiation are highly variable throughout the year. Maximum temperature ranges from 17 to 28 °C, while minimum temperature ranges from 13 to 24 °C. Mean daily solar radiation ranges from 8 to 17 MJ m^{-2}. Both maximum and minimum temperatures and solar radiation follow the same trends and patterns. They are highest during late spring and the entire summer and lowest during winter and early spring (Fig. 24).

Pakistan. Larkana: Larkana is located in Sindh Province in Pakistan. It has a semiarid climate with extremely low rainfall. The annual rainfall for this site is less than 200 mm, with most rains occurring during the kharif season from June to September and very little during the rest of the year. Although rainfall is extremely low, it can be highly variable. During kharif, weekly median rainfall never exceeds 10 mm, but, in some weeks in some years, there could be as much as 90 mm of rain. In the rabi season too, though there is very little weekly median rainfall, there could be 25 mm or more of rain in some weeks in some years (Fig. 25). Weekly average maximum temperature ranges from about 23 °C to more than 40 °C and minimum temperature from 8 to 27 °C, with the highest from April to September and the lowest from November to February. Daily average solar radiation ranges from 10 to 23 MJ m^{-2}, with the highest noted from April to September and the lowest during rabi.

Subtropical to warm-temperate agroecosystem

China. The four sites in China have a subtropical to warm temperate climate with severe cold winter. They have four seasons—spring, summer, autumn, and winter. Spring is generally from March to May, summer from June to August, autumn from

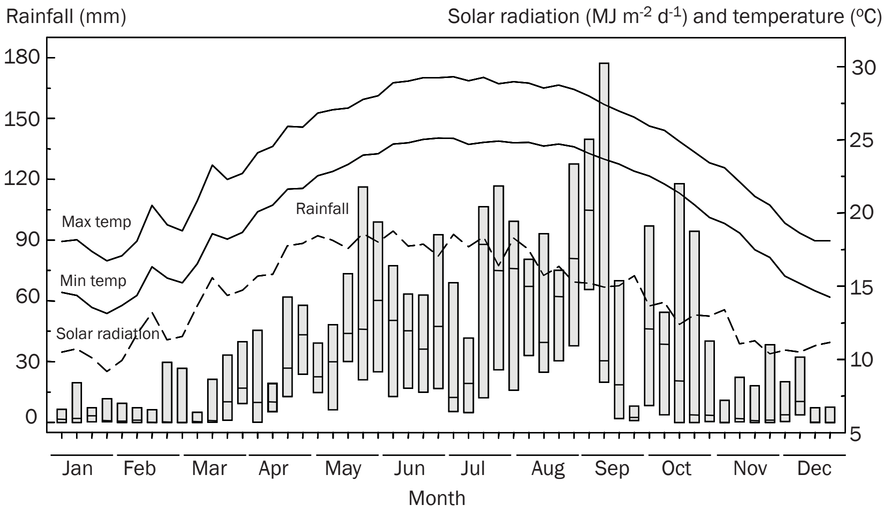


Fig. 24. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Thanh Hoa, northern Vietnam, during the whole year.

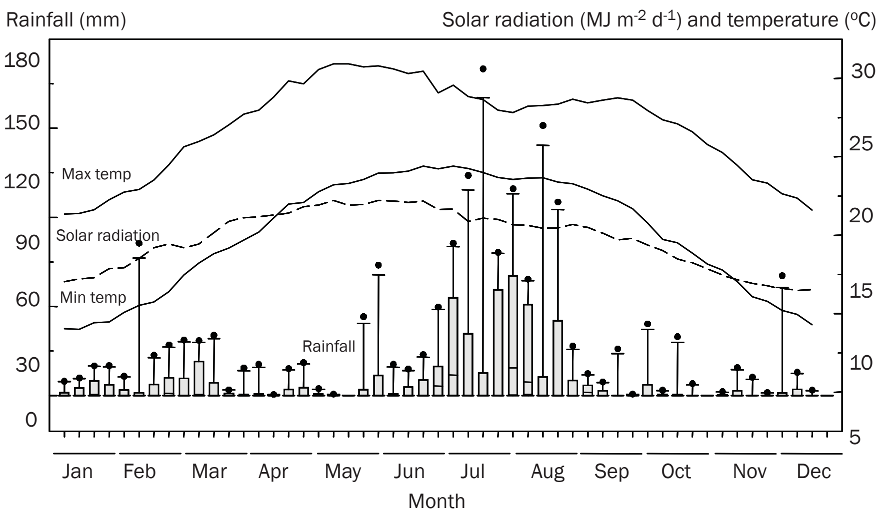


Fig. 25. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Larkana, Sindh, Pakistan, during the whole year.

September to November, and winter from December to February. In Changsha (Hunan) and Wuhan (Hubei), winter is generally short. In Yangzhou (Jiangsu), it is long and in Jinhua (Zhejiang), it is intermediate.

Changsha, Hunan: Rainfall at this site is variable throughout the year, with some extreme rainfall in almost all weeks. The weekly median rainfall during spring and autumn varies from zero to more than 50 mm with somewhat similar median rainfall in both seasons (Fig. 26). Extreme events are more common in the summer than in any season. In many weeks in spring, there is a 10% chance of having more than 100 mm of weekly rain, whereas, in summer, there can be more than 150 mm of weekly rain. In autumn and winter, there is a 10% chance of more than 50 to 75 mm of rain occurring in many weeks. Both daily mean minimum and maximum temperatures and daily mean solar radiation are highly variable throughout the year. Mean maximum temperature ranges from as low as 10 °C to as high as 30 °C, while the mean minimum temperature ranges from 7 to 22 °C. Both maximum and minimum temperatures are highest from June to September and lowest from November to February. Mean daily solar radiation during the year ranges from 7 to 19 MJ m^{-2}, the highest during July/August and the lowest during December/January (Fig. 26).

Wuhan, Hubei: At this site, rainfall is lower than in Changsha, with weekly median rainfall ranging from 0 to about 60 mm (Fig. 27). Rainfall is higher during summer, followed by spring, and then autumn and winter. Mean daily maximum temperature ranges from 9 to 30 °C, while mean daily minimum temperature ranges from 1 to 21 °C. As in Changsha, both mean maximum and minimum temperatures

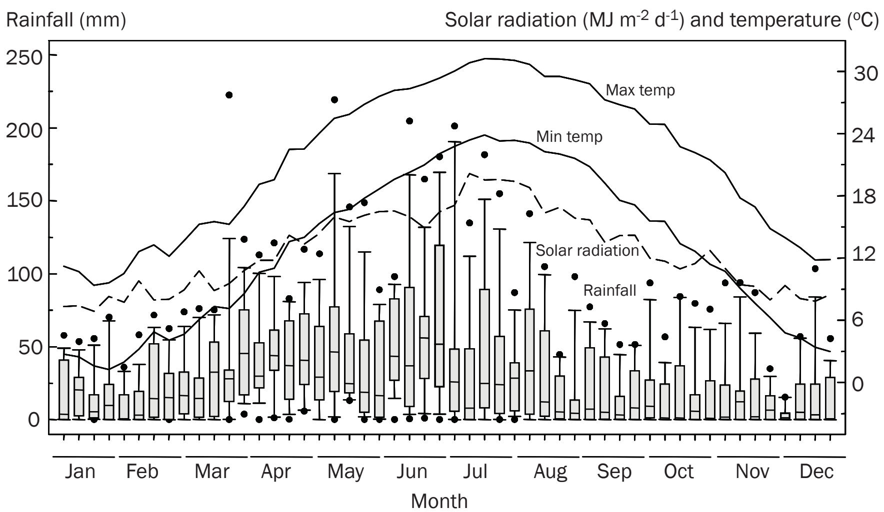


Fig. 26. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Changsha, Hunan, China, during the whole year.

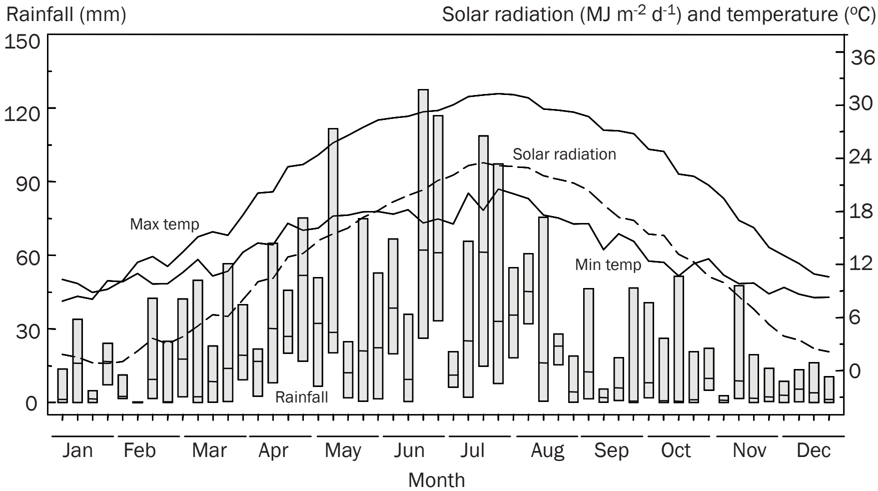


Fig. 27. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Wuhan, Hubei, China, during the whole year.

are highest from June to September and lowest from December to February. Mean daily solar radiation varies from 9 to 21 MJ m^{-2}, with highest values from May to August and lowest from November through February (Fig. 27).

Yangzhou, Jiangsu: At this site, annual rainfall is lower than in Changsha and Wuhan. Weekly median rainfall in Yangzhou ranges from 0 to 90 mm, but with the median rainfall exceeding 40 mm in only 2 weeks (Fig. 28). Rainfall is highest from May to August, followed by that from February to April. Mean maximum temperature ranges from 8 to 30 °C, while minimum temperature ranges from –1 to 21 °C. Both minimum and maximum temperatures are highest from June to September and lowest from November to February. Mean daily solar radiation ranges from 9 to 19 MJ m^{-2} and is higher from April to August than during other months (Fig. 28).

Jinhua, Zhejiang: At this site, weekly median rainfall ranges from 0 to 105 mm, but only for a few weeks does the median rainfall exceed 45 mm (Fig. 29). As in other sites, rainfall is highest during summer, followed by spring and then autumn and winter. The variability in mean maximum and minimum temperatures during the year is quite large, with mean maximum temperature ranging from 8 to 30 °C and mean minimum temperature from 0 to 22 °C. Mean daily solar radiation varies from 8 to 18 MJ m^{-2}, with the highest observed in July/August and the lowest in December/ January (Fig. 29).

India. Ludhiana, Punjab: Ludhiana is located at 247 m asl in Punjab, northwest India. The climate is semiarid with summer monsoon rainfall and cold winter. There are three main seasons—kharif from June/July to October, winter from November to February, and prekharif from March to May/June. In the kharif season, more rainfall occurs from July to September, with least rain in June and October (Fig. 30). The weekly median rainfall during the kharif season ranges from 0 to about 50 mm, with

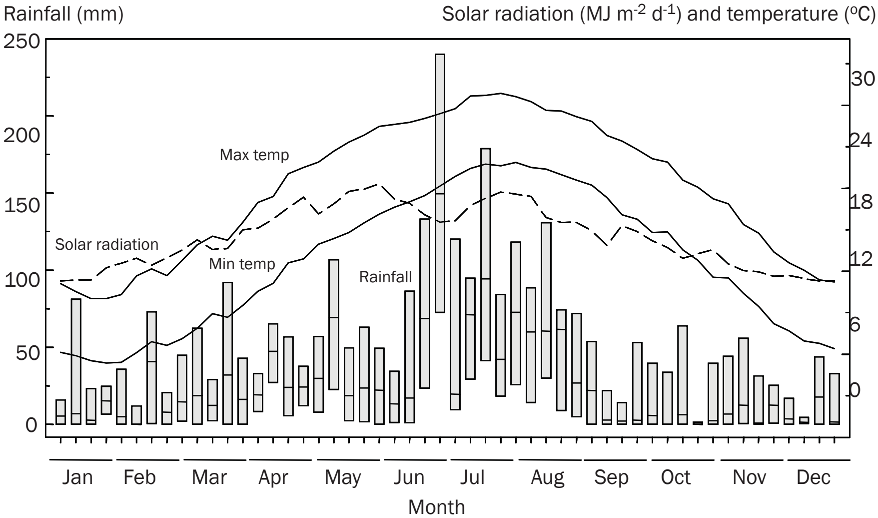


Fig. 28. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Yangzhou, Jiangsu, China, during the whole year.

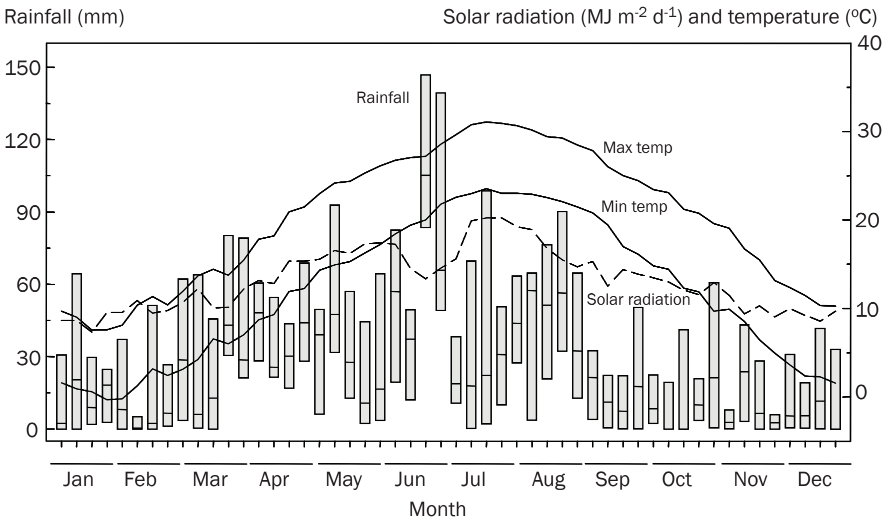


Fig. 29. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Jinhua, Zhejiang, China, during the whole year.

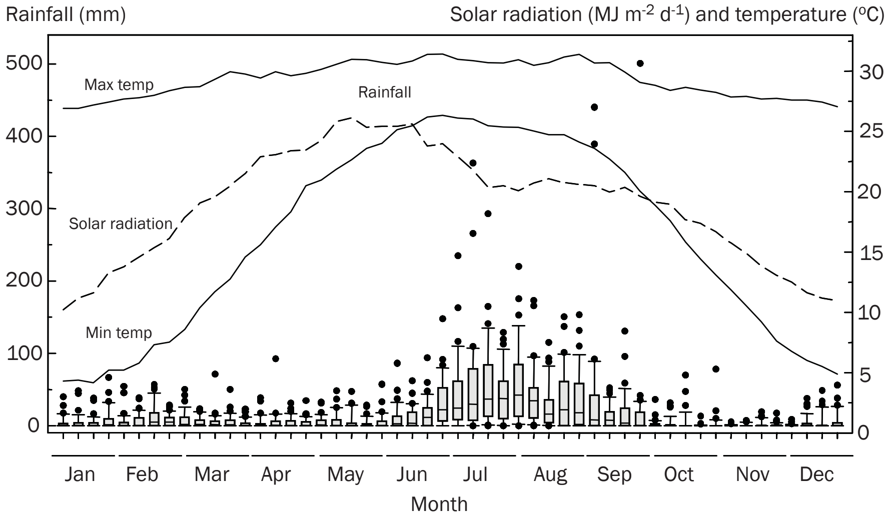


Fig. 30. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Ludhiana, Punjab, India, during the whole year.

10–30% probability of occurrence of greater than 150 mm weekly rain in many weeks. Rainfall from July to September is also highly erratic and variable, with extreme rainfall (10% probability of occurrence) of 300–500 mm occurring occasionally in many weeks in July and September. Although the weekly median rainfall during winter is quite low, there is a 10–30% probability of occurrence of greater than 25 mm of rain in many weeks. The variability in mean maximum temperature during the year is lower compared with mean minimum temperature. Mean maximum temperatures are always 27–32 °C, while mean minimum temperatures vary from 5 to 25 °C. Minimum temperatures are lowest from November to February and highest from April to September. Daily mean solar radiation is also highly variable, from 5 to 25 MJ m^{-2}. Solar radiation is highest from April to September and follows the minimum temperature trend (Fig. 30).

Nepal. Rampur, Chitwan: This site is located at 228 m and has a subtropical climate with cold winter. There are three distinct seasons—prekharif or spring from March to May, kharif or summer from June to October, and rabi or winter from November to February. Most rainfall at this site occurs from June to September, with weekly median rainfall ranging from 10 to 80 mm (Fig. 31). The spring season has very little rain in most weeks, whereas winter is completely rainless. The trends for mean maximum and minimum temperatures are different. Mean maximum temperature ranges from 16 to 27 °C, whereas mean minimum temperature ranges from 4 to 19 °C. Mean minimum temperatures are highest from May to September and maximum temperatures are highest from March to May. Both mean maximum and minimum temperatures are lowest during the November to February period. Mean daily solar radiation is highly variable during the year (13–24 MJ m^{-2}), showing two peaks—March to May and October and November (Fig. 31).

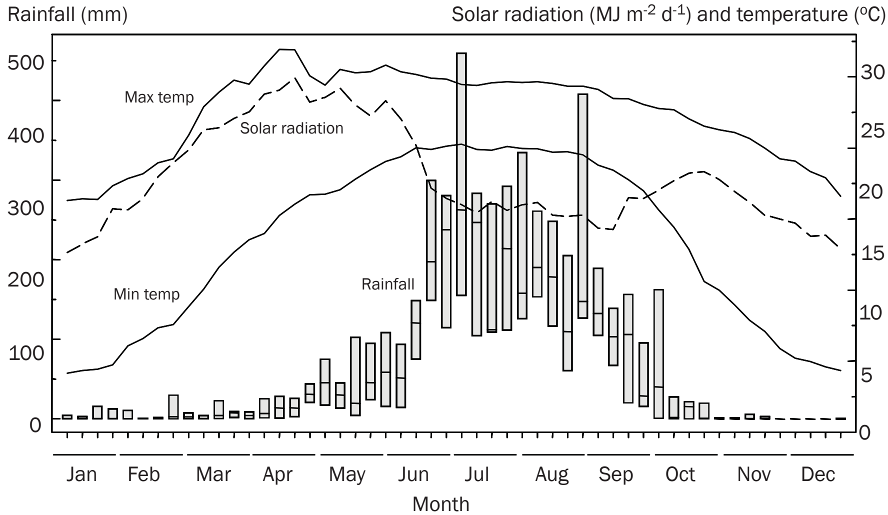


Fig. 31. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Rampur, Chitwan, Nepal, during the whole year.

Dhankuta: This site is located at 1,450 m and has a subtropical to warm temperate climate with cold winter. As in Chitwan, there are three seasons—prekharif or spring from March to May, kharif or summer from June to September, and rabi or winter from October to February. Because of the hills and mountains surrounding this site, the weather data downloaded from NASA seemed unrealistic. Hence, no attempt was made to analyze the weather data for this site; actual historical data will be obtained and analyzed in the future.

Pakistan. Okara, Punjab: Okara has a semiarid climate with very low rainfall. The annual rainfall for this site is about 400 mm, with most rains occurring during the kharif season from June to September; there is very minimum rain during the rest of the months. Although rainfall is low, it can be highly variable during both kharif and rabi. During the kharif season, weekly median rainfall never exceeds 20 mm, but, in some weeks in some years, there could be as much as 150 mm of rain. During rabi also, although there is very little weekly median rainfall, some years could have up to 25 mm of weekly rain (Fig. 32). Daily average maximum temperature ranges from 20 to 40 °C and minimum temperature from 5 to 28 °C. The highest temperatures are noted from April to September, whereas the lowest are observed from November to March. Daily average solar radiation ranges from 10 to 23 MJ m^{-2}, with the highest noted from April to September and the lowest during the rabi season.

Evaluation of NASA weather data

The NASA data have been validated against field-measured data for all weather parameters and variables globally and in the U.S. There was good agreement between solar radiation estimated by SRB ver. 3.0 and that obtained from BSRN network sites,

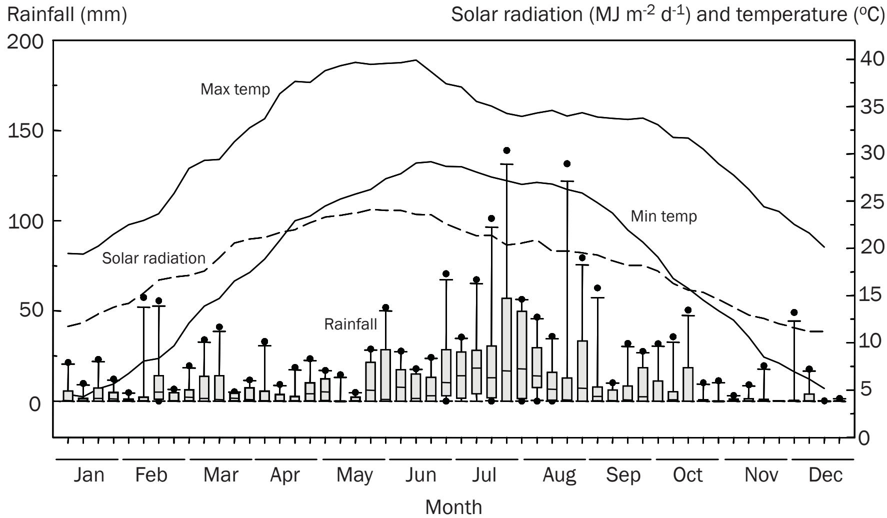


Fig. 32. Variability of weekly total rainfall, weekly mean solar radiation, and mean maximum and minimum temperature at Okara, Punjab, Pakistan, during the whole year.

and also between temperatures estimated by GEOS-4 and those obtained from NCDC (Stackhouse 2006). However, for the mountainous regions of the western U.S., there were large differences between the NCDC and GEOS-4 temperatures, particularly for maximum temperature. Likewise, for the coastal regions, where the 1° GEOS-4 cell is too coarse to capture localized ocean/land gradients, the data tended to exhibit larger differences. A comparison of the POWER/SSE values with ground-site measurements of rainfall for accumulation over a 1-d, 5-d, and 30-d period illustrated virtually identical results, indicating that similar rainfall was observed at all sites, except at the mountainous and coastal sites (Stackhouse 2006, White et al 2008).

Comparison of NASA/POWER-derived and measured weather data

Figures 33 and 34 show a comparison of NASA/POWER-derived daily weather data with the ground-measured daily data for 1998 at Pila, Laguna, a tropical environment in the Philippines. Measured daily maximum temperatures were slightly higher than NASA-derived temperatures, especially during the wet season from June to November, but the temperatures were similar during the dry season. Although the measured daily minimum temperatures were higher in the wet season, there were fewer variations compared with maximum temperatures. In the dry season, the measured daily minimum temperatures were lower than the NASA-derived minimum temperatures. Measured daily solar radiation values were consistently higher than NASA-derived data throughout the year. Highly extreme rainfall events measured by a rain gauge were not captured by NASA. For Ludhiana, Punjab, India, with a subtropical environment, the actual measured daily maximum and minimum temperatures throughout 2000 were in close correspondence with the NASA-derived temperatures. There were, however, some discrepancies between the measured and the NASA-derived daily solar

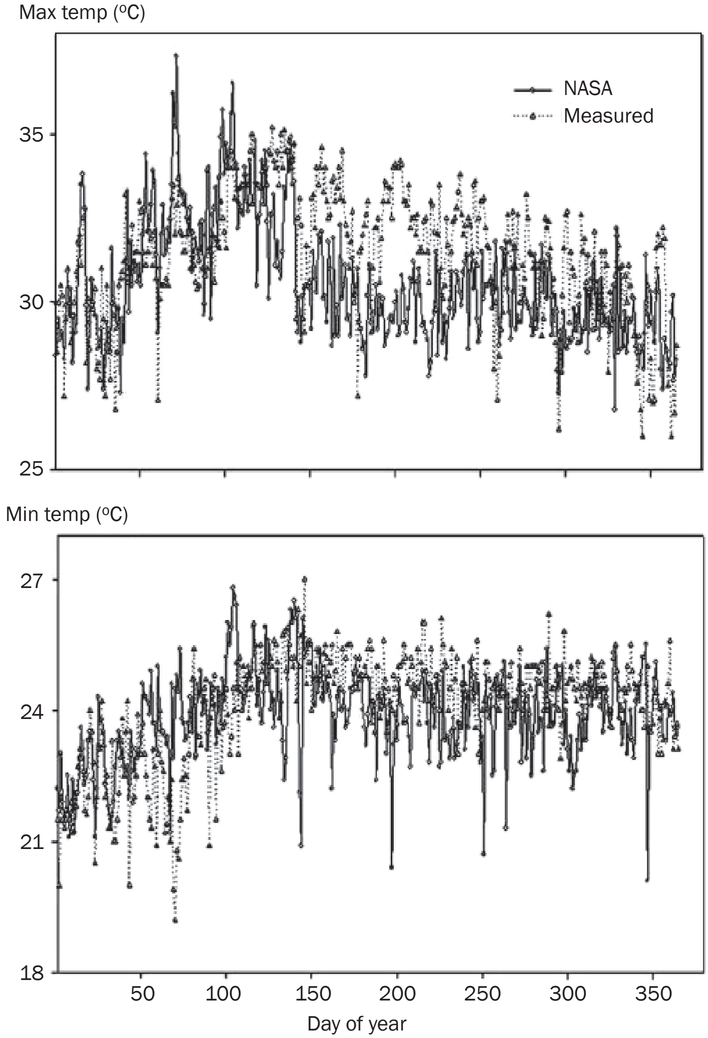


Fig. 33. Maximum and minimum temperature for 1998, Pila, Laguna, Philippines, using ground-measured and satellite-derived NASA data.

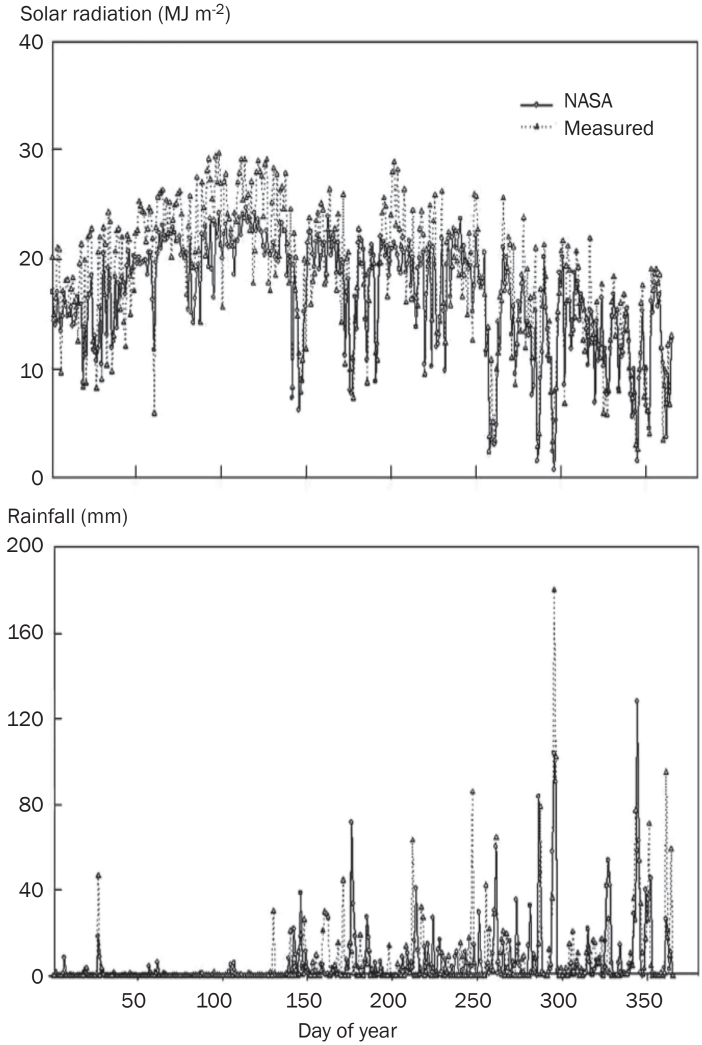


Fig. 34. Solar radiation and rainfall for 1998, Pila, Laguna, Philippines, using ground-measured and satellite-derived NASA data.

radiation; in most cases, NASA-derived data showed higher solar radiation than the ground-measured data. Like in Pila, Laguna, NASA could not estimate the extreme rainfall events observed in Ludhiana (Figs. 35 and 36).

Figures 37 and 38 show comparisons between NASA-derived daily maximum and minimum temperature, solar radiation, and rainfall and ground-measured data for several years from a range of locations in Asia. The maximum temperature for the NASA data ranged from –3.0 to 46.1 °C, whereas the measured temperature ranged from –2.1 to 50.1 °C. The corresponding NASA-derived and measured minimum temperature ranged from –12.0 to 34.9 °C and –10.3 to 38.2 °C, respectively. Daily average NASA-derived solar radiation ranged from 0.5 to 32.2 MJ m^{-2}, while the measured solar radiation ranged from 0 to 35.8 MJ m^{-2}. The overall mean maximum temperature reflected in the NASA data was 1.6 °C cooler than that given by the measured data; values of mean minimum temperature were exactly the same for both sources of data. As for mean solar radiation, NASA data were 0.3 MJ m^{-2} d^{-1} higher than measured data. Although mean daily rainfall was similar (4.8 vs 4.2 mm for NASA and measured data), there were large variations in individual daily rainfall (range: 0–177 mm for NASA data; 0–382 mm for measured data). R^2 values for maximum and minimum temperature were 0.56 and 0.72, respectively, showing satisfactory agreement between NASA-derived and ground-measured data. For solar radiation, R^2 was less satisfactory (0.43); for rainfall, it was least satisfactory (0.13). Although the R^2 values were generally less than desired, the scatter diagrams show similar trends and patterns, indicating a close relationship between NASA-derived and actual ground-measured data, especially for temperature and solar radiation, for a range of sites in Asia.

Comparison of simulated grain yield and growth duration using NASA/POWER and measured data

Comparisons of potential yield and growth duration of maize and rice as simulated by Hybrid Maize and ORYZA2000 using NASA/POWER and measured data are presented in Figures 39 and 40. Although differences at some sites in simulated potential yields of maize of up to 5–6 t ha^{-1} were noted, maize yields using NASA-derived data matched reasonably well those estimated using measured data ($R^2 = 0.62$) when all locations were combined. Likewise, although differences of up to 20 d occurred for some locations, simulated growth duration using the two sources of data matched very well, with an R^2 of 0.88. Except for some cooler environments in Vin Phuc, northern Vietnam, and for sites in Bangladesh, potential yields of rice simulated by ORYZA2000 using NASA-derived data had a good match with those simulated by using measured data ($R^2 = 0.57$). Simulated growth duration using the two sources of data, however, matched extremely well, with the least discrepancy ($R^2 = 0.95$).

Evaluation of Hybrid Maize

The Hybrid Maize model has been evaluated for several locations in north-central U.S. and in Southeast Asian countries. In an experiment in Lincoln, Nebraska, maximum

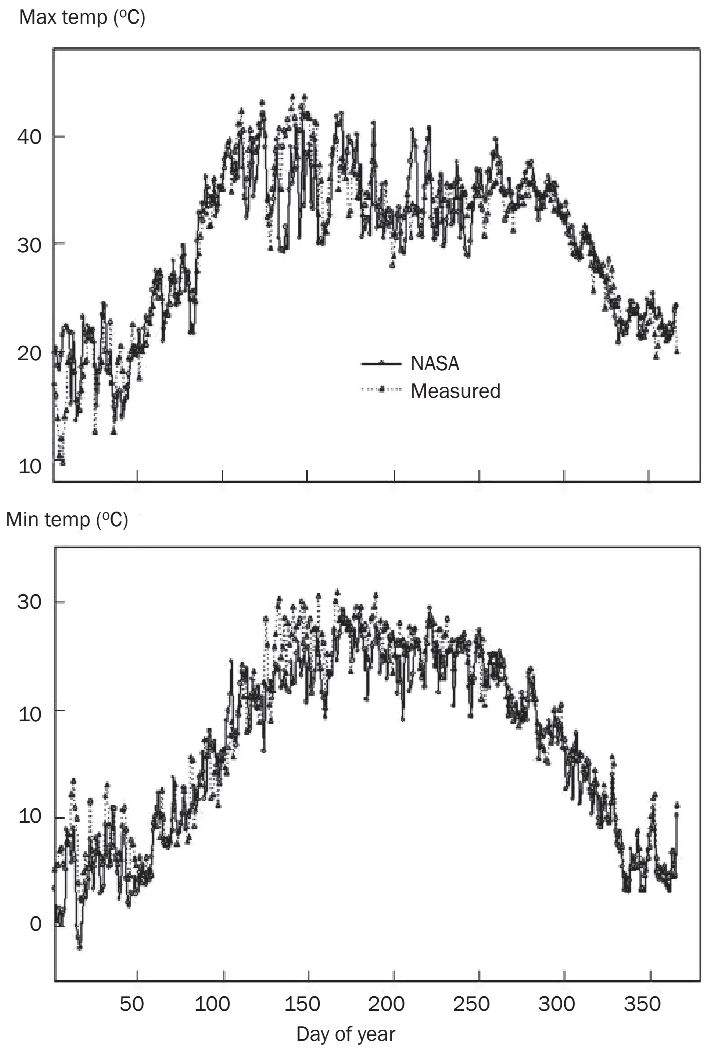


Fig. 35. Maximum and minimum temperature for 2000, Ludhiana, Punjab, India, using ground-measured and satellite-derived NASA data.

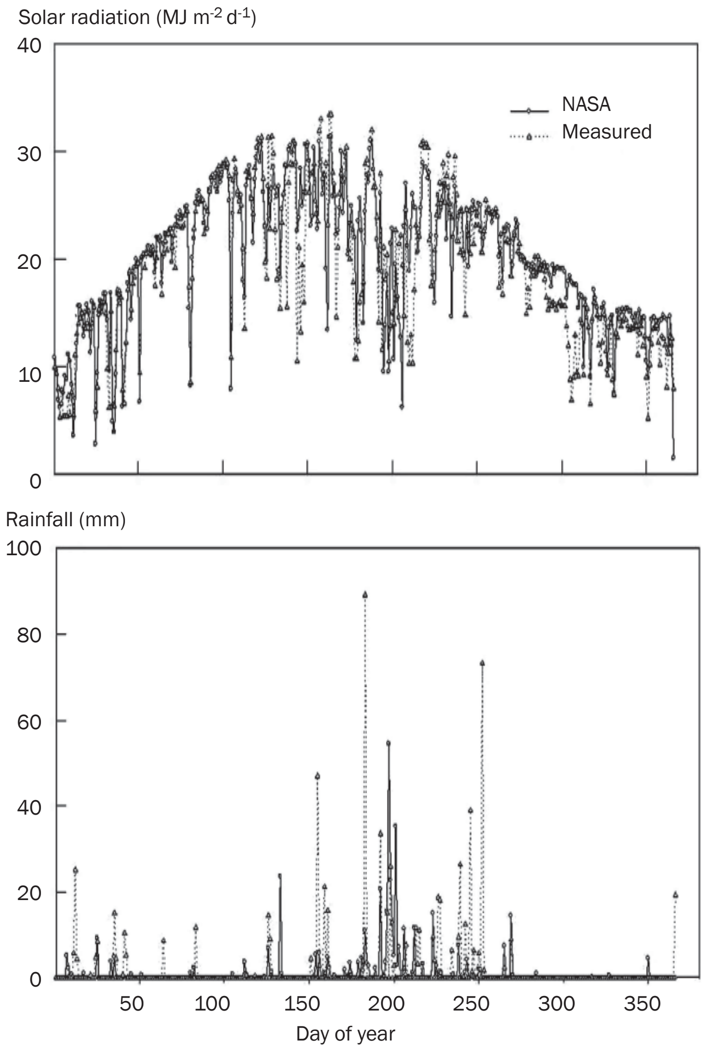


Fig. 36. Solar radiation and rainfall for 2000, Ludhiana, Punjab, India, using ground-measured and satellite-derived NASA data.

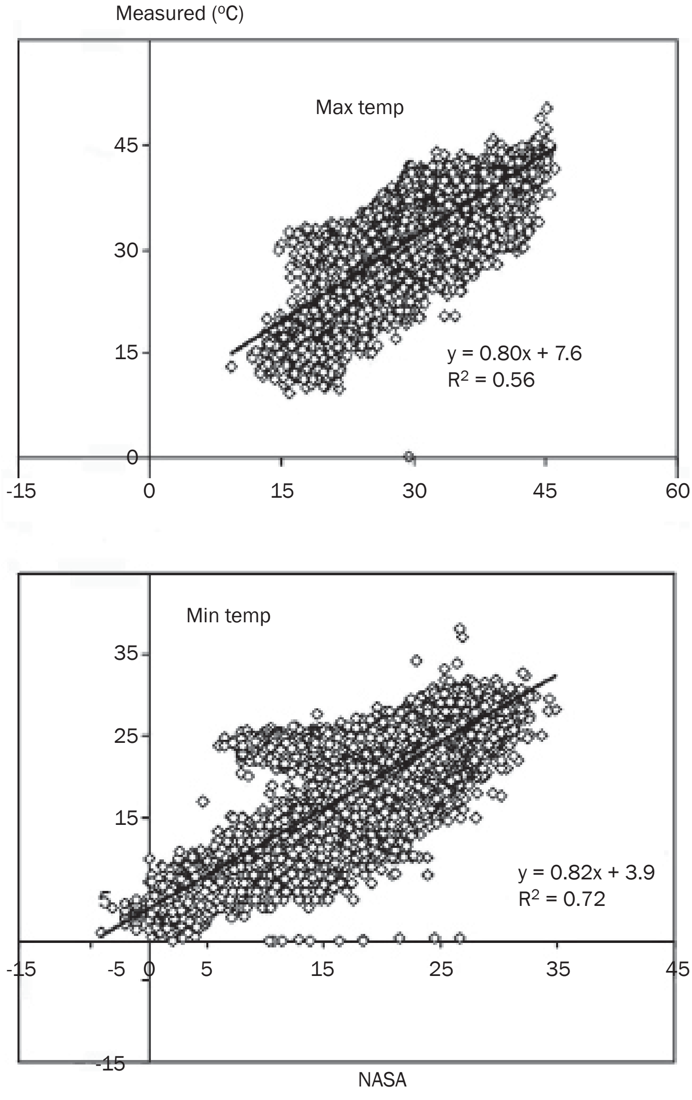


Fig. 37. Comparison of NASA-derived and measured maximum and minimum temperature from 1983 to 2005 in several countries in Asia. Sites with temperature data include Bogra (1984-2002), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Changsha (1990-2000) in China; Ludhiana (1984-2004) and Begusarai (1984-2004) in India; Central Lampung (2000-04) and Maros (1990-2004) in Indonesia; Los Baños (1984-2004) and Muñoz (1994-2001) in the Philippines; and An Giang (1999-2004) and Vin Phuc (1992-2002) in Vietnam.

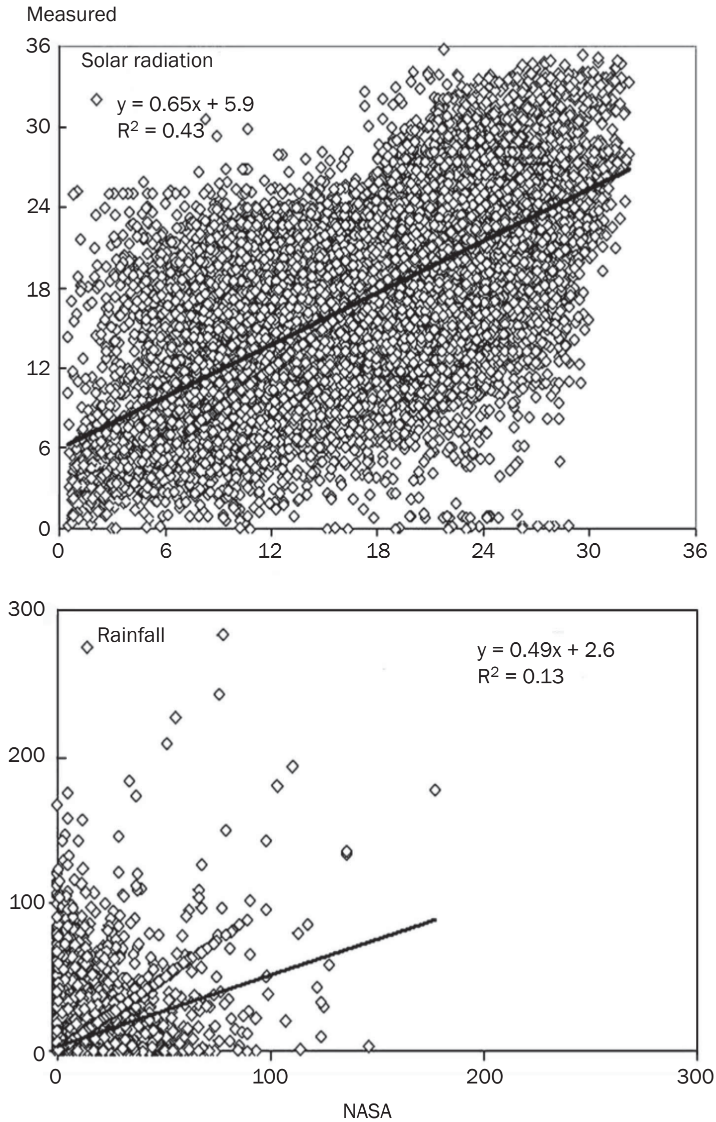
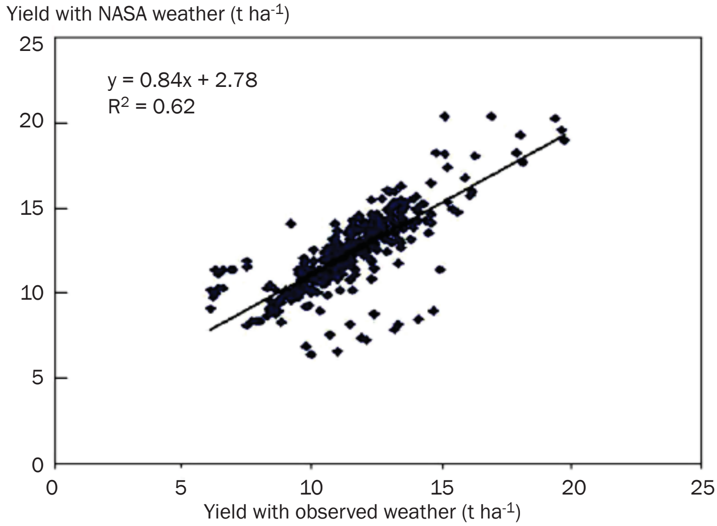


Fig. 38. Comparison of NASA-derived and measured solar radiation and rainfall at several sites in Asia. Sites with solar radiation data include Bogra (1984-2002), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Changsha (1990-2000) in China; Ludhiana (1984-2004) and Begusarai (1984-2004) in India; Central Lampung (2000-04) and Maros (1990-2004) in Indonesia; Los Baños (1984-2004) and Muñoz (1994-2001) in the Philippines; and AnGiang (1999-2004) and Vinh Phuc (1992-2002) in Vietnam. All sites are compared with NASA rainfall data from 1997 only.



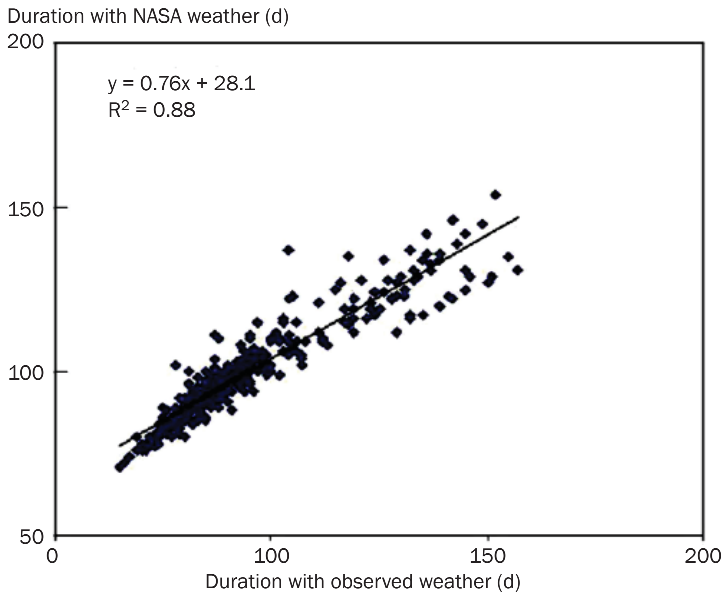


Fig. 39. Comparison of potential yield and growth duration of maize simulated by Hybrid Maize using NASA-derived and ground-measured weather data for selected sites in Asia. Weather data used for the selected sites are as follows: Bogra (1984-2004), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Maros (1990-2004) in Indonesia; Muñoz (1994-2001) and Los Baños (1984-2004) in the Philippines; and An Giang (1999-2004) and Vinh Phuc (1992-2002) in Vietnam. The growing degree days of the hybrid maturity groups were in the 1,400–1,800 range.

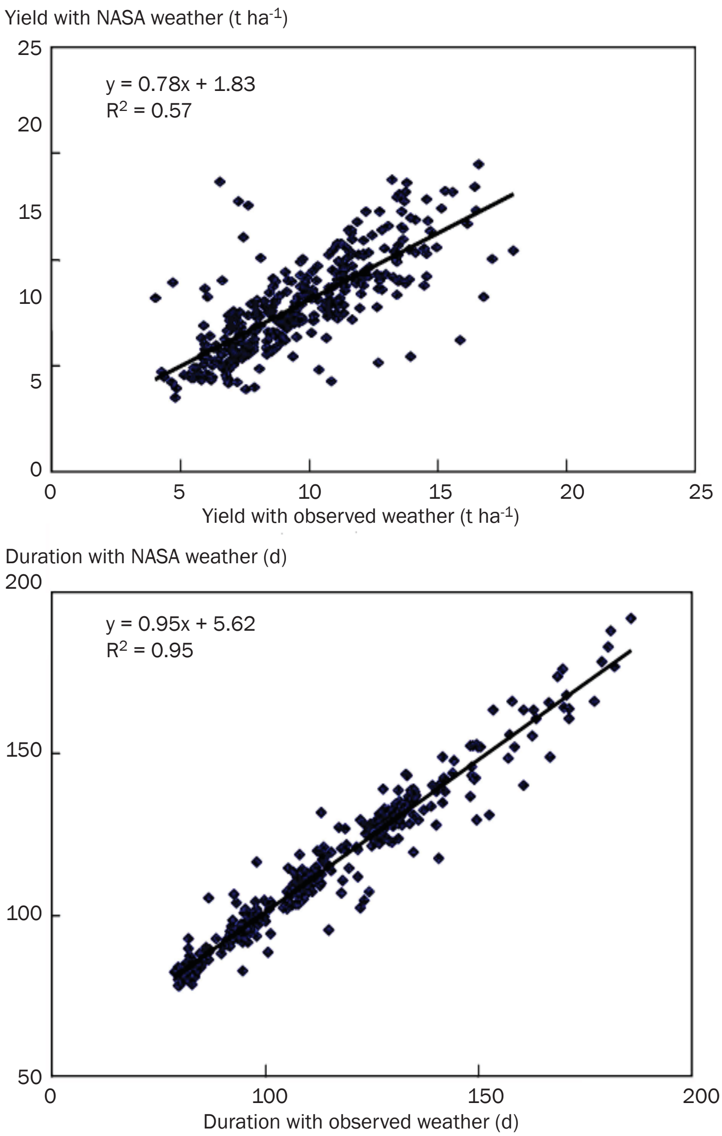


Fig. 40. Comparison of grain yield and growth duration of rice simulated by ORYZA2000 using NASA-derived and ground-measured weather data for selected sites in Asia. Weather data used for the selected sites are as follows: Bogra (1984-2004), Dinajpur (1984-99), and Jessore (1984-2002) in Bangladesh; Maros (1990-2004) in Indonesia; Muñoz (1994-2001) and Los Baños (1984-2004) in the Philippines; and An Giang (1999-2004) and Vinh Phuc (1992-2002) in Vietnam. Maturity groups used were extra short, short, intermediate, and long.

plot yields from the highest yielding treatments were 14.4 t ha^{-1} in 1999 (in a plot with 11.4 plants m^{-2}), 14.0 t ha^{-1} in 2000 (in a plot with 9.8 plants m^{-2}), and 14.5 t ha^{-1} in 2001 (in a plot with 11.2 plants m^{-2}). These maximum measured yields were in close agreement with the simulated Yp of 14.3, 14.0, and 14.1 t ha^{-1} for the same treatment-year combinations. The model was also relatively robust in accounting for differences in grain yield associated with plant density in most years (Yang et al 2004). Overall, grain yields simulated by Hybrid Maize were 5–12% of the measured yields across treatments and years. The model has also been tested and used to predict Yp and quantify yield gaps at several sites in Indonesia, the Philippines, and Vietnam. Table 6 shows the actual, attainable, maximum attainable, and simulated Yp of maize for some selected sites in these three countries from 2004 to 2007 (Witt et al 2008). The data reported were the average of five farms per site in at least three seasons. Attainable yield was estimated in treatments with an ample supply of fertilizer N, P, and K. The maximum attainable yield was the single highest yield observed in an NPK treatment at each site. The simulated potential yield was estimated using actual planting densities used at each site. Except for Wonogiri in Central Java, Indonesia, and An Giang, southern Vietnam, maximum attainable yields were 80–90% of potential yield simulated by Hybrid Maize, indirectly indicating that the potential yields simulated by the model are in agreement with field experimental results across different environments in Southeast Asia.

Table 6. Actual, attainable, maximum attainable, and simulated yield potential (t ha^{-1}) of maize at selected sites in Southeast Asia.[a]

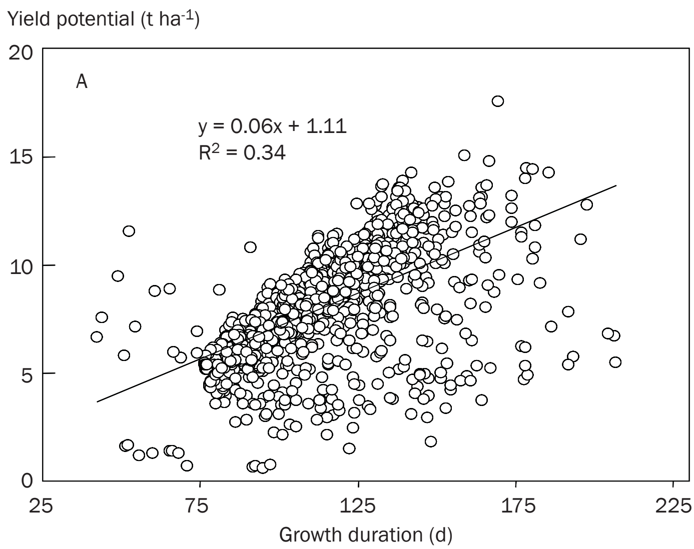
Site	Av farmers' yield	Av attainable yield	Maximum attainable yield	Simulated potential yield
Wonogiri, Central Java, Indonesia	4.9	5.7	7.3	12–14
Lampung, Indonesia	7.2	9.2	13.7	12–14
Nueva Ecija, Philippines	7.9	9.0	14.2	15–18
An Giang, Vietnam	8.3	8.8	10.3	14–16
Cum'gar, Dak Lak, Vietnam	6.2	7.8	12.0	14–15

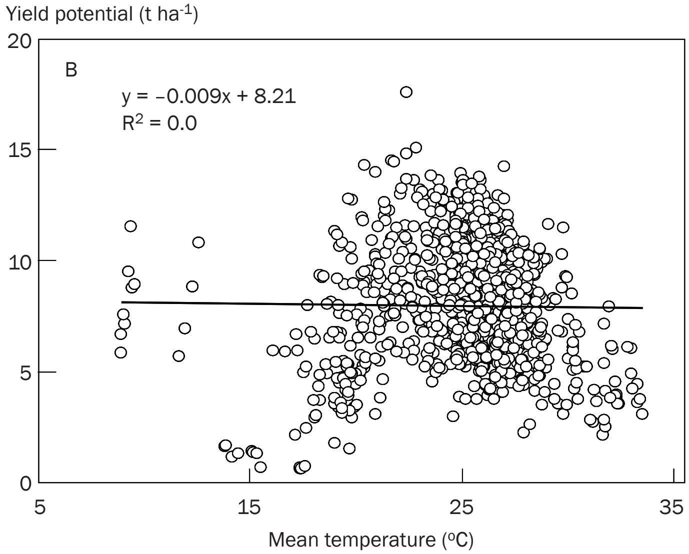
[a]Source: Witt et al (2008).

Rice

Yield potential, growth duration, total growing season solar radiation, and mean temperature during the growing season for four generic rice varieties at key locations across R-M agroecosystems in Asia are summarized in Tables 7–9. The mean Yp of extra short, short, intermediate, and long-duration rice varieties across environments ranged from 1.6 to 9.0, 0.4 to 10.6, 1.9 to 13.0, and 1.2 to 17.6 t ha^{-1}, respectively. There were large differences in Yp among sites within a country or among countries. For each site, Yp was highest for long-duration varieties and lowest for extra short-duration ones (Tables 7–9). The large ranges in Yp for the different varieties were associated with large variations in growth duration, total intercepted solar radiation, and temperature during the growing season. Relationships between Yp and growth duration, solar radiation, and mean temperature across all sites together are presented in Figure 41. The variability in Yp, growth duration, solar radiation, and mean temperature across varieties and sites for three R-M agroecosystems is shown in Figure 42.

Tropical warm agroecosystem. The Yp of four rice varieties for the tropical warm climate (humid, semihumid, semiarid, warm year-round, with no winter environments) ranged from 3.9 to 8.9, 4.7 to 10.6, 5.3 to 13.0, and 7.4 to 15.1 t ha^{-1}, respectively (Table 7; Fig. 43). Yp of all varieties was highest for Chiang Rai in northern Thailand





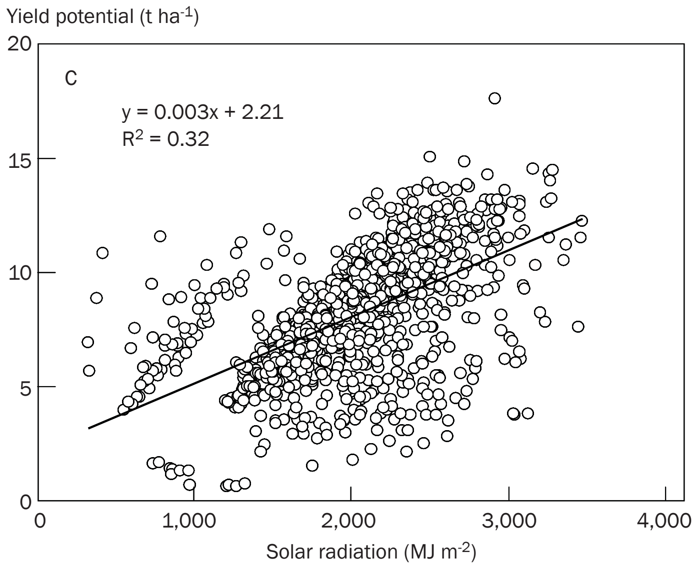


Fig. 41. Relationships between rice yield potential and (A) growth duration, (B) mean temperature, and (C) solar radiation (all sites and varieties combined).

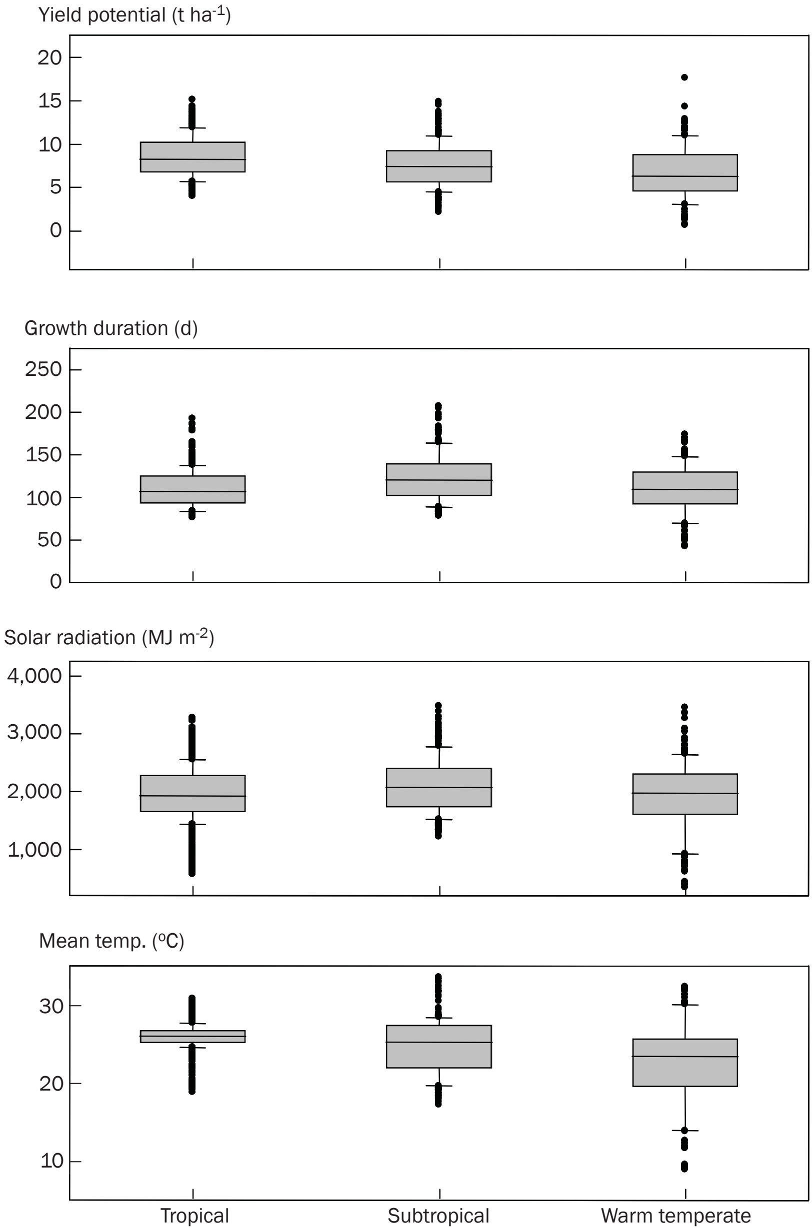
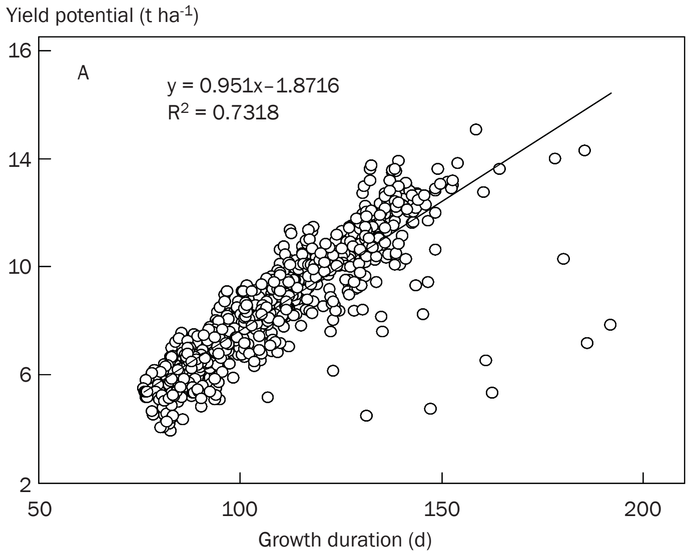


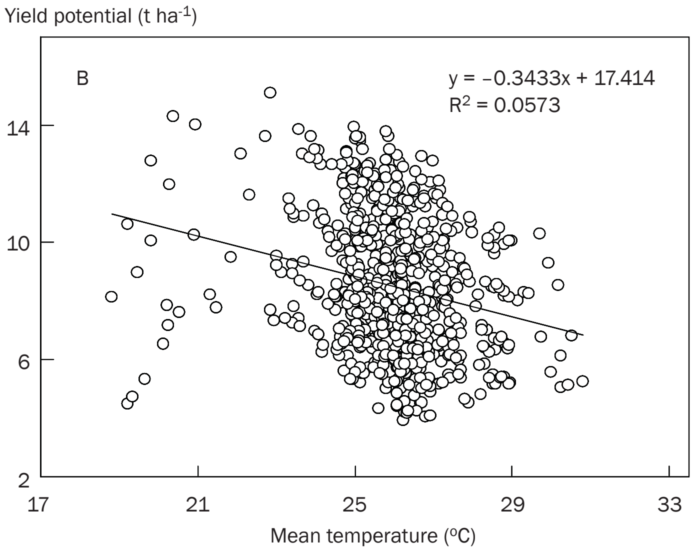
Fig. 42. Variability in Yp, growth duration, solar radiation, and growing-season mean temperature of four rice varieties under three agroecosystems.

Table 7. Summary of yield potential and growing-season characteristics of four rice varieties grown on the first day of each month in tropical Asia.

Country	Location	Variety	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
Philippines	Pila	Extra short	3.9–6.5	81–88	560–960	25.2–27.7
		Short	5.0–8.0	93–100	680–1,100	25.2–27.6
		Intermediate	7.0–10.0	108–115	820–1,310	25.4–27.5
		Long	8.5–12.0	128–135	1,020–1,600	25.5–27.4
	Muñoz	Extra short	4.2–6.8	81–90	1,277–1,757	24.8–27.2
		Short	5.9–8.1	92–102	1,453–1,922	24.9–27.2
		Intermediate	6.5–10.2	106–116	1,643–2,249	25.1–27.0
		Long	8.5–12.4	124–138	1,984–2,622	25.2–27.0
Indonesia	Medan	Extra short	5.4–6.8	86–90	1,320–1,600	24.6–25.6
		Short	5.8–8.2	98–103	1,560–1,800	24.6–25.6
		Intermediate	8.4–10.2	117–119	1,800–2,080	24.7–25.6
		Long	10.4–12.6	134–140	2,140–2,440	24.7–25.6
	Kediri	Extra short	6.2–8.1	93–98	1,620–1,940	24.8–25.8
		Short	6.6–9.2	98–102	1,680–2,000	24.8–25.8
		Intermediate	8.6–11.2	114–118	1,955–2,340	24.9–25.7
		Long	10.4–13.8	132–140	2,310–2,740	25.0–25.7
	Maros	Extra short	4.5–7.5	82–86	1,410–1,960	25.6–26.6
		Short	5.6–9.0	94–98	1,590–2,200	25.8–26.6
		Intermediate	7.4–11.0	109–113	1,810–2,560	25.7–26.6
		Long	9.0–13.6	128–133	2,400–2,970	25.8–26.5
	Sukamandi	Extra short	5.2–7.2	86–89	1,400–1,640	24.9–25.4
		Short	6.7–9.1	99–101	1,600–1,900	24.9–25.4
		Intermediate	8.2–11.2	117–119	1,860–2,200	24.9–25.3
		Long	10.2–13.6	138–139	2,270–2,600	25.0–25.3
	Central Lampung	Extra short	5.2–6.0	83–85	1,325–1,525	25.7–26.3
		Short	6.4–7.5	93–97	1,510–1,730	25.7–26.2
		Intermediate	8.2–9.5	108–113	1,765–2,000	25.7–26.2
		Long	10.1–11.5	128–133	2,085–2,340	25.8–26.2
Thailand	Chiang Rai	Extra short	4.5–8.9	90–131	1,465–2,315	18.8–25.7
		Short	4.7–10.6	102–149	1,615–2,520	19.2–25.6
		Intermediate	5.3–13.0	119–163	1,910–2,870	19.7–25.4
		Long	7.8–15.1	142–192	2,410–3,265	20.2–25.2

Country	Location	Variety	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean tempera-ture (°C)
	SuphanBuri	Extra short	5.9–6.8	81–93	1,450–1,855	24.2–27.4
		Short	7.4–8.2	93–104	1,680–2,085	24.3–27.3
		Intermediate	9.3–10.2	108–122	1,940–2,415	24.5–27.3
		Long	11.1–12.6	127–143	2,295–2,810	24.7–27.2
	Phitsanulok	Extra short	6.0–7.3	82–100	1,460–1,960	23.0–27.4
		Short	7.5–8.4	94–113	1,640–2,150	23.1–27.4
		Intermediate	9.2–11.0	110–131	1,980–2,540	23.4–27.3
		Long	10.4–13.5	128–153	2,280–2,950	23.7–27.1
Vietnam	An Giang	Extra short	5.0–6.1	80–85	1,430–1,760	26.1–27.7
		Short	6.2–7.6	91–96	1,550–1,925	26.1–27.7
		Intermediate	8.0–9.5	106–112	1,775–2,170	26.2–27.7
		Long	10.0–11.6	125–132	2,110–2,540	26.3–27.6
India	Aduthurai	Extra short	4.0–6.3	78–85	1,260–1,770	25.7–29.0
		Short	5.4–7.7	88–96	1,430–2,000	25.7–28.9
		Intermediate	6.5–9.7	103–112	1,680–2,300	25.8–28.9
		Long	8.4–11.9	120–132	2,080–2,670	26.0–28.9
	Thanjavur	Extra short	4.1–6.1	76–84	1,230–1,715	26.0–28.7
		Short	5.1–7.5	87–95	1,435–1,915	26.1–28.7
		Intermediate	6.9–9.4	101–110	1,700–2,240	26.2–28.7
		Long	8.7–11.5	118–130	2,050–2,610	26.3–28.7
	Bangalore	Extra short	6.4–7.7	88–101	1,510-2,010	22.9–27.7
		Short	7.9–9.2	99–115	1,730–2,280	23.0–27.6
		Intermediate	10.0–11.5	116–131	2,015–2,640	23.3–27.3
		Long	12.2–13.8	138–154	2,395–3,075	23.6–27.0
	Nalgonda	Extra short	4.8–7.0	84–95	1,360–2,175	24.1–30.8
		Short	5.1–8.3	96–108	1,560–2,465	24.1–30.5
		Intermediate	6.1–10.6	112–125	1,830–2,765	24.4–30.3
		Long	8.2–12.6	133–147	2,220–3,210	24.7–29.9


Yield potential (t ha-1)
A
y = 0.951x–1.8716
R2 = 0.7318
16
14
10
6
2
50
100
150
200
Growth duration (d)


Yield potential (t ha-1)
B
y = –0.3433x + 17.414
R2 = 0.0573
14
10
6
2
17
21
25
29
33
Mean temperature (ºC)

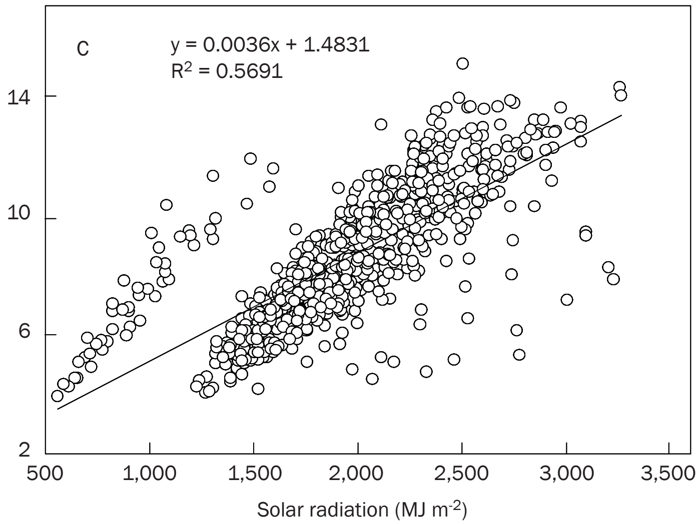


Fig. 43. Yield potential of the and (A) growth duration, (B) mean temperature, and (C) solar radiation (tropical sites).

and lowest for Los Baños, Philippines. Yp for sites in Indonesia, southern India, and the Mekong Delta in Vietnam was in the middle range. The high Yp in Chiang Rai was associated with long growth duration, greater solar radiation, and slightly cooler environment, while the low Yp in Los Baños was due to shorter growth duration and the smaller amount of solar radiation received.

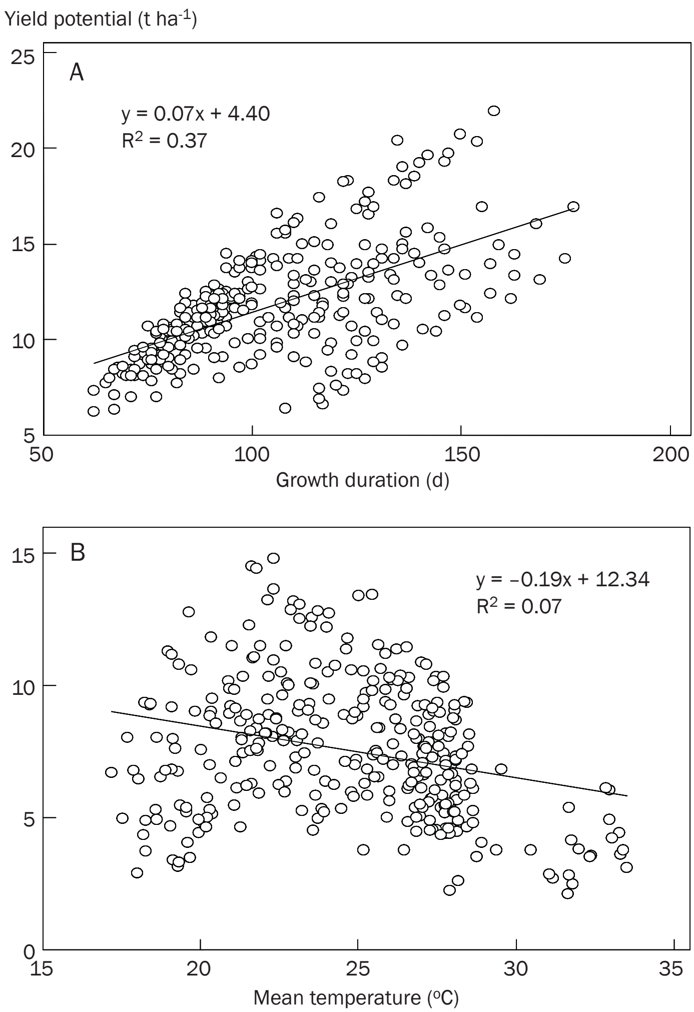
Subtropical warm agroecosystem. The Yp of the four rice varieties for the subtropical climate (subhumid, semiarid, warm summer, with mild cool winter environments) ranged from 2.9 to 9.0, 3.4 to 10.2, 4.7 to 12.3, and 5.5 to 14.5 t ha^{-1}, respectively (Table 8; Fig. 44). It was highest for Dinajpur in Bangladesh and Begusarai in Bihar, followed by Bogra in Bangladesh, and lowest for RRD sites in Vietnam. All varieties at the RRD sites took much longer to mature when transplanted in October and January due to low temperatures during the growing season.

Subtropical to warm temperate agroecosystem. For the four rice varieties for the subtropical to warm temperate climate (subhumid, warm summer, with mild to severe cold winter environments), Yp ranged from 0.6 to 8.8, 0.4 to 9.3, 0.6 to 12.8, and 0.7 to 17.6 t ha^{-1}, respectively (Table 9; Fig. 45). The highest Yp was observed in Punjab, India, followed by Chitwan, Nepal. Yield potential was comparatively lower at the four Chinese sites and in Okara, Pakistan. All the varieties yielded zero when planted from September to February. In the Punjab, the extra short variety planted from November to January suffered from cold injury throughout the season and the plants eventually died. Early, intermediate, and long-duration varieties, when planted in October, also experienced cold injury and died. In Chitwan, Nepal, also, transplanting extra short, short, and intermediate varieties from October to January resulted in cold

Table 8. Summary of yield potential and growing-season characteristics of four rice varieties grown on the first day of each month in subtropical Asia.

Country	Location	Variety	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
Bangladesh	Bogra	Extra short	4.4–8.1	82–121	1,280–2,100	21.1–27.9
		Short	5.2–9.6	90–131	1,405–2,295	21.3–28.0
		Intermediate	6.4–11.0	102–146	1,575–2,580	21.7–27.9
		Long	7.8–11.5	122–168	1,925–3,000	22.3–27.9
	Dinajpur	Extra short	4.5–9.0	79–124	1,300–2,305	20.1–27.4
		Short	5.1–10.2	90–138	1,400–2,500	20.4–27.4
		Intermediate	6.1–12.3	106–156	1,625–2,800	21.0–27.4
		Long	6.2–14.5	125–179	1,950–3,275	21.5–27.3
	Jessore	Extra short	4.3–7.5	78–104	1,208–1,921	21.6–28.2
		Short	5.5–9.0	91–129	1,414–2,266	21.9–28.1
		Intermediate	7.0–10.4	103–142	1,601–2,517	22.2–28.1
		Long	8.2–12.9	122–164	1,928–2,935	22.8–28.1
India	Begusarai	Extra short	4.6–8.9	80–125	1,290–2,235	20.0–28.7
		Short	5.5–9.9	88–140	1,430–2,550	20.3–28.6
		Intermediate	7.4–11.5	105–157	1,730–2,955	21.0–28.5
		Long	6.2–14.8	125–180	2,125–3,470	21.5–28.4
Vietnam	Thanh Hoa	Extra short	2.9–8.0	81–147	1,345–1,795	18.0–26.8
		Short	3.4–9.2	92–164	1,515–2,015	18.3–26.8
		Intermediate	4.7–11.3	107–179	1,735–2,310	18.7–26.8
		Long	5.5–12.8	128–207	2,140–2,630	19.3–26.6
	Vinh Phuc	Extra short	4.4–6.7	82–146	1,325–1,580	17.2–28.1
		Short	4.9–8.0	94–160	1,390–1,690	17.7–28.0
		Intermediate	5.2–9.5	109–178	1,700–1,955	18.3–28.0
		Long	5.4–11.4	130–204	1,910–2,310	19.1–27.7
Pakistan	Larkana	Extra short	2.1–7.0	86–126	1,613–2,367	18.9–33.5
		Short	2.5–8.0	90–131	1,712–2,478	19.1–33.4
		Intermediate	2.8–9.5	107–143	1,937–2,720	19.6–33.1
		Long	3.8–11.5	120–161	2,275–3,130	20.2–33.0

injury and subsequent death of the plants. The long-duration variety, when planted in September, also encountered cold injury, resulting in zero yield. At all sites in China, transplanting extra short and short varieties from October to February resulted in cold injury and subsequent plant death. The intermediate- and long-duration varieties also suffered from cold injury when transplanted in September. For all varieties at all sites, the values in the lower brackets for ranges of yield, growth duration, and solar radiation were very low because of plants dying at an early stage due to cold injury. The result is zero yield.



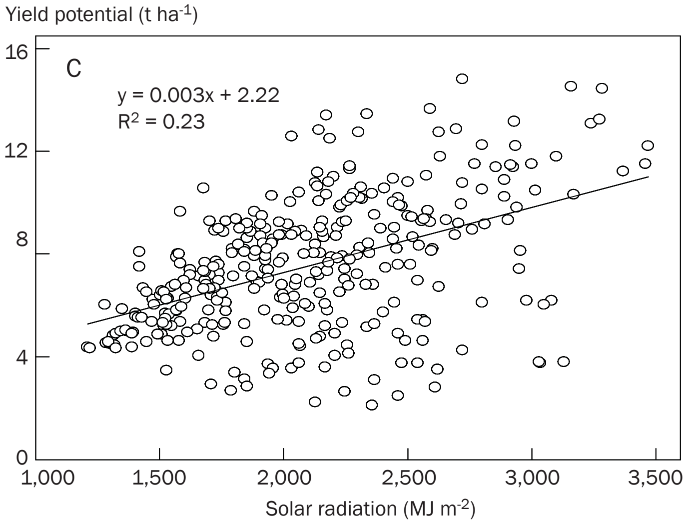
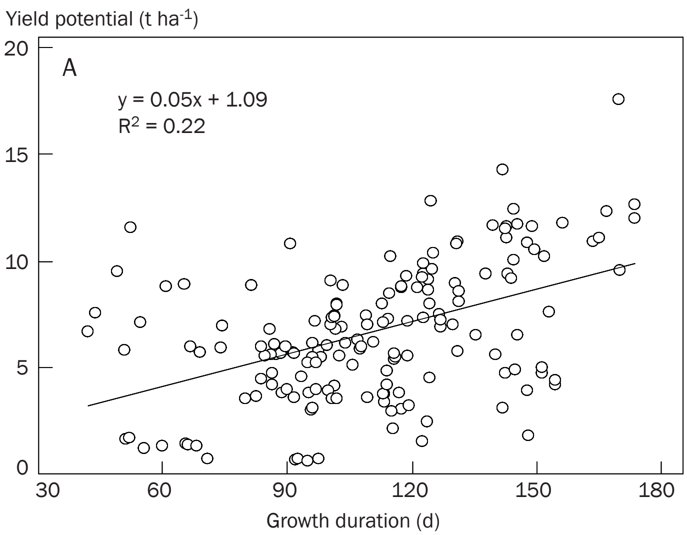


Fig. 44. Relationships between yield potential of rice and (A) growth duration, (B) mean temperature, and (C) solar radiation (subtropical sites).

Table 9. Summary of yield potential and growing-season characteristics of four rice varieties grown on the first day of each month in subtropical to warm temperate Asia.

Country	Location	Variety	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
China	Changsha	Extra short	2.6–6.0	69–118	890–1,625	11.6–26.2
		Short	1.2–8.1	74–131	990–1,940	11.9–25.6
		Intermediate	4.0–9.4	81–151	1,115–2,260	12.3–25.4
		Long	4.0–12.0	91–174	1,280–2,615	12.6–24.7
	Jinhua	Extra short	1.5–5.8	51–116	654–1,685	8.9–25.7
		Short	1.9–7.5	55–145	710–1,890	9.1–24.9
		Intermediate	2.8–10.3	61–143	810–2,170	9.4–24.7
		Long	1.2–11.1	65–170	880–2,470	9.6–23.7
	Wuhan	Extra short	1.7–6.8	42–113	610–1,825	8.9–25.9
		Short	0.4–8.1	44–131	635–2,050	9.0–25.5
		Intermediate	2.4–10.4	49–145	735–2,350	9.3–25.3
		Long	2.3–11.8	53–167	795–2,670	9.4–24.5
	Yangzhou	Extra short	2.6–6.0	69–118	340–1,905	11.6–26.2
		Short	1.2–8.1	74–131	335–2,120	11.9–25.6
		Intermediate	4.0–9.4	81–151	385–2,395	12.3–25.4
		Long	4.2–11.1	91–174	425–2,700	12.6–24.7

Country	Location	Variety	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
India	Ludhiana	Extra short	3.0–8.8	65–109	1,300–2,460	16.1–30.4
		Short	2.9–10.8	74–131	1,490–2,735	16.7–30.2
		Intermediate	3.0–12.8	84–140	1,720–3,075	17.2–30.0
		Long	2.6–17.6	95–170	1,735–3,445	17.7–29.8
Nepal	Chitwan	Extra short	1.6–8.7	30–121	590–2,345	11.4–21.9
		Short	1.7–9.3	30–121	605–2,410	11.4–22.3
		Intermediate	1.9–10.9	32–146	645–2,615	11.5–22.2
		Long	2.1–14.4	35–152	685–2,880	11.6–22.0
Pakistan	Okara	Extra short	0.6–4.7	51–114	746–2,193	13.8–32.3
		Short	0.7–5.6	52–115	782–2,277	13.9–32.2
		Intermediate	0.6–8.0	55–119	862–2,572	14.2–32.1
		Long	0.7–10.0	60–145	969–2,796	14.5–31.9



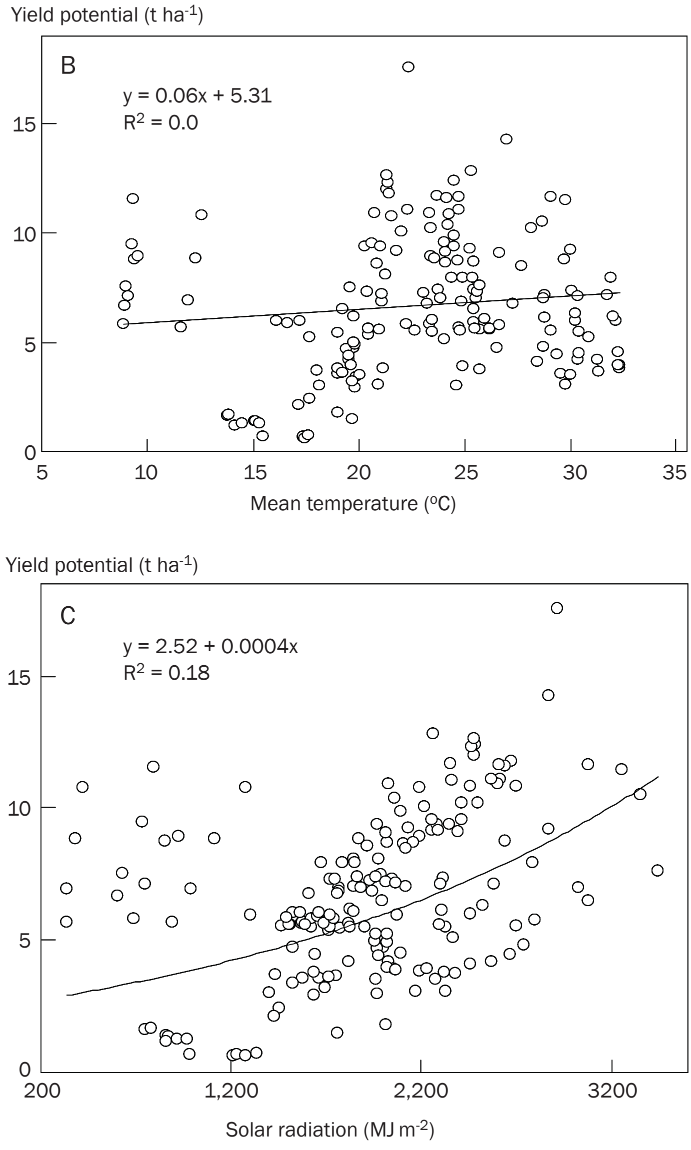
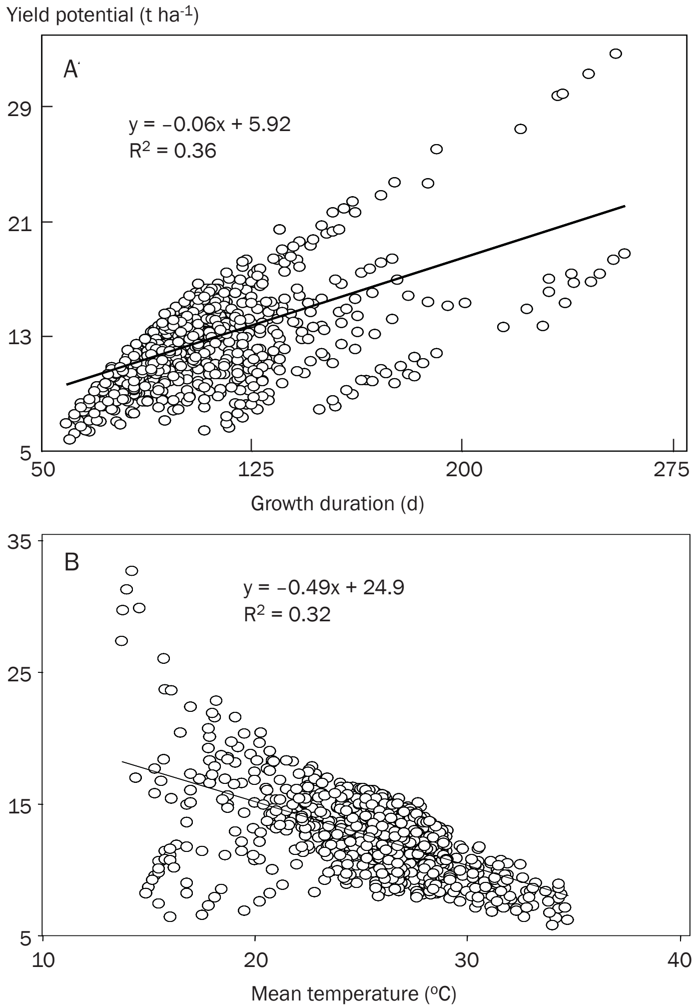


Fig. 45. Relationships between yield potential of rice and (A) growth duration, (B) mean temperature, and (C) solar radiation (subtropical to warm temperate sites).

Maize

Yield potential, growth duration, growing season-intercepted solar radiation, and mean temperature during grain filling for four hybrid maturity groups for key locations across R-M agroecosystems in Asia are summarized in Tables 10–12. The mean Yp of different hybrid maturity groups across tropical, subtropical, and warm temperate R-M agroecosystems ranged from 7.7 to 23.0, 6.4 to 20.4, and 5.6 to 27.4 t ha^{-1}, respectively. Relationships between Yp and growth duration, solar radiation, and mean temperature for all sites combined are presented in Figure 46. The variability in Yp, growth duration, solar radiation, and mean temperature for the different agroecosystems is shown in Figure 47. Relationships between Yp and growth duration, solar radiation and mean temperature for tropical, subtropical, and subtropical to warm temperate sites are separately presented in Figures 48 to 50.



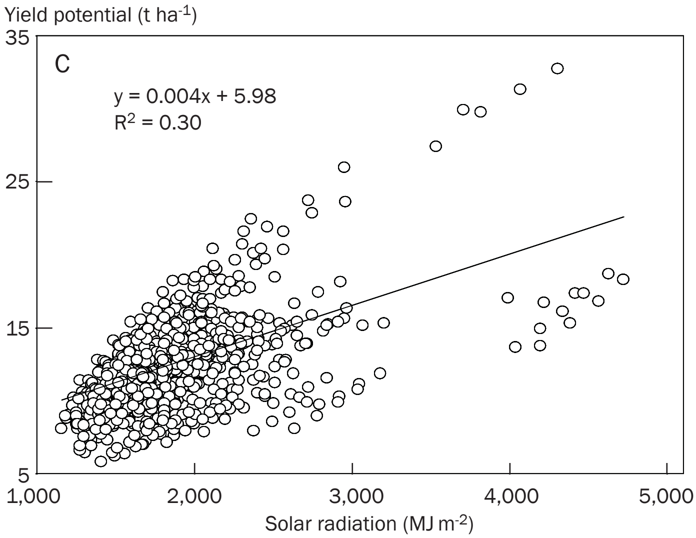
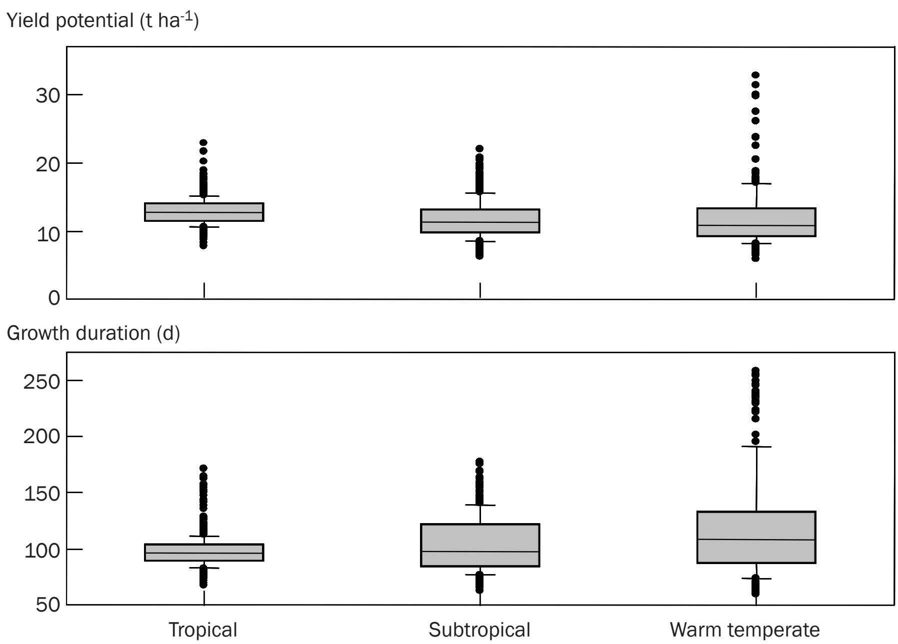


Fig. 46. Relationships between yield potential of maize and (A) growth duration, (B) mean temperature, and (C) solar radiation (all sites combined).



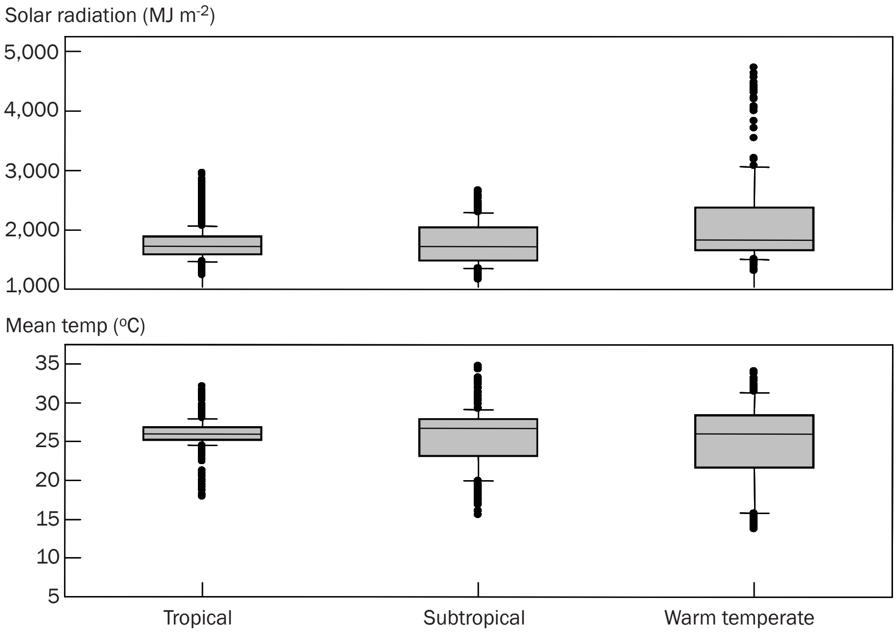


Fig. 47. Variability in Yp, growth duration, solar radiation, and mean temperature during grain filling of four maize hybrids under three agroecosystems.

Tropical and subtropical agroecosystem. In the tropics and subtropics, Yp was always higher for hybrids with high GDD; but, in warm temperate climate, there was no such trend. The growth duration in the respective ecosystems ranged from 67 to 127, 76 to 154, and 63 to 271 days (Tables 10–12). Unrealistically long growth duration during cold climate in warm temperate areas resulted in larger solar radiation being received. Interestingly, mean temperature during grain filling was higher in warm temperate areas than in the tropics and subtropics. This indicates extreme temperatures during parts of the year in temperate locations and fairly even temperatures throughout the year in the tropics.

Subtropical to warm temperate agroecosystem. At all Chinese sites, except for Wuhan, the crops planted from 1 September to 1 March were exposed to cold injury during germination and seedling emergence. This resulted in crop death and zero yield. For the October- and November-planted crops, even if the plants survived, growth duration was excessively long, with a very large amount of solar radiation received. Results suggest that, for Chinese sites, maize should be planted between March and August to avoid cold injury. For Punjab, planting a 1,500-GDD hybrid in January resulted in cold injury, the crop dying, and, ultimately, zero yield. For other hybrids (1,600–1,800 GDD), planting from 1 August to 1 September produced the highest yields due to lower grain-filling temperature, longer growth duration, and higher solar radiation. All hybrids sown from 1 December to 1 February in Chitwan

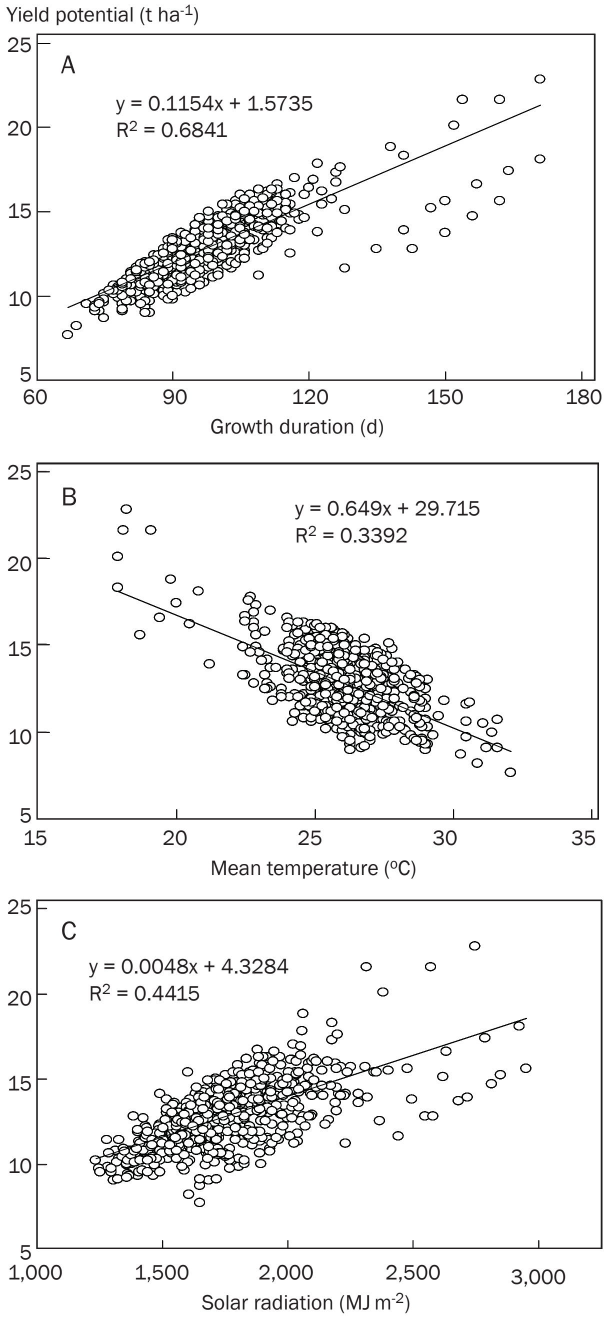


Fig. 48. Relationships between yield potential of maize and (A) growth duration, (B) mean temperature, and (C) solar radiation (tropical sites).

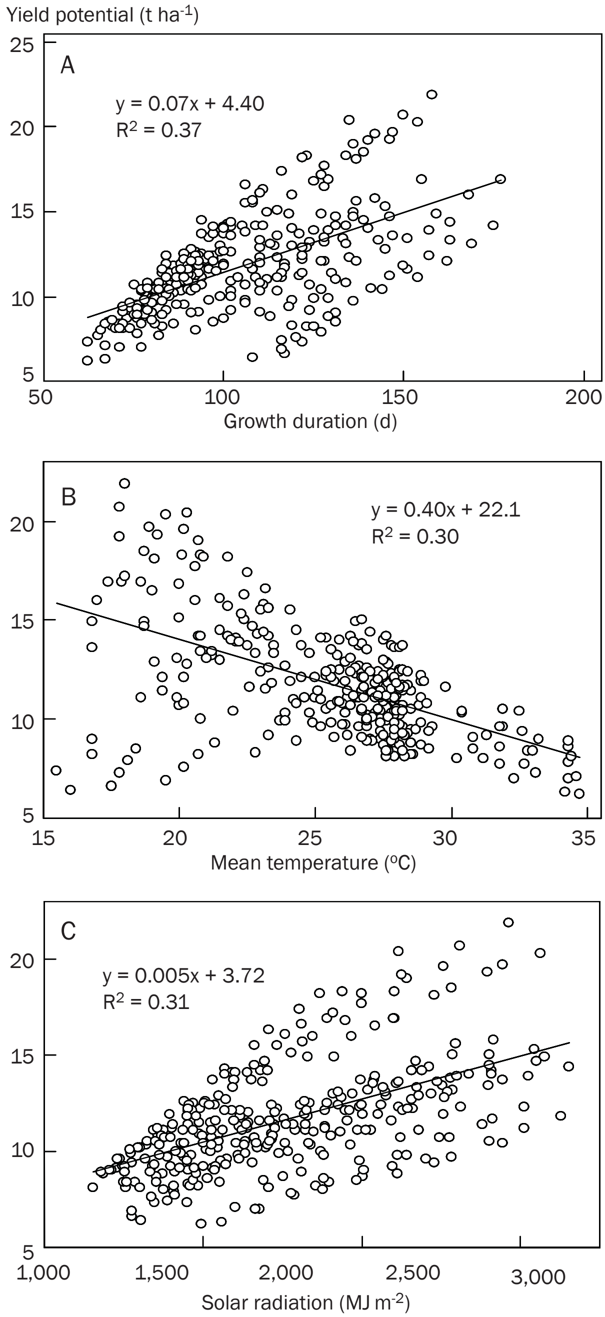


Fig. 49. Relationships between yield potential of maize and (A) growth duration, (B) mean temperature, and (C) solar radiation (subtropical sites).

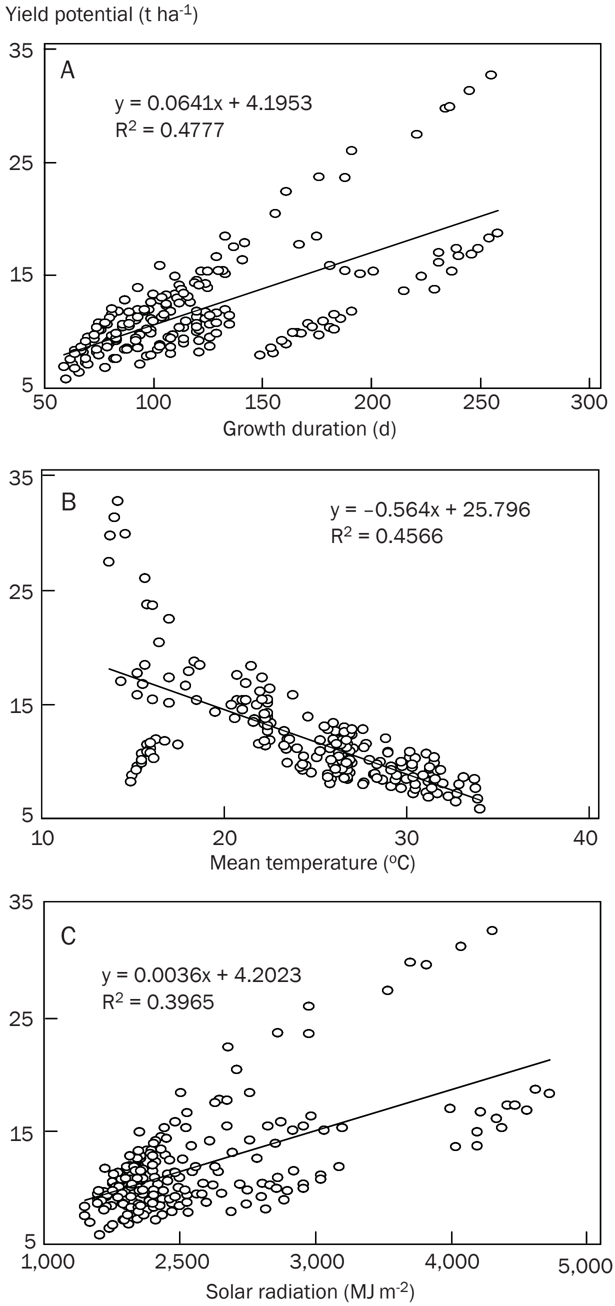


Fig. 50. Relationships between yield potential of maize and (A) growth duration, (B) mean temperature, and (C) solar radiation (subtropical warm temperate sites).

had zero yields because of cold injury. Likewise, the plants took an unrealistically long time to mature when planted between 1 July and 1 November. For those crops, low mean temperature during grain filling resulted in longer grain-filling duration, longer growth duration, and higher solar radiation, thereby contributing to high yield. In Okara, Pakistan, planting of all hybrids in October and January resulted in zero yields as seeds did not germinate due to extreme cold.

Table 10. Summary of yield potential and growing-season characteristics of four maize hybrids grown on the first day of each month in tropical Asia.

Country	Location	Variety (GDD)	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
Philippines	Pila	1,500	9.8–12.0	84–93	1,220–1,700	24.9–27.9
		1,600	10.8–12.8	90–103	1,320–1,800	24.9–27.8
		1,700	11.6–14.2	96–107	1,420–1,910	25.0–27.8
		1,800	12.8–15.4	102–116	1,500–2,020	25.0–27.8
	Muñoz	1,400	8.9–11.4	80–90	1,310–1,680	24.6–27.4
		1,500	10.1–12.9	86–97	1,400–1,800	24.6–27.4
		1,600	11.0–14.1	92–104	1,500–1,910	24.7–27.4
		1,700	11.9–15.4	98–112	1,610–2,040	24.7–27.4
Indonesia	Medan	1,500	10.6–12.2	88–94	1,360–1,630	24.5–25.7
		1,600	11.8–13.3	94–100	1,460–1,740	24.6–25.7
		1,700	13.2–14.6	102–106	1,580–1,860	24.6–25.7
		1,800	14.3–16.0	107–114	1,680–1,980	24.6–25.7
	Kediri	1,400	11.1–12.1	87–93	1,510–1,830	24.5–25.9
		1,500	12.5–13.6	94–100	1,620–1,970	24.5–25.8
		1,600	13.9–15.0	100–106	1,730–2,090	24.5–26.0
		1,700	15.1–16.2	106–113	1,840–2,210	24.6–25.9
	Maros	1,500	9.9–11.9	83–88	1,400–1,950	25.4–26.8
		1,600	11.0–13.2	89–98	1,500–2,050	25.4–26.6
		1,700	12.0–14.6	97–105	1,620–2,230	25.1–26.8
		1,800	13.0–16.0	103–107	1,770–2,360	25.4–26.8
	Sukamandi	1,500	10.9–12.2	90–92	1,500–1,760	24.8–25.5
		1,600	12.0–13.4	96–99	1,560–1,880	24.9–25.5
		1,700	13.0–14.9	103–107	1,680–2,000	24.9–25.4
		1,800	14.1–16.2	109–113	1,800–2,120	24.9–25.4
	Central Lampung	1,500	10.3–11.2	85–88	1,340–1,550	25.7–26.4
		1,600	11.3–12.5	91–94	1,440–1,650	25.7–26.3
		1,700	12.6–13.7	97–100	1,545–1,760	25.6–26.3

Country	Location	Variety (GDD)	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
		1,800	13.6–15.0	103–107	1,650–1,870	25.7–26.3
Thailand	Chiang Rai	1,400	10.5–18.1	87–150	1,450–2,500	17.9–26.2
		1,500	12.0–20.0	94–156	1,550–2,650	17.9–26.2
		1,600	13.0–22.0	101–165	1,660–2,800	17.9–26.2
		1,700	14.5–23.0	110–170	1,800–2,970	18.1–26.1
	Suphan Buri	1,400	10.6–12.4	79–96	1,480–1,750	23.8–27.6
		1,500	11.7–13.6	85–103	1,590–1,880	24.0–27.5
		1,600	12.9–15.2	91–108	1,700–2,000	24.1–27.5
		1,700	14.1–16.5	96–116	1,800–2,110	24.0–27.6
	Phitsanulok	1,400	10.1–13.1	78–105	1,490–1,850	22.5–27.9
		1,500	11.4–14.5	84–112	1,600–2,000	22.7–27.9
		1,600	12.5–16.2	91–118	1,710–2,120	22.8–27.8
		1,700	13.6–17.5	97–126	1,810–2,240	22.7–27.8
Vietnam	An Giang	1,500	9.9–10.8	78–86	1,355–1,600	25.9–27.9
		1,600	11.0–12.2	83–92	1,455–1,715	25.9–27.9
		1,700	12.2–13.4	89–98	1,555–1,830	25.9–27.9
		1,800	13.3–14.6	95–104	1,655–1,935	25.9–27.8
India	Aduthurai	1,500	9.1–11.2	73–87	1,250–1,740	25.4–29.1
		1,600	10.2–12.5	78–93	1,340–1,870	25.4–29.1
		1,700	11.2–14.0	83–100	1,450–1,970	25.5–29.0
		1,800	12.3–5.0	89–106	1,550–2,100	25.5–29.1
	Thanjavur	1,400	9.2–11.1	74–86	1,255–1,700	25.8–28.9
		1,500	10.2–12.4	79–92	1,350–1,825	25.8–28.8
		1,600	11.1–13.6	84–98	1,445–1,940	25.8–28.8
		1,700	12.2–14.7	90–104	1,540–2,020	25.9–28.8
	Bangalore	1,400	10.0–13.3	78–106	1,525–1,940	22.4–28.2
		1,500	11.2–14.9	83–113	1,640–2,070	22.4–28.1
		1,600	12.3–16.4	89–120	1,760–2,195	22.5–28.4
		1,700	13.6–17.6	96–127	1,880–2,320	22.6–27.9
	Nalgonda	1,400	7.7–12.6	67–99	1,300–1,750	23.4–32.1
		1,500	9.1–14.2	73–105	1,390–1,870	23.3–31.6
		1,600	10.0–15.8	78–111	1,490–1,980	23.2–31.4
		1,700	10.7–17.0	83–117	1,590–2,105	23.4–31.6

Table 11. Summary of yield potential and growing-season characteristics of four maize hybrids grown on the first day of each month in subtropical Asia.

Country	Location	Variety (GDD)	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
Bangladesh	Bogra	1,500	8.8–12.6	77–124	1,185–2,030	20.0–28.2
		1,600	9.8–16.8	83–131	1,270–2,160	20.0–28.2
		1,700	10.9–18.3	88–136	1,355–2,285	20.1–28.2
		1,800	12.0–19.6	94–142	1,455–2,415	20.2–28.1
	Dinajpur	1,500	9.0–16.5	79–133	1,210–2,255	19.0–27.4
		1,600	10.2–18.1	85–139	1,300–2,400	19.1–27.4
		1,700	11.2–19.3	91–146	1,405–2,545	19.2–27.5
		1,800	12.2–20.4	97–154	1,510–2,115	19.5–27.5
	Jessore	1,500	8.7–14.2	76–119	1,180–1,935	20.7–28.5
		1,600	9.7–16.0	81–125	1,270–2,045	20.6–28.5
		1,700	10.7–17.7	87–131	1,355–2,180	20.6–28.5
		1,800	11.8–19.0	92–137	1,455–2,300	20.7–28.4
India	Begusarai	1,500	8.1–14.9	68–128	1,155–2,130	18.7–29.2
		1,600	9.2–16.9	74–134	1,255–2,270	18.6–29.3
		1,700	10.4–18.5	79–140	1,350–2,410	18.7–29.1
		1,800	11.4–19.7	84–147	1,450–2,550	18.9–29.0
Vietnam	Than Hoa	1,500	9.8–11.9	84–97	1,235–1,705	24.9–27.9
		1,600	10.8–13.0	90–103	1,330–1,815	24.9–27.8
		1,700	11.6–14.1	96–109	1,425–1,920	25.0–27.8
		1,800	12.7–15.4	102–116	1,515–2,025	25.0–27.8
	Vinh Phuc	1,500	6.4–10.0	71–117	1,250–1,530	16.0–28.3
		1,600	7.3–11.1	76–122	1,345–1,630	15.5–28.3
		1,700	7.9–12.7	82–127	1,405–1,725	16.8–28.2
		1,800	8.5–14.2	88–131	1,470–1,825	16.8–28.3
Pakistan	Larkana	1,400	6.2–17.2	62–145	1,377–2,285	18.0–34.7
		1,500	7.0–19.2	67–151	1,474–2,402	17.8–34.6
		1,600	7.8–20.7	71–157	1,527–2,524	17.8–34.4
		1,700	8.6–21.9	76–163	1,678–2,653	18.0–34.3

Table 12. Summary of yield potential and growing-season characteristics of four maize hybrids grown on the first day of each month in subtropical to warm temperate Asia.

Country	Location	Variety (GDD)	Yield potential (t ha^{-1})	Growth duration (d)	Solar radiation (MJ m^{-2})	Mean temperature (°C)
China	Changsha	1,300	5.6–11.4	79–248	1,400–2,650	17.5–26.9
		1,400	7.1–11.9	86–257	1,510–2,790	16.3–27.0
		1,500	8.3–11.9	92–264	1,615–2,890	15.8–27.1
		1,600	9.4–13.3	99–271	1,715–3,000	15.6–27.0
	Jinhua	1,300	8.0–11.1	82–124	1,410–1,760	16.0–26.8
		1,400	9.0–11.0	89–126	1,510–1,880	15.5–26.9
		1,500	9.5–12.7	96–126	1,615–1,990	15.3–26.8
		1,600	8.7–14.5	103–126	1,665–2,100	15.0–26.6
	Wuhan	1,300	8.5–12.0	80–124	1,443–1,680	16.8–26.8
		1,400	9.7–12.0	86–129	1,563–1,881	16.0–26.8
		1,500	11.0–13.0	93–129	1,686–2,002	15.8–26.9
		1,600	9.8–14.0	100–129	1,728–2,117	15.5–26.9
	Yangzhou	1,300	8.5–10.7	83–120	1,395–1,945	16.0–26.6
		1,400	9.3–11.3	89–121	1,545–2,060	15.5–26.7
		1,500	9.2–13.2	96–121	1,645–2,170	15.2–26.2
		1,600	8.2–15.3	104–126	1,645–2,285	14.9–26.6
India	Ludhiana	1,500	7.1–16.6	63–181	1,430–2,790	15.3–31.7
		1,600	8.2–20.4	68–188	1,555–2,920	16.1–31.5
		1,700	9.0–23.7	73–195	1,680–3,065	15.8–31.4
		1,800	9.8–26.0	79–201	1,800–3,200	15.7–31.5
Nepal	Chitwan	1,500	11.3–27.4	104–231	1,720–4,195	13.7–22.5
		1,600	13.1–29.7	113–240	1,870–4,380	13.8–22.4
		1,700	14.1–31.3	121–249	2,045–4,560	14.0–22.4
		1,800	15.4–32.7	130–258	2,265–4,725	14.2–22.5
Pakistan	Okara	1,300	5.8–17.7	59–168	1,301–2,503	15.3–34.0
		1,400	6.7–18.4	64–175	1,400–2,615	15.7–33.9
		1,500	7.6–18.4	69–183	1,505–2,726	16.2–33.8
		1,600	8.4–22.4	74–183	1,607–2,844	17.0–33.7

Table 13. Current and potential cropping system options in Pila, Laguna, Philippines.

System	Season	Crop	Establishment	Planting	Harvest
Rice-fallow	Wet	Rice	Transplanted	Jun/Jul	Sep/Nov
	Dry	–	–	–	–
	Constraints: fallow not used				
Rice-rice	Wet	Rice	Transplanted	Jun/Jul	Sep/Nov
	Dry	Rice	Transplanted	Dec/Jan	Mar/Apr
	Constraints: typhoon damage to first rice; insufficient water for second rice				
Rice-maize	Wet	Rice	Transplanted	Jun/Aug	Sep/Nov
	Late wet-dry	Maize	Sowing	Nov/Feb	Mar/May
	Constraints: typhoon damage to first rice; excess water at maize planting				
Maize-rice	Late dry- early wet	Maize	Sowing	Apr/Jun	Jul/Sep
	Wet-dry	Rice	Transplanting	Aug/Jan	Nov/Apr
	Constraints: insufficient water for planting and excess water at maturity of maize; typhoon damage and insufficient water for rice				

Strategic assessment of selected sites across Asia

Tropical warm agroecosystem

Pila, Laguna, Philippines. Current cropping systems. In the irrigated and rainfed areas of Pila and surrounding villages in Laguna Province, rice-fallow (R-F), rice-rice (R-R), rice-vegetables, and rice-watermelons are the main cropping systems practiced on farms with clay loam to heavy clay soils. Of these, R-R and R-F are the predominant ones (Table 13). The R-R system is practiced in areas with assured irrigation either through surface water or groundwater. But, in areas without reliable irrigation, a single rice crop is grown using rainfall or some supplemental irrigation.

Rice planted in June could require some irrigation water for land preparation and early crop establishment, but it would be harvested before the period of highest rainfall in October. Rice planted in July or August would not require irrigation, but it would have a high probability of being damaged by typhoons in October and November when rice is at the flowering to grain-filling stages. The second rice crop in the R-R system, planted during December/January and harvested during March/April, would always require irrigation water. There will be insufficient water to grow a second rice crop in the dry season in areas without assured irrigation sources.

In recent years, due to the change in rainfall patterns and intensities, the supply of irrigation water during the dry season has been discontinuous and irregular. Moreover, Typhoon Milenyo in September 2006 damaged the walls and other parts of the water storage dam in Liliw, which is located within the Sta. Cruz River system. As a result, diversion of water to the main canal was completely stopped and many farmers in Pila and surrounding areas within the Sta. Cruz River system were unable to receive irrigation water from the canal, even during the 2007 wet season. Farmers growing rice in the dry season could not plant rice in the 2006-07 dry season. Thus, large areas in the command areas of the Sta. Cruz River system, including Pila, Victoria, and Sta. Cruz, were left with unused and unproductive long fallows. In that season, farmers in the upstream and midstream areas in the command area were most affected as they had previously relied fully on the dam for irrigation. Farmers in the downstream areas near Laguna de Bay were least affected. These farmers previously received less water from the dam, and most of them have tube wells in their fields.

Because of heavy rainfall during the wet season, sufficient water is generally available in the soil profile to plant a dry-season maize crop, but the maize might require supplemental irrigation at the later growth stages. Some rain occurs in April/May before the onset of the wet season, which could be used by maize as a prerice crop. In Pila and surrounding areas, water tables are generally shallow near Laguna de Bay and deeper farther from the Bay. Supplemental irrigation for maize would be available, especially near Laguna de Bay, because there are many shallow and deep tube wells.

Thus, it can be hypothesized that the R-M and M-R systems could be alternative systems to R-R and R-F for those areas. Maize grown in the dry season immediately after wet-season rice could use the residual soil water and thus would require much less irrigation water than dry-season rice. Maize grown before wet-season rice would make use of early-season rainfall in May/June and use indigenous soil nutrients, especially nitrate that might otherwise be lost as gases when the soil is flooded during land preparation for wet-season rice.

Potential cropping systems. In the potential R-M system, wet-season rice could be grown with transplanting from June to August and harvested from September to November. A following maize crop could then conceivably be sown within the time frame from about November to February (Table 13). There will be a transition period following rice in which the soil goes from saturated to aerobic. Soil water content during this transition period will influence the establishment and performance of the maize crop. Excess water will prevent the use of tillage equipment and delay land preparation and sowing for maize. Even after establishment, the maize seedlings could be adversely affected by excess water, ultimately resulting in reduced yield. With adequate drainage for maize cropping, the maize could conceivably be planted as early as November when the rice has been harvested and rains are decreasing.

In the potential M-R system, maize could be planted during the dry-wet transition period from April to June and harvested from July to September. A rice crop could then be transplanted any time after August/September and up to December/January. Maize establishment would need to be sufficiently early to avoid the initial heavy rains at planting time, which could adversely affect maize planting operations and damage seedlings. Irrigation would likely be required during the early growth of maize, especially when rains are delayed. In later stages, there is a probability of high rainfall, which could damage the crop and increase disease and insect incidence. The following rice crop could be affected by typhoons during October-December if planted during August-October. Irrigation water could be insufficient for a later planting of rice during December/January.

Yield potential of rice. The mean Yp of extra short, short, intermediate, and long-duration rice varieties ranged from 3.9 to 6.3, 4.7 to 7.3, 6.3 to 9.6, and 7.1 to 10.9 t ha^{-1}, respectively. Yield potential was always higher for the dry season than for the wet season. The corresponding mean growth durations for these varieties ranged from 84 to 93, 93 to 102, 102 to 115, and 124 to 136 days, respectively. Similarly, the growth durations were always higher for dry-season than for wet-season rice crops. The extra short-duration variety received solar radiation between 600 and 1,000 MJ m^{-2} during the growing season, whereas the long-duration variety received 1,100–1,600 MJ m^{-2}. Mean growing-season temperatures were slightly lower for long-duration varieties than for others. For all dates of planting, the long-duration varieties received higher incident solar radiation and were exposed to slightly cooler days. All these resulted in a higher yield of the long-duration variety. In contrast, the extra short-duration variety matured in 3 months and intercepted the least solar radiation; consequently, it had the lowest yield (Fig. 51).

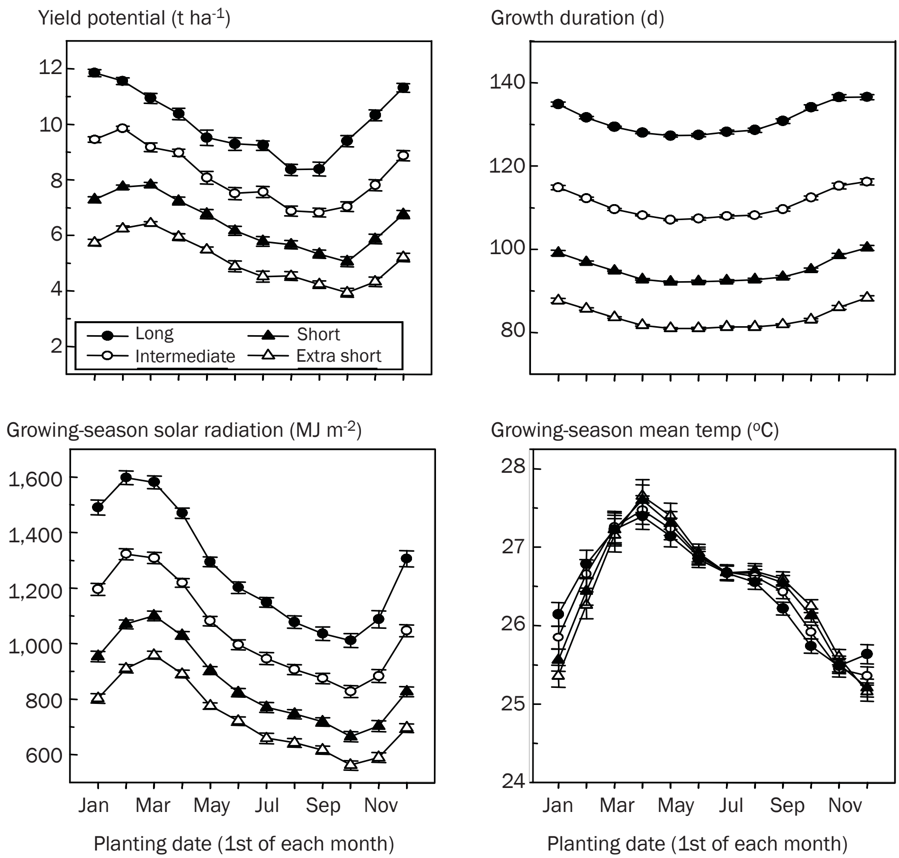


Fig. 51. Yield potential and growing-season characteristics of four rice varieties grown at Pila, Laguna, Philippines.

Yield potential of maize. The mean Yp of hybrids in the four maturity categories (1,500, 1,600, 1,700, and 1,800 GDD) across planting dates ranged from 9.8 to 15.5 t ha^{-1}. Yield potentials were always higher for the dry season (11.3–15.5 t ha^{-1}) than for the wet season (9.8–13.5 t ha^{-1}). The corresponding growth durations for those hybrids across planting dates ranged from 84 to 116 days, with greater durations for the 1 October to 1 January plantings than for plantings on other dates (Fig. 52). The growing-season incident solar radiation was higher for the 1 January to 1 May plantings (1,580–2,100 MJ m^{-2}) than for the other planting dates (1,220–1,700 MJ m^{-2}). Mean temperature from silking to maturity was, however, least for the 1 October to 1 December plantings and was highest for the January to April plantings (Fig. 52). The higher Yp for the 1 November and 1 December plantings was associated with lower

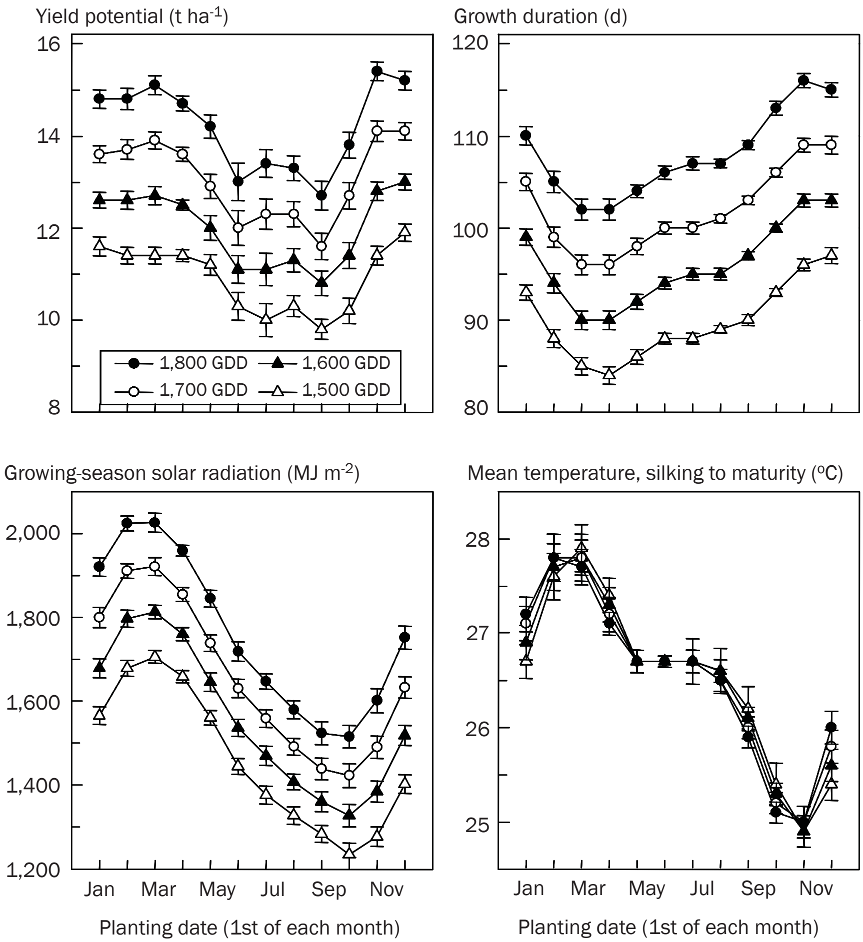


Fig. 52. Yield potential and factors contributing to the yield potential of four maize hybrid maturity groups grown at Pila, Laguna, Philippines.

temperatures during the grain-filling period, which increased the growth duration of maize. In contrast, the higher mean temperature during the grain-filling period slightly reduced the growth duration of crops planted from 1 January to 1 April. Nevertheless, the incident solar radiation during the growing season was higher for those planting dates and thus compensated for the effects of reduced duration (Fig. 52). As a result, all maize maturity groups simulated had a high Yp for the 1 January to 1 April planting. To fit into the cropping calendars, a hybrid maturity of 1,700 GDD was chosen. The Yp of that hybrid across planting dates and seasons ranged from 11.6 to 14.2 t ha^{-1} (Fig. 53).

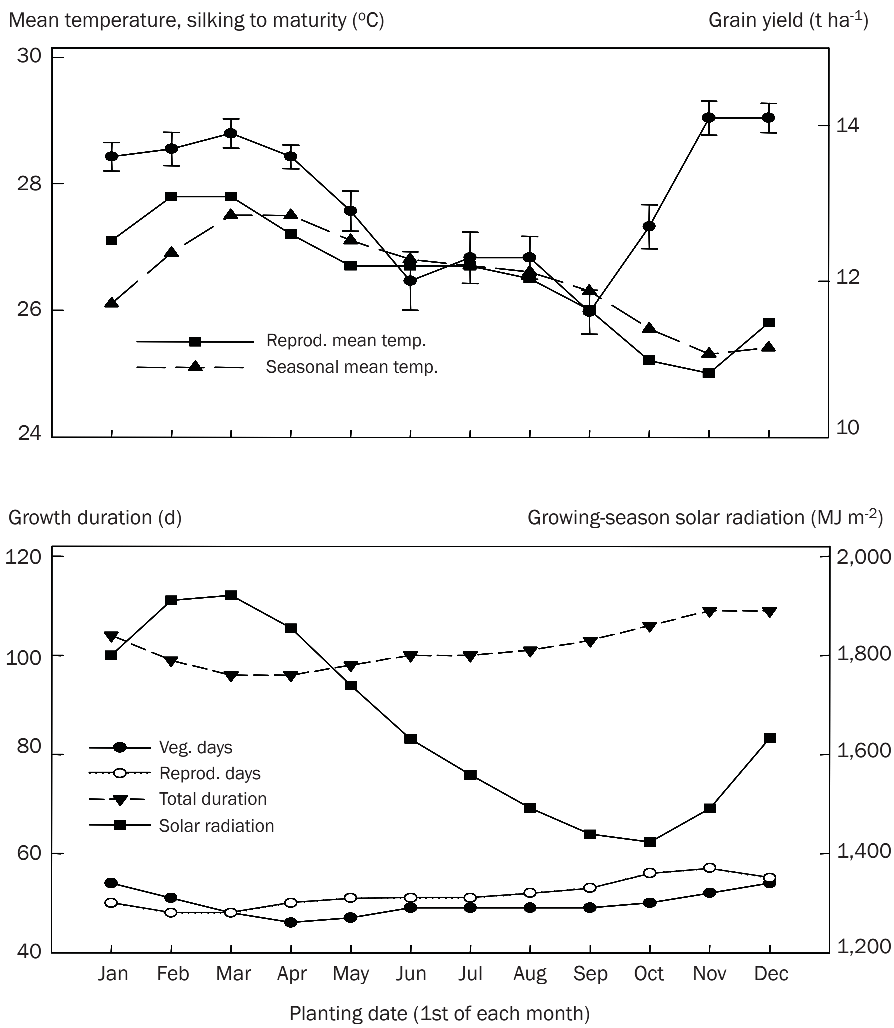


Fig. 53. Maize yield potential at Pila, Laguna, and related growing-season climate characteristics. Hybrid maturity group: GDD 1,700.

Irrigation water requirements for maize. The window of opportunity for planting maize after rice in the dry season is from 1 November to 1 March. Based on the simulations, the optimum period for planting would likely be December and January when maize could use the residual soil water after rice as well as avoid both waterlogging during crop establishment and dry conditions during maturity. Likewise, during the late dry and early wet season, though maize can be planted from 1 April to 1 June, simulations showed that the optimum month for planting would be May, when maize could use rainfall in the early wet season. In both postrice and prerice seasons, some supplemental irrigation for maize might be necessary.

To further examine the effect of planting date, 1 December and 1 January were chosen for planting maize during the postrice season. Variability in Yp of a 1,700-GDD hybrid during the late wet to early dry season, rainfall during the growing season, and irrigation water requirements to achieve Yp is shown in Figure 54. Yield potential for 1 December planting across 20 years of simulations ranged from 12.4 to 15.8 t ha^{-1}, while that for 1 January planting ranged from 12.6 to 15.4 t ha^{-1}. Yield potential across years was less variable for the 1 January than for the 1 December planting. Rainfall during the season for the 1 December planting ranged from 71 to 873 mm; that for the 1 January planting ranged from 27 to 730 mm. Irrigation water requirements to achieve Yp across years ranged from 0 to 100 mm for the 1 December planting or 0 to 242 mm for the 1 January planting. In years with high rainfall, no irrigation water was required. In low-rainfall years, irrigation was needed.

To further evaluate the effect of maize planting date in the prerice season period, 1 May and 1 June were chosen for planting maize. Yield potential across years for the 1 May planting ranged from 10.0 to 14.2 t ha^{-1}, while that for the 1 June planting ranged from 7.8 to 14.4 t ha^{-1} (Fig. 54). Yield potential across years was more variable for the 1 June planting than for the 1 May planting. Rainfall during the growing season ranged from 440 to 1,170 mm for the 1 May planting and from 540 to 1,293 mm for the 1 June planting. Since rainfall was high during the season for the 1 June planting, the crops did not require any irrigation during the season. For the 1 May planting, irrigation water requirement ranged from 0 to 54 mm, with the crop needing irrigation in only 7 out of 20 years.

Optimization of cropping systems. Based on the simulated Yp of rice and maize, various combinations of rice varieties and maize hybrids were examined to obtain maximum R-M and M-R system productivity. Table 14 and Figure 55 show some options for such combinations. For the R-M system, three options for rice were chosen: an intermediate variety planted in late May and late June and an early variety planted in late July. The intermediate variety requires planting earlier than the early-maturing variety to escape damage from typhoons later in the season. Likewise, three options for maize were chosen: planting the optimum maturity type hybrid (1,700 GDD) on either 1 December or 1 January or planting a hybrid with 1,600 GDD on 1 December. Planting an intermediate-maturity rice variety from late May to early July would have a Yp of about 7 t ha^{-1}, whereas planting an early variety from late July to early August would have a Yp of only about 5 t ha^{-1}. When rice is planted in late May or early June, it is harvested in September before the onset of the peak typhoon

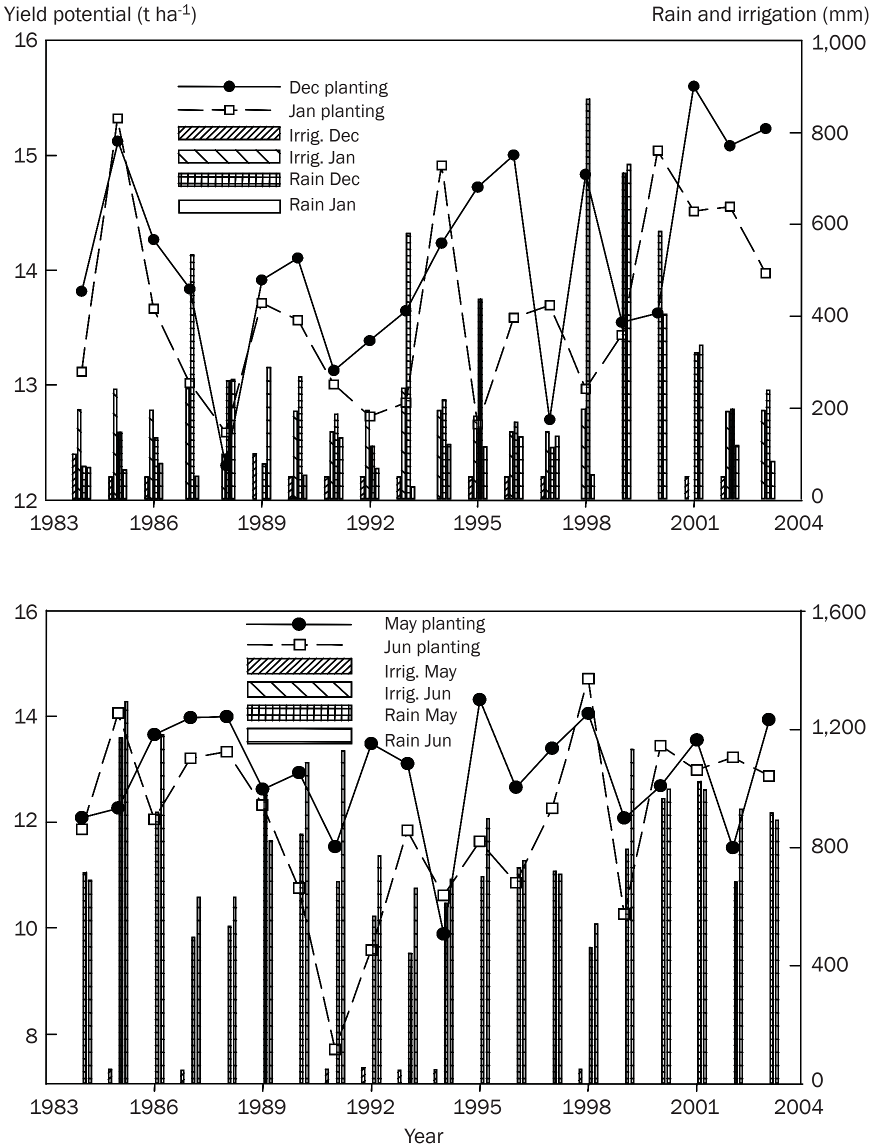


Fig. 54. Variability in yield potential and irrigation water requirements for growing dry-season (Dec-Jan planting) or wet-season (May-Jun planting) maize at Pila, Laguna.

season, but, when planted in late June or early July, it is harvested during the onset of the typhoon season. Both crops would require some irrigation during June/July before the onset of the rains. When planted in late July or early August, rice requires less irrigation but faces higher risks of typhoons. Maize Yp for the 1 December and 1 January plantings would be 13–14 t ha^{-1}, but maize would always require some irrigation from February to April. When maize is planted from late November to early December, there would be some risks of waterlogging during crop establishment, but planting from late December to early January would avoid these risks.

The intermediate variety grown from June to October would be least affected by typhoons and a maize hybrid of 1,700 GDD grown from late December/early January to April would be least affected by waterlogging. This "optimum system"—with an intermediate rice variety planted in late June and a maize hybrid of 1,700 GDD planted in late December/early January—would have a total Yp of 20.5 t ha^{-1}, would require less irrigation water for rice, and would have less typhoon exposure (for rice) and less risk of waterlogging (for maize). From the analysis of 20-yearrainfall data, January 1-sown maize would receive rainfall ranging from 27 to 730 mm during the growing season, and, depending on rainfall, would require a nominal irrigation of 0–242 mm per growing season (Fig. 54).

For the M-R system, maize hybrids of 1,500, 1,600, and 1,700 GDD were chosen and planted between late April and early June. For all crops, there is some potential risk of diseases in maize due to heavy rainfall during the latter part of the season. For rice, the intermediate variety was planted on three dates between late September and early December. Risks due to typhoons in rice are variable, with greater risks for planting earlier. Rainfall during the growing season of the May- and June-planted maize ranged from 440 to 1,293 mm and irrigation water requirement ranged from 0 to 54 mm (Table 14). Irrigation for the June-planted maize would always be nil. Of all combinations of maize and rice planting dates and hybrid/variety types, the maize hybrid of 1,700 GDD planted from late April to early May and IR72 planted from late November to early December would be "optimum," with the greatest Yp of 21.7 t ha^{-1}, but this would require more irrigation for rice.

Table 14. Optimization of cropping system options in Laguna, Philippines.

System	Season	Planting date	Harvest date	Growth duration (d)	Irrigation water use (mm)	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-fallow	Wet	1 Jun	Oct	110–120		7.0	7.0
Rice-rice	Wet	1 Jun	Sep	110–120		7.0	15.7
	Dry	1 Dec	Mar	110–120		8.7	
Rice-maize	Wet	1 Jun	Sep	110–120		7.0	20.5
	Dry	1 Jan	Apr	100–105	0–242	13.5	
Maize-rice	Wet	1 May	Aug	95–100	0–54	13.0	21.7
	Dry	1 Dec	Mar	110–120		8.7	

From the various combinations presented in Figure 55, the best systems are summarized in Table 14. The currently practiced R-F system has a total Yp of 7 t ha^{-1}, which increases to 15.7 t ha^{-1} in R-R, 20.5 t ha^{-1} in R-M, and 21.5 t ha^{-1} in M-R.

Socioeconomic considerations. Laguna Province has 8–10 feed mills that supply the feed requirements of poultry, swine, and fish. Hence, there is a good demand for feed in the province and markets for yellow maize exist. Farmers need inputs and a credit facility if they have to grow maize, especially hybrids, in large areas. Traditionally, farmers obtain credit from the bank, but this entails too much paper work, so there can be delays in planting. Feed mill owners and maize growers have been negotiating arrangements by which feed millers provide inputs and credit to growers. The feed millers in turn buy the maize from the growers, a seemingly win-win situation for both parties.

Quality seeds of yellow corn and sweet corn hybrids are available. Private seed companies (both national and international) such as Syngenta, Monsanto, East West, DuPont, and Allied Botanica have representatives in the vicinity.

An Giang, Mekong Delta, southern Vietnam. Current and potential cropping systems. In An Giang Province (northern Mekong River Delta, MRD) in southern Vietnam, the current lowland rice-based cropping systems are rice-rice (R-R), rice-rice-rice (R-R-R), maize-rice-rice (M-R-R), rice-maize-rice (R-M-R), rice-green bean-rice, rice-groundnut-rice, and maize-maize-rice (M-M-R). In areas with good and assured flood control measures such as dikes, three rice crops are grown, but in areas without proper flood control measures, only two rice crops are possible. The growth duration of varieties used for the R-R system varies from 90 to 95 days, while that for the R-R-R system varies from 85 to 90 days.

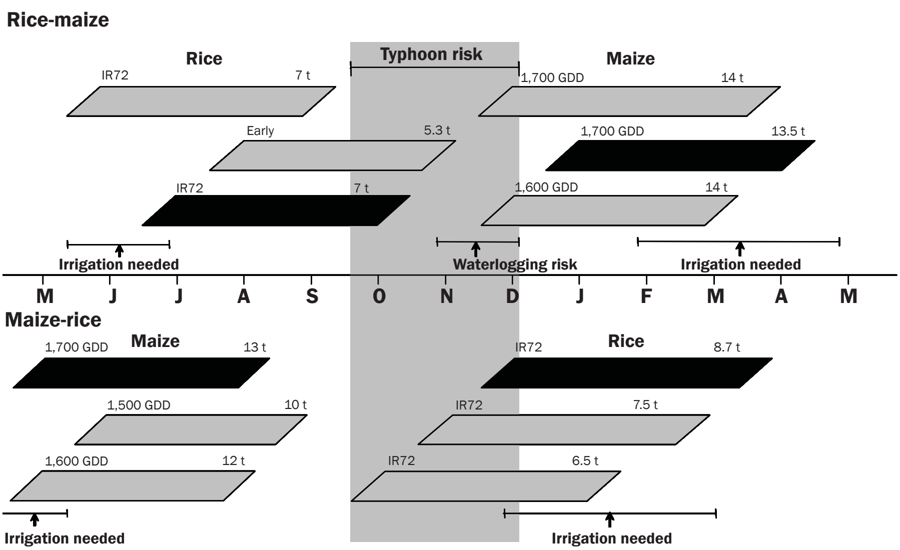


Fig. 55. Options for rice-maize and maize-rice systems for Pila, Laguna, Philippines (shaded areas indicate best options for each system).

In the R-R and R-R-R systems, the first rice is planted during the dry season in November/December, the second rice during the late dry season or early wet season in February/March, and the third rice during the late wet season in June/July (Table 15). In the M-R-R system, dry-season maize (DSM) is planted in tilled fields with furrows but no ridges in November/December. This is different from what is practiced in southern MRD, where maize is grown under zero tillage after lowland rice. DSM is then followed by planting of early wet-season rice (EWR) in February/March and then by late wet-season rice (LWR) in June.

In the R-M-R system, dry-season rice is planted in November/December, early wet-season maize (EWM) in March, and LWR in June. Currently, farmers plant EWM during late March due to the late harvest of dry-season rice. Planting maize before February 1 would not be feasible because dry-season rice would not be harvested by then. The dry-season rice may not be planted successfully before 1 December as rice fields remain flooded due to heavy rain and floodwater coming from the Mekong River until November. Thus, one main requirement for the success of this cropping system is the planting of short-duration rice in November or early December so that it can be harvested by the end of February and the field would be available for planting maize soon after the dry-season rice is harvested. A short-duration maize could be planted in late February or early March so that it would mature and fill grains before the start of heavy rains in June/July.

For the potential M-R-R system, an early-maturing maize hybrid could be planted during mid- to late November and harvested from late February to early March. A following EWR crop could then be sown during February and harvested in early to mid-July. Late wet- season rice could then be planted in June and harvested in October/November (Table 15). In all these systems where maize follows flooded rice, the soil undergoes a transition from saturated to aerobic conditions. Soil water content during this transition period will influence the establishment and performance of the maize crop. With adequate drainage for maize cropping, the maize in the R-M-R system could conceivably be planted as early as 1 March when the rice has been harvested and soil water conditions have become favorable for maize planting. Likewise, in the M-R-R system, maize would be planted in November when rice has been harvested and rainfall has been decreasing.

Yield potential of rice. The mean Yp of extra short and short-duration varieties across planting dates was around 6 to 7 t ha^{-1}. The Yp of the intermediate variety across planting dates varied from 8 to 9.5 t ha^{-1}, while that of the long-duration variety ranged from 9.5 to 11 t ha^{-1} (Fig. 56). The total growth duration of the four varieties across planting dates ranged from 82 to 130 days. Solar radiation during the growing season ranged from around 1,400 to 2,600 MJ m^{-2}. Daily mean temperatures during the growing season varied less among varieties, but these were slightly lower from October to January than from February to September. For the additional fortnightly planting dates simulated for critical planting windows, simulated yields and growth durations were not significantly different from those with main planting dates chosen for the whole-year simulations. In general, Yp was higher for the October to January plantings than for plantings on other dates. Total growth duration and solar radiation

Table 15. Current and potential cropping system options in An Giang, Vietnam.

System	Season	Crop	Establishment	Planting date	Harvest date
Rice-rice-fallow (current)	Dry	Rice	Direct seeding	November	February
	Wet	Rice	Direct seeding	April	July/August
	Constraints: too much irrigation water required for both rice crops; typhoon damage to second (early wet-season) rice; many fields fully submerged after early wet-season rice; brown planthopper and yellow stunt virus damage to early wet-season rice; labor scarcity during dry-season rice harvesting and early wet-season rice transplanting				
Rice-rice-rice (current)	Dry	Rice	Direct seeding	November	February/ March
	Early wet	Rice	Direct seeding	February	July/August
	Late wet	Rice	Direct seeding	June	November/ December
	Constraints: too much irrigation water required for dry-season and early wet-season rice; typhoon damage to both early and late wet-season rice; many fields fully submerged during and after both early and late wet-season rice; brown planthopper damage to early wet-season rice; labor scarcity during harvesting and transplanting of rice				
Rice-maize-rice (current and potential)	Dry	Rice	Direct seeding	November	February
	Dry-early wet	Maize	Direct seeding	March	Late May/ early June
	Late wet	Rice	Direct seeding	June	October/ November
	Constraints: too much irrigation water required for dry-season rice; some probability of typhoon damage to maize; many fields fully submerged during and after late wet-season rice; labor scarcity during dry-season rice harvesting and maize planting, during maize harvesting and late wet-season rice transplanting, and during late wet-season rice harvesting and dry-season rice transplanting				
Maize-rice-rice (potential)	Dry	Maize	Direct seeding	November	Late February/early March
	Wet	Rice	Direct seeding	February	Early to mid-July
	Wet	Rice	Direct seeding	June	Late October/ early November
	Constraints: too much irrigation water required for dry-season rice; some probability of typhoon damage to maize; many fields fully submerged during and after late wet-season rice; labor scarcity during maize harvesting and early wet-season rice transplanting, during early wet-season rice harvesting and late wet-season rice transplanting, and during late wet-season rice harvesting and maize planting				

were also higher, but growing-season mean temperatures were lower for plantings on those dates. Higher yields for planting in the dry season, especially those of intermediate and long-duration varieties, were associated with slightly lower mean temperatures, slightly longer crop duration, and slightly greater solar radiation as compared with those for other planting dates (Fig. 56).

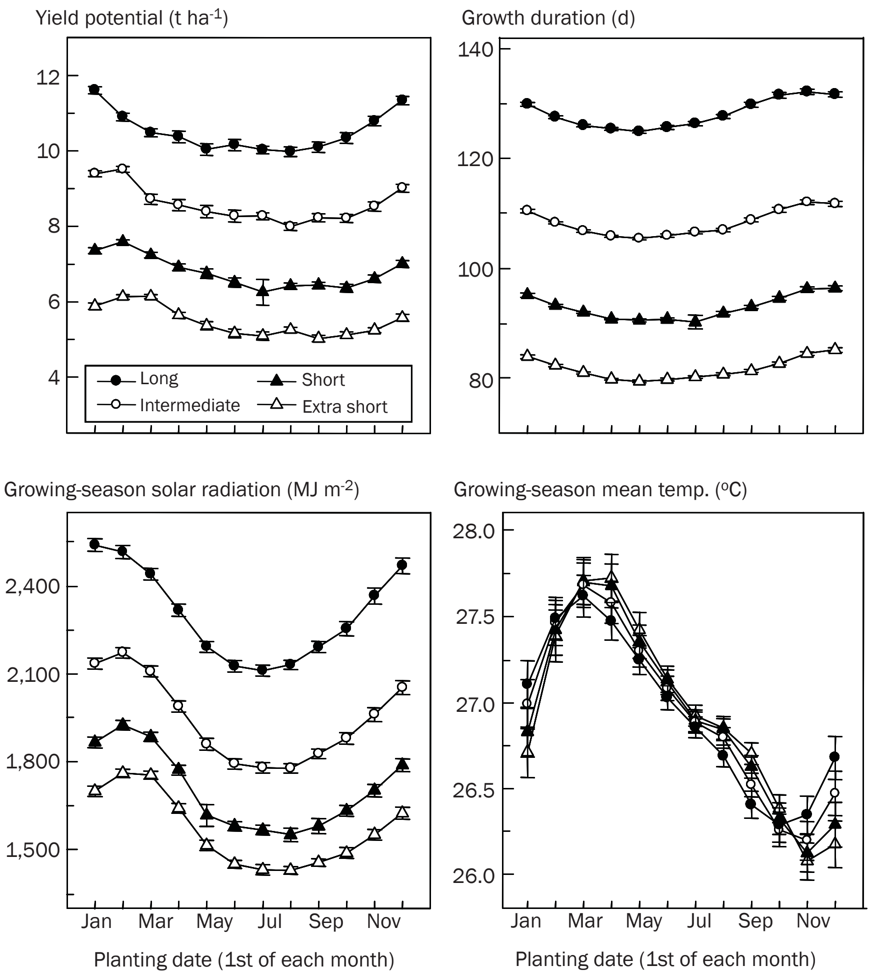


Fig. 56. Yield potential and growing-season characteristics of four rice varieties grown in An Giang, southern Vietnam.

<u>*Yield potential of maize.*</u> The mean Yp of maize hybrids in the four maturity categories across planting dates in An Giang ranged from 10.0 to 14.5 t ha^{-1}. Yield potentials were higher for plantings done during the latter part of the late wet season to the latter part of the dry season (1 September-1 March planting; 10.1–14.5 t ha^{-1}) than for the wet-season planting (1 April-1 August planting; 10.0–14.0 t ha^{-1}). The corresponding growth durations for those hybrids across planting dates ranged from 78 to 104 days, with greater durations for the 1 September to 1 December planting than for plantings on other dates (Fig. 57).

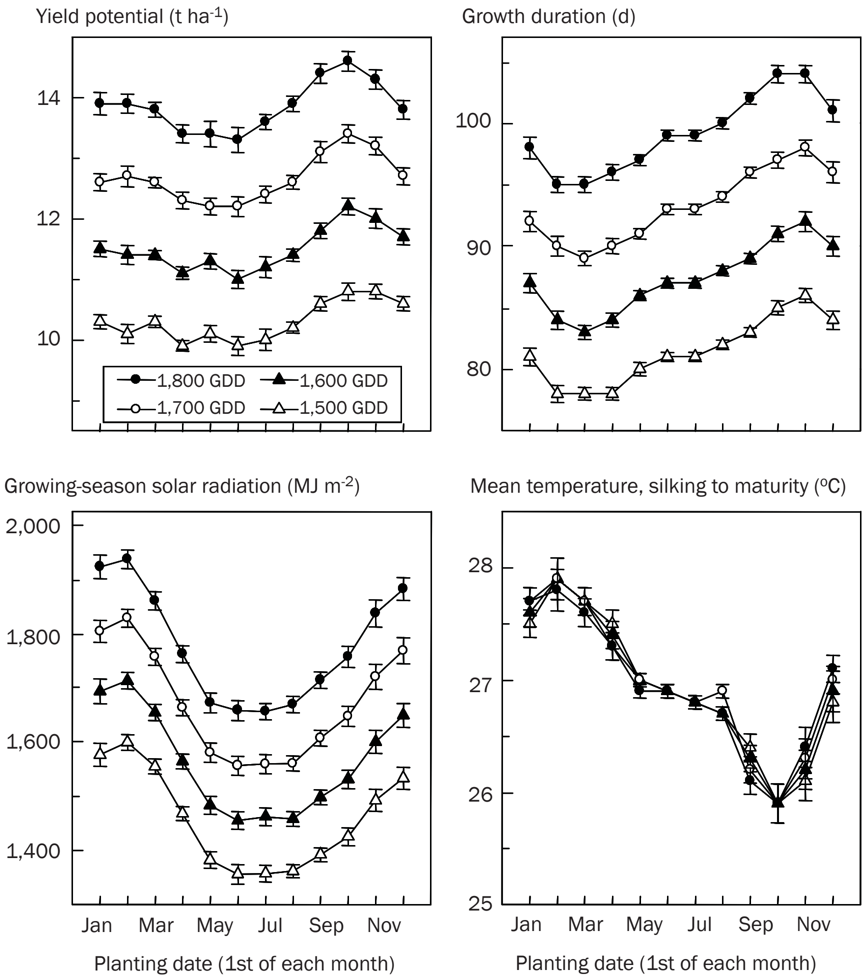


Fig. 57. Yield potential and factors contributing to yield potential of four maize hybrids grown in An Giang, southern Vietnam.

Growing-season incident solar radiation was highest for the 1 January to 1 February plantings (about 1,940 MJ m^{-2}) followed by the 1 March, 1 November, and 1 December plantings (about 1,850 MJ m^{-2}). Mean temperature from silking to maturity was least for the 1 September to 1 November planting and highest for the 1 January to 1 March planting (Fig. 57). The higher Yp for the 1 January to 1 March planting was associated with higher solar radiation during the growing season, that for the 1 September to 1 November planting was associated with lower temperatures during the grain-filling period, and that for the 1 December planting was associated with intermediate solar radiation during the season and moderate mean temperatures during the grain-filling period. Lower mean temperatures during the grain-filling period for the 1 September to 1 December planting increased the growth duration of maize. In contrast, the higher mean temperatures during the grain-filling period slightly reduced the growth duration of crops planted from 1 January to 1 March. Nevertheless, the incident solar radiation during the growing season was higher for those planting dates and thus compensated for the effects of reduced duration (Fig. 57). As a result, for the 1 January to 1 March planting, all maize maturity groups had high Yp.

Our hypothesis regarding a possible replacement of the first and/or second rice in the R-R-R and R-R-fallow by a short-duration maize hybrid was tested by simulating a hybrid with a maturity of 1,600 GDD for some additional dates. For all those dates, there were no significant differences in Yp (12.6–12.7 t ha^{-1}), and those were similar to the Yp for the 1 January to 1 March planting. This implies that, from the Yp point of view, maize could potentially replace the first and/or second rice in the R-R-R systems.

Yield potential of soybean. The mean Yp of soybean planted from 1 November to 1 April ranged from 2.0 to 3.5 t ha^{-1}, with the highest yield noted for the 1 April planting and the lowest for the 1 November planting. Mean growth duration increased from 90 to 109 days for different plantings over the 6-month period (Fig. 58). The later planted soybean received a greater amount of solar radiation during its crop growth than the earlier planted crops. However, there were no trends in the increase or decrease of minimum, maximum, and mean temperatures during the growing season for different planting dates.

Irrigation water requirements for maize. The time for planting maize during the early wet season after the harvest of dry-season rice in the R-M-R system in An Giang is from early March to late April. Based on simulations, the optimum period for planting would likely be mid-March to mid-April, when maize could use rainfall during most of its growth. Likewise, during the onset of the winter season in Vinh Phuc, the window for planting maize after the second (summer) rice in the R-R-M system would be from mid-August to late September. Simulations showed that the optimum time for planting would be from early to mid-September when maize could use the residual soil water after the summer rice as well as avoid cold damage during flowering and grain filling in November and December. In both provinces, depending on seasonal rainfall, some irrigation water may be required.

To further examine the effect of maize planting date in An Giang, 16 March and 1 April were chosen as the dates for planting maize during the early wet season.

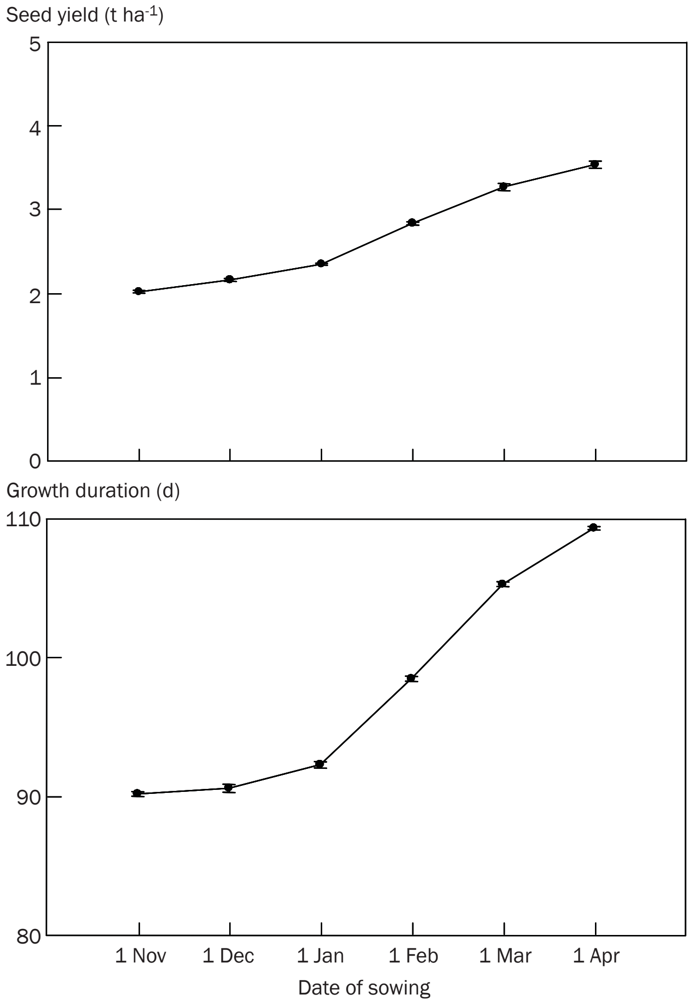


Fig. 58. Yield potential and growth duration of soybean planted in monthly intervals from 1 September to 1 April in An Giang, southern Vietnam.

Variability in Yp of a 1,600-GDD hybrid, rainfall during the growing season, and irrigation water requirements to achieve Yp are shown in Figure 59. Yield potentials for the 16 March and 1 April plantings across 12 years (1992-2003) were fairly similar, ranging from 11.2 to 13.4 t ha^{-1} (Fig. 59). Yp values across years were slightly less variable for the 16 March planting than for the 1 April planting. Rainfall during the season for the 16 March planting ranged from 100 to 800 mm, while that for the 1 April planting ranged from 180 to 920 mm. Since rainfall was high, irrigation water requirements to achieve Yp were nil in all years for the 1 April planting. For the 16 March planting, however, irrigation water was required in 4 years, but it was less than 40 mm in all those years.

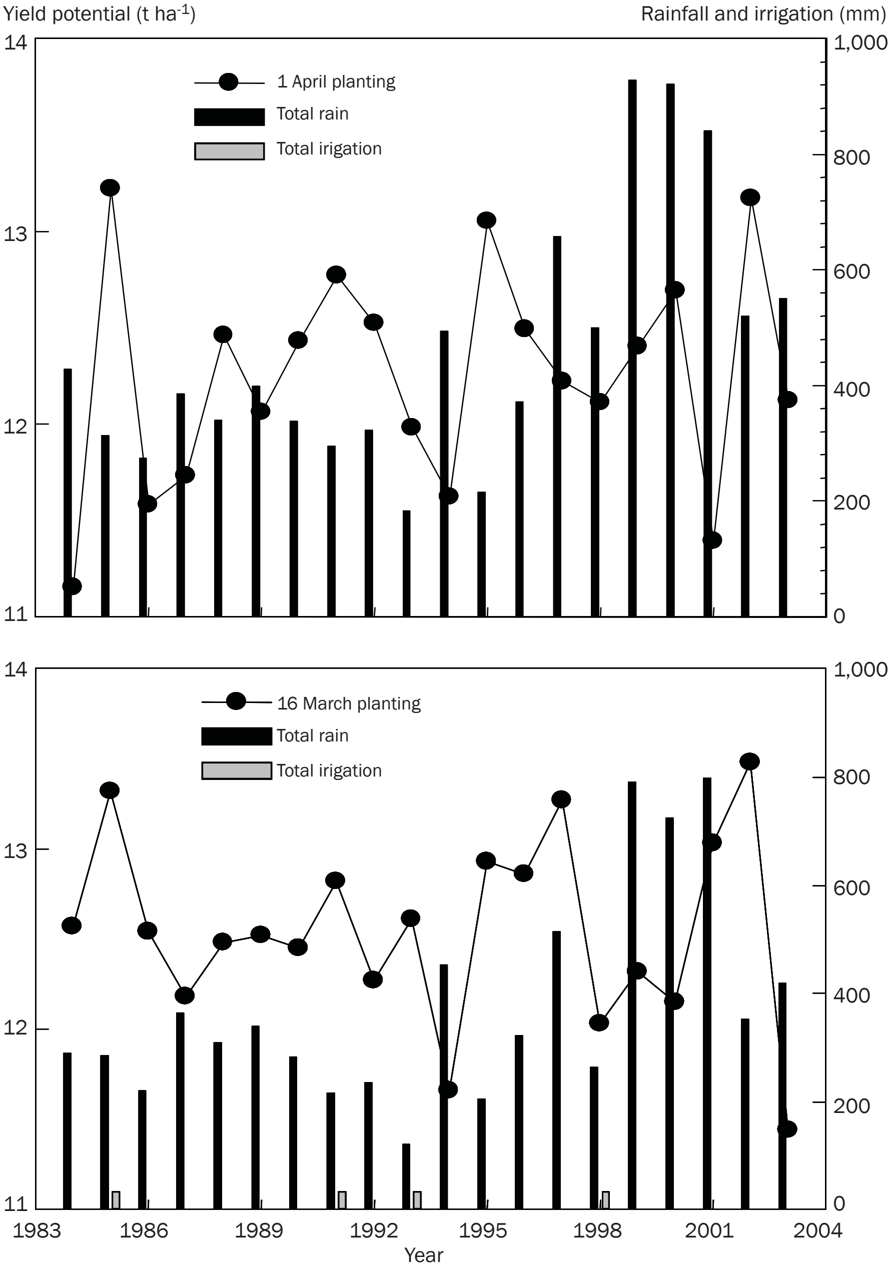


Fig. 59. Variability in yield potential, rainfall during the growing season, and irrigation water requirements for 16 March and 1 April plantings, An Giang, southern Vietnam.

Risk assessment and system optimization. Analysis of long-term records (1954-91) of frequency of typhoons for three main regions in Vietnam revealed that, except in January and February, typhoons occurred in all other months across Vietnam, with most typhoons occurring from June to November (Table 16) (Imamura and Van To 1997). Over the study period, more typhoons occurred in northern Vietnam (97), followed by the central region (81); typhoons were fewest in southern Vietnam (47). The peak season for typhoons in northern, central, and southern Vietnam is August, October, and November, respectively. The peak occurrences of typhoons clearly shift from the north to the south as the season progresses. Such a shift is related to the seasonal changes in water and air temperatures. Records of typhoons, tropical storms, and flash floods across Vietnam from November 1996 to February 2006 from various sources can be found online (www.notes.reliefweb.int/w/rwb.nsf/vCD/Viet+Nam?OpenDocument&Start=1&Count=1000&ExpandView&StartKey=Viet+Nam).

Based on the simulated Yp, various combinations of rice varieties and maize hybrids were examined to obtain maximum productivity from the R-M-R and M-R-R systems. Figure 60 and Table 17 show some options for An Giang. For the R-M-R system, two planting dates (15 and 25 November) for an early-maturing dry-season rice and two planting dates for EWM (25 March and 1 April) were chosen. For LWR for both options, 1 July was the optimum planting date. For the M-R-R system, two planting dates for DSM (15 November and 15 December), two for EWR (1 March and 1 April), and two for LWR (10 June and 1 August) were chosen (Fig. 60). The key to the success of the R-M-R system is to avoid heavy typhoons during maturity and harvest of LWR in October and during early growth of dry-season rice, and to avoid heavy rains and waterlogging damage during maturity and harvest of EWM. For the M-R-R system, typhoons must be avoided during the maturity of LWR and waterlogging must be eluded during the establishment and early growth of DSM. For maize in the R-M-R system, a very minimal amount of irrigation would be required during the vegetative stage, but there would be enough rainfall during the reproductive stage. For maize in the M-R-R system, some irrigation may be necessary during the reproductive period of the crop.

Soybean in An Giang seems to have a higher Yp than that grown in the RRD. It could be an alternative crop to maize or rice in the early wet season in the R-R-R or R-M-R systems. However, the Yp of soybean in both systems is much lower than that of maize (Fig. 58). Soybean can be grown under zero tillage, generally requires fewer inputs, and is a less risky crop than maize. Maize, on the other hand, requires high inputs (especially hybrid seeds, abundant fertilizers, etc.). Which one has better markets needs further investigation.

Based on the Yp and all constraints considered, dry-season rice planted between 15 November and 1 December, EWM planted between 15 March and 1 April, and LWR planted between 15 June and 1 July would give a total system productivity of 25–26 t ha^{-1}. This would be the best option for the R-M-R system. For M-R-R, DSM planted between early and mid-December, EWR planted between mid-March and 1 April, and LWR planted between mid-July and 1 August would be the best option.

Socioeconomic profile. In Tanchau (104°45′ longitude; 10°20′ latitude) in An Giang Province, for which Yp values were estimated and cropping systems were optimized, average household size is 5.2, with an average of three members working on the farm. Average farm size of the household is 1.2 ha (range: 0.5–3.8 ha), all of which is owned by the households themselves. Mostly family labor is used in farming, but sometimes labor is hired for tillage, weed and pest and disease control, transplanting, and harvesting of rice and maize. No exchange labor is used in the village. More labor is used for rice than for maize. About 20–30% of the household laborers (mostly

Table 16. Monthly frequency of typhoons that struck three regions in Vietnam from 1954 to 1991 (adapted from Imamura and Van To 1997).

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Northern	0	0	0	0	0	15	24	28	22	7	1	0	97
Central	0	0	0	1	2	0	0	14	23	35	6	0	81
Southern	0	0	3	1	1	7	0	0	3	6	20	6	47
Total	0	0	3	2	3	22	24	42	48	48	27	6	225

Table 17. Optimization of cropping system options in An Giang, southern Vietnam.

System	Season	Planting date	Harvest date	Growth duration[a] (d)	Yield potential ($t\ ha^{-1}$)	System yield potential ($t\ ha^{-1}$)
Rice-rice-fallow (current)	Dry	Nov/Dec	Mar/Apr	125–130*	9.5–10	17–18
	Early/late wet	May/Jun	Aug/Sep	105–110**	8.0–8.5	
Rice-rice-rice (current)	Dry	Nov/Dec	Feb/Mar	95–100***	6.5	19–20
	Early wet	Mar/Apr	Jun/Jul	90–95***	6.5–7.0	
	Late wet	Jul/Aug	Oct/Nov	85–90***	6.0–6.5	
Rice-maize-rice (current & potential)	Dry	Mid-to-late Nov	Feb/Mar	95–100***	7.0	25–26
	Early wet	Mid-to-late Mar	Mid-to-late June	90–95****	12.5	
	Late wet	Jul/Aug	Oct/Nov	85–90***	6.0–6.5	
Maize-rice-rice (current & potential)	Dry	Early-to-mid-Dec	Early-to-mid Mar	90****	11.5–12	23–24
	Early wet	Late Mar/ early Apr	Mid-to-late July	90–95***	6.5–7.0	
	Late wet	Late Jul/ early Aug	Early-to-mid Nov	85–90***	6.0–6.5	

[a]* = long, ** = intermediate; short (growth duration increases during dry season); *** = short or extra short; **** = 1,300/1,400 GDD hybrid.

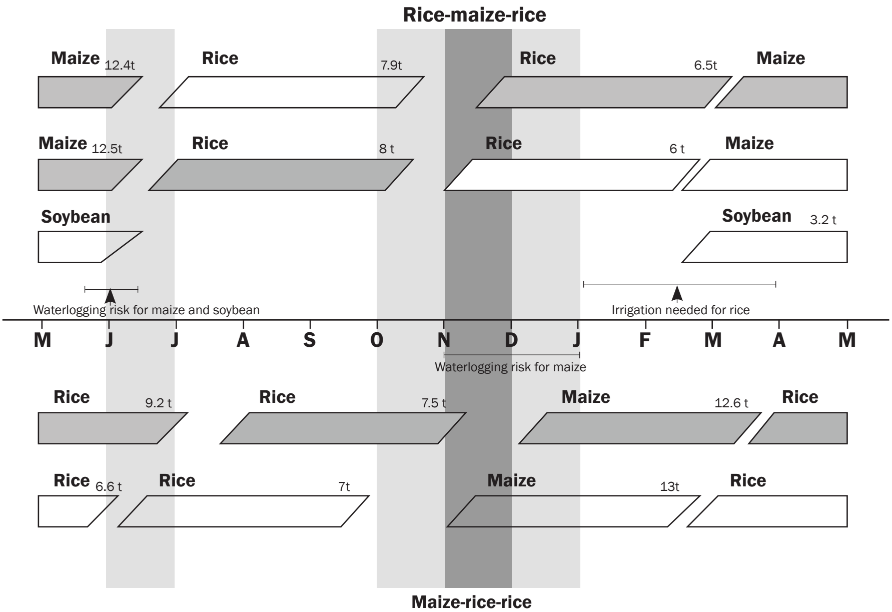


Fig. 60. Cropping system optimization for rice-maize-rice and maize-rice-rice systems in An Giang, southern Vietnam (dark-shaded and light-shaded vertical bars, respectively, indicate higher and lower intensity of storms and floods; shaded horizontal bars indicate better options for system optimization).

young males and young females) work off-farm during September, October, January, and March.

Tanchau has a predominantly sandy loam soil. In terms of fertility, the soil is intermediate to good with an average pH of 6.2 (range: 5.6–6.8). Major land types are lowlands (94%) and flat uplands (6%), with good water retention characteristics and good internal drainage. All land is irrigated for rice and maize. Dry-season rice contributes most and both EWR and LWR contribute significantly to meeting own food requirements. Rice, maize, green beans, and groundnuts are all important contributors to cash income. Some 80–85% of the maize grown is hybrids; the rest is open-pollinated or local varieties.

Raising of cattle, pigs, and poultry and aquaculture are the main livestock activities in the village. Poultry is used for own consumption but cattle, pigs, and fish/seafood are sold for cash income. Maize and other feeds are purchased for raising pigs and aquaculture but not for cattle and poultry. Crops, livestock, Mekong catfish and other kinds of fish, off-farm activities, and remittances from overseas jobs are the various sources of income, with crops and fish being the main sources. Household members generally have access to various sources of credit. The banks, private lenders, seed and fertilizer companies, input dealers, and close relatives are the main sources. Credit is used to buy fertilizers, pesticides, and machinery (mostly tractors) and to pay for irrigation bills and hired labor.

Maize is generally in surplus amount in the village. Some 75–100% of the maize grain is sold directly to the feed mills. The average distance from the maize fields or farmers' houses to the maize market is 12 km (range: 2–40 km). Generally, maize traders buy the grains from trade dealers, and many times maize traders go directly to farmers' fields or houses to buy maize. The traders then sell the grains to seed companies or factories that then sell the grains to feed mills. The average distance from the maize fields or farmers' houses to the feed mills is 20 km (range: 2–50 km). Maize is transported using trucks, with cost ranging from 30,000 to 50,000 VND.

There is also surplus rice in the village and this is generally sold. Dry-season rice is sold after harvest and farmers then buy white rice for their own consumption from the local market. The average distance from the rice fields or farmers' houses to the rice market is 8 km (range: 5–15 km). Like maize, rice traders buy rice grains from trade dealers, and many times the traders go directly to farmers' fields or houses to buy the rice grains. The traders then sell the grains to seed companies or factories that, in turn, sell the grains to import/export companies. On average, about 20,000 Vietnam dong (VND) (range: 15,000–35,000 VND) is needed to transport rice.

Farmers in the village can access public and private seed services existing in the area. The main private seed companies in the area are Cargill, An Giang Seed, Southern Seed, and Bio-seed. There is adequate grain storage infrastructure in the village and adjoining areas, so storage of grains does not seem to be a constraint. Maize is traded from the local village to import and export companies for other regions. The most commonly used planting dates are 1-25 November for dry-season rice, 15-25 February for EWR, 15-25 June for LWR, 1-25 November for DSM, 1-20 April for EWM, and 1-25 November for groundnut. River water is the main source of irrigation for dry-season rice, DSM, and groundnut; river plus rain water for EWR and EWM; and rain water for LWR. Urea, diammonium phosphate, muriate of potash, and complete fertilizers are used in the different crops.

Maize yields are generally higher than rice yields. Farm-gate prices of EWR and LWR are higher than EWM, but that of DSM is higher than dry-season rice. However, maize prices generally fluctuate more than rice prices. Rice straw is sold and used as a substrate for mushroom cultivation.

Although the current area under the R-M systems is small, there is great potential for their expansion in Tanchau and the surrounding areas. Local and provincial governments target an expansion of maize area by 20–40% in the early wet season and some areas in the dry season in the lowlands and medium lowlands in the village. New technologies such as the use of improved varieties, optimum spacing, good water management, and pest and disease management determine the scope of expansion. Some of the biophysical constraints to growing maize are poor hybrids and poor crop management, while socioeconomic constraints are the low prices of rice and maize grains and the high prices of inputs (seed, fertilizers, pesticides, etc.). The researchers working on the R-M systems have these priorities: fertilizer management (rate and timing) for system optimization, plant spacing and density in relation to fertilizer management, and system profitability.

Phitsanulok, Central Plain, Thailand. Current cropping systems. In the irrigated areas of Phitsanulok, the main traditional cropping system is the R-R. Here, the first rice (intermediate duration) is grown during the wet season from June to September, whereas the second rice (intermediate duration) is grown during the dry season from December to March (Table 18). Irrigation water is available through surface-water resources, but water use by a double rice crop is quite high. Dry-season rice has significant weed problems. Other issues are high prices of inputs and low prices of rice for farmers.

Yield potential of rice. The mean Yp of extra short-, short-, intermediate-, and long-duration rice varieties ranged from 6 to 7.5, 7.8 to 9.1, 9.1 to 11, and 10.2 to 13.5 t ha^{-1}, respectively. Yield potential was always higher for the dry season (October to February planting) than for the wet season (June to August planting). The corresponding mean growth durations of those varieties ranged from 82 to 100, 92 to 112, 110 to 130, and 124 to 152 days, respectively. The growth durations were always higher for the dry-season than for the wet-season rice crop. The extra short-duration variety received solar radiation of 1,800- 1,950 MJ m^{-2} during the growing season, whereas the long-duration variety received from 2,350 to 2,950 MJ m^{-2}. Mean growing-season temperatures were slightly higher for long-duration varieties than for others, especially during the dry season. For all planting dates, the long-duration variety received the highest incident solar radiation and the extra short-duration variety intercepted the least (Fig. 61).

Yield potential of maize. The mean Yp of maize hybrids in the four maturity categories (1,400, 1,500, 1,600, and 1,700 GDD) across planting dates ranged from 10.0 to 17.5 t ha^{-1}. Yield potentials were always higher for the 1 September to 1 November planting than for plantings in other months. The corresponding growth durations for those hybrids across planting dates ranged from 76 to 125 days, with longer durations noted for the 1 September to 1 December plantings than for plantings on other dates (Fig. 62). Growing-season incident solar radiation was higher for the 1 October to 1 January plantings than for other planting dates. Mean temperature from silking to maturity was least for the 1 September and 1 October plantings and highest for the 1 January to 1 March plantings. The highest yields of the 1 September and 1 October plantings were associated with lower temperatures during grain filling, which increased the growth duration of maize and increased solar radiation interception. In contrast, the higher mean temperatures during the grain-filling period slightly reduced the growth duration of crops planted from 1 January to 1 March; as a result, there was less radiation interception by the crops and yields were lower.

Potential cropping systems and system optimization. Two potential systems that can alternate with the existing R-R system have been identified. One is the R-M system in which maize replaces dry-season rice. In this system, a maize hybrid of about 1,600 GDD can be grown from November to February after harvesting a rice crop of intermediate duration. This system diversifies from rice to maize but does not involve any intensification. Although more productive (Yp = 23.5 t ha^{-1}) and less water-consuming than the existing R-R system (Yp = 19.0 t ha^{-1}), it results in less annual rice production. Excess moisture during maize establishment can be a problem, but choosing the best planting time for rice and growing the right maize hybrid can minimize damage. The second system, R-R-M, follows both intensification and diversification. The two rice crops have a Yp of 20 t ha^{-1} and an additional maize crop of 1,600 GDD has a Yp of about 13 t ha^{-1}. Thus, the total Yp of this system, at 33 t ha^{-1}, is quite high (Table 18; Fig. 63). This system maintains the rice yield but uses a high amount of water. There can be nutrient mining from such a triple-crop system involving only cereals if nutrients are not managed properly. Low prices of rice and maize, high prices of inputs, and lack of labor and mechanization for planting maize to enable a rapid turnaround are the other constraints in this system.

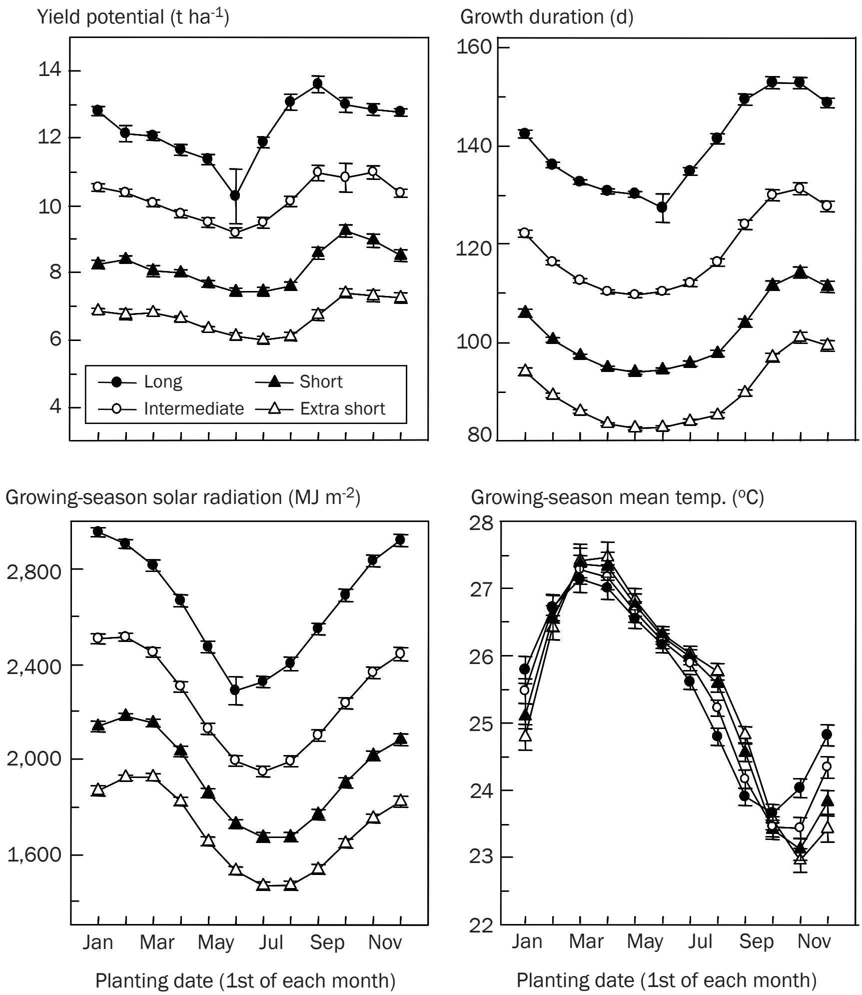


Fig. 61. Yield potential and growing-season characteristics of four rice varieties grown at Phitsanulok, Thailand.

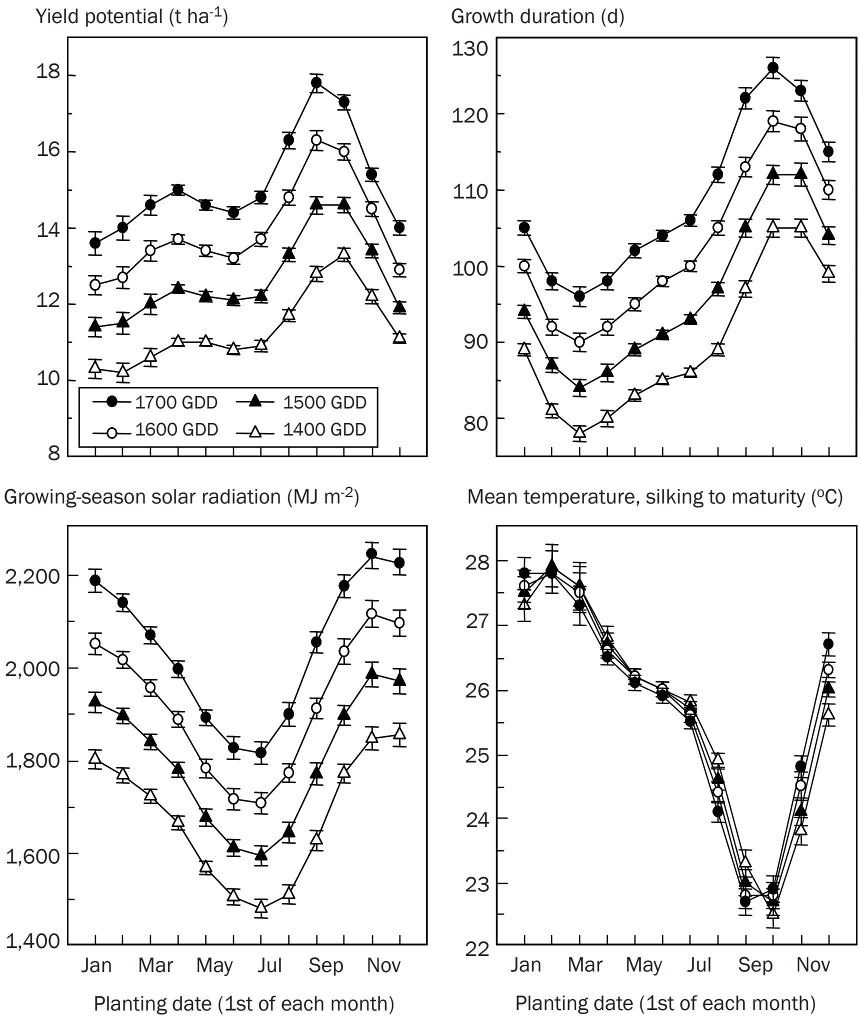


Fig. 62. Yield potential and factors contributing to yield potential of four maize hybrids grown in Phitsanulok, Thailand.

Table 18. Current and potential cropping system options in Phitsanulok, Thailand.

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-rice (current)	Wet	Rice	June	September	9.0	19.0
	Dry	Rice	December	March	10.0	
	Constraints: high water use by double rice; irrigation (surface) water availability; weed problems in dry-season rice; low price of rice; high prices of inputs					
Rice-maize (potential)	Wet	Rice	June	September	9.0	23.5
	Dry	Maize	November	February	14.5	
	Constraints: excess moisture during maize establishment; low prices of rice and maize; high prices of inputs; low labor availability in maize					
Rice-rice-maize (potential)	Wet	Rice	June	September	9.0	33.3
	Dry	Rice	October	February	11.0	
	Dry	Maize	March	May	13.3	
	Constraints: high water use by double rice; irrigation (surface) water availability; weed problems in dry-season rice; excess moisture during reproductive stage of maize; nutrient mining from three-crop system involving only cereals; low prices of rice and maize; high prices of inputs; low labor availability in maize; lack of mechanization for planting maize to enable rapid turnaround					

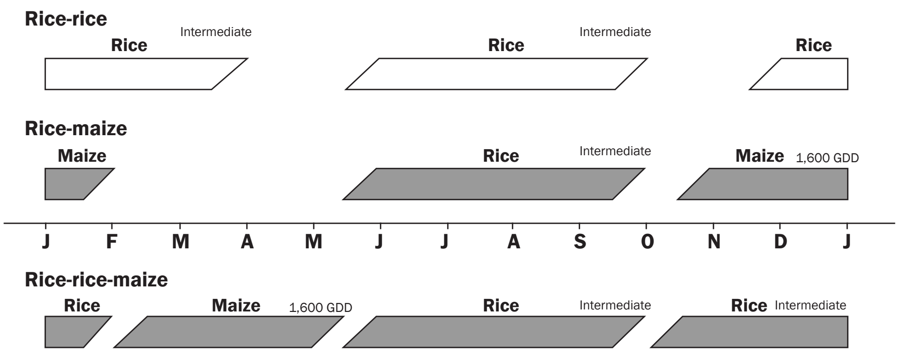


Fig. 63. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Phitsanulok, Thailand.

Central Lampung, Indonesia. Current cropping systems. In Central Lampung, R-R is the main existing system: the first wet-season rice is grown from January to April and the second wet-season rice is from September to December. The system Yp is 14.3 t ha^{-1} (Table 19).

Yield potential of rice. The mean Yp of extra short-, short-, intermediate-, and long-duration rice varieties ranged from 5 to 6.1, 6.5 to 7.7, 8.2 to 9.7, and 10.2 to 11.5 t ha^{-1}, respectively (Fig. 64). The corresponding mean growth durations for those varieties across planting dates were 85, 95, 110, and 130 days, respectively. There were very small differences in Yp and growth duration across planting dates but large differences among varieties. The extra short-duration variety received solar radiation ranging from 1,300 to 1,500 MJ m^{-2}, while the long-duration variety received 2,050-2,375 MJ m^{-2} during the season across planting dates. Mean growing-season temperatures were highly variable throughout the year. For all planting dates, the long-duration variety received higher incident solar radiation, while the extra short-duration variety intercepted the least, thus explaining the yield differences among different varieties (Fig. 64).

Table 19. Current and potential cropping system options in Central Lampung, Indonesia.

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-rice (current)	Wet	Rice	January	April	7.4	14.3
	Wet	Rice	September	December	6.9	
	Constraints: high water use by double rice; irrigation water availability					
Rice-maize (potential)	Wet	Rice	January	April	7.4	20.2
	Dry	Maize	May	August	12.8	
	Constraints: no shallow or deep tube wells but supplementary water through river available for maize					
Rice-maize-maize (potential)	Wet	Rice	January	April	7.4	33.6
	Dry	Maize	May	August	12.8	
	Wet	Maize	September	December	13.4	
	Constraints: no shallow or deep tube wells but supplementary water through river available for maize; high nutrient mining in triple-crop system involving only cereals; high labor use					
Rice-maize-rice (potential)	Wet	Rice	January	April	7.4	27.1
	Dry	Maize	May	August	12.8	
	Wet	Rice	September	December	6.9	
	Constraints: high water use in double rice; supplementary water through river available for maize; high nutrient mining in triple-crop system involving only cereals; high labor use					

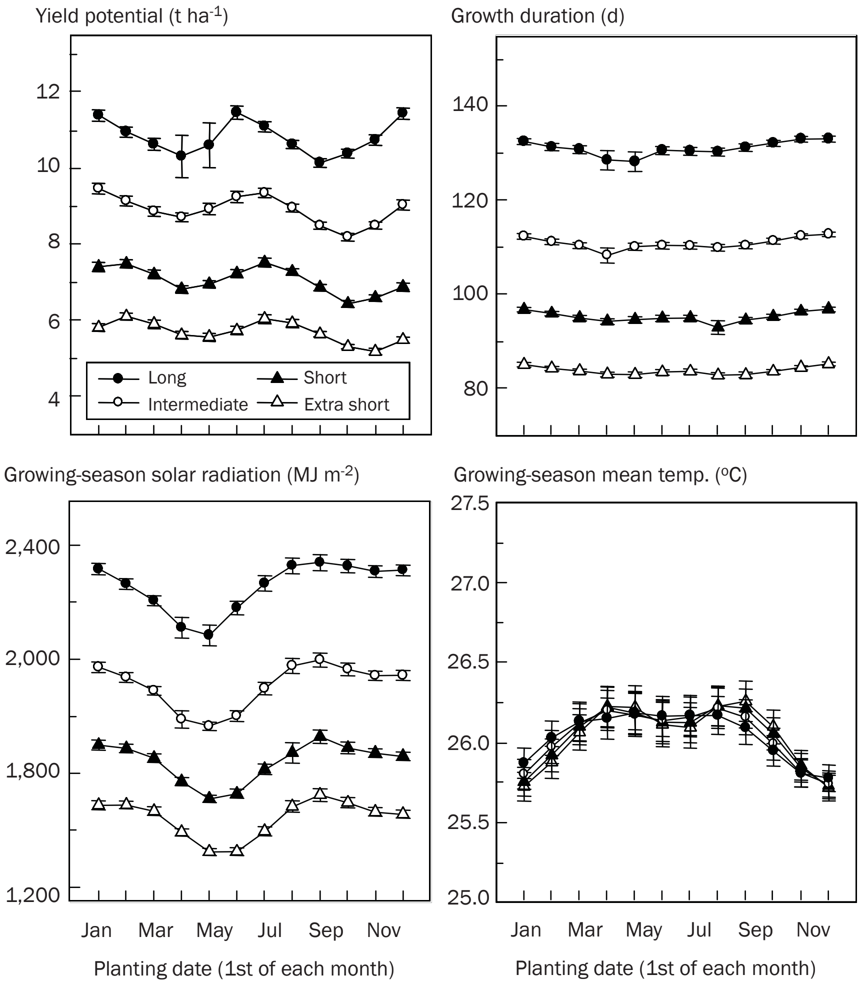


Fig. 64. Yield potential and growing-season characteristics of four rice varieties grown at Central Lampung, Indonesia.

<u>*Yield potential of maize.*</u> The mean Yp of maize hybrids in the four maturity categories (1,400, 1,500, 1,600, and 1,700 GDD) across planting dates ranged from 10.1 to 15.0 t ha^{-1}. Yield potentials of any hybrid did not vary much across planting dates but large differences among the hybrids were noted. The corresponding growth durations of those hybrids across planting dates ranged from 85 to 105 days, with minimum variations across planting dates for a given hybrid (Fig. 65). Growing-season

incident solar radiation differed across planting dates and hybrids and was higher for the August to February planting than for other planting dates. Mean temperature from silking to maturity was least for the October to December planting; it fluctuated greatly when the crop was planted in other months. The higher yields for the August to January planting were associated with higher intercepted solar radiation and lower temperatures during the grain-filling period.

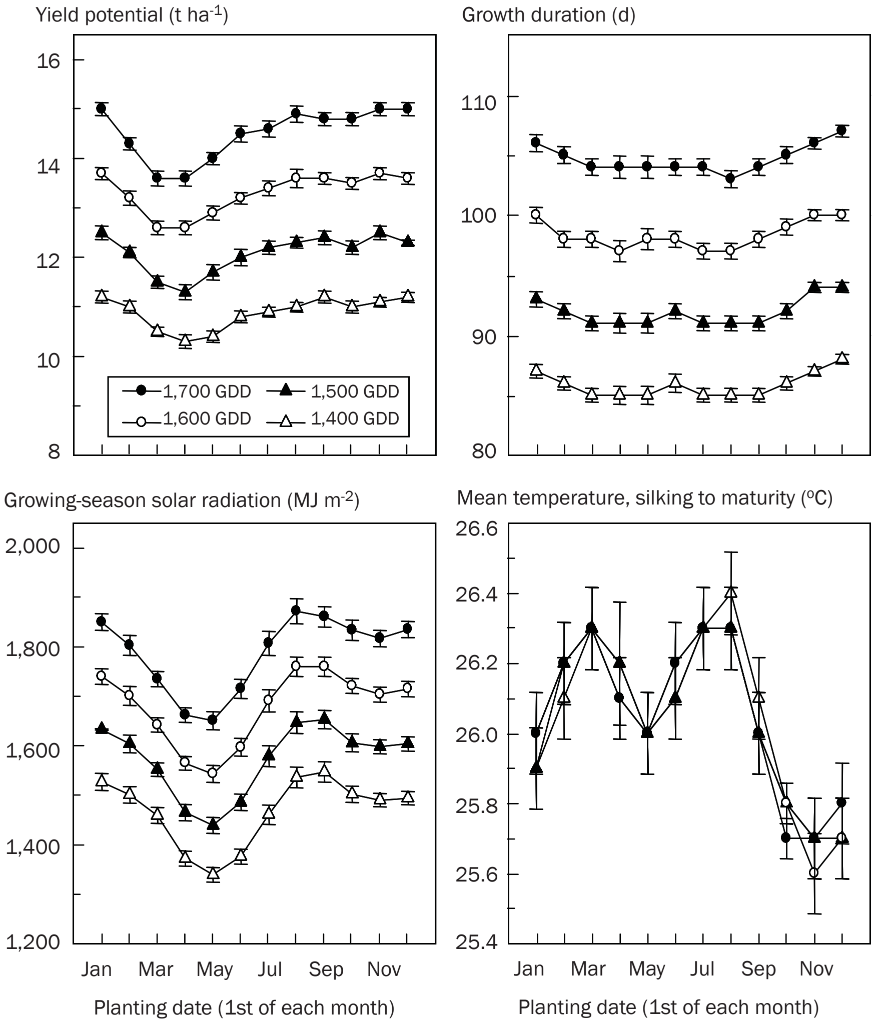


Fig. 65. Yield potential and factors contributing to yield potential of four maize hybrids grown in Central Lampung, Indonesia.

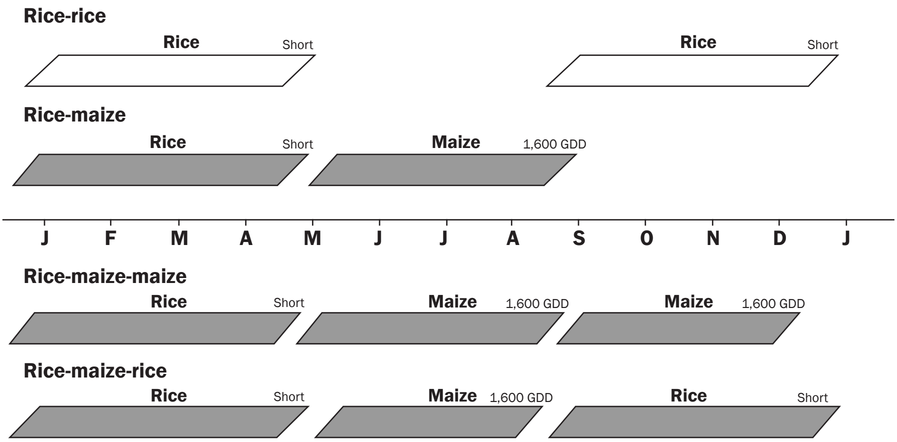


Fig. 66. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Central Lampung, Indonesia.

Potential cropping systems and system optimization. In the potential systems that involve maize, R-M, R-M-M, and R-M-R are proposed (Table 19). The proposed R-M system involves diversification from rice to maize but no intensification. In this system, a short-duration rice can be grown from January to April, followed by a maize hybrid of 1,600 GDD during the dry season from May to August. This system will increase total system productivity and profitability and will reduce water use. This system will, however, also result in smaller annual rice production. Rice-rice systems can be further intensified and diversified in Central Lampung in two ways (Table 19; Fig. 66). First, a maize crop with about 1,600 GDD can be grown from May to August in the R-R system, resulting in an R-M-R system with a total Yp of 27.1 t ha^{-1}. Second, the second rice crop can be replaced by a maize crop from September to December, and an additional maize crop can be grown from May to August, resulting in a total Yp of 33.6 t ha^{-1}. The intensive systems with two rice crops will result in high water use and the systems with three cereals may result in nutrient mining. The three-crop systems will also require more labor. Economic analysis of alternative systems and the requirements of and availability of supplementary irrigation water need to be determined to find out whether these systems are viable.

Thanjavur, Tamil Nadu, southern India. Current and potential cropping systems. The Cauvery Delta Zone (CDZ), with Thanjavur as the main district, covering about 11–12% (or 1.45 million ha) of the whole Tamil Nadu area, lies in the eastern part of the state. The east-flowing water of the Cauvery River is diverted at the Grand Anicut gate into the Old Cauvery Delta (OCD; fed by the Cauvery and Venna rivers) and the New Cauvery Delta (NCD; fed by the Grand Anicut Canal), thereby forming large irrigation systems with different characteristics. In Thanjavur located in the NCD, irrigation water is sourced from the Cauvery River. The traditional cropping systems in Thanjavur are R-fallow, R-R-fallow, R-R-pulses (R-R-P), and R-R-sesame (Table 20). Of these, R-R-P is the major system. The main pulses grown are blackgram and mungbean. Pulses are grown with residual soil moisture after rice and do not generally require supplemental irrigation. The Yp of pulses is generally low. The main rice crop is grown during thaladi season from October to January, and a second rice crop is grown during kuruvai season from June to September. Rice is grown on approximately 0.17 million ha in kuruvai season, 0.14 million ha in thaladi season, and 0.30 million ha in samba season. The main constraint seen in R-R-F and R-R-P is high water use, especially the high irrigation water requirement for rice during kuruvai. The alternative potential systems with three crops are M-R-P, R-R-M, and M-R-M (Table 20; Fig. 69). In the first system, maize replaces rice in the kuruvai season and, in the third system, maize replaces rice in the kuruvai and the pulses in summer. In the second system, maize replaces pulses in summer, but two rice crops are retained.

Yield potential of rice. The mean Yp of extra short-, short-, intermediate-, and long-duration rice varieties ranged from 4 to 6.1, 5.0 to 7.7, 7.0 to 9.5, and 9.0 to 11.5 t ha^{-1}, respectively (Fig. 67). The corresponding mean growth durations of these varieties across planting dates were 80, 90, 105, and 125 days, respectively. There were very small differences in growth duration but there were large differences in Yp across planting dates. The extra short-duration variety received solar radiation from 1,200 to 1,750 MJ m^{-2} during the growing season, whereas the long-duration variety got 2,050–2,625 MJ m^{-2}. Mean growing-season temperature was highest for the May to August planting and lowest for the November to January planting. For all dates of planting, the long-duration variety received the highest incident solar radiation and the extra short-duration variety received the least, thus explaining the differences in yield among different varieties (Fig. 67). The Yp of the four maturity types is from 4 to 9.5 t ha^{-1} for the June planting (kuruvai season) and from 4.5 to 10.5 t ha^{-1} for the October planting (thaladi season). ORYZA1, a precursor of ORYZA2000, also predicted a Yp of 8.3 t ha^{-1} for thaladi and 9.8 t ha^{-1} for kuruvai (Matthews et al 1995). Mean yields from site-specific nutrient management (SSNM) plots, aimed at receiving yields close to Yp, in 1998-2000 (thaladi) and in 1997-99 (kuruvai) seasons were 5.0 and 6.3 t ha^{-1} in Thanjavur and 6.0 and 7.0 t ha^{-1}, respectively, in Aduthurai (Nagarajan et al 2004), reflecting yields close to the climatic potential yields predicted by ORYZA1 and ORYZA2000.

Yield potential of maize. The mean Yp of the four maize hybrid maturity groups (1,400, 1,500, 1,600, and 1,700 GDD) across planting dates ranged from 9.1 to 15.5 t ha^{-1}. The mean growth durations of those hybrids ranged from 75 to 105 days, while the growing-season intercepted solar radiation ranged from 1,250 to 2,150 MJ m^{-2} (Fig. 68). There were large differences in Yp, growth duration, intercepted solar radiation, and growing-season mean temperature among the four hybrids across planting dates. Yield potentials were higher for the November to February planting than for other planting dates. Although the crops intercepted comparatively less solar radiation for the November and December planting, the mean temperature from silking to maturity was lowest and growth durations were highest in those months. For the January and February plantings, although mean temperatures were slightly higher and growth durations were slightly lower, intercepted solar radiation was much higher. This explained the higher yields of crops planted in those months.

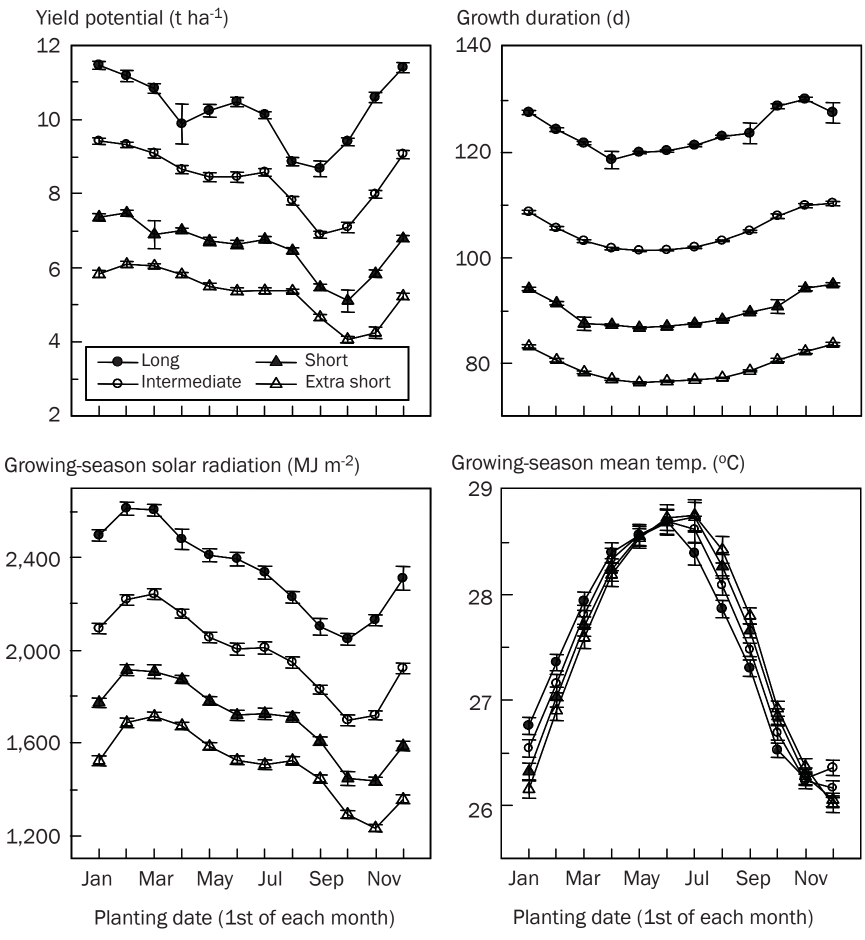


Fig. 67. Yield potential and growing-season characteristics of four rice varieties grown at Thanjavur, India.

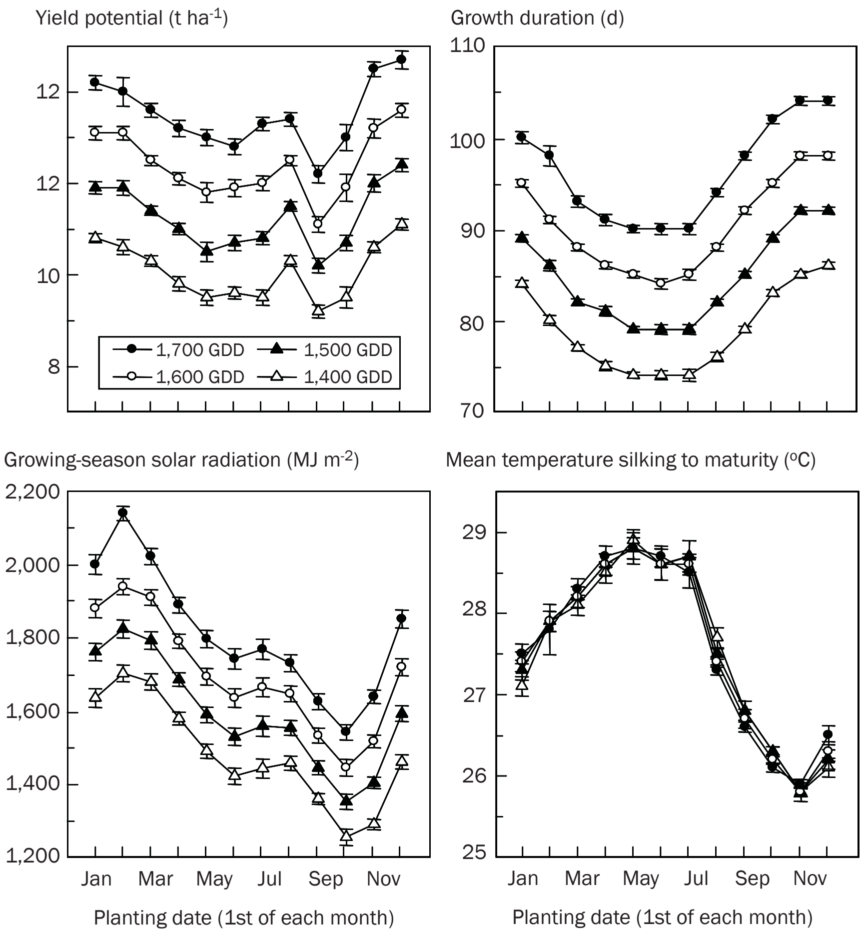


Fig. 68. Yield potential and factors contributing to yield potential of four maize hybrids grown in Thanjavur, India.

Table 20. **Current and potential cropping system options in Thanjavur, India.**

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-rice-pulses (current)	Kuruvai	Rice	June	September	8.4	17.5
	Thaladi	Rice	October	January	7.1	
	Summer	Pulses	March	May	2.0	
		Constraints: high water use in double rice; high irrigation water requirement for rice in kuruvai season; low Yp of pulses; shortage of labor				
Maize-rice-pulses (potential)	Kuruvai	Maize	June	September	12.8	21.9
	Thaladi	Rice	October	January	7.1	
	Summer	Pulses	March	May	2.0	
		Constraints: supplementary irrigation through bore holes needed for maize in kuruvai season; low Yp of pulses; low price of maize; shortage of labor				
Rice-rice-maize (potential)	Kuruvai	Rice	June	September	8.4	29.1
	Thaladi	Rice	October	January	7.1	
	Summer	Maize	March	May	13.6	
		Constraints: high water use in double rice; high irrigation water requirement for rice in kuruvai season; low prices of maize; shortage of labor; high water use and high nutrient mining from triple-crop system involving only cereals				
Maize-rice-maize (potential)	Kuruvai	Maize	June	September	12.8	33.5
	Thaladi	Rice	October	January	7.1	
	Summer	Maize	March	May	13.6	
		Constraints: supplementary irrigation through bore holes needed for maize in kuruvai and summer seasons; low prices of maize; shortage of labor; high water use and high nutrient mining from triple-crop system involving only cereals				

System optimization. Three alternative systems have been optimized with the use of optimum rice varieties and maize hybrids (Fig. 69). For the first M-R-P system, a maize hybrid of about 1,600 GDD can be grown from June to September in kuruvai with a maize Yp of 12.8 t ha^{-1} and a system Yp of 21.9 t ha^{-1}. In the second M-R-M system, a maize hybrid of 1,600 GDD can be grown in kuruvai and another hybrid of 1,700 GDD can be grown in summer, the latter with a Yp of about 13.6 t ha^{-1}. This system with two maize crops and one rice crop has a total Yp of 33.5 t ha^{-1}. For systems that replace rice with maize, water use by cropping systems will be lower than that with rice. However, for systems (e.g., R-R-M) in which maize is grown as an additional crop to the current system (e.g., R-R-F), total water use will increase.

Since the two systems involving three cereals are highly productive, their nutrient requirement will be high. Nutrient management should be implemented appropriately to make these systems sustainable. Further, although there is a good market demand for maize in Thanjavur District and in the whole Tamil Nadu State, the current maize price in the state is quite low. Hence, economic analysis of potential and optimized systems has to be carried out to identify those that are productive, profitable, and sustainable.

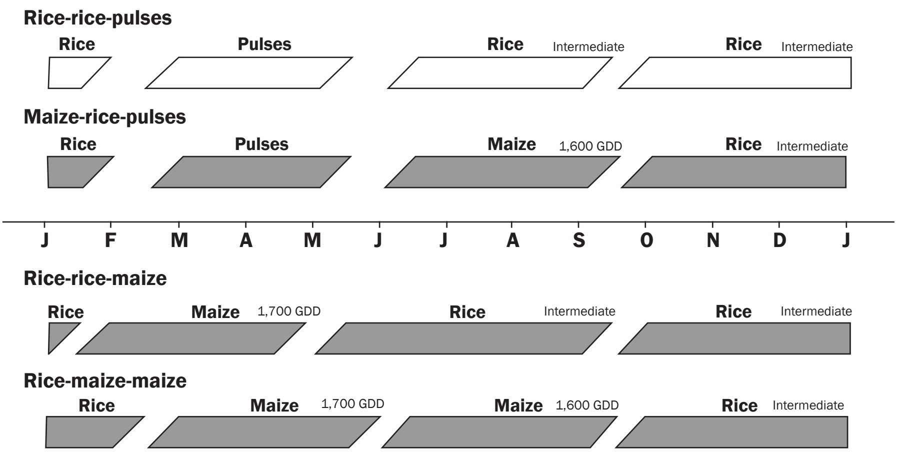


Fig. 69. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Thanjavur, India.

Subtropical warm agroecosystem

Dinajpur, northwest Bangladesh. Current and potential cropping systems. Various forms of cropping systems with varying intensities are practiced on different land types in Bangladesh. The rice-based systems, which are implemented in the medium uplands or medium lowlands, include a main rice (predominantly transplanted and locally known as T. aman) during the hotter kharif II (or monsoon) season and, where water is available, a boro rice in the cooler rabi (or winter) season. Where irrigation water is scarce during rabi, especially in central and northern districts, wheat and short-duration crops such as potato, legume, or oilseed are grown. Market forces and availability and cost of irrigation water increasingly affect the decisions of farmers on whether to grow rice, wheat, maize, potato, legumes, or other crops in the rabi season. Of all systems, rice-rice (R-R) and rice-wheat (R-W) are the main traditional systems in northwest Bangladesh. Ali et al (2009) provided a detailed assessment of R-M systems in Bangladesh. The potential and emerging systems in Dinajpur are R-R-M, R-M-M, rice-potato-maize (R-P-M), and rice-legume-maize (R-L-M) (Table 21). Existing and potential constraints are also shown in Table 21.

Yield potential of rice. The mean Yp of extra short-, short-, intermediate-, and long-duration rice varieties for Dinajpur ranged from 4.5 to 8.0, 5.5 to 9.0, 6.0 to 12.0, and 8.0 to 14.0 t ha^{-1} (Fig. 70). Yield potential was always higher for the winter (boro) season (December to February planting) than for kharif I (aus) and kharif II (aman) seasons (April to November planting). The corresponding mean growth durations for those varieties were 80–130, 90–140, 105–150, and 125–178 days, respectively. The growth durations were always higher for boro than for aus and aman crops. The extra short-duration variety received solar radiation from 1,250 to 2,325 MJ m^{-2} during the growing season, while the long-duration variety received from 1,975 to 3,275 MJ m^{-2}. For all planting dates, the intermediate- or long-duration varieties had longer growth duration and higher incident solar radiation and were exposed to slightly cooler days. All these attributes resulted in higher yields of the intermediate- or long-duration varieties compared with extra short- or short-duration varieties (Fig. 70).

Yield potential of maize. The mean Yp of four hybrids across planting dates ranged from 9.0 to 20.3 t ha^{-1} (Fig. 71). Yield potentials were always higher for the rabi (winter) season (September-February plantings; 10.0–20.3 t ha^{-1}) than for the kharif I and kharif II seasons (March-August plantings; 8.5–14.0 t ha^{-1}). The corresponding growth durations for those hybrids across planting dates ranged from 77 to 155 days, with greater duration for rabi than for kharif I and II. Growing-season incident solar radiation ranged from 1,200 to 2,600 MJ m^{-2} and was higher for rabi than for kharif I and II plantings. Mean temperature from silking to maturity was least for the September to November plantings and highest for the January to July plantings (Fig. 71). The higher Yp for the September to November plantings was associated with lower temperatures during the grain-filling period, which increased growth duration and intercepted greater solar radiation. In contrast, the higher mean temperatures during the grain-filling period slightly reduced growth duration for the January to July plantings.

Table 21. Current and potential cropping system options in Dinajpur, Bangladesh.

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice- rice (current)	Kharif II	Rice	August	November	9.0	19.8
	Rabi	Rice	February	May	10.8	
		Constraints: high water use by double rice; irrigation water availability for boro rice; groundwater table decline due to excessive pumping of water for boro rice				
Rice-wheat (current)	Kharif II	Rice	July	October	7.4	13.9
	Rabi	Wheat	November	March	6.5	
		Constraints: low Yp of current wheat varieties; diseases in wheat; heat and high temperature injury in wheat; low profit from wheat				
Rice-rice-maize (potential)	Kharif II	Rice	August	November	9.0	29.5
	Rabi	Rice	January	April	10.5	
	Kharif I	Maize	May	July	10.0	
		Constraints: high water use by double rice; lack of irrigation water availability for boro rice; groundwater table decline due to excessive pumping of water for boro rice; high nutrient mining from triple-crop cereal systems; lack of fertilizers for all crops; lack of access to credit to go into triple-crop system				
Rice-maize-maize (potential)	Kharif II	Rice	July	October	7.4	31.5
	Rabi	Maize	November	March	13.4	
	Kharif I	Maize	April	June	11.1	
		Constraints: high nutrient mining from triple-crop cereal systems; lack of fertilizers for all crops and access to credit to enable triple-cropping				
Rice-potato-maize (potential) (exc. potato)	Kharif II	Rice	July	October	7.4	19.9
	Rabi	Potato	November	February	–	
	Late rabi to kharif I	Maize	February	May	12.5	
		Constraints: high nutrient mining from triple-crop cereal systems; lack of fertilizers for all crops, access to credit to enable triple-system, and storage facilities for potato				
Rice-pulses-maize (potential)	Kharif II	Rice	July	October	7.4	21.7
	Rabi	Pulses	November	February	3.0	
	Kharif I	Maize	March	June	11.3	
		Constraints: low Yp of winter pulses (chickpea and lentil); low profit from pulses; pests and diseases in pulses				

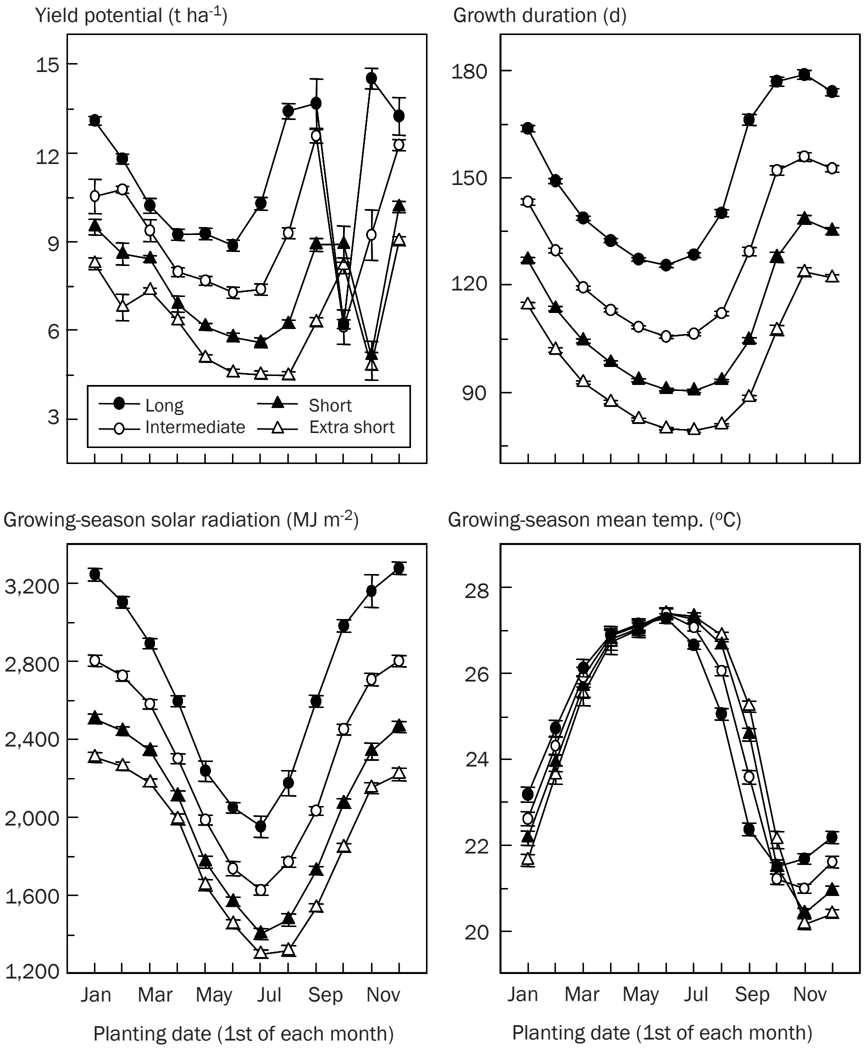


Fig. 70. Yield potential and growing-season characteristics of four rice varieties grown at Dinajpur, northwest Bangladesh.

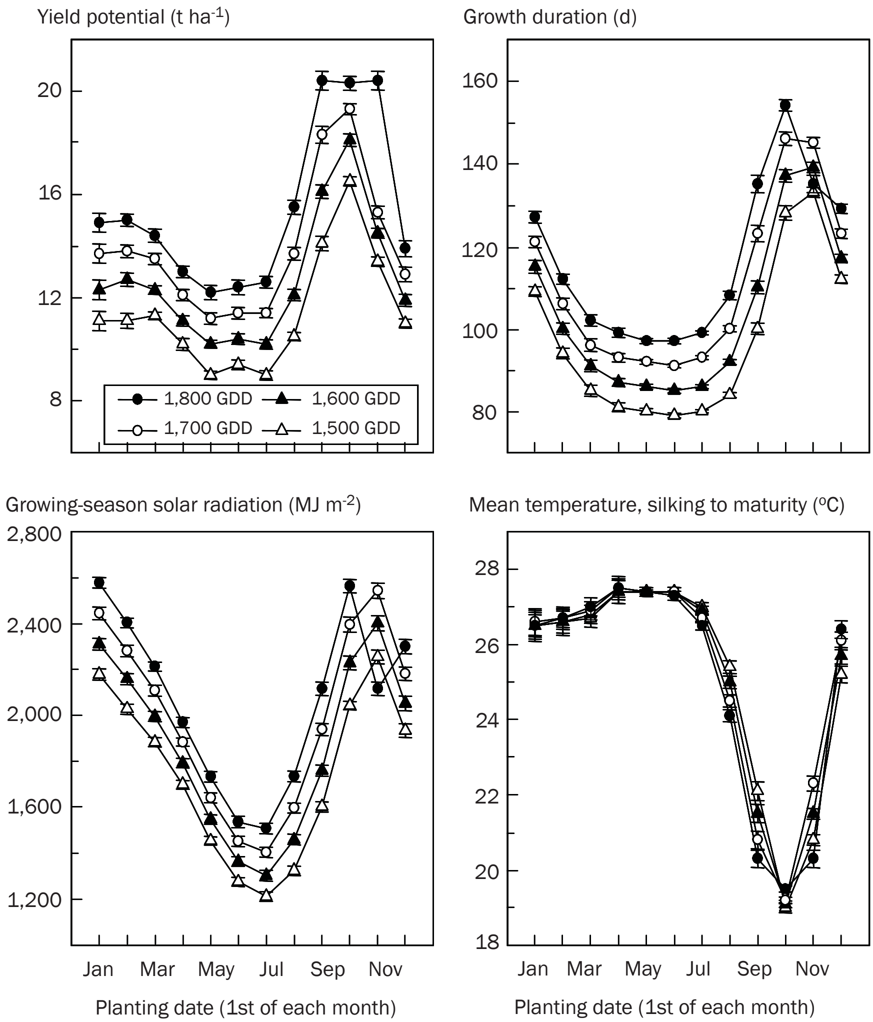


Fig. 71. Yield potential and factors contributing to yield potential of four maize hybrids grown at Dinajpur, northwest Bangladesh.

Irrigation water requirements for maize. The window for planting maize after aman rice in the rabi season is from November to February. Simulations suggest that the optimum period for planting is probably from November to January when maize could use the residual soil water after rice as well as minimize both waterlogging during crop establishment and the dry conditions during maturity. Likewise, during kharif I, though the window for planting maize would be from late February to late May, the optimum time for planting from the Yp point of view would be from late March to early May, when maize could use rainfall during the early to mid-kharif II season. If planted too late, the crop will mature during the rainy months in July and August and may cause disease and postharvest-and processing-related problems. During both rabi and kharif I seasons, some supplemental irrigation for maize might be necessary.

Although planting in November would give the highest Yp under the current management practices and technologies, it might not be practical and feasible to plant at that time in most areas of Bangladesh due to the late harvest of rice and soil waterlogging problems. Thus, to illustrate the effect of maize planting date, 1 December and 1 January were chosen for planting during rabi. Variability in Yp of a hybrid of 1,700 GDD during the rabi and kharif I seasons, rainfall during the growing seasons, and irrigation water requirements to achieve Yp of the hybrid in Dinajpur for the two planting dates is shown in Figure 72. Yield potential for 1 December planting across 20 years of simulation ranged from 11.0 to 15.8 t ha^{-1}, while that for 1 January planting ranged from 10.6 to 15.6 t ha^{-1}. Yield potential across years was less variable for the 1 December planting than for the 1 January planting. Rainfall during the season for the 1 December planting ranged from 1 to 10 mm, while that for the 1 January planting ranged from 3 to 13 mm. Irrigation water requirements to achieve Yp across years ranged from 130 to 227 mm for the 1 December planting and from 97 to 227 mm for the 1 January planting. In all the 20 years, there was virtually no rainfall, so irrigation was needed in all years. Suitable small-scale machinery for planting and management practices such as planting on raised beds need to be developed, evaluated, and refined for fast turnaround and timely planting.

For kharif I, the 1 April and 1 May planting dates were chosen for calculating irrigation water requirements of maize to achieve a yield close to Yp. Planting maize in April and May would allow the full use of most of the growing-season rainfall and would thus require less irrigation water. Yield potential across years for the 1 April planting ranged from 9.7 to 13.5 t ha^{-1}, while that for the 1 May planting ranged from 9.6 to 12.2 t ha^{-1} (Fig. 72). Yield potential across years was more variable for the 1 April planting than for the 1 May planting. Rainfall during the growing season ranged from 366 to 1,060 mm for the 1 April planting and from 531 to 1,465 mm for the 1 May planting. Since there was high rainfall during the season for the 1 May planting, the crops did not require any irrigation. For the 1 April planting, however, irrigation water requirement ranged from 0 to 130 mm, with crops needing irrigation in 13 out of 20 years. As mentioned earlier, if planted too late, the crops may be waterlogged and damaged by high rainfall events during the grain-filling stage and may also face postharvest- and processing-related problems. Hence, selection of appropriate planting dates, the use of suitable varieties and hybrids of rice and maize, and optimization of cropping systems are important.

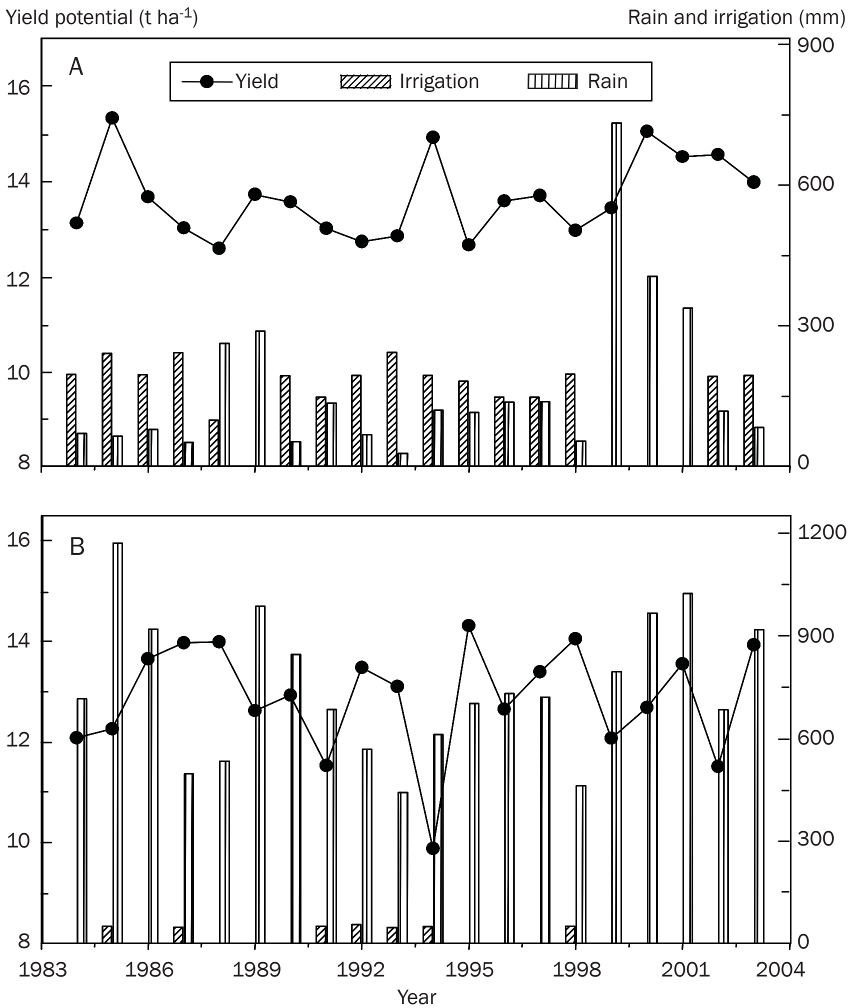


Fig. 72. Variability in yield potential and irrigation water requirements for growing kharif-I season (A, Apr-May planting) or rabi-season (B, Dec-Jan planting) maize (hybrid maturity: 1,600 GDD) at Dinajpur, northwest Bangladesh.

System optimization. The current main systems in Dinajpur are R-R and R-W. The total system Yp of R-W is quite low (13.9 t ha^{-1}) (Fig. 73). Based on Yp, four alternative triple-cropping systems are proposed. The first involves the addition of a 1,600-GDD maize crop in kharif I to the existing R-R system (with both intermediate-duration rice), thereby increasing the total system yield from 19.8 to 29.5 t ha^{-1}. The second involves growing one rice (intermediate) and two maize crops (1,600 GDD) in rabi and kharif I, with a total system Yp of 31.5 t ha^{-1}. The third and fourth systems involve growing an intermediate-duration rice in kharif II, a potato or a pulse crop in rabi, and maize (1,600 GDD) in kharif I. The first two systems involving only rice and maize require high amounts of nutrients and high water use by rice (especially for the two rice crops in the R-R-M system). Some supplemental irrigation is needed for maize, but it is quite nominal and should be met with existing surface-water sources or shallow tube wells. Potato yields are very high and the crop also needs lots of nutrients and water. Thus, appropriate nutrient and water management and the best cultivars are required for these systems to be sustainable.

Begusarai, Bihar, eastern India. *Current cropping systems.* In parts of Begusarai, Samastipur, Vaishali, and Muzafarpur districts of Bihar, the main cropping systems are R-F, R-M, and R-W, with kharif rice grown from July to October. These areas are severely affected by floods. The Yp of an intermediate-duration kharif rice is <9 t ha^{-1}

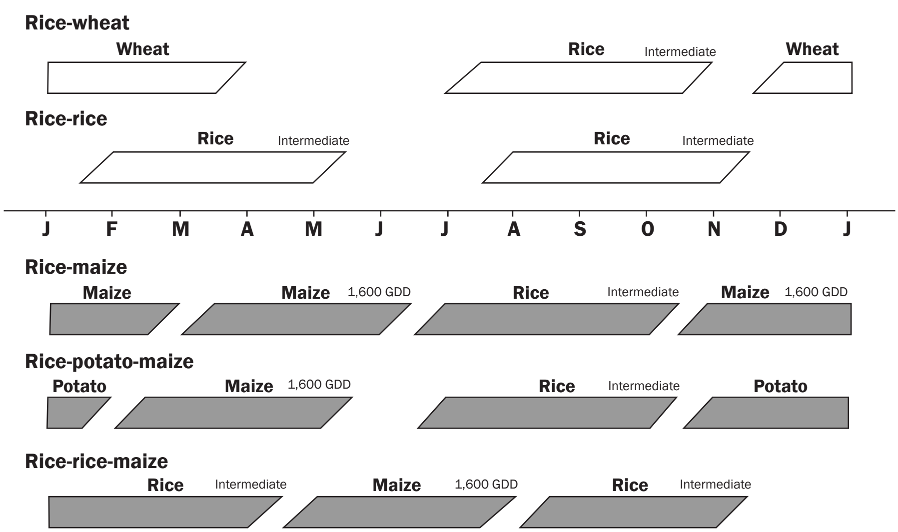


Fig. 73. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Dinajpur, Bangladesh.

and that of wheat is 5.2 t ha^{-1}. Thus, the total system Yp of R-F is <9 t ha^{-1}, while that of R-W is about 14.2 t ha^{-1} (Table 22). Cyclones and waterlogging are the main abiotic constraints in rice, although drought also occurs in some years. Diseases, insects, and weeds are the main biotic constraints in both rice and wheat. Lack of timely access to fertilizers and unavailability of credit are the main socioeconomic constraints.

Yield potential of rice. The mean Yp of extra short-, short-, intermediate-, and long-duration rice varieties for Begusarai ranged from 4.4 to 8.9, 5.3 to 9.9, 5.5 to 12.8, and 6.2 to 14.8 t ha^{-1} (Fig. 74). The corresponding mean growth durations for those varieties ranged from 78 to 125, 88 to 140, 105 to 157, and 128 to 181 days, respectively. The extra-short variety received solar radiation from 1,293 to 2,237 MJ m^{-2} during the growing season, while the long-duration variety received from 2,200 to 3,500 MJ m^{-2}. Mean temperature during the growing season for different planting dates ranged from 20 to 28.7 °C. There were no significant differences in growing-season mean temperature among different varieties. Mean yields were highest for the October, December, and January plantings for extra short-duration varieties; September and December plantings for short-duration varieties; August and September plantings for intermediate varieties; and September and November plantings for long-duration varieties. Because of cold injury during grain filling, the intermediate- and long-duration varieties planted in October gave lower yields. Extra short- and short-duration varieties, however, avoided cold injury. For all planting dates, the intermediate- or long-duration varieties had higher growth duration and higher incident solar radiation, and they were exposed to slightly cooler days. All these attributes resulted in higher yields of intermediate or long-duration varieties compared with those of extra short- or short-duration varieties (Fig. 74).

Yield potential of maize. The mean Yp of four hybrids across planting dates ranged from 8.1 to 19.7 t ha^{-1} (Fig. 75). Yield potentials were always higher for the rabi (winter) season (September-November planting; 11.5–19.7 t ha^{-1}), with highest yields noted for the October planting. The corresponding growth durations of those hybrids across planting dates ranged from 68 to 147 days, with greater duration for the October and November plantings. Growing-season incident solar radiation ranged from 1,156 to 2,550 MJ m^{-2}, with the highest seen for the October to December plantings. Mean temperature from silking to physiological maturity was least for the September to November plantings (18.6–23.2 °C), with the lowest observed for the October planting (Fig. 75). The higher Yp for the September to November planting was associated with lower temperature during the grain-filling period, which lengthened growth duration and intercepted greater solar radiation.

Potential cropping systems and system optimization. The potential alternatives for Begusarai are the R-M and R-W-M systems. In the R-M system, a maize hybrid of about 1,400 GDD can be planted in October and harvested in March. However, if planted during heavy rainfall at the end of the rice season, maize can be affected by the excess moisture. Maize can also be injured by low temperature in some years. October-planted maize, however, in most years, can escape from low-temperature injury and can have a very high yield. In the R-W-M system, a maize crop of 1,500 GDD can be grown in the prekharif season from March to May with a Yp of 10.7 t

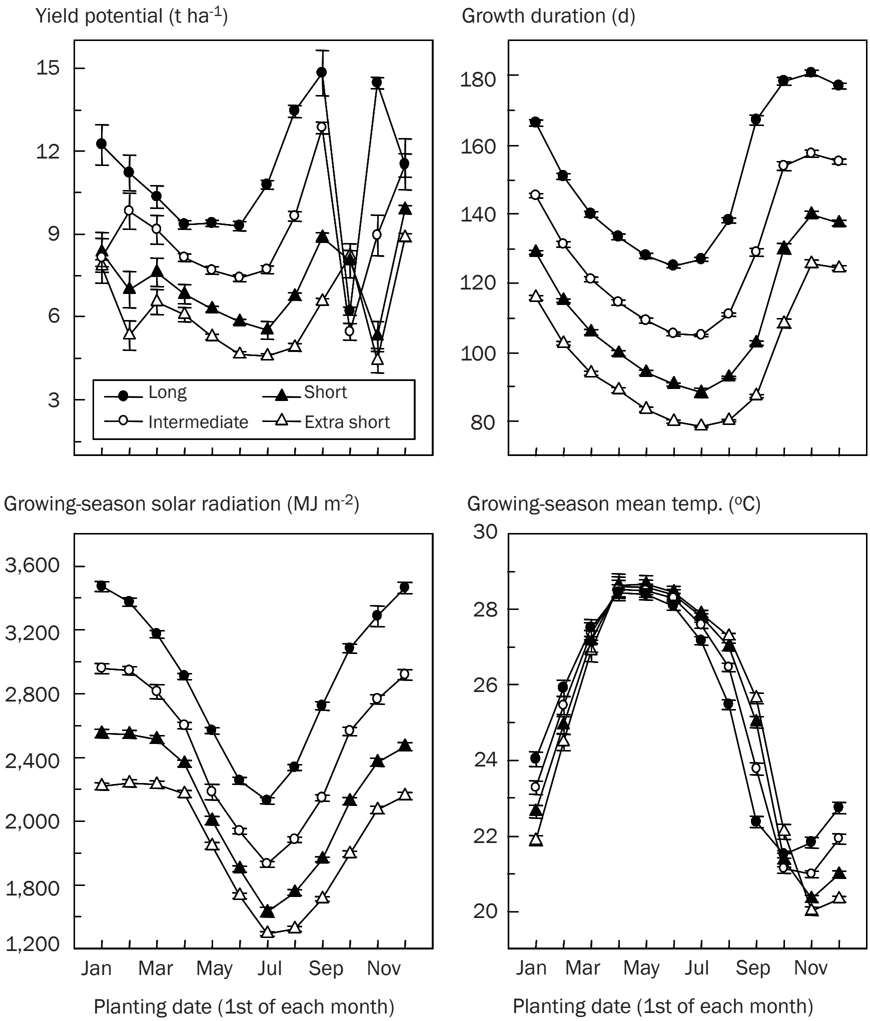


Fig. 74. Yield potential and factors contributing to yield potential of four rice varieties grown at Begusarai, Bihar, India.

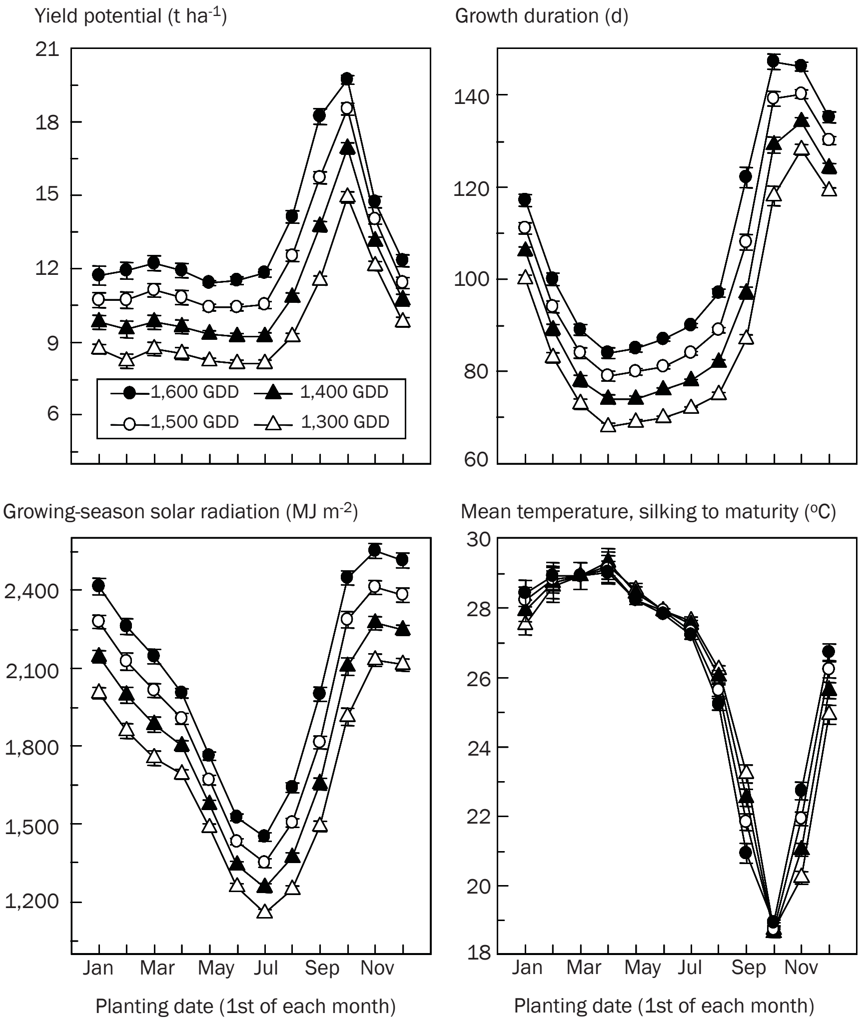


Fig. 75. Yield potential and factors contributing to yield potential of four maize hybrids grown at Begusarai, Bihar, India.

ha^{-1} and total system Yp of more than 23 t ha^{-1} (Table 22, Fig. 76). There are disease, insect, and weed problems in both rice and wheat. Water use by the three cereals remains very high. There is also the problem of nutrient mining from three-crop systems involving cereals only. Availability and accessibility to credit and fertilizers are important requirement for all these systems to be viable. There is potential for maize area expansion in Bihar because the big seed companies such as Pioneer, Monsanto, and Bayer are working there. There is also a QPM-based industry as well as an NGO called Krishi Vigyan Kendra located in Khagaria near Begusarai.

Table 22. Current and potential cropping system options for Begusarai, Bihar, India.

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-fallow (current)	Kharif	Rice	July	October	8.7	8.7
Rice-wheat (current)	Kharif	Rice	July	October	8.7	14.2
	Rabi	Wheat	November	March	5.5	
		Constraints: low Yp of wheat; lack of availability of supplemental irrigation water for wheat; cyclones and waterlogging in rice; high temperature stress in wheat; terminal drought in rice and wheat; high incidence of diseases (leaf spot and blast), insects (stem borers and leaffolders), and weeds (*Echinochloa*, *Cyperus*) in rice; incidence of foliar blight disease and weeds (*Phalaris*, *Chenopodium*, *Parthenium*) in wheat; low profit from wheat; lack of access to fertilizers and credit				
Rice-maize (potential)	Kharif	Rice	June	September	7.5	24.0
	Rabi	Maize	October	March	16.5	
		Constraints: excess moisture and cold injury for maize not planted on time; lack of availability of supplemental irrigation water for maize; high incidence of diseases (*Maydis* leaf blight, rust), insects (stem borers), and weeds (*Brachiaria*, *Solonum*, *Convolvulus*, *Parthenium*) in maize; lack of access to fertilizers and credit				
Rice-wheat-maize (potential)	Kharif	Rice	July	October	7.5	23.6
	Rabi	Wheat	November	February	5.4	
	Prekharif	Maize	March	May	10.7	
		Constraints: low Yp of wheat; lack of availability of water for supplementary irrigation for wheat and maize; premonsoon damage in maize; high nutrient mining from a three-crop system involving only cereals; high incidences of insects (stem borers, aphids), diseases (*Maydis* leaf blight, stalk rot), and weeds (*Brachiaria*, *Commelina*, *Echinochloa*, *Cyperus*) in maize; lack of access to fertilizers and credit				

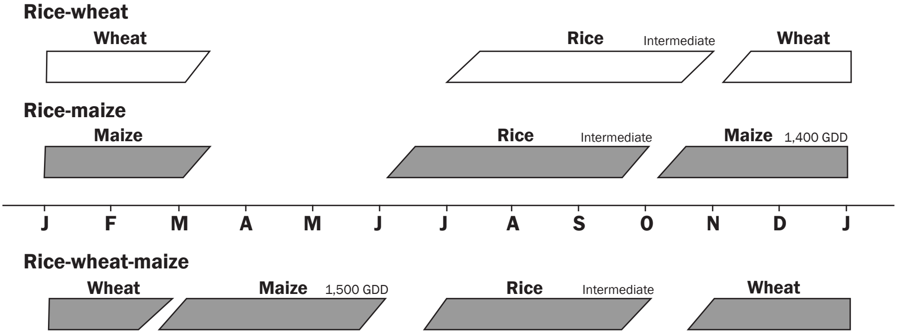


Fig. 76. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Begusarai, Bihar, India.

Rampur, Chitwan, central Nepal. Current and potential cropping systems. Rampur is located at 228 m in Chitwan District in central-southern Nepal. The main cropping systems in the irrigated and favorable rainfed lowlands are R-W, rice-mustard, and rice-kidney bean (*Phaseolus vulgaris*) (Table 23). In the R-W system, an intermediate rice variety is grown from July to October and wheat is cultivated from November to March, with a total system Yp of 16.0 t ha^{-1}. However, because of the prevalence of many diseases and insects in both rice and wheat, farmers' actual yields are quite low. In some areas, farmers also practice rice-mustard-maize, rice-lentil-maize, and rice-potato-maize (R-P-M). Because of the low prices of wheat and mustard, the low yield of lentil, and some new diseases in kidney bean, these crops are now grown in fewer areas than before and are being replaced by winter maize. There is also potential to grow a short-duration maize after a wheat crop, thus intensifying and diversifying the current R-W system into an R-W-M system. In fact, some farmers have already been practicing the R-W-M system for many years, but total system Yp is low because of a lack of good varieties and hybrids and lack of good crop management.

Yield potential of rice. Rice crops planted from October to January were affected by the cold; they died early in the season without reaching maturity and forming grains. For the February and September plantings, many crops died but some survived; mean yields and mean growth durations as well as mean solar radiation were extremely low. Many crops planted in February died early in the season as mean growing-season temperature was less than 12 °C and those planted in September died due to low temperature during grain filling. Crops planted from March onward survived. The Yp of rice varieties for the March to August planting ranged from 6 to 14 t ha^{-1}, with 6 to 9 t ha^{-1} for short- and extra short-duration varieties and 9 to 10.5 t ha^{-1} for the intermediate-duration varieties (Fig. 77). The growth duration of different varieties planted between March and August ranged from 90 to 150 days; that of short- and extra short-duration varieties was from 90 to 120 days. Solar radiation intercepted during the growing season for those planting dates ranged from 1,500 to 2,800 MJ m^{-2}, while the growing-season mean temperature ranged from 17 to 22 °C.

Table 23. Current and potential cropping system options in Rampur, Chitwan, Nepal.

System	Season	Crop	Planting date	Harvest date	Yield potential ($t\ ha^{-1}$)	System yield potential ($t\ ha^{-1}$)
Rice-wheat (current)	Summer	Rice	July	October	10.5	16.0
	Winter	Wheat	November	March	5.5	
	Constraints: Yp of existing wheat variety low; high incidence of insects (caseworms, leaffolders, and stem borers), disease (blast, bacterial leaf blight, sheath blight, and loose smut), and weeds (grassy and *Cyperus*) in rice; some incidence of insects (termites and stem borers), and diseases (*Helminthosporium* leaf blight, rust, and false smut) in wheat; lack of availability of fertilizers for all crops; low profit from wheat					
Rice-potato-maize (potential)	Summer	Rice	July	October	10.5	22.5 (exc. potato)
	Winter	Potato	November	February	–	
	Spring	Maize	March	June	12.0	
	Constraints: high water use and high nutrient mining in triple-crop system with only cereals; same disease, insect, and weed problems in summer rice as for R-W system; stem borers, aphids, and *H. maydis* in maize; high labor use and unavailability; uncertain availability of fertilizer for all crops; lack of access to credit to enable a triple-crop system					
Rice-wheat-maize (potential)	Summer	Rice	July	October	10.5	28.0
	Winter	Wheat	November	March	5.5	
	Spring	Maize	March	June	12.0	
	Constraints: Yp of existing wheat variety low; high water use and high nutrient mining in triple-crop system with only cereals; pests and diseases in rice and wheat as for R-W system; uncertain availability of fertilizers for all crops; lack of access to credit to enable a triple-crop system; low profit from wheat					
Rice-maize-maize (potential)	Summer	Rice	Mid-June	Late August	7.5	35.5
	Winter	Maize	September	December	16	
	Spring	Maize	March	Early June	12.0	
	Constraints: high incidence of pests and diseases; excess moisture and cold injury to winter maize not planted on time; high water use and high nutrient mining in triple-crop system with only cereals; uncertain availability of fertilizers for all crops; lack of access to credit to enable triple-crop system					

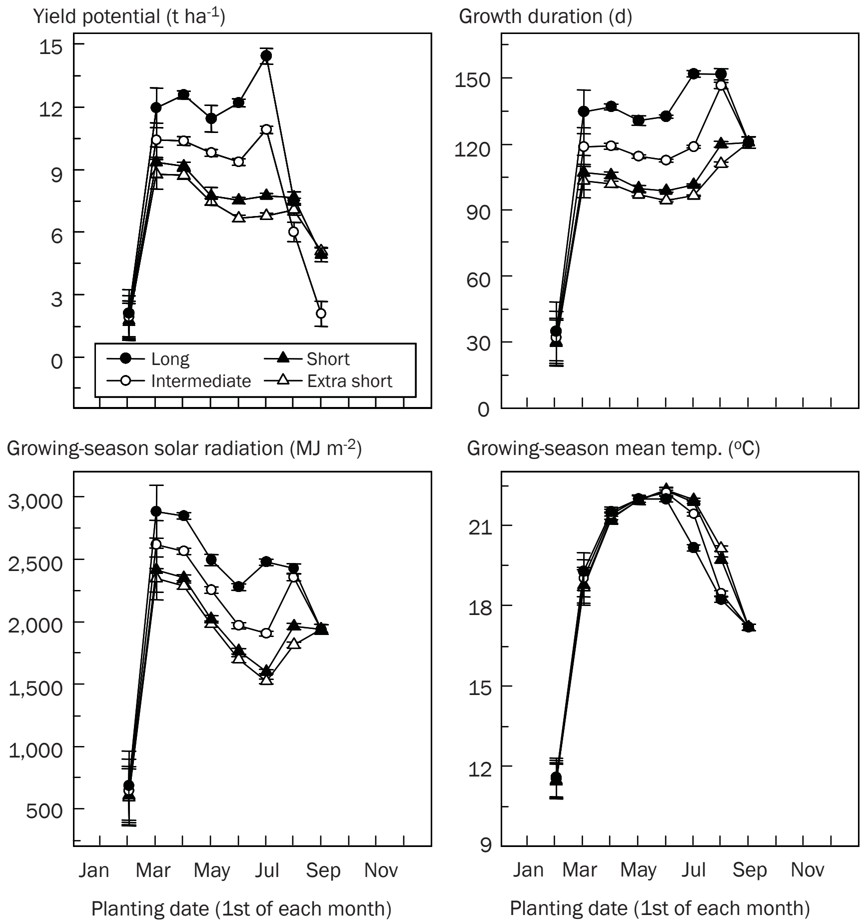


Fig. 77. Yield potential and factors contributing to yield potential of four rice varieties grown at Rampur, Chitwan, Nepal.

Yield potential of maize. Maize crops sown from December to February were affected by the cold□the seeds either did not germinate or the seedlings died early in the season. The Yp of maize hybrids for the March to November planting ranged from 12 to 32 t ha^{-1}, growth duration was from 105 to 255 days, growing-season solar radiation was from 2,200 to 5,000 MJ m^{-2}, and mean temperature during grain filling was 14–22 °C. Crops planted from August to November took very long to mature (>225 days) as mean temperature during grain filling was 14–21 °C (Fig. 78).

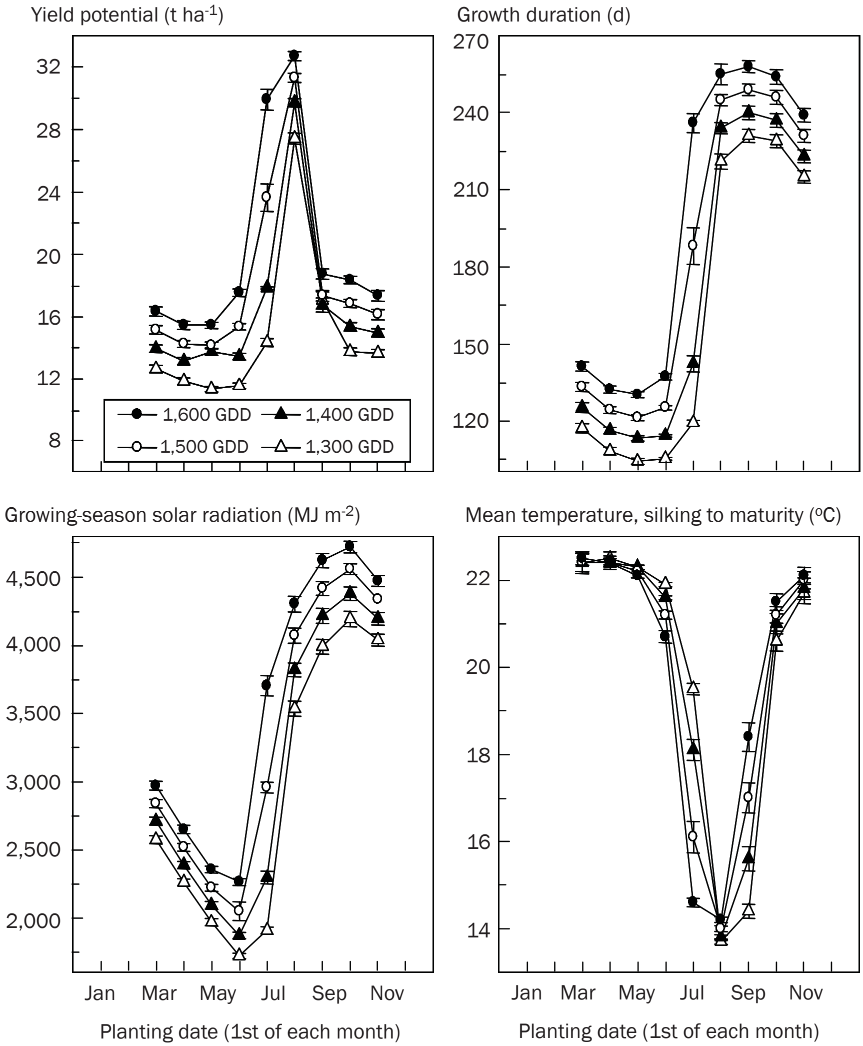


Fig. 78. Yield potential and factors contributing to yield potential of four maize hybrids grown at Rampur, Chitwan, Nepal.

System optimization. Three alternative and potential cropping systems, each involving three cereals, are optimized with suitable rice varieties and maize hybrids. The potential systems are R-W-M, R-P-M, and R-M-M (Table 23, Fig. 79). In the potential R-P-M system, an intermediate-duration rice can be grown from July to October, then potato from November to February, and a maize hybrid of 1,300 GDD from March to June. This system has a Yp of 22.5 t ha^{-1} from rice and maize only. In addition, there will be a substantial yield from potato. In the R-W-M system, a maize hybrid of about 1,300 GDD can be grown from March to June after the harvest of wheat. This system results in a total Yp of 28 t ha^{-1}. In the R-M-M system, winter maize of 1,300 GDD can be grown from late August or early September to December with a Yp of 16 t ha^{-1}. Spring maize (also with 1,300 GDD) can then be grown from March to early June with a Yp of 12 t ha^{-1}. This potential system results in a very high system Yp of 35.5 t ha^{-1} (Fig. 79).

All three potential systems involving three cereals require some supplemental irrigation water and better nutrient management to avoid nutrient mining. Currently, fertilizers are costly and not always available on time, so a better delivery mechanism for fertilizer is required. Farmers should also have access to credit and machinery to hasten crop turnaround and to enable triple-crop systems.

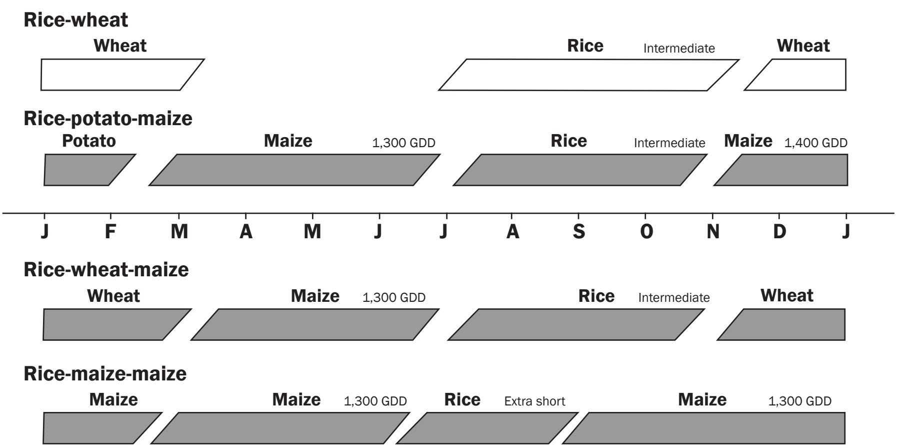


Fig. 79. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Rampur, Chitwan, Nepal.

Vinh Phuc, Red River Delta, northern Vietnam. In the lowlands of Vinh Phuc Province in the RRD, northern Vietnam, the R-R-F, R-R-M, R-R-SB, rice-rice-vegetables, rice-fish, soybean/peanut-rice-maize, and soybean/peanut-rice-vegetables are the main cropping systems. In alluvial soils, mostly R-R-SB is practiced, but, in most degraded soils and also in some alluvial soils, R-R-M is common.

Spring rice is grown from January to April/May, summer rice from May/June to September/October, and winter maize from September/October to December/January (Table 24). Seedlings for the first crop (spring rice) in all systems are grown in plastic/polythene for 15–20 days before they are transplanted to the main field to avoid cold injury. Farmers generally sow seeds in nursery beds from late December to early January, aiming to transplant from late January to early February. For the second crop (summer rice), 10–15-day-old seedlings are used for transplanting in the main field. The spring rice harvest is immediately followed by land preparation and transplanting of a second rice crop (summer rice) in June. Depending on the growth duration of the rice varieties, summer rice is harvested from late August to late September.

The third crop (maize) in the R-R-M system is grown in winter. Maize seedlings are often raised for 5–7 days after emergence in nurseries and transplanted in the tilled field in September/October. Soybean is generally planted slightly earlier than maize under zero tillage and is also harvested slightly earlier in January. Farming practices, production constraints, and nursery bed management and transplanting techniques for maize in the RRD are described in detail by Tinh et al (1992) and Uy and Marathee (1996).

Potential cropping systems. For the R-R-M system, spring rice could be planted from mid- to late January and harvested during mid- to late May. In the following summer, a short-duration rice could then be planted from late May to early June and harvested from late August to early September. That will be followed by planting a maize crop in early to mid-September and harvested from late December to early January (Table 25). There is also potential for an M-R-R system. In this system, maize can conceivably be planted during mid- to late January and harvested during mid- to late May. A short-duration summer rice can then be planted in early June and harvested in early September. Winter maize can then be planted in early to mid-September and harvested from late December to early January.

The growth duration of the maize hybrids for the third maize in R-R-M and M-R-M systems should be such that the transplanting of maize would be completed by early to mid-September when temperatures are still warmer (when median minimum or mean temperatures are above 20 °C), and flowering and pollination of maize would be completed before the onset of cold temperature around mid-November. For the first maize in the M-R-M system, planting of maize should be done in mid- to late January when temperatures start to go up.

In addition to monthly planting dates, Yp for additional planting dates for fortnightly intervals was also estimated for critical planting windows for maize and rice for key cropping systems (e.g., for R-R-M and M-R-M). The additional planting dates for the two rice seasons considered were 16 January, 16 February, 16 May, and 16 June. For maize, the additional planting dates were 16 January and 16 February

Table 24. Current and potential cropping system options in Vinh Phuc, RRD, Vietnam.

System	Season	Crop	Establishment	Planting date	Harvest date
Rice-rice-fallow (current)	Dry	Spring rice	Transplanted	Late January/ early February	Late May/early June
	Wet	Summer rice	Transplanted	June	Late August/ late September
	Constraints: fallow not used; use of long-duration summer rice does not permit timely planting of winter crops; some land after summer rice severely waterlogged; too much irrigation water required for and cold damage to spring rice; typhoon damage to summer rice; labor scarcity during summer rice harvest and winter crop planting does not permit timely planting of winter crops; low prices of rice; and farmers' poor accessibility to credit and input and output markets				
Rice-rice-maize (current and potential)	Dry	Spring rice	Transplanted	Late January/ early February	Late May/early June
	Wet	Summer rice	Transplanted	Mid- to late June	Mid- to late September
	Winter	Maize	Transplanted	Late September/ early October	Mid- to late January
	Constraints: some land after summer rice severely waterlogged; too much irrigation water required for and cold damage to spring rice; cold damage to maize; typhoon damage to summer rice; labor scarcity during summer rice harvest and maize planting and during spring rice harvest and summer rice planting; low maize price; poor accessibility to credit and input and output markets of maize				
Rice-rice-winter crops (current and potential) direct-seeding	Dry	Spring rice	Transplanted	Late January/ early February	Late May/early June
	Wet	Summer rice	Transplanted	June	Late August/ late September
	Winter	Maize, soybean, vegetables	Transplanted	Late September/ October	Late January/ early February
	Constraints: some land after summer rice severely waterlogged; too much irrigation water required for and cold damage to spring rice; cold damage to winter crops; typhoon damage to summer rice; labor scarcity during summer rice harvest and winter crop planting, and during spring rice harvest and summer rice planting; low prices; poor accessibility to credit and input and output markets of winter crops				
Maize-rice-maize					
(current and potential)	Dry	Maize	Transplanted	Mid- to late January	Mid- to late May
	Wet	Rice	Transplanted	Early June	Early to mid-September

Winter	Maize	Transplanted	Mid- to late September	Late December/early January

Constraints: some land after summer rice severely waterlogged; some irrigation water required for and cold damage to dry-season maize; cold damage to winter maize; typhoon damage to summer rice; labor scarcity during summer rice harvest and winter maize planting and during dry-season maize harvest and summer rice planting; low maize price; poor accessibility to credit and input and output markets of maize

Table 25. Optimization of cropping system options in Vinh Phuc, northern Vietnam.

System	Season	Planting date	Harvest date	Growth duration (d)	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-rice-fallow	Spring	Late January/ early February	Late May/ early June	120	6.5	13.0
	Summer	Mid- to late June	Late August/ late September	95	6.5	
Rice-rice-maize (current and potential)	Spring	Mid- to late January	Mid- to late May	120*	6.5	22.9
	Summer	Late May to early June	Late August/ early September	95*	6.4	
	Winter	Early to mid-September	Late December to early January	105**	10.0	
Rice-rice-Winter crops (current and potential)	Spring	Mid- to late January	Mid- to late May	120	6.5	
	Summer	Late May to early June	Late Aug/ early September	90	6.5	
	Winter					
Maize-rice-maize (potential)	Spring	Mid- to late January	Mid- to late May	115**	11.0	27.5
	Summer	Early June	Early September	95*	6.5	
	Winter	Early to mid-September	Late December/ early January	105**	10.0	

*Short-duration rice (growth duration increased during spring and winter); ** = 1,300 GDD hybrid.

for the first maize crop and 16 August and 16 September for the third maize crop, respectively, in the M-R-M and R-R-M systems.

Yield potential of rice. Yield potential of four rice varieties across planting dates ranged from 2.2 to 11.0 t ha^{-1} in Vinh Phuc (Fig. 80). The Yp of later maturing varieties was higher than that of earlier maturing varieties and was higher for the January to August plantings than for the September to December plantings. ORYZA2000 assumes 12 °C as the lower temperature threshold for growth, and the crop dies if there were 3 consecutive days below that threshold (Bouman et al 2001). Hence, all varieties planted from 1 October to 1 March failed to grow, mature, and form and fill grains due to cold injury in 9, 11, 12, 12, 11, and 7 years out of 20 years for transplanting on 1 October, 1 November, 1 December, 1 January, 1 February, and 1 March, respectively. There were small differences in cold responses among varieties. Hence, the results shown in Figure 80 are based on simulations for the remaining 13 years in which the rice varieties grew, matured, and formed and filled grains.

For transplanting from November to February, crops failed to mature and form grains in 55–60% of the years. In the remaining years, however, crops planted in January and February had quite a high Yp but those planted in November and December had very low Yp (Fig. 80) because of cold. Growth duration of the four varieties ranged from 82 to 125, 87 to 140, 110 to 155, and 130 to 180 days, respectively. Long-duration varieties took an unusually long time to mature, especially in winter (October to December planting). Growing-season solar radiation for those varieties, respectively, ranged from 1,300 to 1,600, 1,350 to 1,700, 1,700 to 1,950, and 1,900 to 2,350 MJ m^{-2}. Growing-season solar radiation during the seasons for crops planted at various dates did not fluctuate much for short and extra short varieties but differed across planting dates for intermediate- and long-duration varieties. For the additional fortnightly planting dates, simulated yields and growth durations were not significantly different from those with main planting dates chosen for the whole-year simulations. These simulated potential yields were identical to the potential yields of 7.3 and 8.2 t ha^{-1} predicted by WOFOST for 16 January and 10 June planting in Tam Duong District in northern Vietnam (Mai et al 2008).

Yield potential of maize. The mean Yp of hybrids in the four maturity categories across planting dates ranged from 6.0 to 14.0 t ha^{-1}. Yield potentials were higher for the February to September plantings (8–14 t ha^{-1}) than for the October to January plantings (6–10.8 t ha^{-1}). The corresponding growth durations for those hybrids across planting dates ranged from 70 to 135 days, with greater durations for the September to January plantings than for planting on other dates (Fig. 81). Growing-season incident solar radiation was highest for the January to March plantings (1,750–1,820 MJ m^{-2}), decreasing progressively with delayed planting (from 1,600 to 1,300 MJ m^{-2}). Mean temperature values from silking to maturity were relatively lower (16–28 °C) compared with those in An Giang (26–28 °C) in the Mekong Delta. The very low temperatures increased growth duration, but solar radiation was also low. So, even though growth duration was longer, the Yp were lower for the October to December plantings. In contrast, favorable temperatures during grain filling resulted in higher Yp for the February to August plantings (Fig. 81). The simulated Yps for early- to

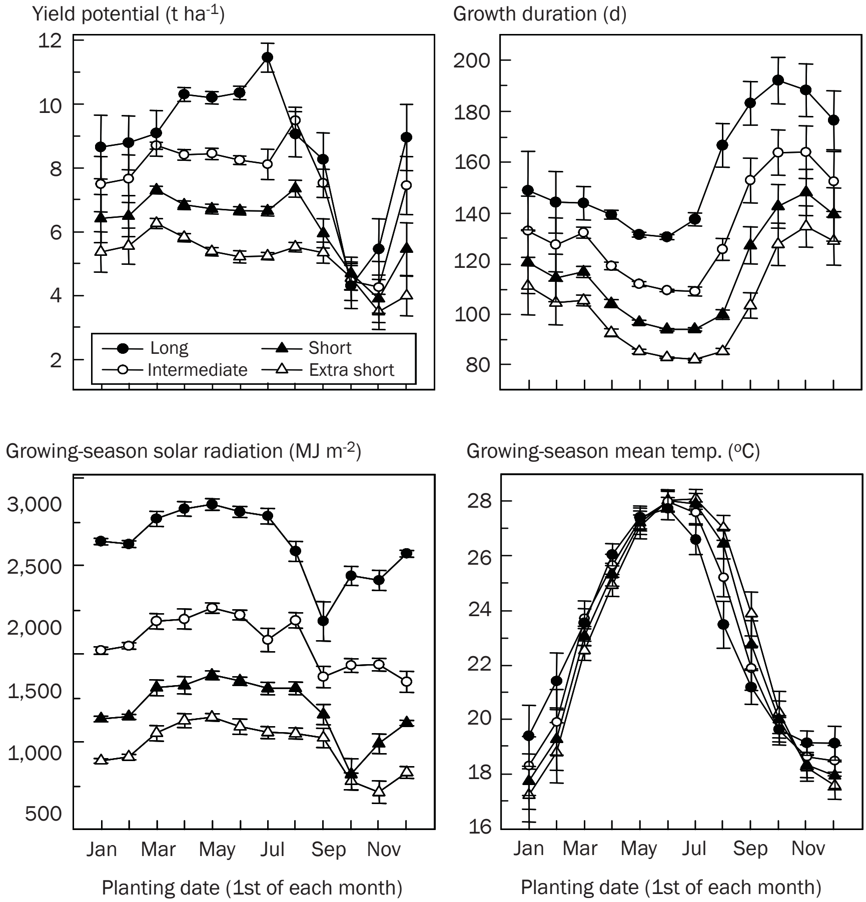


Fig. 80. Yield potential and growing-season characteristics of four rice varieties grown in Vinh Phuc, northern Vietnam.

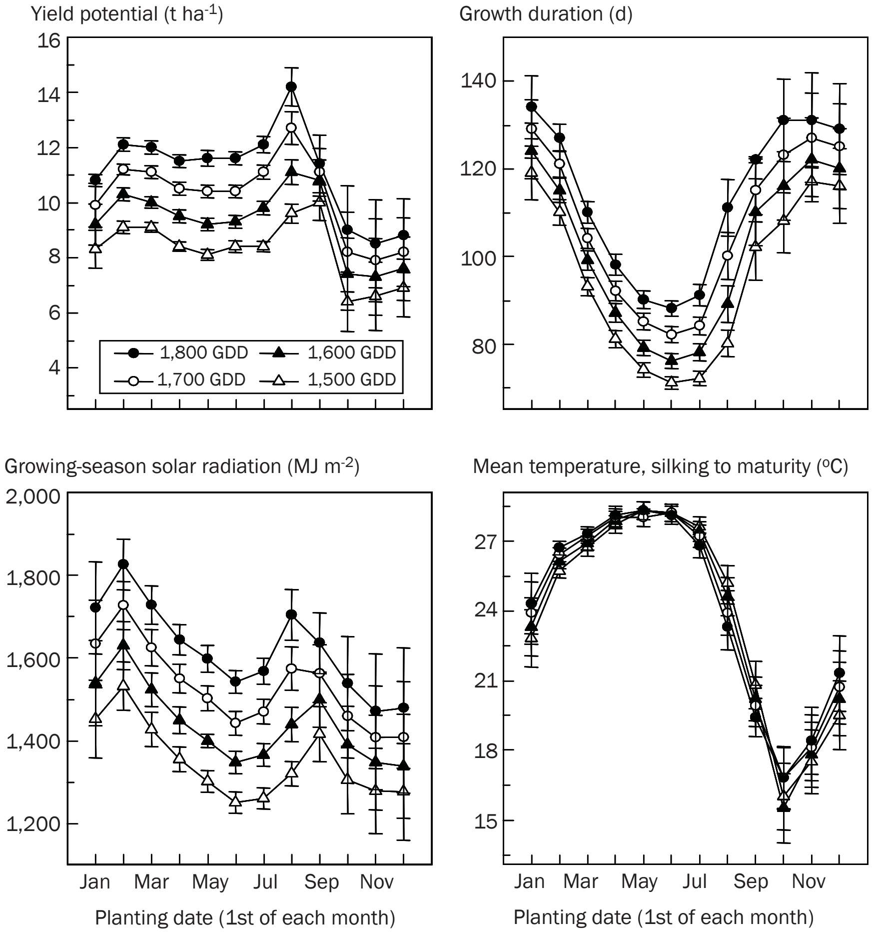


Fig. 81. Yield potential and factors contributing to yield potential of four maize hybrids grown in Vinh Phuc, northern Vietnam.

mid-maturing hybrids predicted by Hybrid Maize for the mid- to late-September planting were slightly less than the Yp of 7.4 t ha^{-1} estimated by WOFOST for the late-September planting in Tam Duong District in northern Vietnam (Mai et al 2008).

Yield potential of soybean. The mean Yp of soybean decreased from 3.0 t ha^{-1} for the 1 September planting to 1.6 t ha^{-1} for the 1 and 16 October plantings. Mean growth duration, however, was greatest for the later plantings (Fig. 82). Early-planted crops received more solar radiation and had higher mean temperature during the growing season than the late-planted crop. In addition to lower temperatures, the late-planted crops, on the other hand, had greater variability in minimum, maximum, and mean temperatures during the growing season than the early-planted ones. The smaller amount of solar radiation and lower temperature during the growing season, especially during the reproductive stage, reduced the photosynthesis of the late-planted crops.

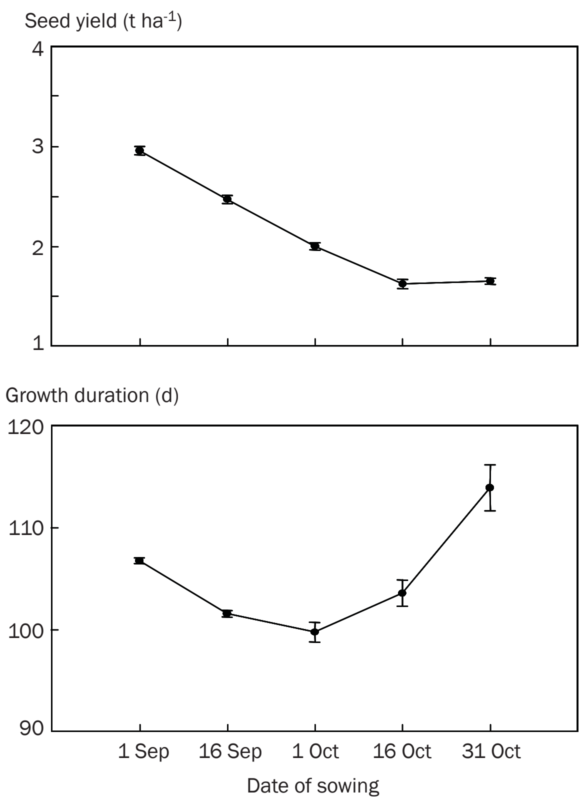


Fig. 82. Yield potential and growth duration of soybean varieties planted on different dates after summer rice in Vinh Phuc, northern Vietnam.

Our hypothesis related to the addition of a third crop such as maize or soybean to the existing R-R system or the choice of short-duration maize hybrids or soybean varieties and replacing the first rice by a suitable maize hybrid was tested by simulating the Yp of maize for additional planting dates. Simulations showed that the August-to-December-sown crops had highly variable yields across the years. In 7 out of 20 years for the 16 January planting, the soil was too cold for germination. Excluding those 7 years, the mean yields of maize hybrids with 1,300- and 1,400-GDD were 8.9 and 9.9 t ha^{-1}, respectively. For the 16 February planting, although plants were under low-temperature stress, the respective mean yields of the two hybrids were 9.1 and 10.3 t ha^{-1}. For the 16 August planting, the mean yield of a hybrid reaching maturity after 1,300 GDD was 10.3 t ha^{-1} with a probability of frost damage of 10%, while that for 1,400 GDD was 11.8 t ha^{-1}, with a frost probability of 15%. For the 16 September planting, the mean yield of 1,300 GDD was 9.4 t ha^{-1} with 30% frost probability. For the September planting, varieties with 1,300 GDD seem to be the best choice. Simulations showed that the Yp of soybean estimated by CROPGRO was quite low (2–3 t ha^{-1}) compared with maize (8–10 t ha^{-1}). The highest potential yield (3 t ha^{-1}) was identical, however, with the maximum experimental yield of 2.9 to 3.1 t ha^{-1} for five locations in northern Vietnam, including Vinh Phuc (Singh et al 2001), but lower than the potential yield of 4.0 t ha^{-1} predicted by WOFOST for Tam Duong Province in northern Vietnam (Mai et al 2008). Genetic coefficients for different varieties need further refinements and the model needs to be recalibrated to predict more realistic Yp.

Irrigation water requirements for maize. During the onset of the winter season in Vinh Phuc, the window for planting maize after the second (summer) rice in the R-R-M system would be from mid-August to late September. To further examine the effect of planting date, 1 and 16 September planting dates were chosen. Yp across years for the 1 September planting ranged from 10.0 to 12.8 t ha^{-1}, whereas that for 16 September ranged from 7.2 to 12.6 t ha^{-1} (Fig. 83). Variability in Yp across years was similar for both planting dates. Rainfall during the growing season ranged from 160 to 420 mm for the 1 September planting and from 50 to 470 mm for the 16 September planting. Since the crops were grown after flooded rice under field capacity to saturated conditions, rainfall during the maize season was reasonably sufficient. Hence, the crops did not require much irrigation water; it ranged from just 30 to 85 mm for the 1 September planting and from 10 to 80 mm for the 16 September planting.

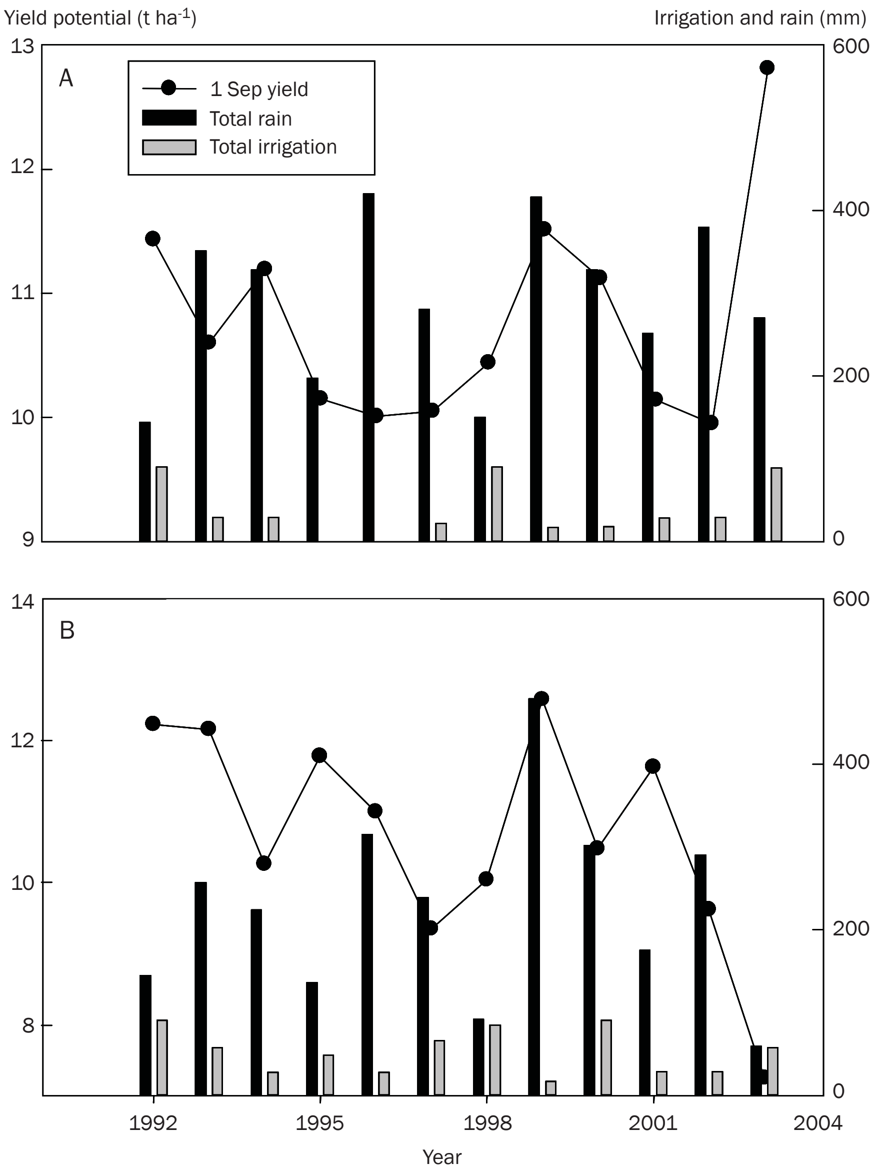


Fig. 83. Variability in yield potential, rainfall during the growing season, and irrigation water requirements for the 1 (A) and 16 September (B) plantings in Vinh Phuc, northern Vietnam.

System optimization. Rice-rice, R-R-M, R-R-SB, and R-R-sweet potato (or Irish potato) are the existing cropping systems in Vinh Phuc. To meet the food requirements of the growing population, fallows must be used by growing a crop that is productive, profitable, and ecologically sustainable. Although potato and sweet potato are also grown after the second rice, maize and soybean seem to be the farmers' best options. The ultimate choice of a third crop in the system depends on the profits that farmers get from growing it.

Currently, there is a small area (about 40,000 ha) under winter maize in the RRD. There are several reasons for the small area: (i) farmers prefer other crops such as winter vegetables, sweet potato, and Irish potato; (ii) farmers grow long-duration rice for various reasons, so land is unavailable for timely planting of winter maize (late planting will result in cold damage); (iii) some land parcels after rice harvest are severely waterlogged, whereas others are heavily degraded (not suitable for growing maize); (iv) labor is scarce during maize planting because of the rice harvest that takes place at the same time; and (v) maize commands a low price at harvest time and so does pork that uses maize as feed. From the Yp point of view, maize certainly seems to be a better option than soybean. However, socioeconomic factors such as reliable markets, input costs, and product prices would determine the acceptability and adoption of maize, soybean, or vegetables in the R-R-winter crop system. Maize production in the RRD can potentially be expanded, depending on movements of relative prices of maize, labor availability, relative profitability from competing winter crops, and pork price. Whether the third crop in R-R-winter crop systems should be maize, soybean, or vegetables would be dictated by production costs as well as returns above variable costs.

For the R-R-M system, two planting dates for a short-duration spring rice (10 and 25 January), two planting dates for summer rice (15 May and 1 June), and two planting dates for winter maize (10 and 25 September) were chosen. For the M-R-M system, two planting dates for maize (15 January and 1 February), two for summer rice (1 and 15 June), and two for winter maize (15 September and 1 October) were chosen (Table 25, Fig. 84). To ensure a successful R-R-M system, cold damage must be avoided during emergence and seedling stage in spring rice and during flowering and grain filling in winter maize. Likewise, typhoons during summer rice cropping and waterlogging damage during establishment and seedling stage in maize need to be avoided. In the M-R-M system, soil under spring maize could remain saturated from March to May; hence, waterlogging could be an issue for spring maize. As in the R-R-M system, typhoons during growing periods of summer rice, waterlogging during establishment and early growth, and cold damage during the reproductive stage of winter maize must be avoided.

Many farmers already grow soybean in the R-R-SB system in the RRD, but Yp is quite low (Fig. 82), lower than that for An Giang (Fig. 58). Thus, based on Yp and all constraints considered, spring maize planted between 1 and 15 September, summer rice planted between 1 and 15 June, and winter maize planted between 15 September and 1 October would give a total M-R-M system productivity of 22.6 t ha^{-1}. Likewise, for the R-R-M system, spring rice planted between 15 January and 1

February, summer rice planted between 15 May and 1 June, and winter maize planted between 1 and 15 September would give a total system productivity of 20.7 t ha^{-1} and would be the best option.

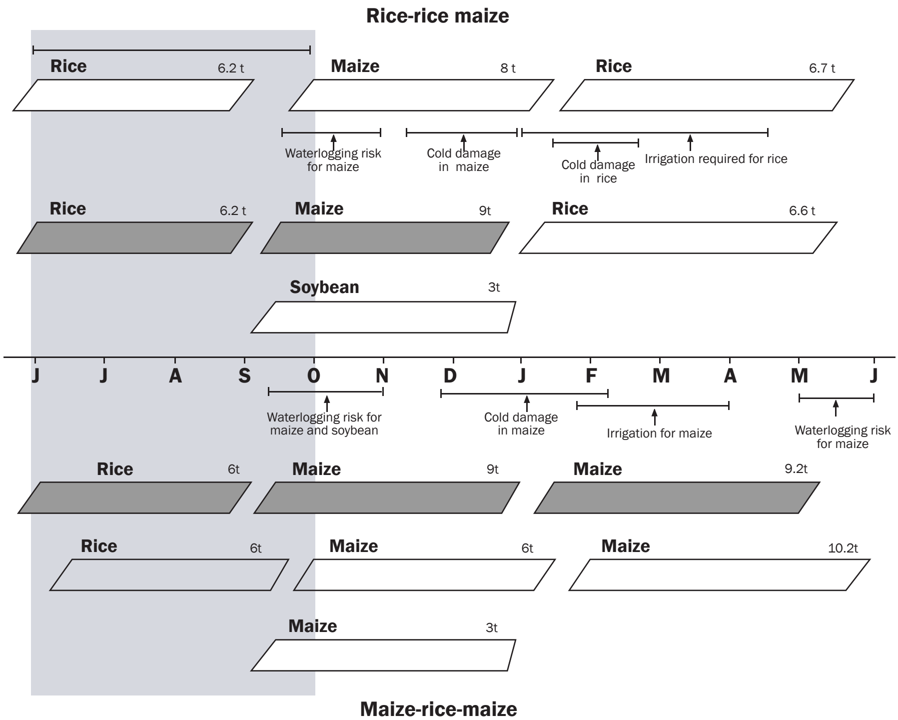


Fig. 84. Cropping system optimizations for the rice-rice-maize and maize-rice-maize systems in Vinh Phuc, northern Vietnam (shaded vertical bar indicates typhoons; shaded horizontal boxes indicate better options for system optimization).

Warm temperate agroecosystem

Changsha, Hunan, southern China. Current cropping systems. The agroecological zone II of China includes areas in central China, with three subzones, all with single and double rice cropping. Subzone I includes areas in the middle or lower reaches of the Yangzi River Plain, subzone II includes those in the Sichuan-Shanxi Basin, and subzone III includes the hilly and plain areas south of the Yangzi River, including Changsha. The current cropping systems in Changsa are either rice-fallow (R-F) with rice grown during the summer season or rice-rice (R-R) with the first rice grown in spring and the second rice in summer. In the R-F system, a "single" rice of about 135 days is transplanted in May/June and harvested in September/October. The total system Yp is about 9.0 t ha^{-1}. In the R-R system, an "early" rice (first rice) of about 115-day duration is transplanted in late March or early April and harvested from mid- to late July. The second (or "late") rice crop of about 125-day duration is then transplanted from mid- to late July and harvested in November. The total system Yp is about 15.2 t ha^{-1} (Table 26). The main constraint in both systems is the declining availability of irrigation water. In addition, in the double-rice system, the labor requirement is high. This poses a great constraint as both farm family labor and hired labor are in a decline, in general, all over China, including Changsha.

Yield potential of rice. Rice crops planted from October to February were affected by the cold and they died early in the season without reaching maturity and forming grains. The Yp of rice varieties planted from March to September ranged from 1 to 12 t ha^{-1}, with 1–8 t ha^{-1} for short and extra short varieties and 4–12 t ha^{-1} for intermediate- and long-duration varieties. The growth duration of different varieties ranged from 70 to 180 d, whereas solar radiation intercepted during the growing season ranged from 900 to 2,600 MJ m^{-2} (Fig. 85). The growing-season mean temperature—calculated on the basis of actual crop survival and actual duration in the field—of April-to-August-planted crops ranged from 20 to 26 °C. In contrast, for the March planting, it dropped to 12–13 °C as many crops died early in the season. The Yp of different rice varieties predicted by an earlier version of ORYZA for Changsha is 8–8.5 t ha^{-1} (Matthews et al 1995).

Yield potential of maize. Maize crops planted from September to February were affected by the cold. The seeds sown in those months either did not germinate or died early in the season without reaching maturity and forming grains. The Yp of maize hybrids for the March to August planting ranged from 8.4 to 13.4 t ha^{-1}, growth duration was from 80 to 135 days, and growing-season solar radiation was from 1,400 to 1,950 MJ m^{-2} (Fig. 86). Mean temperature during grain filling was high (23–27 °C) for the April to July plantings, but it dropped to 16–17 °C for the August planting as the hybrids took a long time to mature due to the cold that affected later plantings.

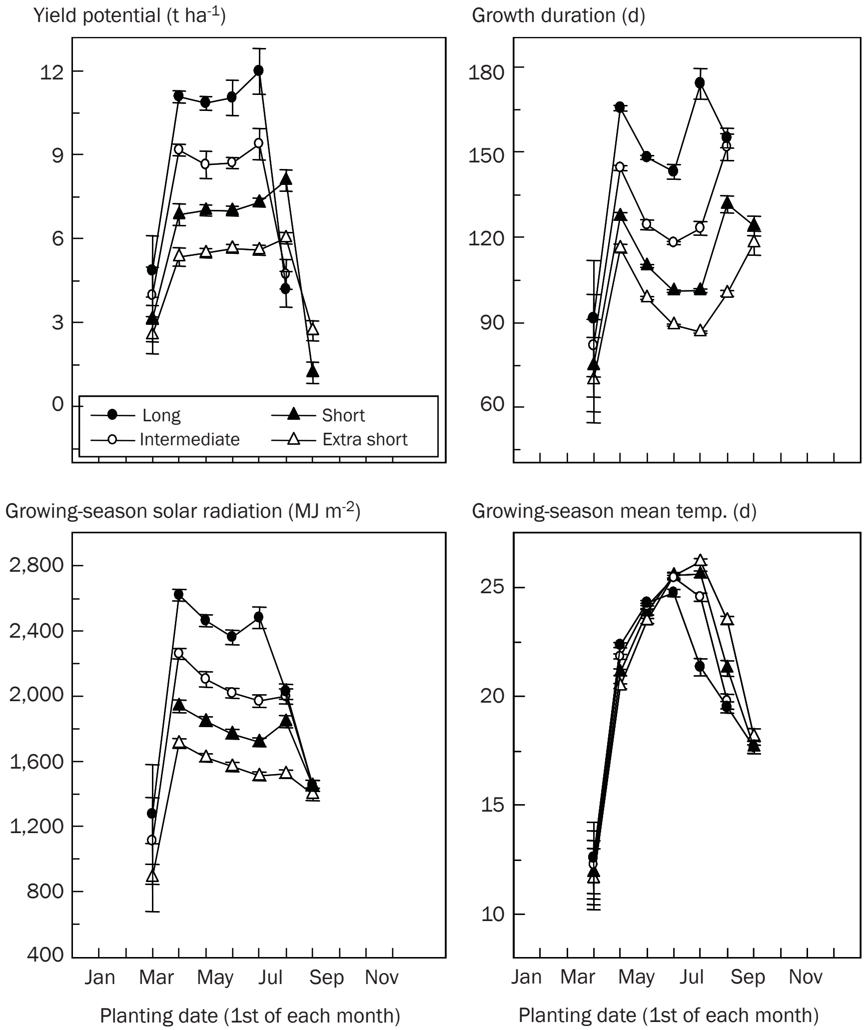


Fig. 85. Yield potential and growing-season characteristics of four rice varieties grown at Changsha, China.

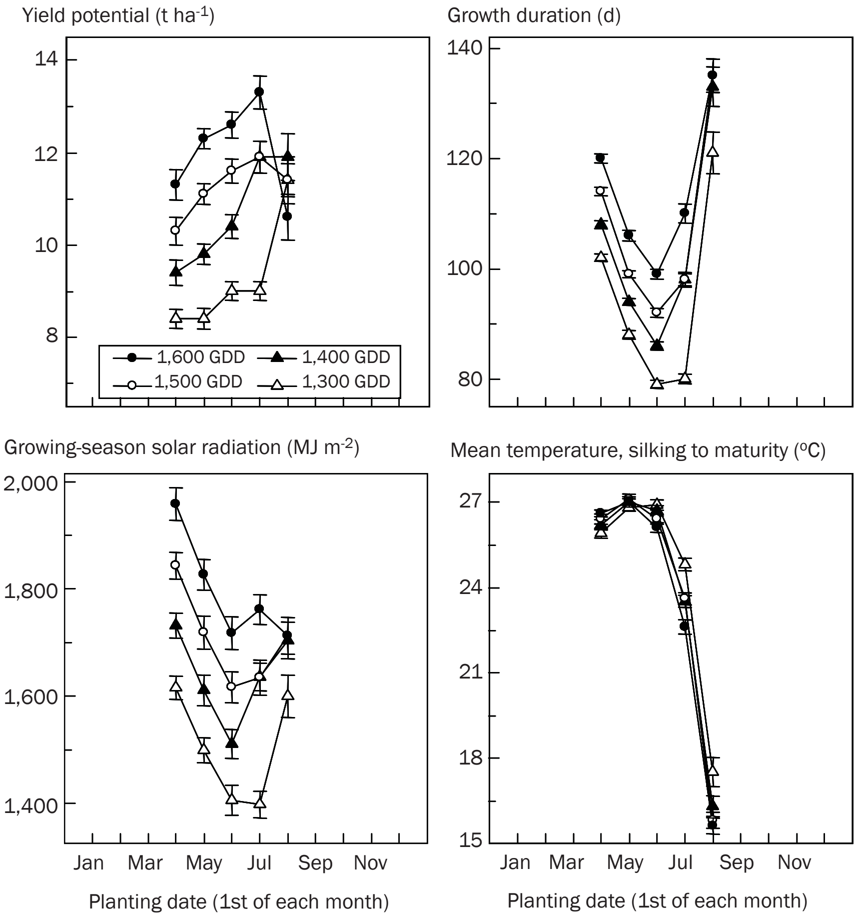


Fig. 86. Yield potential and factors contributing to yield potential of four maize hybrids grown at Changsha, China.

Potential cropping system options and system optimization. The potential alternative cropping systems for Changsha are R-M and M-R. In the R-M system, a short-duration rice can be grown in spring with a Yp of 9.0 t ha^{-1}. It can then be followed by an autumn maize planted in summer during mid- and late July and harvested in November. Thus, the total Yp for this system is 18.2 t ha^{-1} (Fig. 87; Table 26). For the M-R system, a maize hybrid of about 1,500 GDD can be planted in late March or April and harvested in July, with a Yp of about 10.4 t ha^{-1}. It can then be followed by an intermediate-duration summer rice with a Yp of about 8.2 t ha^{-1}. Thus, the total Yp for this system is 18.6 t ha^{-1}. These two potential systems involving maize will require much less water than the current R-R system and will help meet the demand for maize. However, there are still some biophysical constraints such as excess moisture during establishment and drought and heat effects in autumn maize, and sheath and culm blight damage in spring maize. Labor shortage is an emerging constraint for both systems.

Table 26. Current and potential cropping system options for Changsha, China.

System	Season	Crop	Planting date	Harvest date	Yield potential (t ha^{-1})	System yield potential (t ha^{-1})
Rice-fallow (current)	Summer	Late rice	July	October	9.0	9.0
	Winter					
	Constraints: fallow not used; supplemental irrigation water needed for rice; insufficient production to meet cereal demand					
Rice-rice (current)	Spring	Early rice	April	Mid-July	7.0	15.2
	Summer	Late rice	Late July	November	8.2	
	Constraints: high irrigation water requirement by double rice; labor shortage					
Rice-maize (potential)	Spring	Early rice	April	Mid-July	7.0	18.2
	Autumn	Maize	Late July	November	11.2	
	Constraints: excess moisture during maize establishment; drought and heat effects on autumn maize; supplementary irrigation water needed for both crops; labor shortage					
Maize-rice (potential)	Spring	Maize	April	July	10.4	18.6
	Summer	Late rice	Late July	November	8.2	
	Constraints: sheath and culm blight damage in spring maize; supplemental irrigation water needed for both crops; labor shortage					

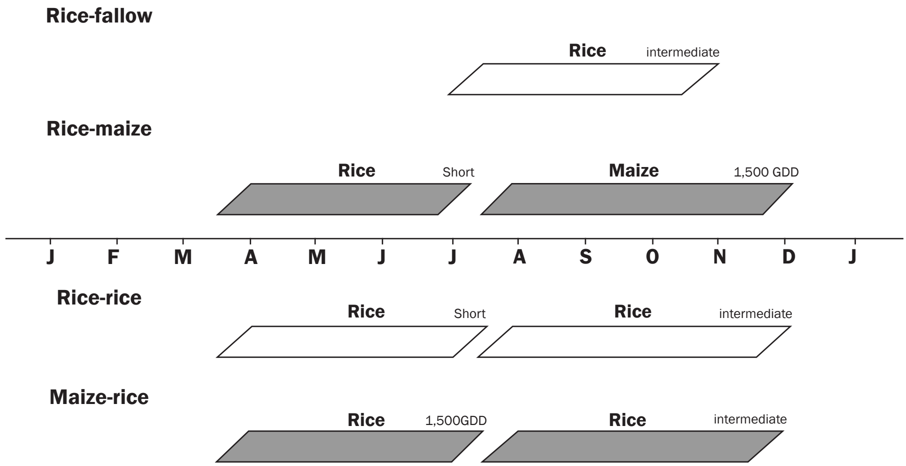


Fig. 87. Current (unshaded areas) and potential (shaded areas) rice-maize systems for Changsha, China.

General discussion and conclusions

Rice, wheat, and maize are major cereals that contribute to food security and income in Asia. These crops are grown either as a monoculture or in rotation in tropical, subtropical, and warm temperate areas of Asia. In the irrigated and favorable rainfed lowland areas, R-R, R-W, and R-M are the predominant cropping systems. R-R is common in areas with tropical climate with distinct dry and wet seasons such as those in the Philippines, Indonesia, Vietnam, and southern India, and in subtropical areas with mild cool winter such as Bangladesh, eastern India, and eastern Nepal. Rice requires full or partial irrigation if grown in the dry or winter season. R-W is common in subtropical areas of South Asia and in south-central and southeastern China with cool winter climate. The R-M system is practiced in many tropical and subtropical areas, but it is not as extensive as R-R or R-W. Unlike the large irrigation water requirement for rice grown in the dry season, wheat or maize in R-W and R-M systems requires only supplemental irrigation. All these double-crop systems often include an additional crop such as potato, lentil, chickpea, mustard, etc. in rabi, and jute, aus or spring rice, mungbean, cowpea, etc. during kharif I or the premonsoon season (Timsina and Connor 2001). The strategic assessment work presented in this report characterizes the climate and assesses the Yp of rice and maize for R-M systems for 29 sites in nine countries in Asia.

Climate, sites, and R-M agroecosystems

Climate at the 29 sites analyzed in this study ranges from humid tropical monsoon in the Philippines to subtropical cold winter in northern India, Nepal, Bangladesh, and northern Vietnam, and to subtropical to warm temperate with severe cold winter in China. Total annual rainfall across locations ranges from as low as 707 mm (Punjab, India) to as high as 3,134 mm (Medan, Indonesia). Annual mean minimum temperature ranges from as low as 11.1 °C (Yangzhou, Jiangsu) to as high as 25.7 °C (Thanjavur, Tamil Nadu), while annual mean maximum temperature ranges from 20 °C (Yangzhou) to 31.4 °C (Nalgonda, Andhra Pradesh). Annual daily mean incident solar radiation ranges from 12.6 MJ m^{-2} d^{-1} (Changsha, Hunan) to 19 MJ m^{-2} d^{-1} (Indian Punjab). There are large differences in climate variables between seasons and among locations. Soils range from sandy and silty loam in Bangladesh, Nepal, and Indian Punjab to light to heavy clay in other countries.

The study identified four main R-M agroecosystems with four broad climates. The first agroecosystem (tropical, warm, humid, and subhumid, no winter) includes locations in Indonesia, the Philippines, and southern Vietnam with high rainfall with distinct dry and wet seasons. The second agroecosystem (tropical, warm, semiarid, no winter) includes locations in southern India with tropical monsoon and a longer dry season. In both agroecosystems, both rice and maize are not limited by low temperature and can be grown year-round. The third agroecosystem (subtropical, subhumid, warm summer, mild cool winter) includes locations in Bangladesh, Nepal, northern India, and northern Vietnam. In this agroecosystem, winter is mild cool and so rice may be limited by low temperature. Maize, however, will have a long grain-filling period and will perform well due to the mild cool winter. The fourth agroecosystem (subtropical to warm temperate, subhumid, warm summer, mild to severe cold winter) has been classified into three subclasses. The first subclass is subtropical monsoon with cold winter and summer rainfall such as that found in northern and northwestern India and in the Terai and hills of Nepal. The second subclass has a subtropical to warm temperate climate with severe cold winter such as that found in locations in China. In this agroecosystem, both rice and maize will be limited by low temperature and cannot be grown for some time in winter. The third subclass has a subtropical to warm temperate, semiarid, hot summer, and cool to cold winter with very low rainfall such as that found in Punjab and Sindh provinces in Pakistan.

Simulation of yield potential

The yield potential of rice and maize in this study was estimated using ORYZA2000 and Hybrid Maize; that of wheat and soybean, for selected locations and cropping systems, was assessed using CERES Wheat and CROPGRO, respectively. Because of the double- or triple-cropping systems prevalent in tropical and subtropical Asia, high-yielding short- and extra-short-duration varieties that would fit into the local crop calendar are needed. Intermediate- and long-duration varieties may be required in some less intensive systems. Simulation results showed large differences in Yp of rice among sites within a country or among countries (Tables 7–9). There were also differences in planting dates at each site (Figs. 51–87). For each site, Yp was highest for the longer duration variety and lowest for the extra-short-duration variety. The large ranges in Yp for different varieties were associated with large variations in growth duration, total intercepted solar radiation, and temperature, which all lead to differences in grain-filling period (Tables 7–9, Fig. 41). In the tropical warm climate, Yp was highest for Chiang Rai in northern Thailand and lowest for Los Baños in the Philippines. Yp for sites in Indonesia, central and southern India, and the Mekong Delta in Vietnam was in the middle range (Table 7, Figs. 42–43). In the subtropical climate, Yp was highest for Dinajpur in Bangladesh and Begusarai in Bihar, followed by Bogra in Bangladesh, and was lowest at RRD sites in Vietnam. In the latter, all varieties took much longer to mature when transplanted in October and January due to low temperatures during the growing season (Table 8, Fig. 44).

In the tropical to warm temperate climate, Yp of all rice varieties was highest in Punjab in India, followed by Chitwan in Nepal. It was comparatively lower at the four Chinese sites. None of the varieties produced any yield when planted from September to February (Table 9, Fig. 45). In Punjab, an extra-short variety planted from November to January suffered from cold injury throughout the season and the plants died. The short-, intermediate-, and long-duration varieties also experienced cold injury and the plants died when planted in October. In Chitwan also, transplanting extra short, short, and intermediate varieties from October to January resulted in cold injury and subsequent dying of plants. The long-duration variety likewise encountered cold injury and did not produce any yield when planted in September. At all sites in China, transplanting extra short and short varieties from October to February resulted in cold injury and subsequent death, while the intermediate- and long-duration ones also suffered from cold injury when transplanted in September.

In the tropics and subtropics, Yp of maize hybrids was always higher for high-GDD crops but, in warm temperate areas, no such trend was seen (Tables 10–12, Figs. 46–50). Unrealistically longer growth duration in warm temperate areas resulted in greater solar radiation interception. Interestingly, mean temperature during grain filling was higher in warm temperate areas than in the tropics and subtropics. This indicates extreme temperatures during parts of the year in temperate areas and fairly even temperatures throughout the year in the tropics. At all Chinese sites, except for Wuhan, cold injury occurred during germination and seedling emergence for crops planted from 1 September to 1 March. This resulted in crop death and no yield. For the 1 October- and 1 November-planted crops, even if the plants survived, growth duration was excessively long, with very large amounts of solar radiation received. Results suggest that, for the Chinese sites, maize should be planted between March and August to avoid cold injury. For Punjab, planting a 1,500-GDD hybrid on 1 January resulted in cold injury, the crop dying, and ultimately zero yield. For other hybrids (1,600–1,800 GDD), planting on 1 August and 1 September produced the highest yields. In Chitwan, Nepal, all hybrids planted between 1 December and 1 February did not produce any yield because of the cold. Exceptionally high yields, however, were obtained from crops planted between 1 July and 1 November. Likewise, in Dinajpur in northwest Bangladesh, the Yp of maize was very high for the 1 September and 1 October plantings.

The Yp simulations described above show exceptionally high yields of maize for planting between September and November in the subtropical environments of South Asia due to low growing-season mean temperatures as well as low mean grain-filling temperatures resulting in longer crop duration and large reception of incident solar radiation. In reality, in most areas in the northern and northeastern parts of South Asia, fields are flooded and soils are waterlogged most of the time in August and September. Thus, sometimes there is excess moisture during October and November. Hence, those Yp, though possible from a climatic point of view, would never be achieved under field conditions because of soil waterlogging. Planting maize during August and September in large parts of South Asia will not be feasible as most of the rice crop will still be in the field and land will not be available for planting maize in those months. Thus, from a practical point of view, plantings in August and September could, in many circumstances, be unrealistic. For rabi planting of maize after rice, October and November plantings would have high Yp; this would also facilitate a successful intensification of the rice-based system. Likewise, for kharif I, late March to early May planting of maize would result in a reasonably high Yp and the maize crop would fit easily into the rice-based system.

Yield potentials estimated by crop models, however, have potential uncertainties due to limitations in model processes and insufficient evaluation of the models.

The Yp and subsequent cropping system optimization figures and tables for different locations presented in this report are based on satellite-derived weather data from NASA sites. Although, as mentioned previously, NASA data have been validated globally (and especially in the U.S.), these data are prone to uncertainties. Thus, the Yp estimated by the crop models using NASA data might increase uncertainties due to uncertainties in weather data. It is generally considered that quality ground-measured data are more accurate than satellite-derived values. However, ground-measured data will be difficult to obtain in many locations due to constraints in funding and the lack of qualified staff to do the measurements. Moreover, these data may also carry measurement uncertainties from calibration drift and operations; data gaps are likewise unknown or unreported for most ground-site data sets. In 1989, the World Climate Research Program estimated that most routine-operation solar radiation ground sites had "end-to-end" uncertainties from 6% to 12% (http://power.larc.nasa.gov/common/MethodologySSE6/POWER_Methodology_Content.html).

ORYZA2000 has been validated against data from drought experiments in many locations in Asia, and the model has performed satisfactorily in most cases, especially in tropical and subtropical Asia under optimum temperature ranges (Boling et al 2007, Feng et al 2007, Wopereis et al 1996). However, for extreme cold and heat conditions and especially for yields less than 2–3 t ha^{-1}, the model does not seem to perform well enough. Based on simulations across locations in Asia, it appears that simulations of LAI development, tiller dynamics, and spikelet fertility under drought are the key processes that need improvements in ORYZA2000. Hybrid Maize has been evaluated in the north-central U.S. (Yang et al 2004, 2006) and has been tested and used in Indonesia, the Philippines, and Thailand (Witt et al 2008). The model, however, has not yet been evaluated under conditions of water and/or nutrient stress. Thus, in our work, Hybrid Maize predicted unrealistically high yields under low-rainfall and dry situations for many locations in Asia. Efforts are currently being made to develop and validate water and nitrogen balance components for the Hybrid Maize model (H.Yang, UNL, Lincoln, pers. commun., 2008). Both rice and maize models could not accurately predict yield under cold conditions. ORYZA2000 killed the plants under mild to severe cold conditions, while the plants seem to be growing longer and producing reasonable amounts of grain under actual field conditions. In mild to severe winter conditions, Hybrid Maize allowed the plants to grow for an unrealistically longer time, allowing the interception of a large amount of solar radiation and producing exceptionally high yields. Although the primary objective of our study is a prediction of Yp, the data presented in this report reveal some uncertainties, and hence need to be interpreted carefully. It is suggested that the model processes relating to the effects of cold and heat injury in both rice and maize and the effects of waterlogging in maize be refined in both ORYZA2000 and Hybrid Maize. This would give better yield estimations under different production-level situations.

Optimization of R-M systems

Based on individual crop Yp, total system productivity, and irrigation water availability, various combinations of rice varieties and maize hybrids can be examined to optimize R-M systems. Then, planting dates for those optimized high-yielding systems can be further refined and cropping calendars optimized by considering the risks brought about by monsoons, typhoons, or cyclones during premonsoon and monsoon seasons. For the rabi season, such risks could arise from either heavy and extreme rainfall events or waterlogging during planting and maturity or drought or heat stress during the reproductive stage. Such a risk analysis could help refine planting dates and identify suitable varieties/hybrids to minimize damage caused by waterlogging or high rainfall, as well as drought and heat stress during the growing seasons. Cropping systems can be further refined and optimized for high and economically profitable yield by further considering other abiotic constraints such as soil acidity, alkalinity, and salinity.

We selected 10 representative sites for detailed assessment of current and potential R-M systems. Five sites represent tropical climate: Pila, Laguna, in the Philippines; An Giang, Mekong Delta in Vietnam; Phitsanulok in the Central Plain in Thailand; Central Lampung in Indonesia; and Thanjavur in Tamil Nadu in southern India. Four include sites with subtropical climate: Dinajpur in northwest Bangladesh; Begusarai in Bihar, India; Rampur in Chitwan, Nepal; and Vinh Phuc in the RRD in northern Vietnam. The 10th site is Changsha, in China, which represents the warm temperate climate.

In tropical and subtropical climate, rainfall is quite erratic. There are times when there is virtually no rain during the growing season, leading to droughts, and times when there is too much rainfall, causing flooding or waterlogging of soils. Further, cyclones or typhoons occur, causing crop lodging and subsequent yield loss as a minimum and total crop damage in large areas as a maximum. Cyclone damage to monsoon rice occurs occasionally in northeast India and Bangladesh, resulting in massive damage to standing rice crops. Typhoons also occur frequently and almost every year in Southeast Asian countries, especially in the Philippines and Vietnam. However, crops can be planted at such a time that they can escape from these catastrophic events, if the probability of their occurrence is known. Although excessive rainfall and cyclone/typhoon events can cause total failure of rice crops, soil waterlogging is generally a problem for nonrice crops such as maize or wheat planted after rice. Soil waterlogging can be avoided either by selecting waterlogging-tolerant varieties or by adopting appropriate management practices such as timely planting or planting crops on raised beds. By selecting an optimum planting time, the crops can avoid seedling damage caused by waterlogging. Planting crops under zero tillage will permit timely planting, and raised beds can alleviate waterlogging by draining excess water through furrows. Raised beds to alleviate waterlogging problems have been extensively used in dryland as well as in irrigated cropping systems of Australia (Bakker et al 2005).

Some soil-related constraints are acidity, alkalinity, sodicity, and salinity. To alleviate the effects of these constraints, either varieties with some tolerance need to be chosen or management practices must be devised to minimize the adverse effects. Agricultural lime or dolomite (calcium carbonate) and gypsum (calcium sulfate) can be used to ameliorate the effect of soil acidity, while sulfates of iron and ammonium can be used to reduce soil pH. Saline soils require leaching fraction by irrigation. Management practices such as growing crops on raised beds have been useful to lessen the effect of sodicity or salinity in Haryana, India (Samar Singh, HAU, India, pers. commun., 2008; authors' personal observations).

In addition to the need for desirable varieties with appropriate maturity to fit into the crop calendar, the following must also be considered: suitable planting dates to avoid excessive rainfall and cyclone/typhoon events in rice and soil waterlogging in maize; appropriate management practices to minimize waterlogging, especially in maize, and lessen biotic constraints such as weeds, pests, and diseases. Pests and diseases can be minimized by selecting varieties with host-plant resistance or using prophylactic sprays or other means. For weed control, weed-suppressing cultivars can be selected or management practices that minimize weed incidence can be adopted. Some conservation agriculture (CA)-based technologies such as planting crops on raised beds or under zero tillage have the potential to reduce weeds, but they need to be tested under a range of conditions and environments in farmers' fields.

Finally, a range of socioeconomic factors such as family and hired (on-farm and off-farm) labor availability; farm size; availability of and accessibility to inputs such as quality seeds, fertilizers, and supplemental irrigation; availability of and access to credit and seasonal markets; prices of commodities; and the existence of marketing institutions need to be considered. All these factors influence the selection and adoption of "optimal" cropping calendars that include rice and maize in the cropping systems. The availability of on-farm and off-farm labor can be a serious constraint, especially for intensive systems that require timely planting and harvesting of crops. However, with the use of CA implements, planting and harvesting have become easier, reducing the need for physical labor. Zero-till or strip-till seed-cum-fertilizer drills, hand-operated small-sized 12–16-hp power tillers, and small combine harvesters are now available in most South Asian countries. These help increase cropping intensity, diversify cropping systems, and reduce labor requirement. Small farm machinery is now quite popular and used extensively in Bangladesh (Haque et al 2008).

Small farm size can be a constraint because, even if the Yp of rice and maize in a location is high, small farmers may not grow these crops because of other priorities on their small farms. Policy reforms in the individual countries will be required to enable small farmers to adopt the improved technologies. Availability of and accessibility to quality seeds, fertilizers, and irrigation water are extremely important because high Yp assumes the use of good-quality seed, optimum fertilizers, and irrigation. This requires availability of and accessibility to credit. Finally, proper marketing channels and institutions should be in place for the proper functioning of the supply and demand chains. An important consideration for R-M systems is finding good markets for maize. As mentioned earlier, maize demand will increase if livestock feed industries are in the area. In most Asian countries, an increasing number of poultry producers require more and more maize. However, the situation differs from country to country. Hence, this must be studied to determine whether such a demand in a given country really exists. High Yp based on climatic and genetic factors alone does not make much sense, unless the crops are grown profitably (with reduced cost) and markets for the products exist locally or regionally.

Concluding remarks

R-M systems can make significant contributions to reaching the MDGs and national development goals such as food security, poverty reduction, saving water, and reducing local, regional, and global threats to sustainability and the environment. However, the impacts of intensive R-M systems on long-term productivity, profitability, and sustainability (soil quality and fertility, water use and depletion, weeds, pests, and diseases, etc.), biodiversity, greenhouse gas emissions, and other ecosystem services are largely unknown.

Achieving the future potential of R-M systems will require (i) a thorough understanding of the suitability of the major lowland rice areas for crop diversification; (ii) sustainable, system-level management practices for achieving high resource-use efficiency and income; and (iii) improved mechanisms and public-/private-sector partnerships for delivering new technologies and knowledge to farmers. The research contemplated under the then IPSA and now the new CSISA projects will ensure that the grain baskets of Asia remain full. This report is an important milestone for achieving that goal.

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Annex A
Economic and development indicators

Population projections by the UN

The world now has almost 6.9 billion people (World Bank 2007a, 2008). The UN provides estimates on percent distribution and annual growth rate of the population in rural and urban areas for several years in the future. Populations for several Asian countries and the world, as well as population estimates for 2015 and 2050, are presented in Tables A.1.1 to A.1.3. Current UN projections show a slightly higher population in rural areas, but, over the projection period from 2005 to 2050, a large number of rural people will move to cities. In 2050, about 70% of the world population will live in urban areas compared with about 49% in 2005. From 2005 to 2015, there will be a negative growth rate of rural populations in China, Indonesia, and Thailand but a positive growth rate in other countries. However, from 2015 to 2050, all countries will have a negative rural population growth rate (Tables A.1.1 to A.1.3). From 2005 to 2015, all countries will become urban at much higher rates than during 2015-50, with the greatest growth rates of urbanization in Bangladesh and Nepal, followed by India and Pakistan. The growth rates of the rural population are also less negative for these four South Asian countries than for those in other Asian countries. This implies that, while the rural population will move to cities at higher rates, there will still be a high rural population due to high rates of annual population growth. In all countries, except Nepal, more than 50% of the population will be in urban areas in 2050. The countries where the largest percentages of people will live in urban areas are China, Indonesia, and the Philippines. Nevertheless, in Bangladesh, India, Thailand, and Vietnam, 40–45% of the people will still live in rural areas.

With the poverty line of $1 a day, the world had about 1,165 million poor people in 2002, of which 883 million lived in rural areas and 283 million lived in urban areas. In 2002, the percentage share of the poor in urban areas was 24.2%, whereas that in urban areas was 42.3% (Table A.2). With the poverty line of $2 a day, there were 2,843 million people in 2002, of which 2,097 million lived in rural areas and 746 million lived in urban areas. There was a slightly higher share of the poor (26.2%) in urban areas compared with the $1-a-day group. South Asia, particularly India, had the largest number of poor (regardless of poverty line used) in both urban and rural areas, while China had a very small poor sector in urban areas. In South Asia (and also in India), about 28% of the population lived in urban areas, and, of the total population, 24–26% was poor, irrespective of poverty rate (Table A.2).

Table A.1.1. Distribution of rural and urban population in nine Asian countries.

Country	2005 (actual)		2015 (projected)		2050 (projected)	
	Rural	Urban	Rural	Urban	Rural	Urban
World (billion)	3,310	3,200	3,450	3,800	2,790	6,400
China (billion)	780	530	710	700	380	1,030
India (billion)	810	330	890	400	740	910
Bangladesh (million)	113.9	39.4	124.6	55.5	110.8	143.3
Nepal (million)	22.8	4.3	26.0	6.9	27.9	24.0
Philippines (million)	31.5	53.0	30.8	70.3	22.6	117.8
Thailand (million)	42.7	20.3	42.6	24.1	27.0	40.4
Vietnam (million)	62.6	22.5	66.0	30.5	51.6	68.4
Indonesia (million)	117.2	108.8	104.4	147.2	61.0	235.9
Pakistan (million)	103.0	55.1	115.1	75.6	106.2	186.0

Source: www.esa.un.org/unpp.

Table A.1.2. Distribution of rural and urban population (%) in nine Asian countries.

Country	2005 (actual)		2015 (projected)		2050 (projected)	
	Rural	Urban	Rural	Urban	Rural	Urban
World	51.4	48.6	47.3	52.7	30.4	69.6
China	59.6	40.4	50.8	49.2	27.1	72.9
India	71.3	28.7	68.1	31.9	44.8	55.2
Bangladesh	74.3	25.7	69.2	30.8	43.6	56.4
Nepal	84.2	15.8	79.1	20.9	53.7	46.3
Philippines	37.3	62.7	30.4	69.6	16.1	83.9
Thailand	67.7	32.3	63.8	36.2	40.0	60.0
Vietnam	73.6	26.4	68.4	31.6	43.0	57.0
Indonesia	51.9	48.1	41.5	58.5	20.6	79.4
Pakistan	65.1	34.9	60.3	39.7	36.3	63.7

Source: www.esa.un.org/unpp.

Table A.1.3. Annual rural and urban population growth rates (%) in nine Asian countries.

Country	2005-15		2015-50	
	Rural	Urban	Rural	Urban
World	0.22	1.91	–1.18	1.08
China	–1.08	2.37	–2.36	0.50
India	0.77	2.50	–1.25	1.69
Bangladesh	0.78	3.41	–1.13	1.97
Nepal	1.20	4.67	–0.61	2.75
Philippines	0.32	2.60	–1.41	0.89
Thailand	–0.18	1.75	–1.94	0.93
Vietnam	0.41	3.02	–1.48	1.59
Indonesia	–1.23	2.70	–2.01	0.70
Pakistan	1.05	3.27	–1.0	1.85

Source: www.esa.un.org/unpp.

Table A.2. Rural and urban poverty measures using the poverty line (2002).

	Number of poor people (million)			Urban share of poor (%)	Urban share of population (%)
	Rural	Urban	Total		
			$1/day		
EAP[a]	223.2	16.3	239.5	6.8	38.8
China	175.0	4.0	179.0	2.2	37.7
SA[a]	394.3	125.4	519.7	24.1	27.8
Indi[a]	316.4	106.6	423.0	25.2	28.1
Total	882.8	282.5	1,165.3	24.2	42.3
			$2/day		
EAP	711.5	126.7	838.2	15.1	–
China	507.5	53.4	560.9	9.5	–
SA	876.3	290.3	1166.6	24.9	–
India	667.9	229.9	897.8	25.6	–
Total	2,097.3	745.9	2,843.2	26.2	–

[a]EAP = East Asia and the Pacific; SA = South Asia.

Source: Ravallion et al (2007).

Projections for economic and nutrition indicators for the world and South Asia

Economic and nutrition indicators as reported by FAO (2007) are presented in Table A.3. The table reveals that, in both South Asia and the world, population continues to increase from now to 2015 and to 2030 but at a slower rate. There will be a slight increase in per capita calorie intake as well as in the intake of cereals, meat, milk, and dairy products. Especially in South Asia, there will be a significant increase in the consumption of meat, milk, and dairy products. Although the absolute number and percentage of undernourished people will decrease in South Asia in 2030 compared with 2015, there will still be a large number of people who will remain undernourished. Cereal production will continue to increase in 2015 and 2030 in South Asia. However, cereal demand for food, feed, and other uses will be higher, so there will be a net shortage of cereals. The world will have just enough production to meet demand.

Table A.3. Projections for economic and nutrition indicators for 2015 and 2030 for South Asia and the world.

Indicator	South Asia		World	
	2015	2030	2015	2030
Population (million)*	1,672	1,969	7,207	8,270
Growth rate (% per year)**				
Population	1.6	1.1	1.2	0.9
Total GDP	5.5	5.4	3.5	3.8
Per capita GDP	3.9	4.3	2.3	2.9
Incidence of undernourishment				
Population (%)	12	6	–	–
Population (million)	195	119	–	–
Per capita calorie intake (kcal/capita/d)	2,700	2,900	2,940	3,050
Consumption (kg/capita/year)				
Cereals	177	183	171	171
Meat	7.6	88	41.3	45.3
Milk and dairy	11.7	107	83	90
Cereal demand (million t)				
Food	295	360	1,227	1,406
Feed	11	22	911	1,148
All uses	335	416	2,379	2,831
Cereal production (million t)	323	393	2,387	2,839

*Based on UN projections. **Growth rate to 2015 is computed for 1997-99 to 2015; that to 2030 is computed for 2015 to 2030.
Source: FAO (2007). World agriculture: towards 2015 and 2030 summary report, FAO, Rome. www.fao.org/docrep/004/y3557e/.

Economic and development indicators

Economic and development indicators in 2006 for nine Asian countries, as reported by the World Bank, are presented in Table A.4. These estimates indicate large differences in various economic and development indicators among the nine countries. The table shows population and its distribution, by age, for each country. Some 22–39% of the population is under 14 years of age, while 57–70% belongs to the 15–64 age group. Very few people (4–7%) are above 65 years of age. In China and Thailand, a large percentage of the people is in the active age group; in Nepal and Pakistan, a large segment of the population is under 14. Gross national income (GNI) per capita ranges from as low as $290 in Nepal to as high as $2,990 in Thailand. Average annual growth rate of population (2000-06) ranges from 0.6% in China to 2.4% in Pakistan, whereas average growth rate of the labor force over the same period ranges from 1.0% in China to 3.8% in Pakistan. The labor force working in the agricultural sector ranges from 37.1% in the Philippines to 92.8% in Nepal. The percentage of the population below the national poverty line ranges from 18% in Indonesia to 50% in Bangladesh. Life expectancy at birth is highest in China (72 years) and lowest in Nepal (63 years). Infant mortality rate (number per 1,000 live births) is highest in Pakistan (79) and lowest in Vietnam (16). Child malnutrition (% of children under 5) is highest in Nepal (45%) and lowest in China (8%). Literacy rate (% of population above 15 years of age) is lowest in Pakistan (47%) and highest in the Philippines and Thailand (93%). The unemployed labor force ranges from 2% in Thailand and Vietnam to 10% in Indonesia and the Philippines.

Average annual growth rates of GDP and GDP per capita, respectively, range from 1.9% and –0.1% (Nepal) to 10.7% and 10.1% (China). The percentage of GDP contributed by agriculture, industry, and the service sectors varies widely among countries. The contribution by the agricultural sector is largest for Nepal (39.5%) and smallest for Thailand (10.7%), while the contribution by the industrial sector is largest for China (48.4%) and smallest for Nepal (21.0%). The contribution by the service sector is largest in India (54.6%) and smallest in Vietnam (38.1%).

Cereal imports and stocks

Based on FAO estimates (FAO 2008), in all countries, there were almost no (or very small) cereal stocks in 2007 and this would continue to be so in 2008 (Table A.5). As a result of the lack of stocks and the increasing population, these countries imported cereals in the form of commercial purchases and food aid in 2007 and would continue to do the same in 2008. Bangladesh, India, Indonesia, and the Philippines imported the largest amounts of cereals in 2007. In 2008 also, Bangladesh, Indonesia, and the Philippines would remain the largest importers. Despite the food shortages, surprisingly, Nepal would receive only 8,000 t of cereals though food aid in 2008, and it was not clear what amount it would import through purchases.

Table A.4. Economic and development indicators for rice-maize-growing countries, 2006.

Indicator	Bangladesh	China	India	Indonesia	Nepal	Pakistan	Philippines	Thailand	Vietnam
Population (million)	144.3	1311.8	1109.8	223.0	27.7	159.0	84.6	64.7	84.1
Population age (%)									
0–14	36	22	32	29	39	39	36	24	30
15–64	61	70	62	66	57	57	61	69	64
65 and over	4	7	5	5	4	4	4	7	5
GNI per capita (US$)	490	2,000	820	1,420	290	800	1,420	2,990	690
Average annual growth (2000-06)									
Population (%)	1.9	0.6	1.5	1.3	2.1	2.4	1.8	0.9	1.3
Labor force (%)	2.2	1.0	1.9	1.9	2.8	3.8	3.7	1.2	2.1
Agricultural labor force (%)[a]	51.8	64.3	57.8	45.7	92.8	45.1	37.1	53.3	65.7
Poverty (% of population below national poverty line)	50	–	29	18	31	–	–	–	29
People below poverty line ($1 or $2 basis) (%)									
Life expectancy at birth (y)	64	72	64	68	63	65	71	71	71
Infant mortality (per 1,000 live births)	54	23	56	28	56	79	25	18	16
Child malnutrition (% of children under 5)	48	8	–	28	45	38	28	–	28
Literacy (% of population age 15+)	61	91	61	90	49	47	93	93	–
Unemployment rate (% of labor force)	3	–	4	10	–	8	10	2	2
Average annual growth (2005-06)									
GDP (%)	6.8	10.7	9.2	5.5	1.9	6.9	5.4	5.0	8.2
GDP per capita (%)	5.1	10.1	7.7	4.3	-0.1	4.7	3.5	4.2	6.9
% of GDP									
Agriculture	19.6	11.7	17.5	12.9	39.5	19.4	14.2	10.7	20.4
Industry	27.9	48.4	27.9	47.0	21.0	27.2	31.6	44.6	41.6
Services	52.5	39.9	54.6	40.1	39.5	53.4	54.2	44.7	38.1

[a]2004 data. Source: Gender Stats: The World Bank Group (http://devdata.worldbank.org). Education statistics version 5.3 (http://web.worldbank.org). World Bank 2007a, 2008.

Table A.5. Cereal imports and stocks.[a]

Country	Cereal import requirements (000 t)[b]		Cereal stocks (million t)	
	Estimated (2007)	Forecast (2008)[c]	Estimated (2007)	Forecast (2008)
Bangladesh	3,047	1,892	–	–
China	2,566	406	153.3	160.0
India	6,765	1,991	29.2	31.6
Indonesia	8,193	4,308	5.6	5.8
Nepal	240	8	–	–
Pakistan	424	1,001	3.2	3.6
Philippines	5,355	2,854	2.6	2.7

[a]Not available for Thailand and Vietnam. [b]Includes commercial purchases and food aid. [c]Estimates based on information available as of end of January 2008. Source: FAO (2008). FAO crop prospects and food situation – February 2008, FAO, Rome. www.fao.org/docrep/010/ah881e/ah881e08.htm.

Annex B
Trends in area, production, yield, trade, and calorie and protein intakes from rice, maize, and wheat

Historical trends in the contribution of rice and maize to calorie and protein intake

The contribution from rice in terms of average calories/capita/day from 1994 to 2003 ranged from 750 to 1,700, that from maize ranged from 0 to 560, and that from wheat, from 25 to 600. The calorie contribution from rice was highest for Vietnam (1,600–1,700 calories) and lowest for India (700–800 calories). For wheat, calorie contribution was highest for China, followed by India; it was lowest for Vietnam. For maize, such a contribution was consistently higher for Nepal (400–550 calories), followed by Indonesia (200–250 calories), and then lowest for Bangladesh (Figs. B.1-B.3). The share of calories from paddy rice remained stable over the years in all countries, ranging from 45% (Nepal) to 90–95% (Vietnam). The share of calories from wheat varied from <5% in Vietnam to around 35% in China and India (Figs B.4-B.6). The share of calories for maize, however, varied slightly over the years, ranging from

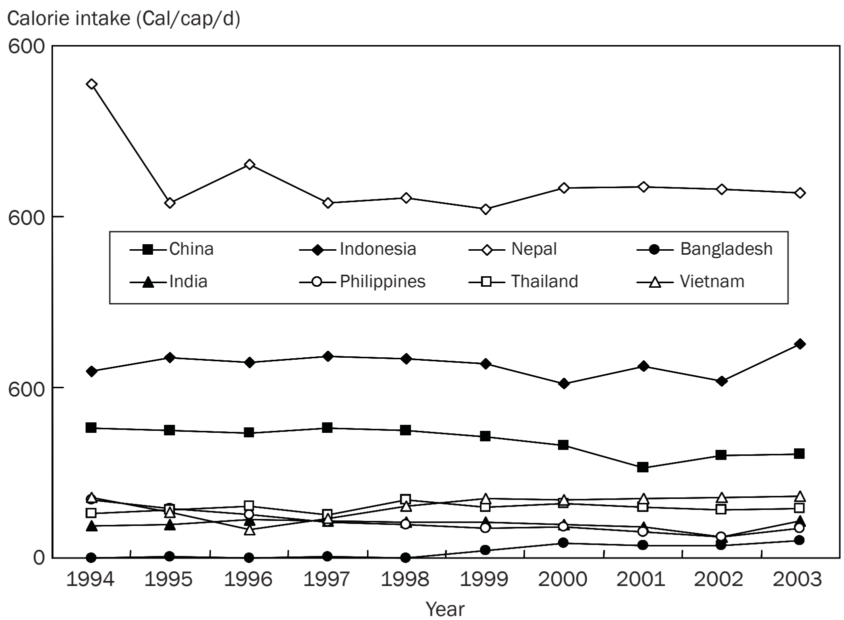

Fig. B.1. Trends in calorie intake through maize for eight Asian countries (1994-2003).

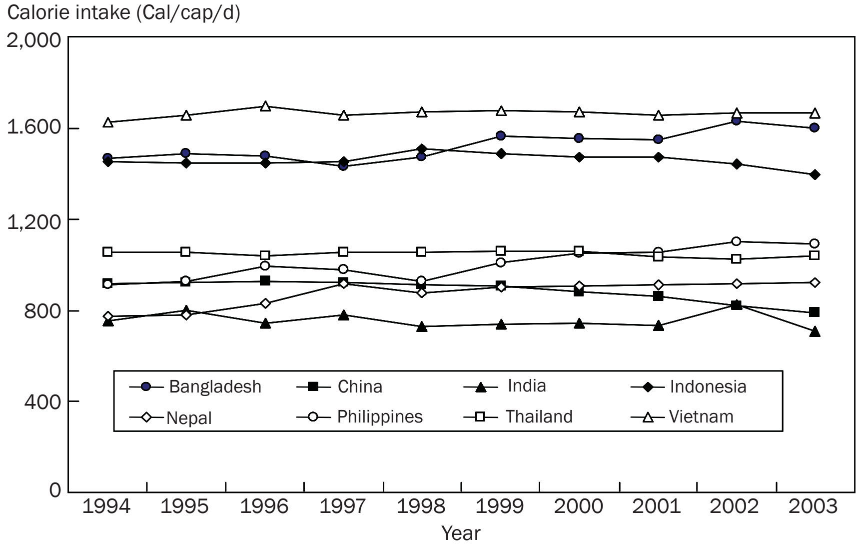

Fig. B.2. Trends in calorie intake through rice for eight Asian countries (1994-2003).

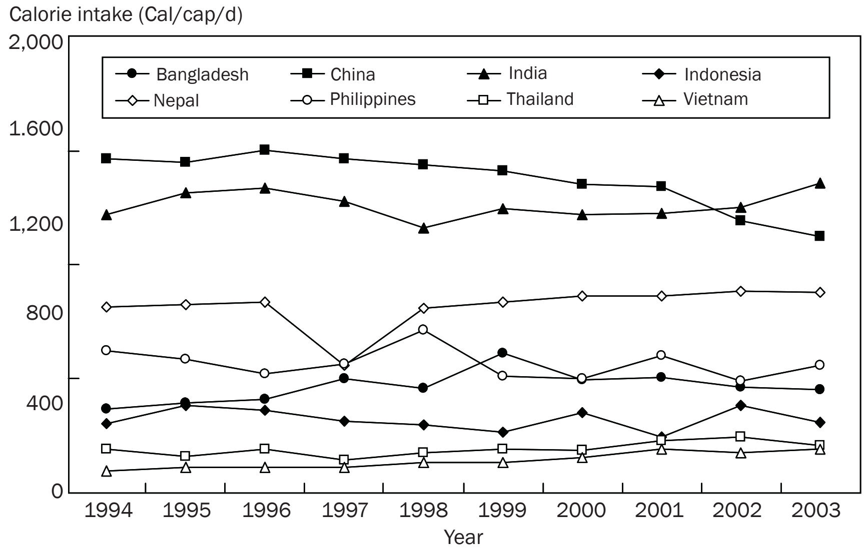

Fig. B.3. Trends in calorie intake through wheat for eight Asian countries (1994-2003).

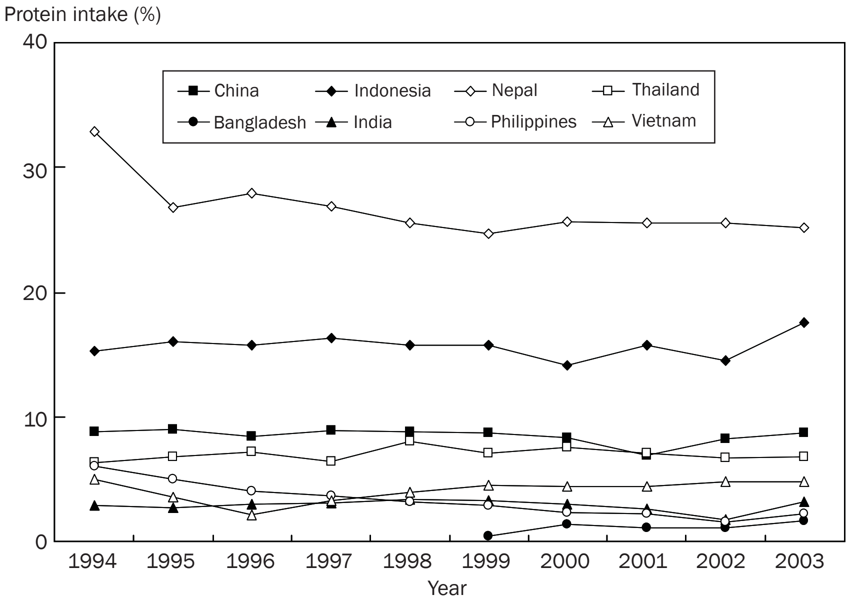

Fig. B.4. Trends in share of maize in total protein intake through cereals in eight Asian countries (1994-2003).

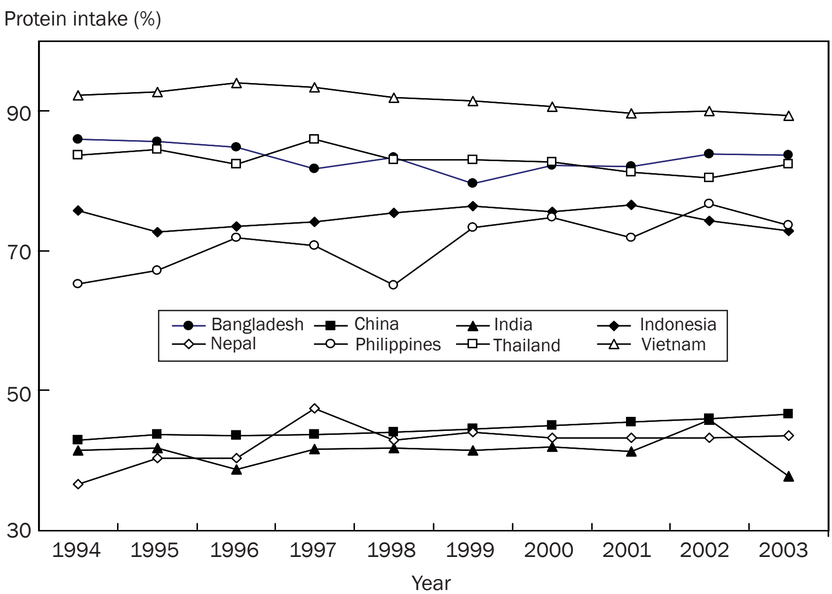

Fig. B.5. Trends in share of rice in total protein intake through cereals in eight Asian countries (1994-2003).

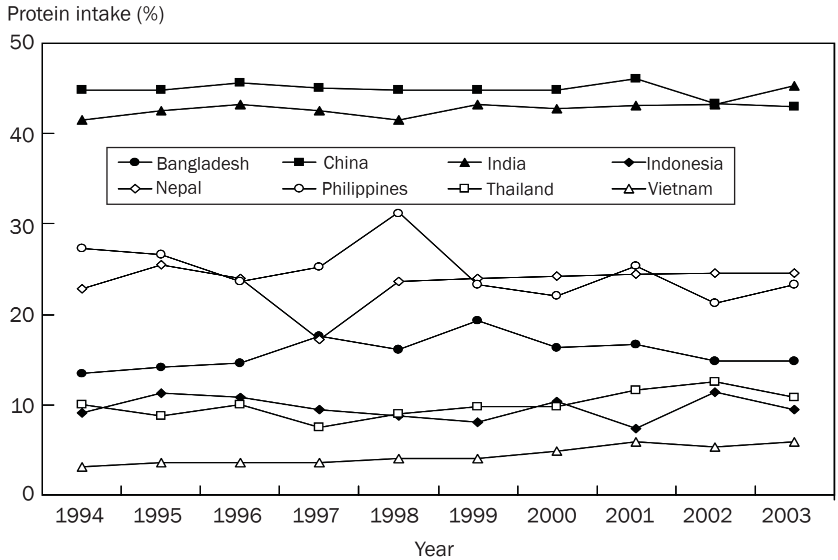

Fig. B.6. Trends in share of wheat in total protein intake through cereals in eight Asian countries (1994-2003).

zero in the initial years (Bangladesh) to 25–30% (Nepal). The share of protein from rice in most countries varied little over the years; the range was around 40% (China, India, Nepal) to around 90% (Vietnam). The share of protein from maize, however, remained less than 30% in all countries, with the highest noted for Nepal (25–30%), followed by Indonesia (15–20%), and the lowest observed for Bangladesh (<5%). The share of protein from wheat remained less than 45% in all countries (highest for China and India, 40–45%, and lowest for Vietnam, <10%) (Figs. B.7-B.9).

Historical trends in area, production, and yield of rice, wheat, and maize

The statistics presented regarding historical trends are derived from the FAO (www.faostat.fao.org) for all countries from 1995 to 2006, except for Bangladesh and Indonesia. As the FAO statistics for Bangladesh and Indonesia were found to be unrealistic, other sources of data were used for these two countries. For Bangladesh, the data sources included government periodical records, crop cuts, farmers' surveys, field monitoring, and records of research station yields. For Indonesia, USDA data were used.

The average yields of all cereals in the nine rice-maize (R-M) practicing countries increased from 1994 to 2006. The yield of maize over the same period averaged 1.5–5.9 t ha^{-1}. The lowest yields over the years were for India, Nepal, and the Philippines (1.5–2.1 t ha^{-1}), while the highest yields were for Bangladesh and China (3–5.9 t ha^{-1}). Indonesia, Thailand, and Vietnam had intermediate yield. Among all countries, maize yield increased fastest in Bangladesh, from 2.98 in 1996 to 5.15 t ha^{-1} in 2005, followed by Indonesia, the Philippines, and Vietnam (Figs. B10-B.12). In China, aver-

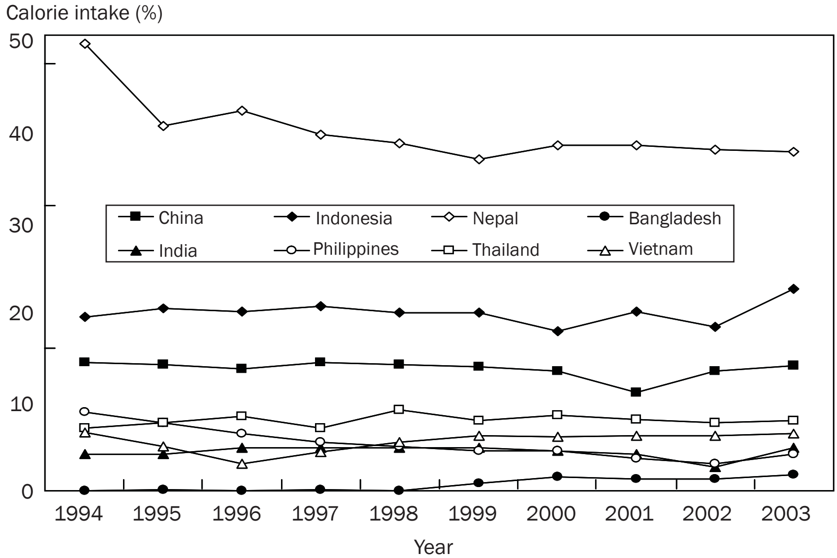

Fig. B.7. Trends in share of maize in total calorie intake through cereals in eight Asian countries (1994-2003).

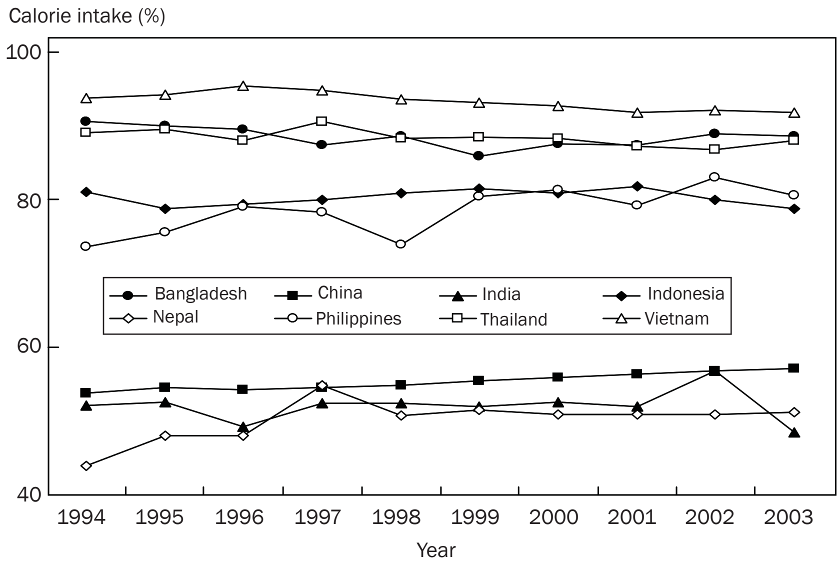

Fig. B.8. Trends in share of rice in total calorie intake through cereals in eight Asian countries (1994-2003).

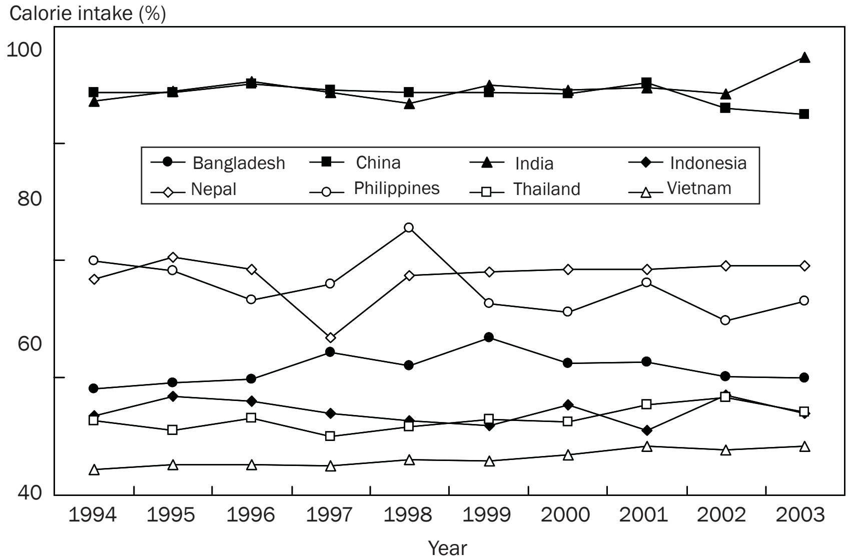

Fig. B.9. Trends in share of wheat in total calorie intake through cereals in eight Asian countries (1994-2003).

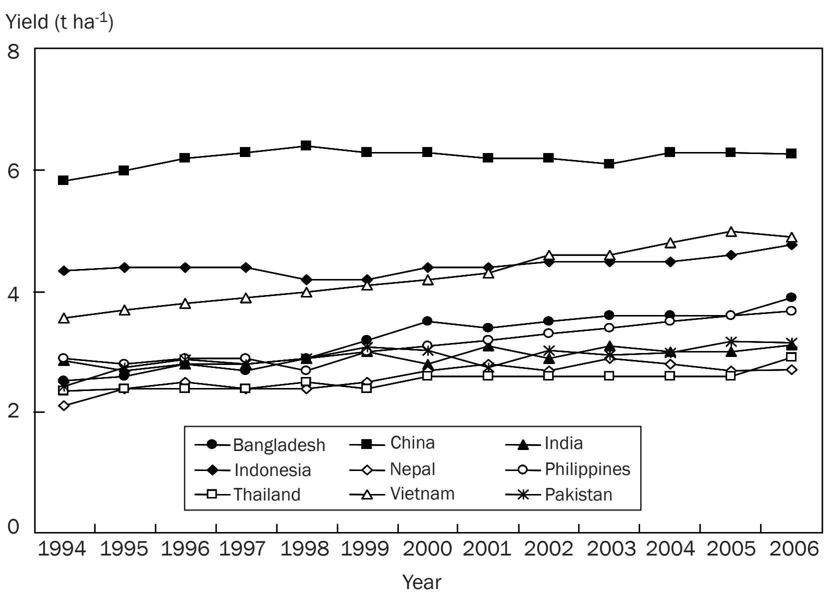

Fig. B.10. Trends in rice yield in nine Asian countries (1994-2006).

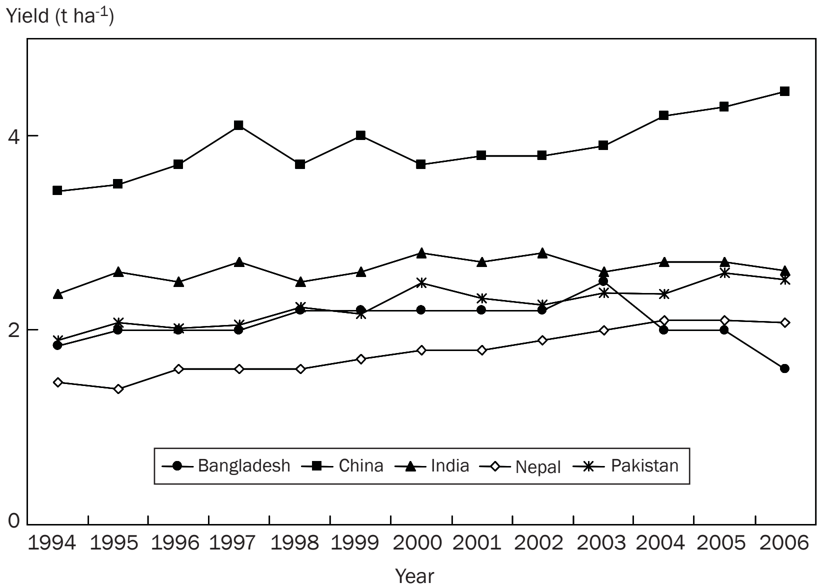

Fig. B.11. Trends in wheat yield in five Asian countries (1994-2006).

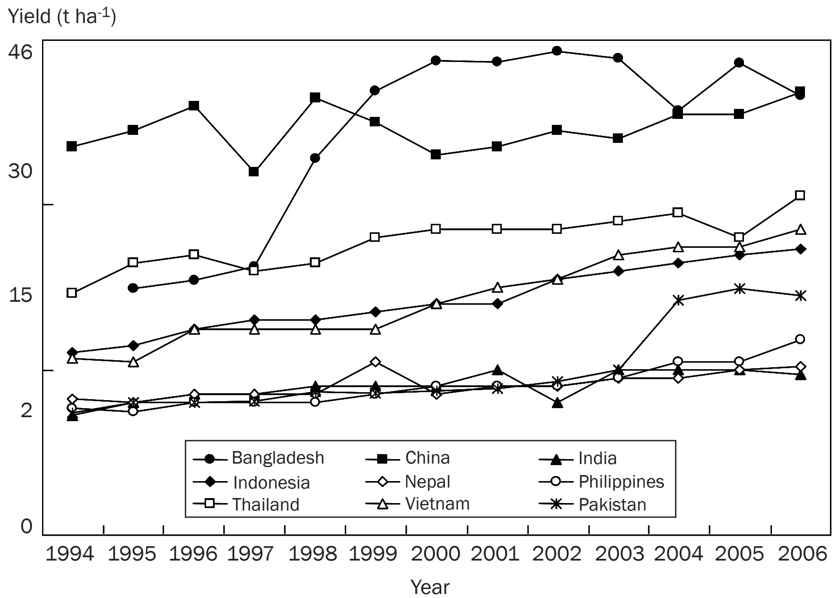

Fig. B.12. Trends in maize yield in nine Asian countries (1994-2006).

age maize yield was already high at 4.7 t ha^{-1} in 1994. The yields fluctuated slightly over the years and settled at 5.1 t ha^{-1} in 2005. The average yield of rice during that period ranged from 2.1 to 6.3 t ha^{-1}. The lowest yields were for Nepal (2.1–2.4 t ha^{-1}) and Thailand (2.3–2.4 t ha^{-1}); the highest were for China (5.9–6.3 t ha^{-1}). In Vietnam, average rice yields increased faster than in any other country, followed by the Philippines. The average yield of wheat across the nine countries during the same period ranged from 1.4 to 4.5 t ha^{-1}. Yields were lowest in Nepal (1.4–2.0 t ha^{-1}) and highest in China (3.5–4.5 t ha^{-1}). Wheat yields increased in all countries until about the beginning of 2000-01. Since then, yields have increased in China, stagnated in Pakistan, India, and Nepal, and decreased in Bangladesh.

Production, use, and trade of rice, wheat, and maize

Bangladesh

Rice production and the use of rice as food and seed increased consistently from 1994 to 2005 (Fig. B.13). Rice production increased from about 25 million t in 1994 to about 40 million t in 2005. Rice imports were almost nil, except for a small amount in 1995 and 1996. Area and production of wheat in Bangladesh increased until the late 1990s and then decreased in early 2000. The use of wheat as food kept on increasing until it stabilized in early to mid-2000. Wheat imports first increased substantially but have since then fluctuated in recent years (Fig. B.14). Maize hybrids were introduced in Bangladesh in the early nineties. Until the 1980s, there was negligible area under maize in Bangladesh. Maize was grown on only about 10,125 ha in 1994 but increased at rapid rates each year—93,180 ha in 2005 and 137,000 ha in 2006 (Fig. B.15). As a result, production also increased from 32,000 t in 1996 to 0.48 million t in 2005 and 0.78 million t in 2006 (Ali et al 2009).

China

Rice production remained highest at around 200 million t in the mid- to late 1990s, followed by a decrease in early 2000 and an increase recently (Fig. B.16). The use of rice as food and feed has remained stable, with a slight decrease recently. The wheat area decreased continuously from 1994 to 2005. Wheat production, however, first increased, then decreased; it increased slightly again in recent years. Consumption likewise decreased, and so wheat imports were quite minimal (Fig. B.17). Maize production increased from 100 million t (1994) to 135 million t (2005) (Fig. B.18). Its use as food continuously decreased until 2001; in 2002 and 2003, it again increased. The use of maize as feed remained stable with around 75–80 million t consumed each year. Maize grain imports were higher in 1995 but have remained lower and more stable in all other years.

India

Rice production in 1994 was 123 million t. This value increased to 140 million t in 2001. Production then decreased for some time, followed again by a slight increase

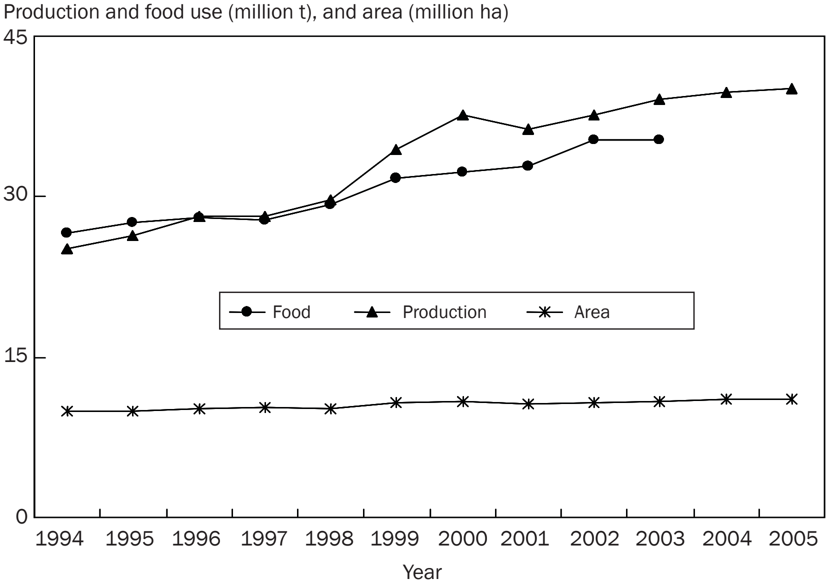

Fig. B.13. Trends in rice supply and use in Bangladesh (1994-2005).

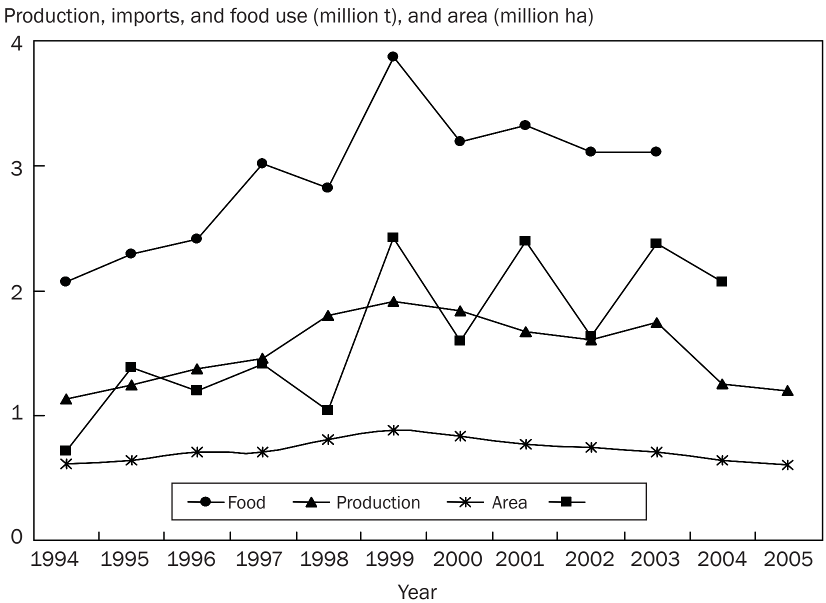

Fig. B.14. Trends in wheat supply and use in Bangladesh (1994-2005).

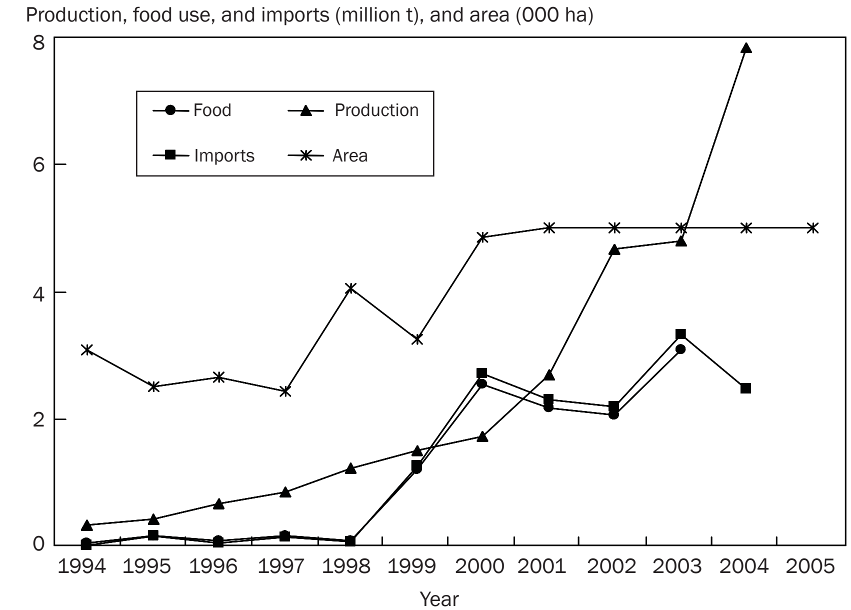

Fig. B.15. Trends in maize supply and use in Bangladesh (1994-2005).

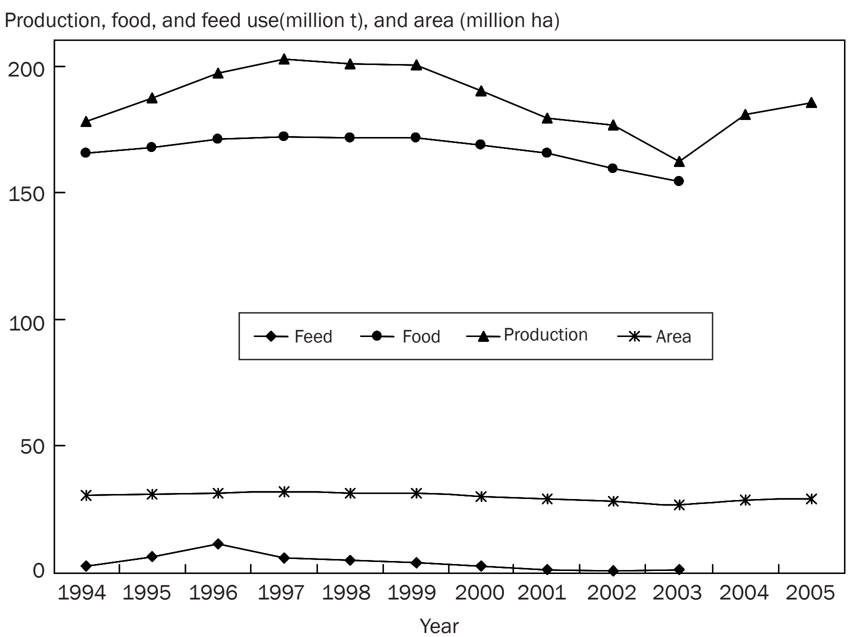

Fig. B.16. Trends in rice supply and use in China (1994-2005).

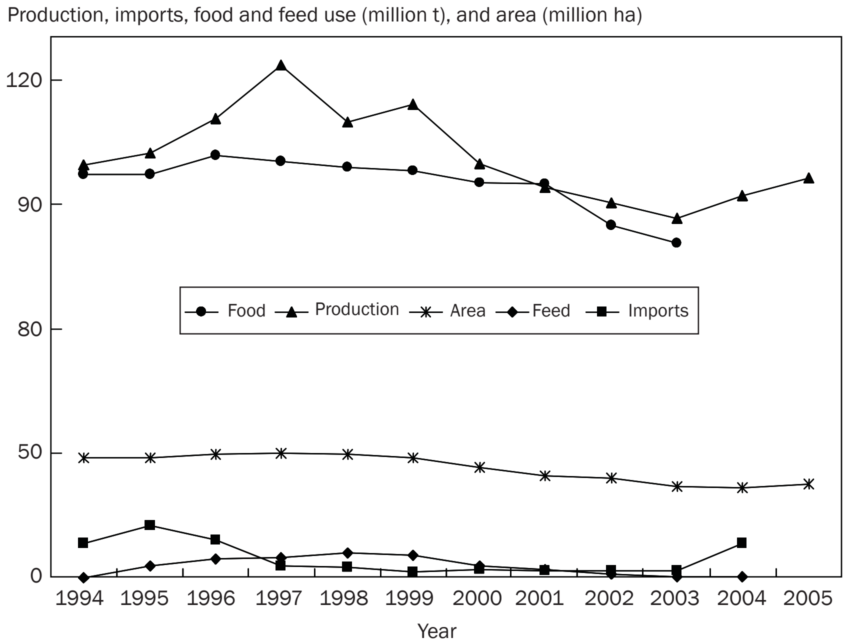

Fig. B.17. Trends in wheat supply and use in China (1994-2005).

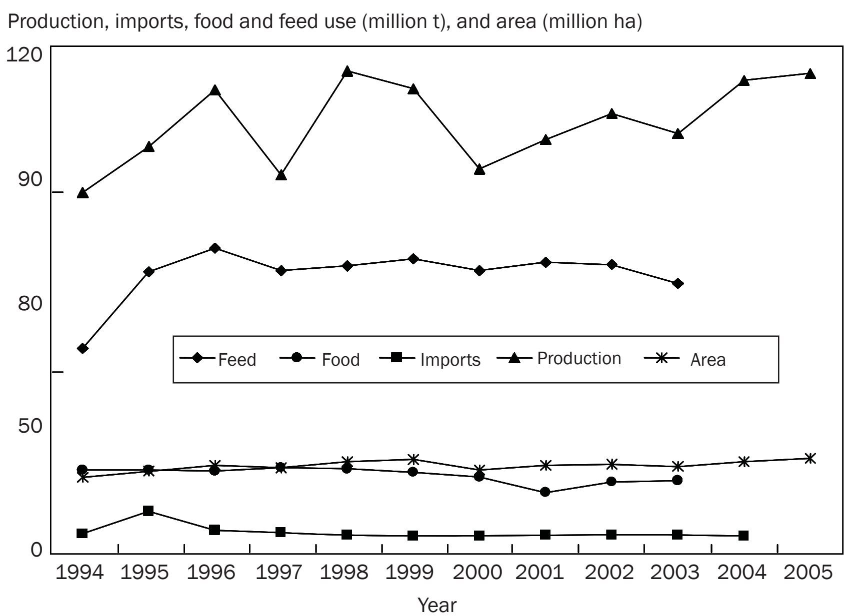

Fig. B.18. Trends in maize supply and use in China (1994-2005).

to 129 million t. Its use as food has been increasing in all years, except for a decrease in 2003. India has been one of the major rice exporters, and hence the country's rice imports remained almost nil throughout the years (Fig. B.19). Wheat area in India remained constant from 1994 to 2005, while production kept on increasing because of the increase in yield. The use of wheat as food increased, but its use as feed remained constant. India imported wheat from 1996 to 1999 (Fig. B.20). Maize production increased from around 9 million t in 1994 to 14.5 million t in 2005. The use of maize as food was higher (4–5 million t) than its use as feed (3–3.5 million t) in the initial years, but the opposite trend was seen in later years (5.2–6 million t as feed vs 3.1–5.7 million t as food). Imports remained negligible in all years (Fig. B.21).

Nepal

Rice production increased from around 3.0 million t (1994) to 4.5 million t (2003) and then decreased to 4.1 million t (2005). Its use as food also increased over the years, from 2.6 to 3.5 million t. The use of rice grain as feed and rice imports were minimal (Fig. B.22). The area under wheat in Nepal increased slightly from 1994 to 2005, but production increased quite substantially over the same period. Its use as food increased consistently over the years, but its use as feed increased dramatically in 2003. Nepal imported substantial amounts of wheat in the late 1990s and again in 2003 and 2004 (Fig. B.23). Maize production increased from 1.2 million t (1994) to 1.7 million t (2005), but use as food and feed remained stable over the years, at about 1 million t and 0.2 million t, respectively. Maize grain imports were minimal until 2005 (Fig. B.24). The authors recently observed a substantial increase in maize imports because of huge demand for feed from the poultry industry.

Indonesia

Rice production increased from around 46 million t (1994) to 54 million t (2005). Its use as food also increased from 43 to 47 million t over that same period. Imports remained minimal from 1994 to 2005 but were substantial in recent years. Its use as feed was also small, ranging from 1.7 to 4.0 million t over the years (Fig. B.25). The use of wheat as food fluctuated initially but increased substantially in recent years. Thus, wheat importation was deemed necessary. Imports followed a similar trend as the use of wheat as food (Fig. B.26). Maize production increased from around 5.4 million t (1994) to 7.4 million t (2005). Its use as food and as feed increased from 3 to 4 million t over the same period. Imports remained unstable over the years, ranging from 0.4 to 1.9 million t (Fig. B.27).

The Philippines

Rice production from 1994 to 2005 increased from 10.5 to 15 million t, most of which was used as food. The use of rice as feed remained at 0.4 to 0.7 million t. The country has always imported 0.5–0.7 million t of rice each year. In 2008, it imported about 2.7 million t of rice (Fig. B.28). The use of wheat as food and as feed increased from 1994 to 2005; as a result, wheat imports also increased (Fig. B.29). Maize produc-

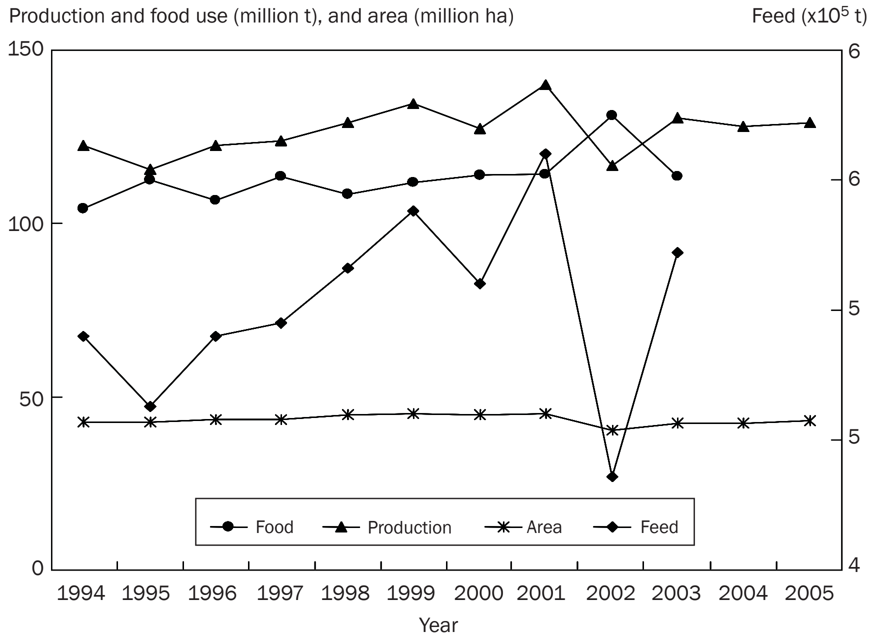

Fig. B.19. Trends in rice supply and use in India (1994-2005).

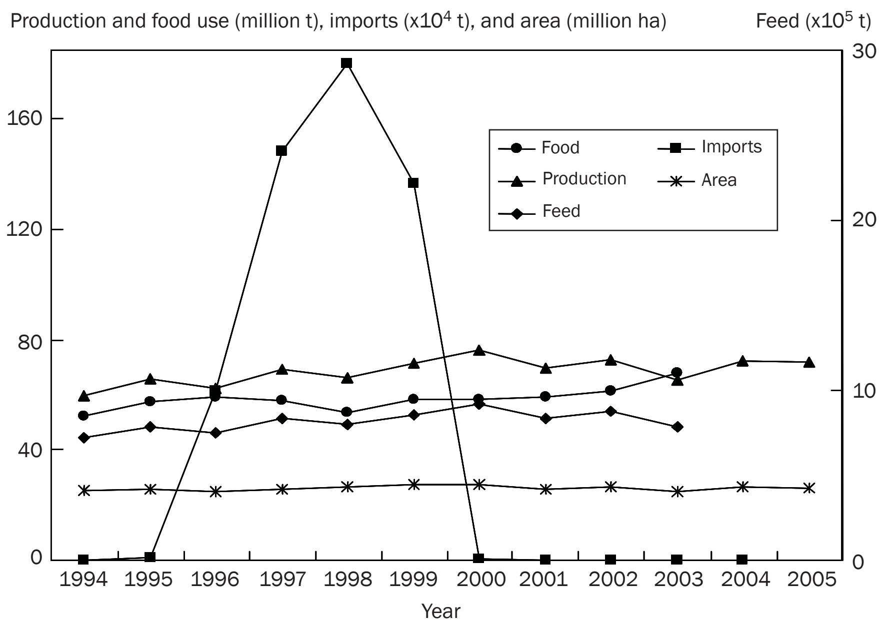

Fig. B.20. Trends in wheat supply and use in India (1994-2005).

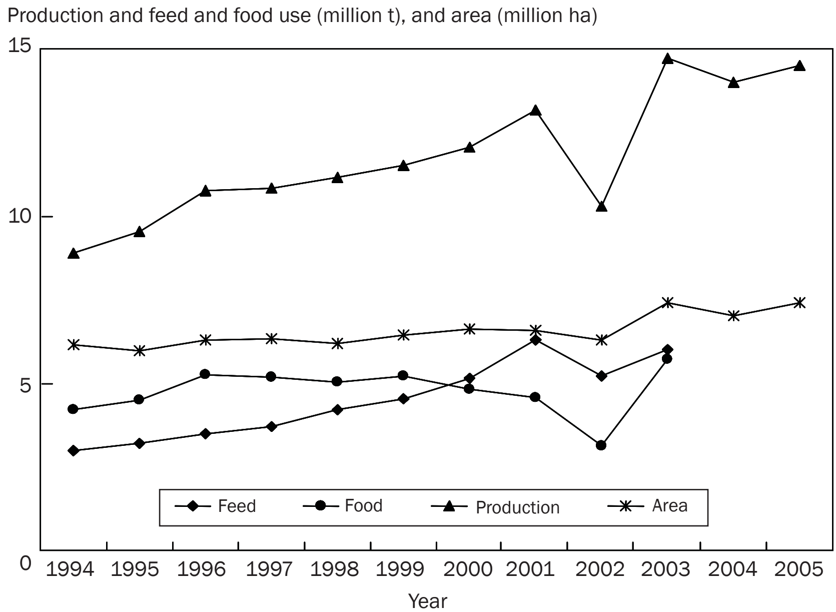

Fig. B.21. Trends in maize supply and use in India (1994-2005).

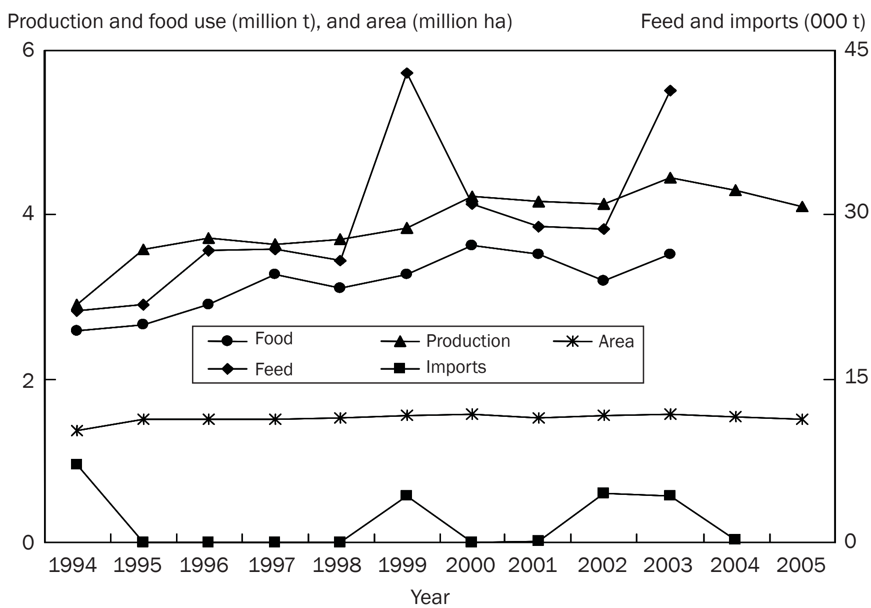

Fig. B.22. Trends in rice supply and use in Nepal (1994-2005).

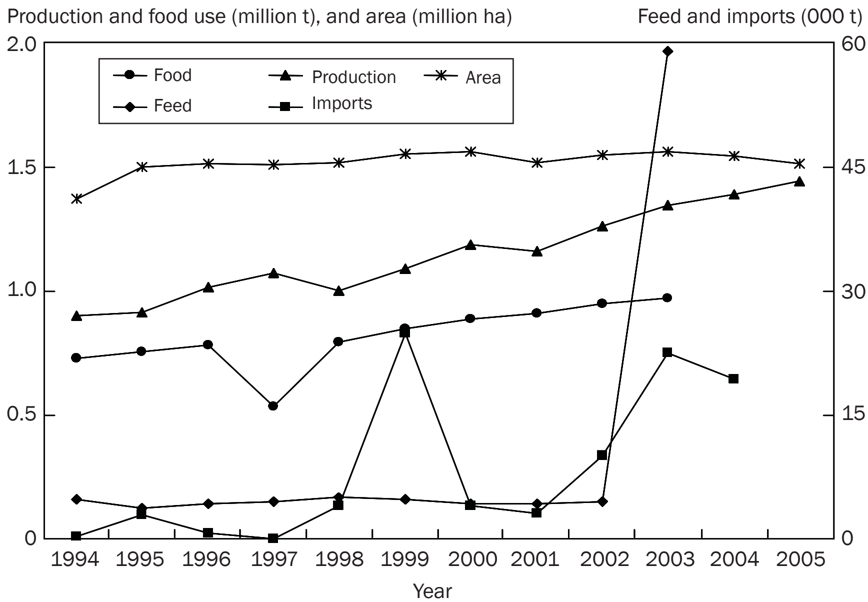

Fig. B.23. Trends in wheat supply and use in Nepal (1994-2005).

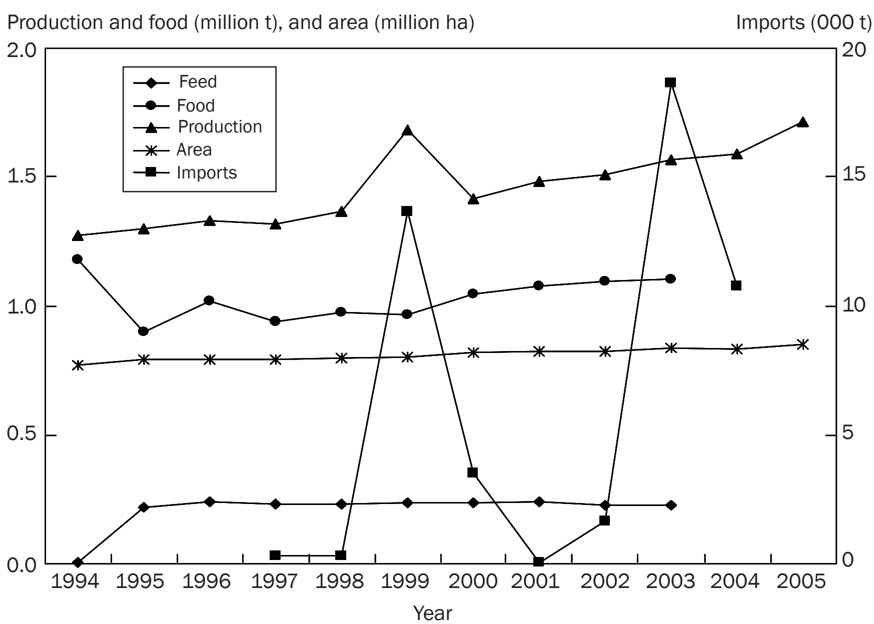

Fig. B.24. Trends in maize supply and use in Nepal (1994-2005).

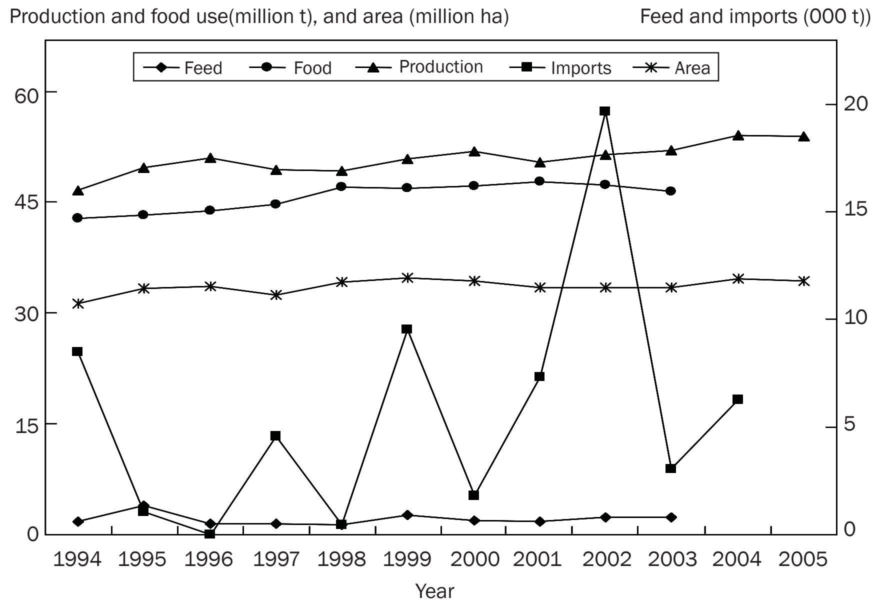

Fig. B.25. Trends in rice supply and use in Indonesia (1994-2005).

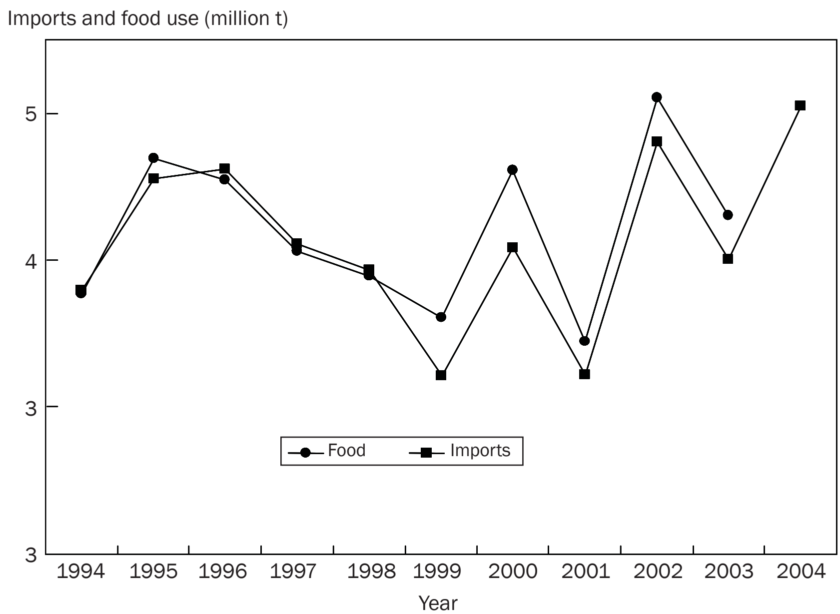

Fig. B.26. Trends in wheat supply and use in Indonesia (1994-2005).

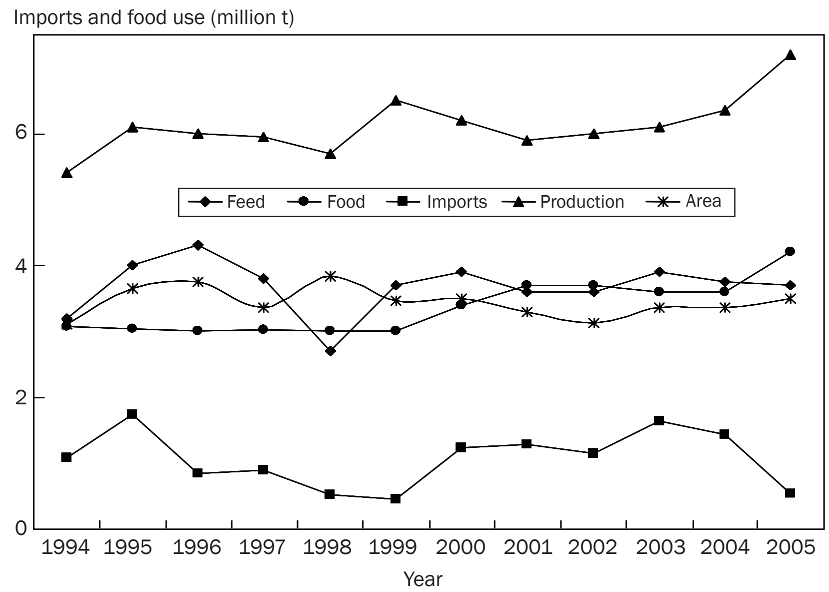

Fig. B.27. Trends in maize supply and use in Indonesia (1994-2005).

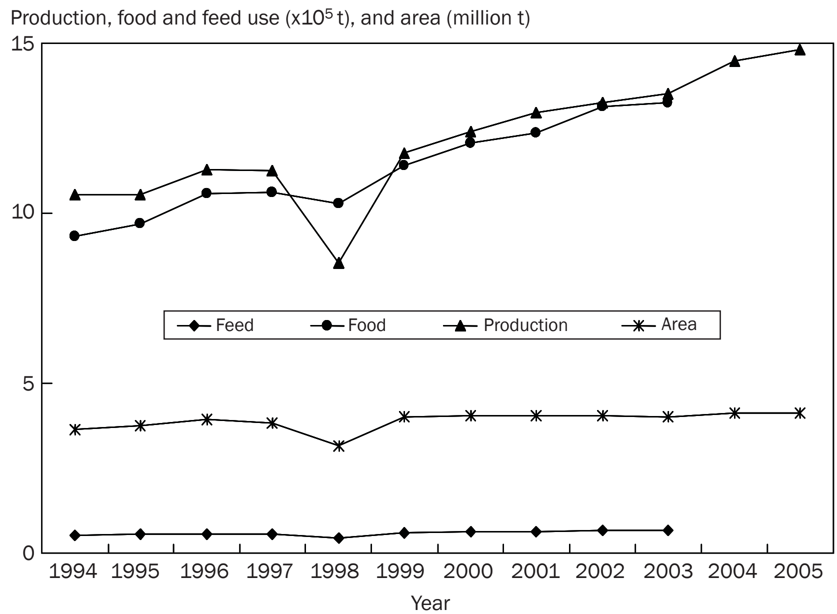

Fig. B.28. Trends in rice supply and use in the Philippines (1994-2005).

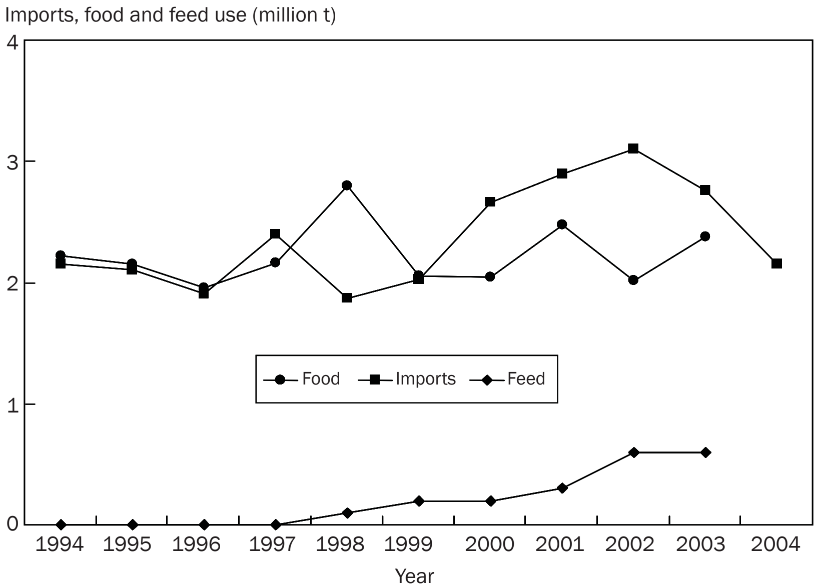

Fig. B.29. Trends in wheat supply and use in the Philippines (1994-2005).

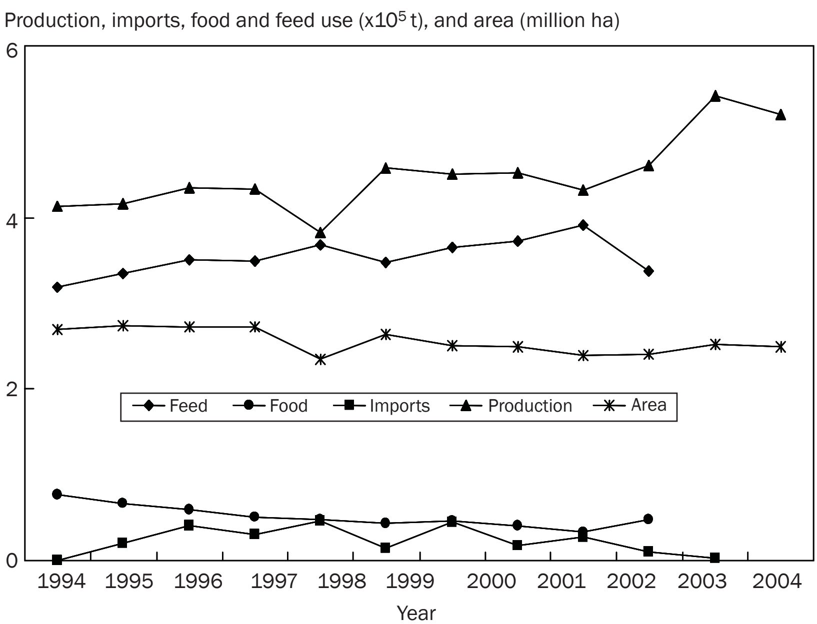

Fig. B.30. Trends in maize supply and use in the Philippines (1994-2005).

tion over the same period increased from 4.1 to 5.3 million t, most of which was used as feed. The use of maize as food was very small, around 53,000 t annually. Maize imports were variable across years, with the highest being 0.47 million t in the late 1990s (Fig. B.30).

Thailand

Rice production increased from 20 to 26 million t during the 1994-2005 period, with domestic food consumption of around 10 million t annually (Fig. B.31). Its use as feed increased from 0.6 to 0.7 million t; as feed, the increase was from 1.1 to 1.4 million t (Fig. B.32). Area and production of wheat increased only slightly from 1994 to 2005, but its use as food and the amount of imports increased substantially. Maize production was variable in the initial years (at around 3.8–4.6 million t) but remained stable in later years (at around 4.2 million t). Maize was mostly used as feed though variably in different years. Its use as food and seed was very much less; imports were likewise minimal (Fig. B.33).

Vietnam

Rice production increased from 24 to 36 million t over the years, with consumption at around 18 million t annually. Its use as feed was minimal at 1.2–1.6 million t annually (Fig. B.34). The use of wheat as food increased from 0.35 to 0.8 million t; as a result, imports also increased substantially, from 0 to 0.9 million t over the same period (Fig. B.35). Maize production over the same period increased rapidly from 1.1 to 3.5 million t, with its use as feed also increasing rapidly from 0.4 million t in 1994 to 2.4 million t in 2003. Its use as food remained slightly stable at around 0.5 million t over the years. Maize imports were minimal in the initial years but they started to increase recently (Fig. B.36).

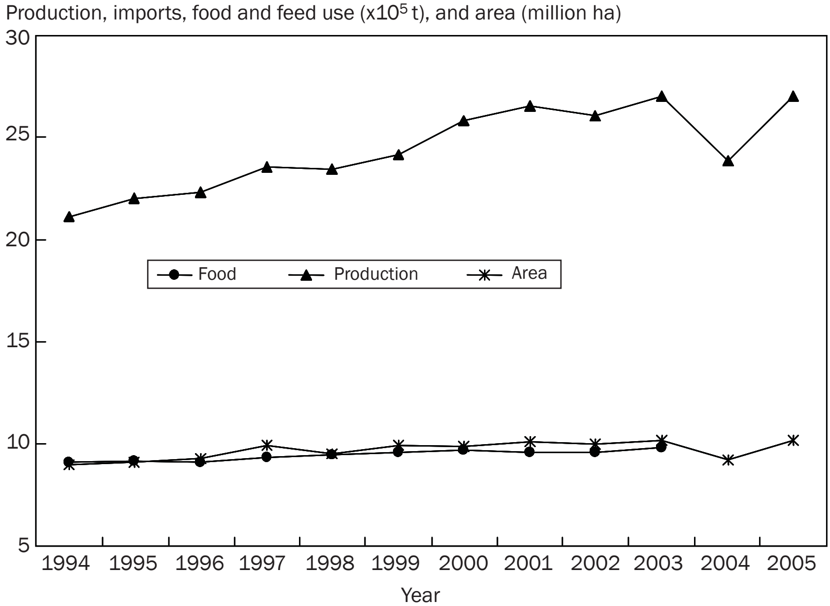

Fig. B.31. Trends in rice supply and use in Thailand (1994-2005).

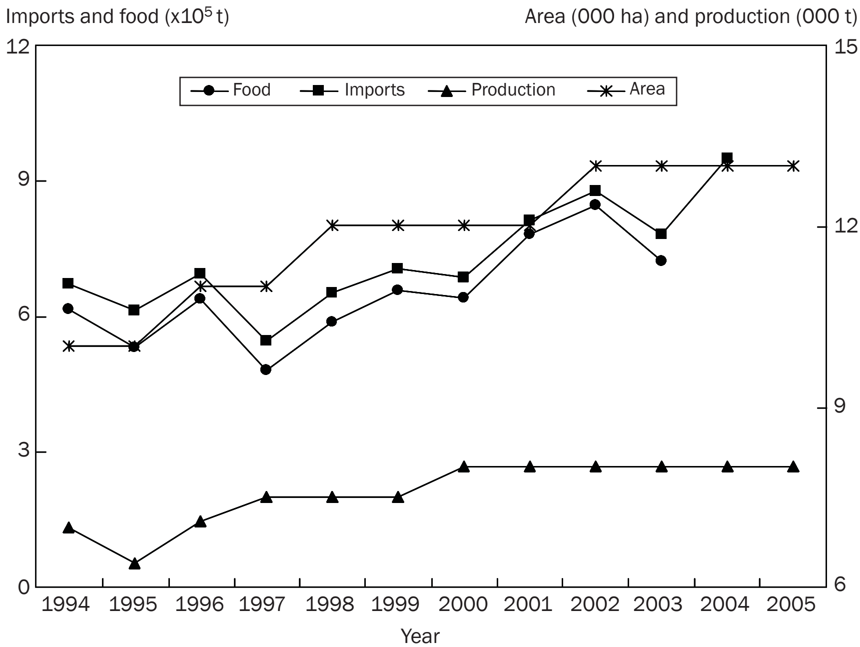

Fig. B.32. Trends in wheat supply and use in Thailand (1994-2005).

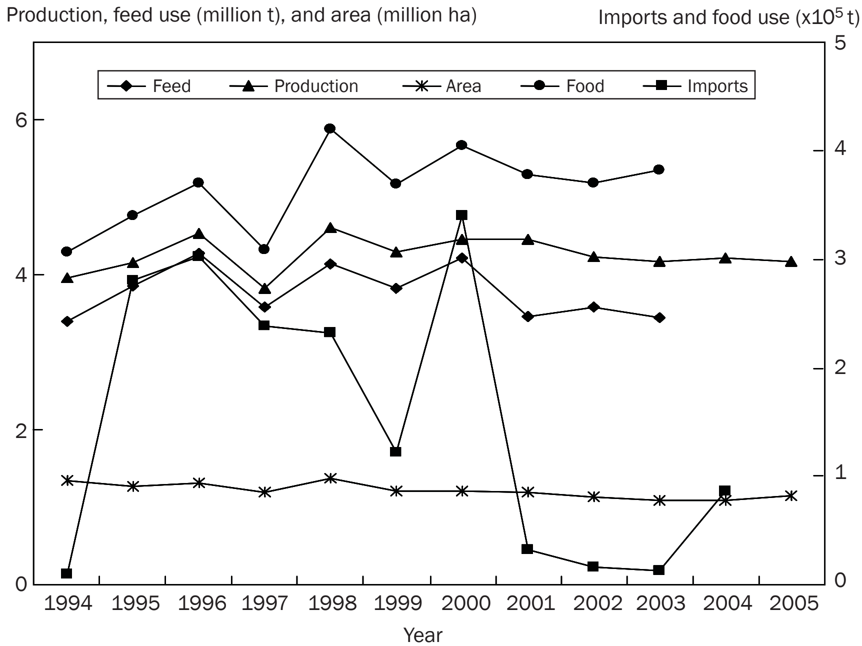

Fig. B.33. Trends in maize supply and use in Thailand (1994-2005).

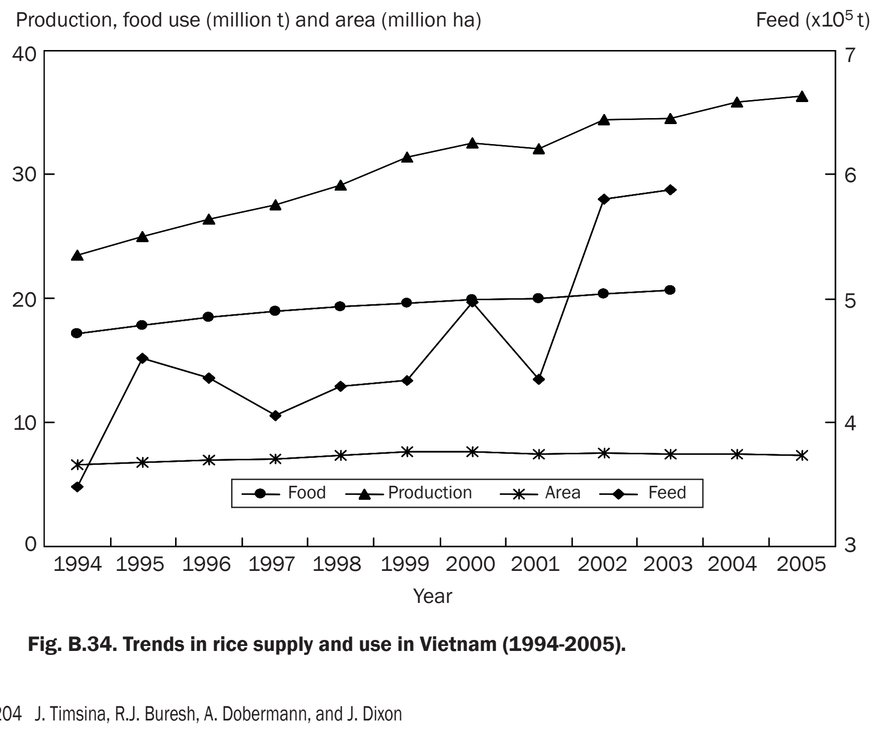

Fig. B.34. Trends in rice supply and use in Vietnam (1994-2005).

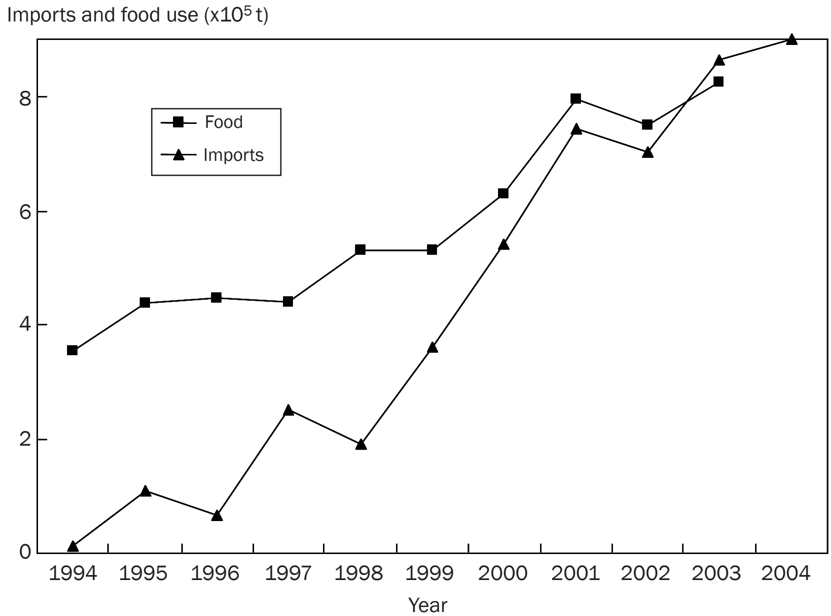

Fig. B.35. Trends in wheat supply and use in Vietnam (1994-2005).

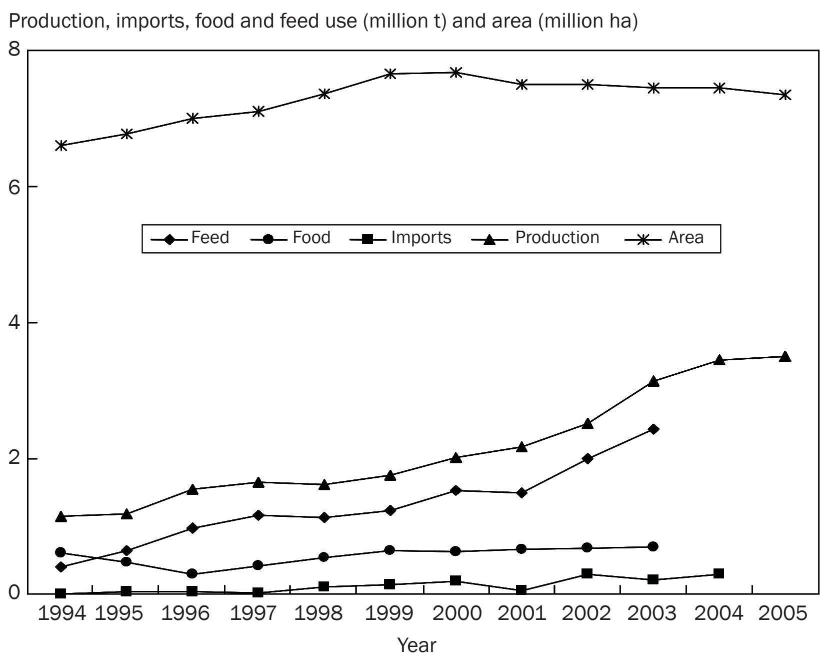

Fig. B.36. Trends in maize supply and use in Vietnam (1994-2005).

Annex C
Trends in production, consumption, and trade of fertilizers

Production of N fertilizer increased from 1973 to 2005 in both China and India, but the rate of increase was much faster in the former than in the latter. Indonesia also kept on producing N fertilizer but the increase was at a much a slower rate than in China and India (Fig. C.1). Consumption of N, P, and K fertilizers in all the countries increased each year over the past 43 years (1962-2005), except for Nepal and the Philippines, where it decreased in recent years (Figs. C.2–C.9). Consumption of all fertilizers was greatest in China, followed by India, and was smallest in Nepal, followed by the Philippines. Although the population figures for China and India are similar, fertilizer consumption in China was more than double that in India. Considering the very large population of Indonesia, consumption of all fertilizers was quite low.

Except for Nepal, all countries produce some N and P fertilizers, but all of them also import N fertilizers. Likewise, all countries (except for Nepal) export some amount of N fertilizers. Except for Bangladesh, India, and Nepal, all other countries export P fertilizers. Only China produces and exports K fertilizers, but all countries, including China, import K fertilizers (www.fao.org/site/575/default.aspx).

Bangladesh

Consumption of N, P_2O_5, and K_2O fertilizers in Bangladesh started from very low amounts of 20,000, 2,000, and 1,000 t, respectively, in 1962. Consumption of fertilizers increased consistently over the past 43 years, but the rate of increase was much slower for P_2O_5 and K_2O than for N. In 2005, N, P_2O_5, and K_2O consumption was 1.17, 0.31, and 0.20 million t, respectively (Fig. C.2).

China

Consumption of N, P_2O_5, and K_2O fertilizers in China was very low□0.88, 0.12, and 0.01 t in 1962. Consumption of all fertilizers increased consistently in the 43-year period, but the rate of increase was much slower and consumption was quite smaller for K_2O than for N and P_2O_5. In 2005, N, P_2O_5, and K_2O consumption was very large at 26.9, 10.6, and 5.7 million t, respectively (Fig. C.3).

India

Compared with China, consumption of N, P_2O_5, and K_2O fertilizers in India started from much lower amounts of 0.31, 0.07, and 0.04 t in 1962. Consumption of all fertilizers, however, increased consistently over the 43 years, but the rate of increase was much slower for P_2O_5 and K_2O than for N. K fertilizer use has been much lower than N and P use over all the years. In 2005, consumption of N, P_2O_5, and K_2O was 11.7, 4.6, and 2.1 million t, respectively (Fig. C.4).

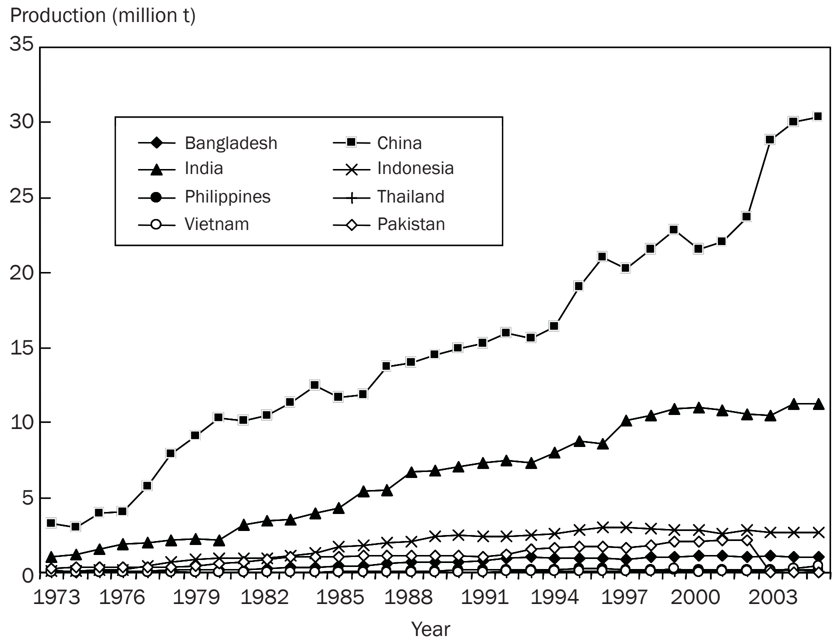

Fig. C.1. Trends in nitrogen fertilizer production in nine Asian countries (1973-2005).

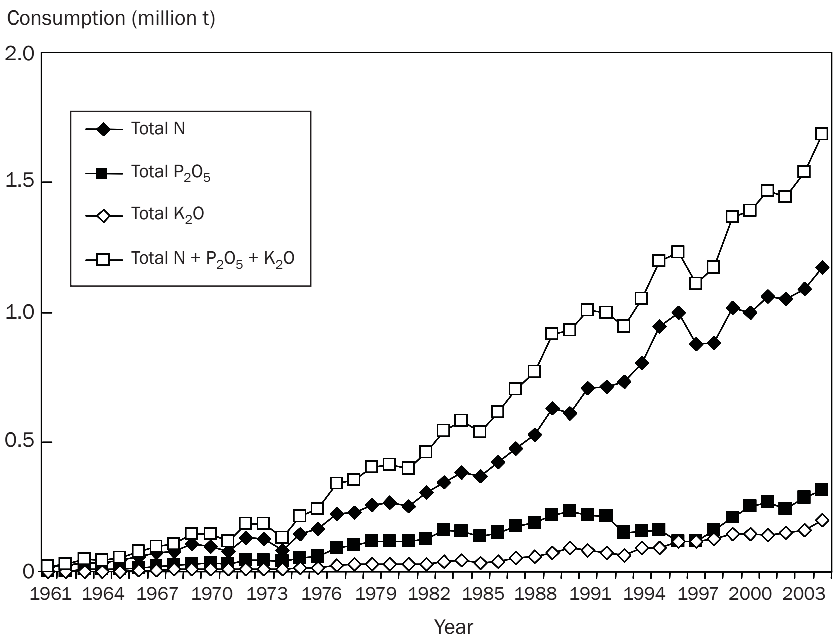

Fig. C.2. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Bangladesh (1973-2004).

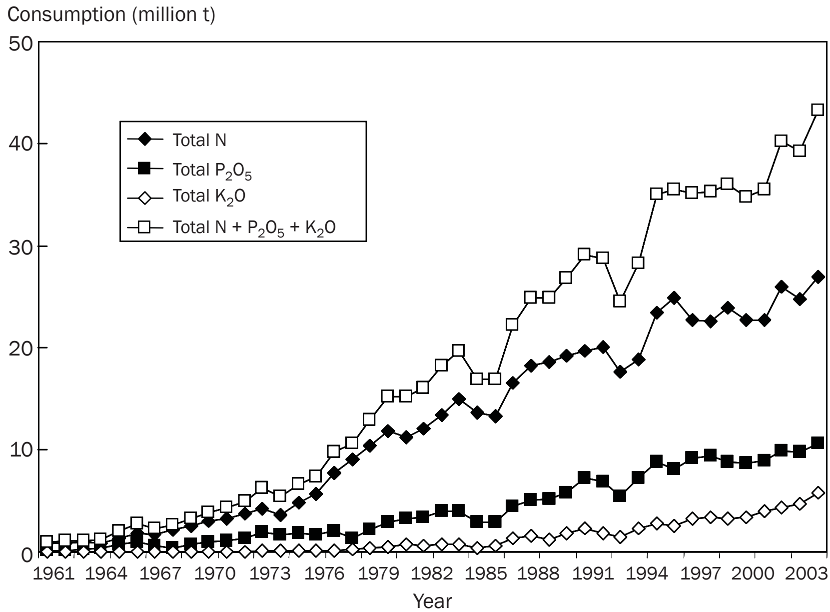

Fig. C.3. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in China (1973-2004).

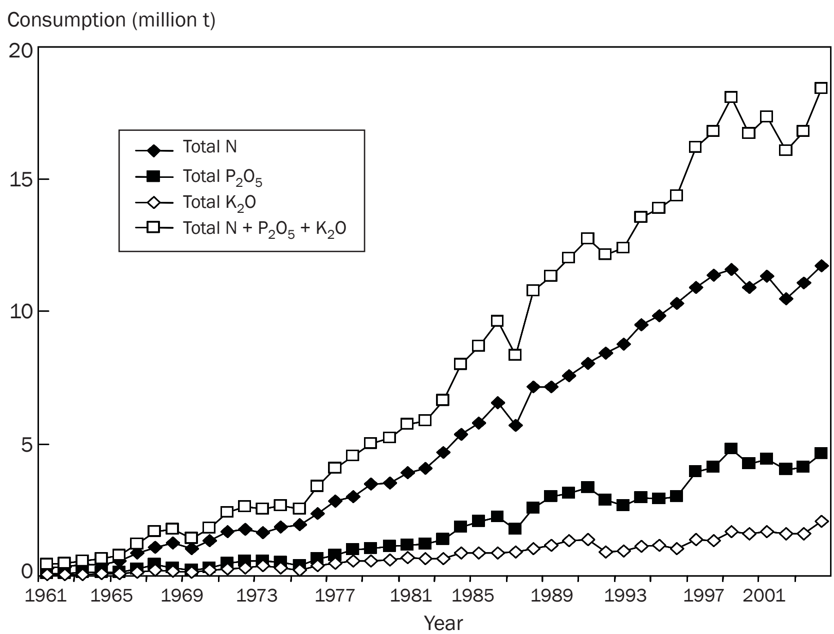

Fig. C.4. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in India (1973-2004).

Nepal

There was insignificant or almost no consumption of any fertilizer in Nepal in 1962. Consumption of all fertilizers increased gradually, but then it decreased in recent years. K use has been very low and stable over the years. In 2005, consumption of N, P_2O_5, and K_2O was still very low at 51,000, 2,100, and 3,000 t, respectively (Fig. C.5).

Pakistan

There was minimal consumption of N fertilizers and almost no consumption of P_2O_5 and K_2O fertilizers in Pakistan in 1961. Consumption of N fertilizers increased rapidly from 1965 to 1986; it then decreased dramatically in the following years. Over that period, consumption of P_2O_5 fertilizers increased slowly up to 1986 and then decreased, as in the case of N fertilizers. Consumption of K_2O fertilizers was almost nil. From the late 1980s, consumption of all fertilizers increased but at slower rates. Today, consumption of N, P_2O_5, and K_2O fertilizers is much lower in Pakistan than in other South and Southeast Asian countries (Fig. C.6).

The Philippines

Consumption of N, P_2O_5, and K_2O fertilizers in the Philippines started with very low amounts—36,000, 27,000, and 19,000 t, respectively, in 1962. Consumption of all fertilizers increased over the years. The consumption, as well as the rate of increase, however, was much slower for P_2O_5 and K_2O than for N. In 2005, consumption of N, P_2O_5, and K_2O was still quite low: 0.51, 0.14, and 0.12 million t, respectively (Fig. C.7).

Thailand

Consumption of N, P_2O_5, and K_2O fertilizers in Thailand started from very low amounts of 11,000, 5,000, and 4,000 t, respectively, in 1962. Consumption of N and K fertilizers increased over the years, but that of P increased initially and then decreased in recent years. The rate of increase was much slower for P_2O_5 and K_2O than for N. In 2005, consumption of N, P_2O_5, and K_2O was still quite low at 1.05, 0.39, and 0.37 million t, respectively (Fig. C.8).

Vietnam

Consumption of N, P_2O_5, and K_2O fertilizers in Vietnam started from very low amounts of 32,000, 61,000, and 5,000 t, respectively, in 1962. Fertilizer use was quite low until the late 1980s, but, since 1990, it has increased significantly. In 2005, though the consumption of all fertilizers increased significantly compared with pre-1990 amounts, the amounts used remained small at 1.43, 0.58, and 0.55 million t, respectively (Fig. C.9).

Indonesia

Considering Indonesia's large human population, consumption of N, P_2O_5, and K_2O fertilizers in the country started from very low amounts (85,000, 55,000, and 4,000 t) in 1962. Over the past 43 years, consumption of N and K_2O fertilizers increased consistently, albeit the latter only slightly. Consumption of P_2O_5 fertilizer increased

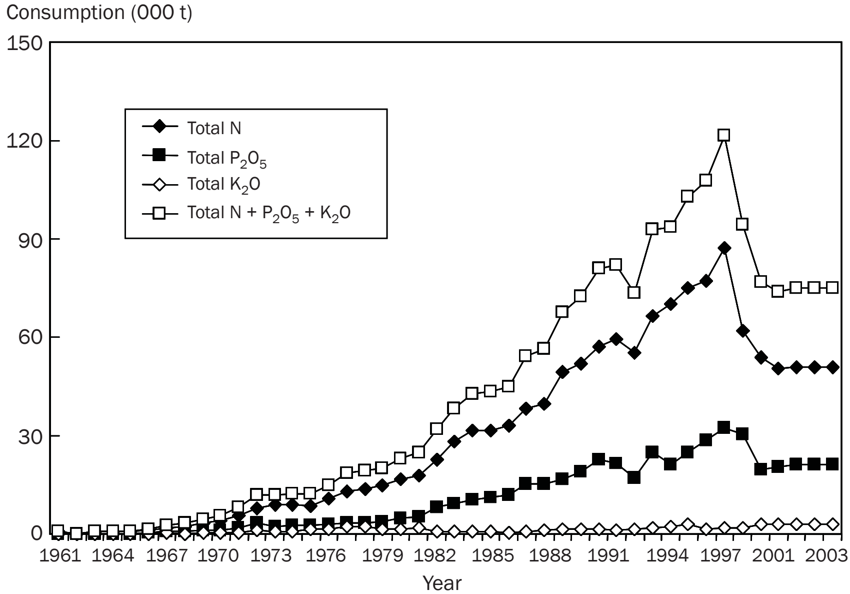

Fig. C.5. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Nepal (1961-2004).

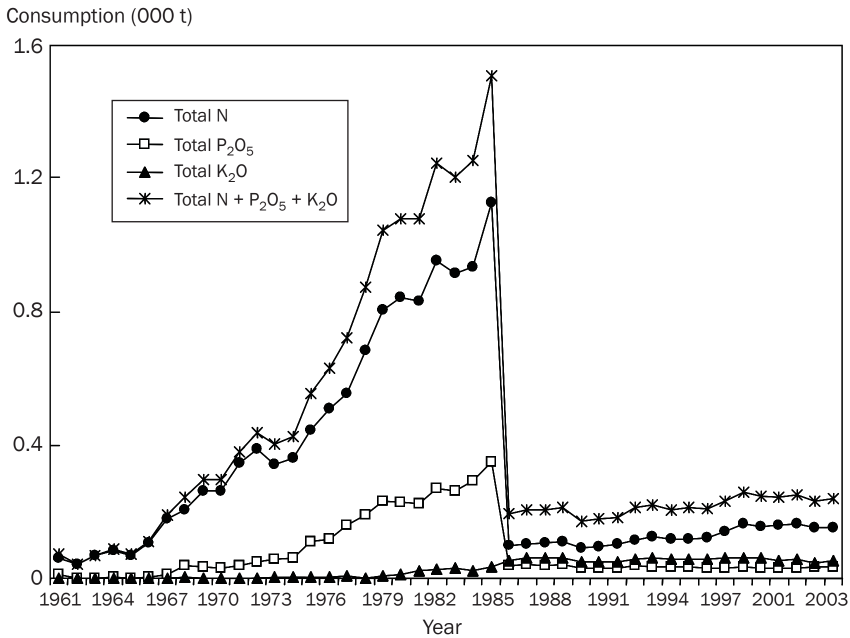

Fig. C.6. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Pakistan (1961-2004).

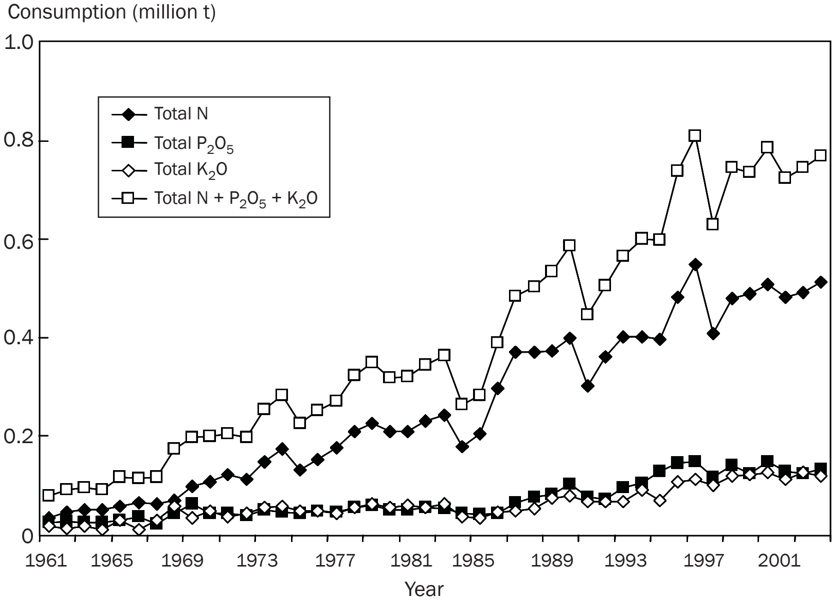

Fig. C.7. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in the Philippines (1961-2004).

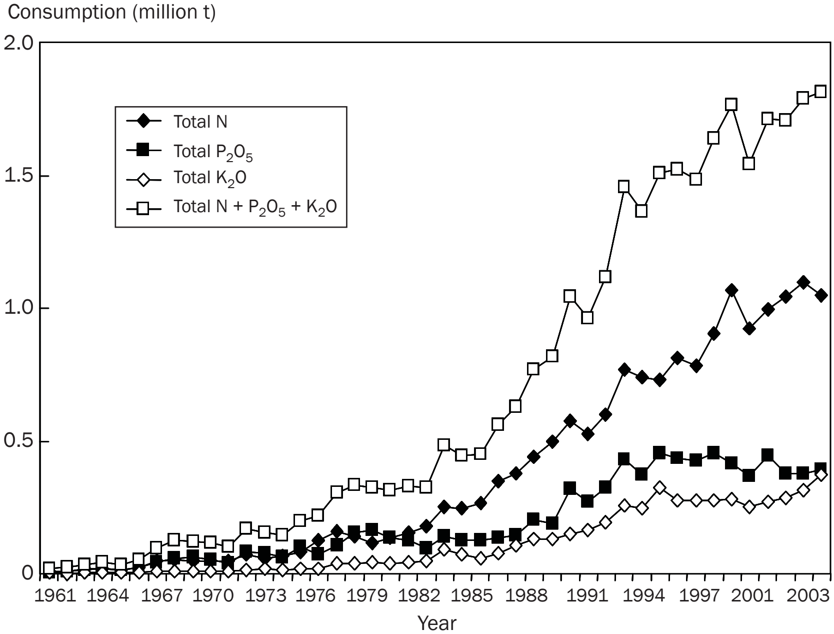

Fig. C.8. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Thailand (1961-2004).

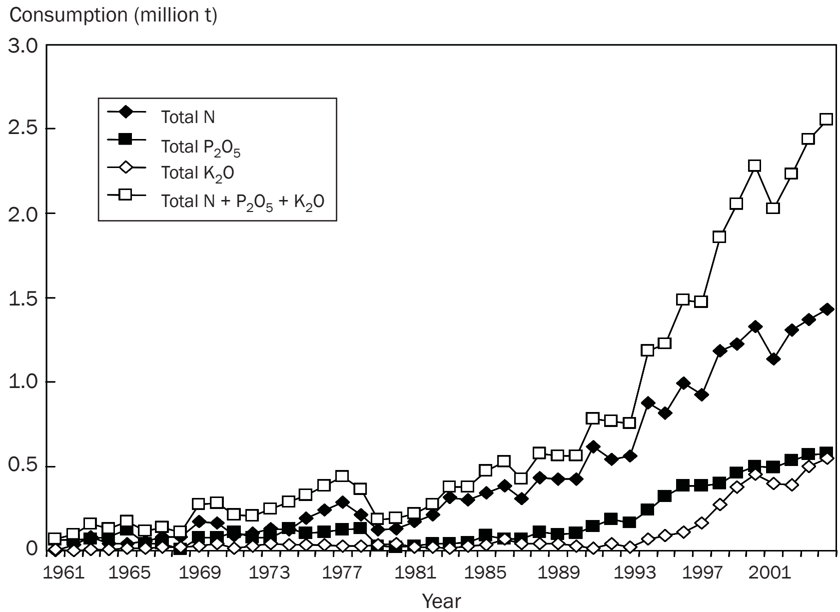

Fig. C.9. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Vietnam (1961-2004).

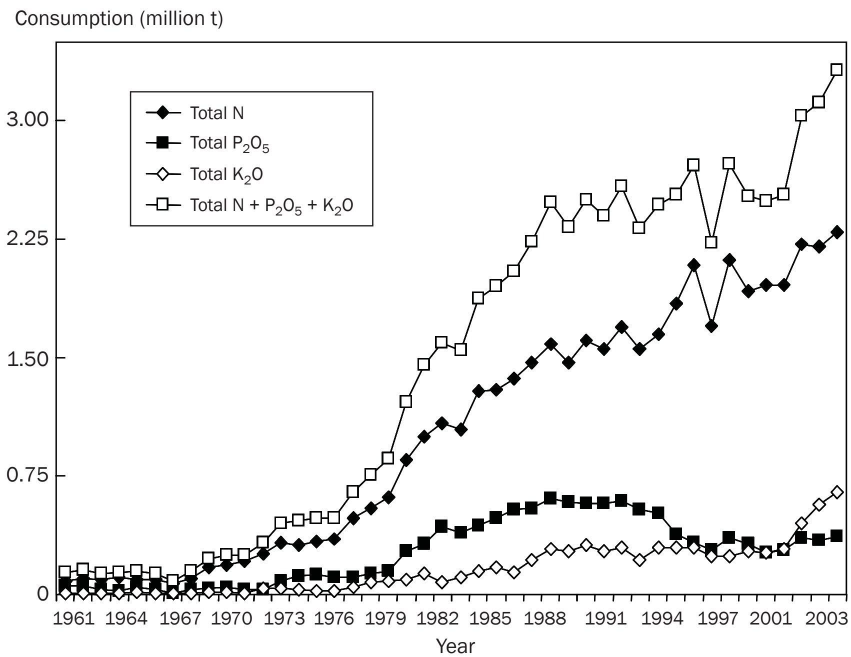

Fig. C.10. Trends in nitrogen, phosphorus, and potassium fertilizer consumption in Indonesia (1961-2004).

initially but decreased in recent years. In 2005, consumption of N, P_2O_5, and K_2O was still small at 2.3, 0.37, and 0.65 million t, respectively (Fig. C.10).

Annex D
Trends in growth of livestock and livestock products in different Asian countries

Production, consumption, and trade of livestock

Swine

In China and the Philippines, the swine population continued to increase from 1988 to 2006 (Fig. D.1). In Vietnam, swine production started from about 25 million in 2001 and increased rapidly every year after that, reaching 42 million in 2006. In Thailand, swine production remained stable from 1993 to 1999 but decreased beginning in 2000. Swine head in China increased consistently from 300 million (1988) to nearly 800 million (2006). In the Philippines, the increase was from 16 million to more than 26 million during the same period. Swine imports were minimal in all these countries, including China. Both China and the Philippines imported some swine in variable numbers until 2000; Thailand and Vietnam imported only a few and only in some years. China, however, imported a large number of swine in 1995. China also had huge exports in the late 1980s, but these declined consistently over the years. Thailand also exported swine during the late 1990s until 2000.

Pork

The swine population trend was reflected in pork production data, with production in China and the Philippines continuing to increase over the years; in Vietnam, the increase began in 2001 (Figs. D.2-D.4). Pork production increased each year from 20 million t CWE (1988) to 60 million t CWE (2006). The Philippines and Vietnam had much lower pork production than China. Domestic consumption of pork continued to increase over the years in China and the Philippines; there was a rapid rise in recent years in Vietnam. The trends in swine importation also reflected pork importation. Vietnam also exported pork in recent years. All these countries had not imported much pork over the years, although, in the late 1990s and early 2000s, China and Vietnam imported a significant amount. Recently, China has reduced its pork imports due to large production in the country. Vietnam, however, has recently been importing a lot of pork though production is going up. Thus, the export of pork in most countries is quite lower, except in China, where it has recently increased.

Cattle

Cattle head in China, India, and the Philippines increased each year from 1988 to 2006 (Figs. D.5-D7). In 1988, China had fewer cattle than India. Although the cattle number kept on increasing in both countries, China had more cattle than India in 2006. The rate of increase was thus much higher for China than for India, with 10 million cattle in 1988 to more than 60 million in 2006. The cattle population in the Philippines increased from 0.8 million in 1988 to 1.1 million in 2006. In Thailand, the cattle number started to decrease from 1993, remaining very low in 2000. China did not import any cattle, except for a few head lately. Thailand started importing cattle in 1993 at a diminishing rate every year; it also exported a few cattle in the 1990s. The Philippines imported a few head initially, with maximum imports being attained from the mid- to late 1990s. China and India had negligible cattle imports and exports annually. India imported a few cattle initially but not in recent years. Likewise, it exported a few cattle until 1997, but not thereafter. China had large exports initially, but they declined over the years; exportation has been stable since 1998.

Beef and veal

The trends in cattle population, imports, and exports were also reflected in beef and veal production. There was a continuous increase in beef and veal production from 1988 to 2007 in China but it remained low and static in India and the Philippines (Fig. D.8). Over that period, production increased at higher rates in China (from 1 million to 8 million t carcass weight equivalent [CWE]) and at slower rates in India (1 million to 2 million t CWE). As for production, domestic consumption of beef and veal also increased rapidly in China; it was low and static in India and the Philippines (Fig. D.10). Beef and veal imports were minimal in China, but the Philippines imported a significant amount with increasing quantity each year (Fig. D.9). China did not export much beef and veal; exports even declined in later years. India, however, exported beef and veal at increasing rates in recent years (Fig. D.11).

Poultry

Poultry meat production in China, Indonesia, and the Philippines increased rapidly over the years but at slower rates in India and Thailand (Fig. D.12). Poultry meat production increased at a significantly higher rate in China, from around 2 million t (1988) to around 10.5 million t (2007). In Indonesia and the Philippines too, poultry production has increased recently. China imported poultry meat in significant amounts, the Philippines imported a moderate amount, but Indonesia and Thailand imported little and only occasionally. China imported poultry meat at increasing rates until 2002; there was then a decline in recent years due to large domestic production and consumption. The Philippines, however, has been exporting at rapid rates recently. India and Indonesia have been exporting small amounts of poultry meat annually.

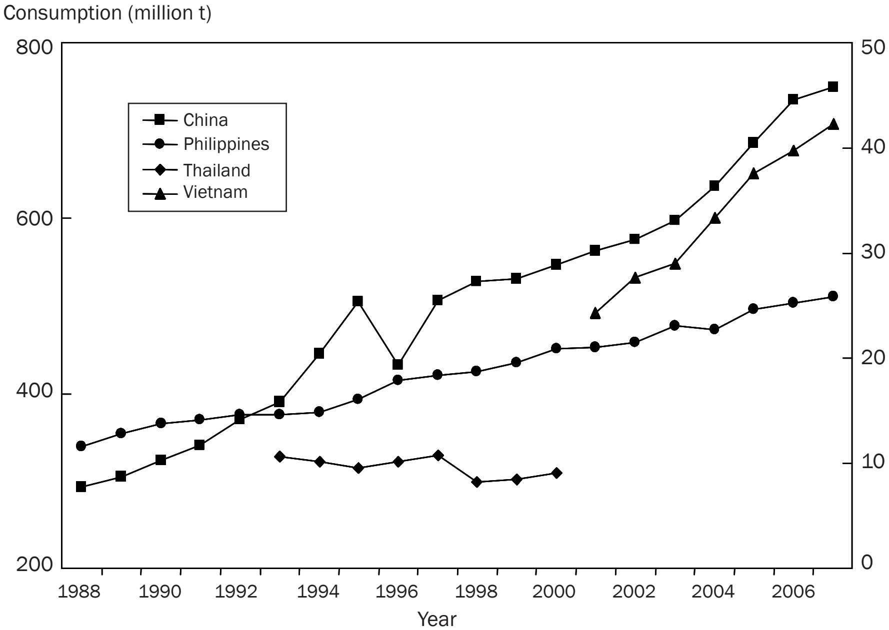

Fig. D.1. Trends in swine population in four Asian countries (1988-2007).

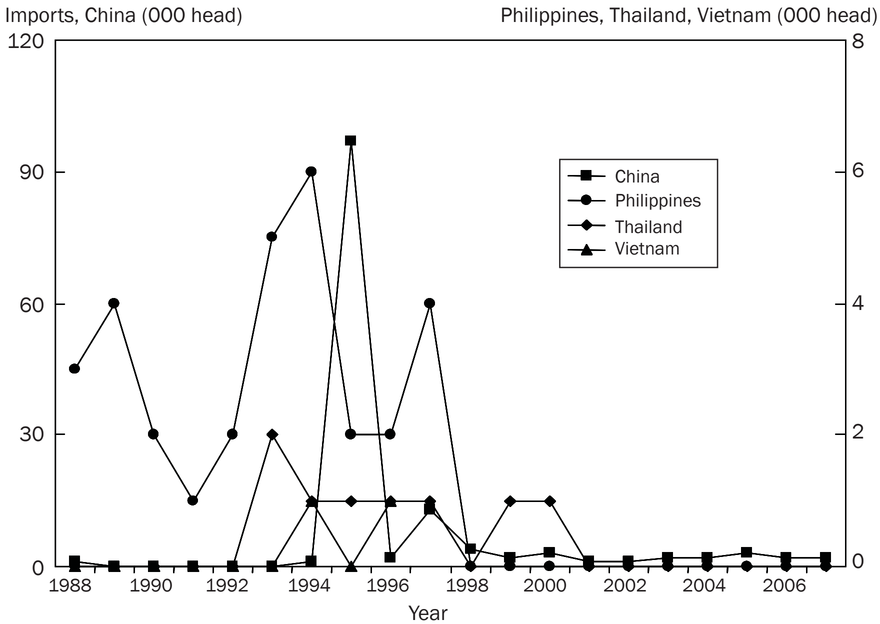

Fig. D.2. Trends in swine importation in four Asian countries (1988-2007).

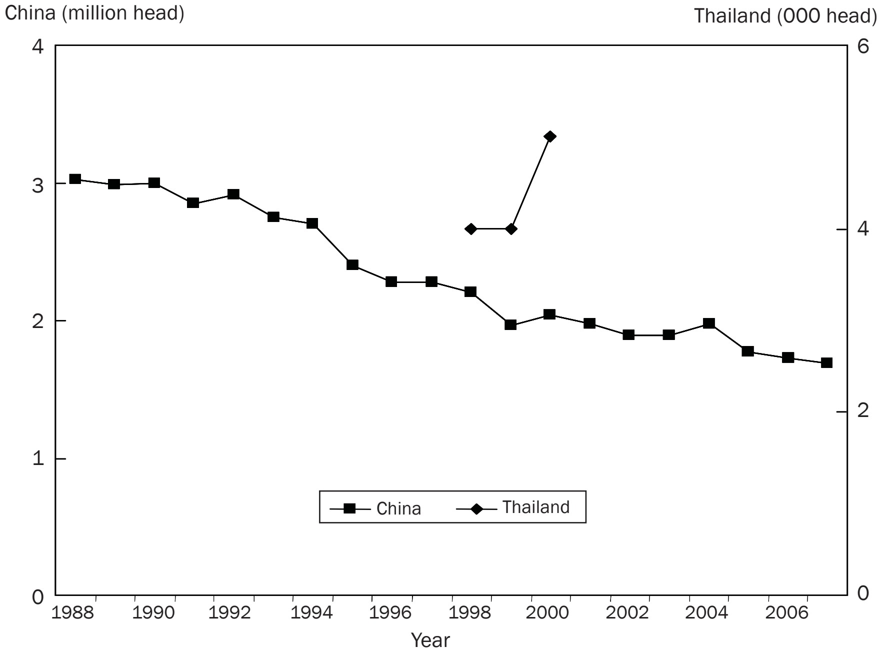

Fig. D.3. Trends in swine exportation in two Asian countries (1988-2007).

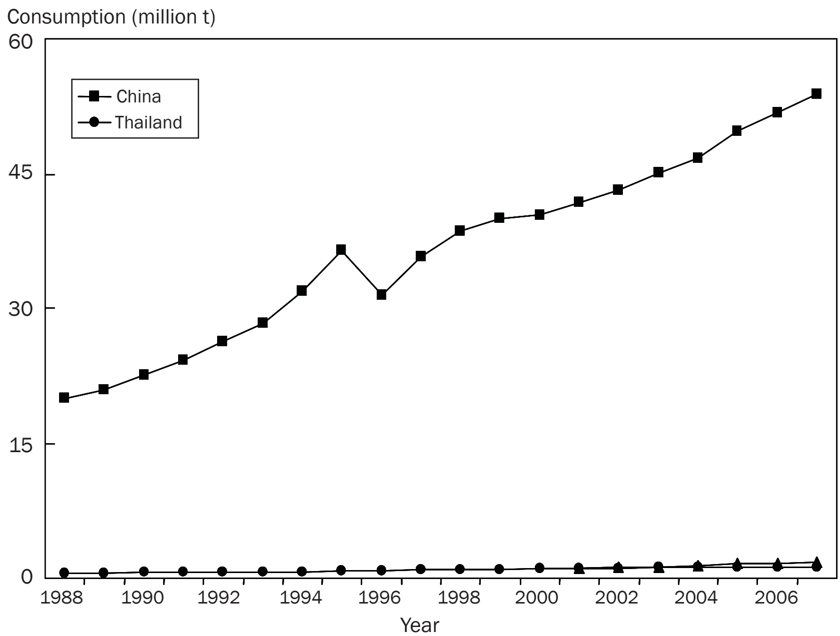

Fig. D.4. Trends in domestic consumption of pork in two Asian countries (1988-2007).

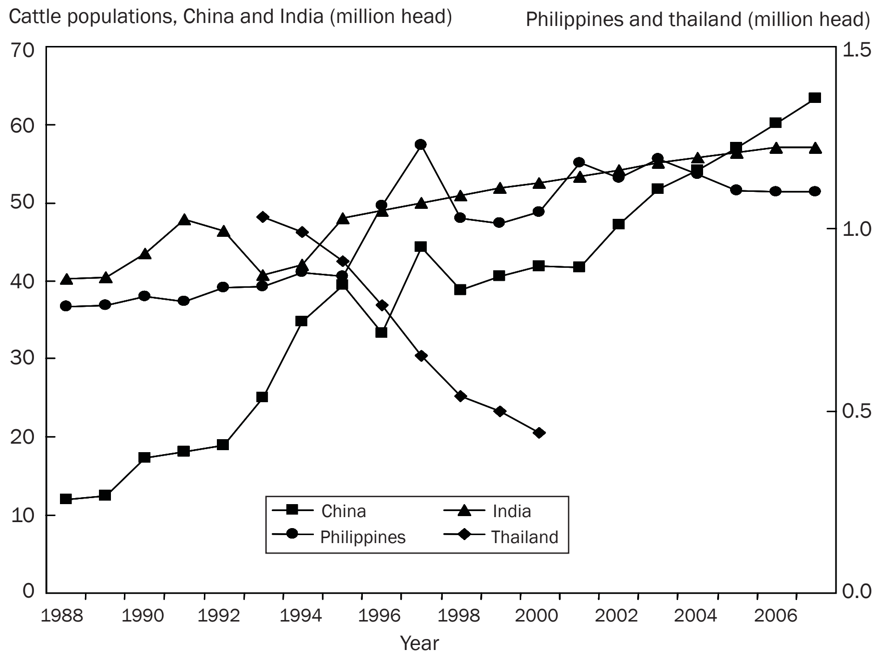

Fig. D.5. Trends in cattle population in four Asian countries (1988-2007).

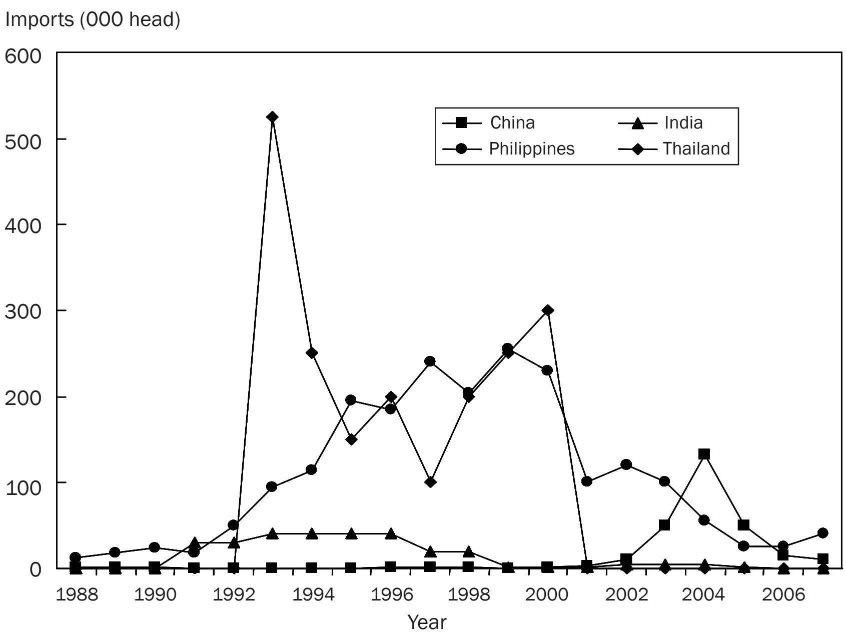

Fig. D.6. Trends in cattle importation in four Asian countries (1988-2007).

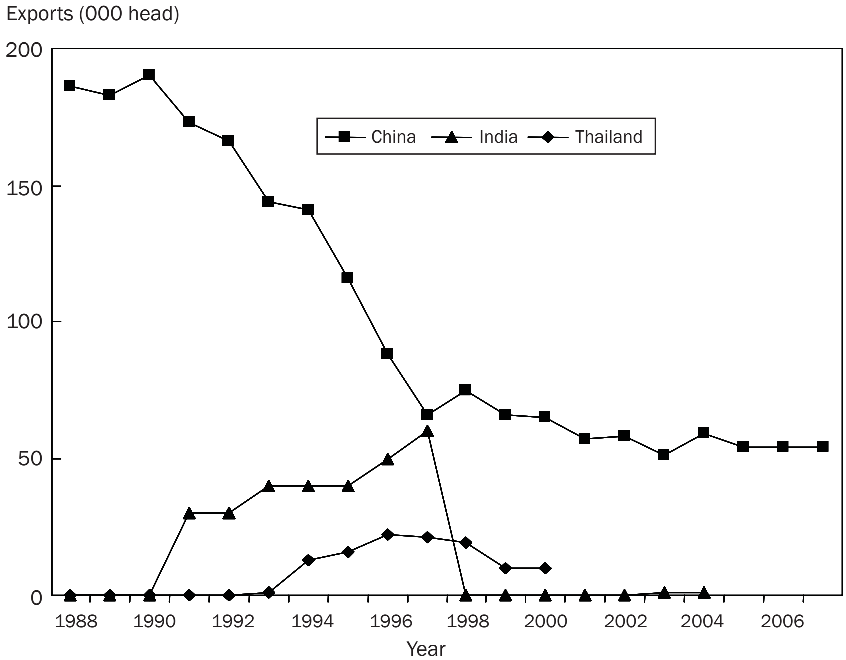

Fig. D.7. Trends in cattle exportation in three Asian countries (1988-2007).

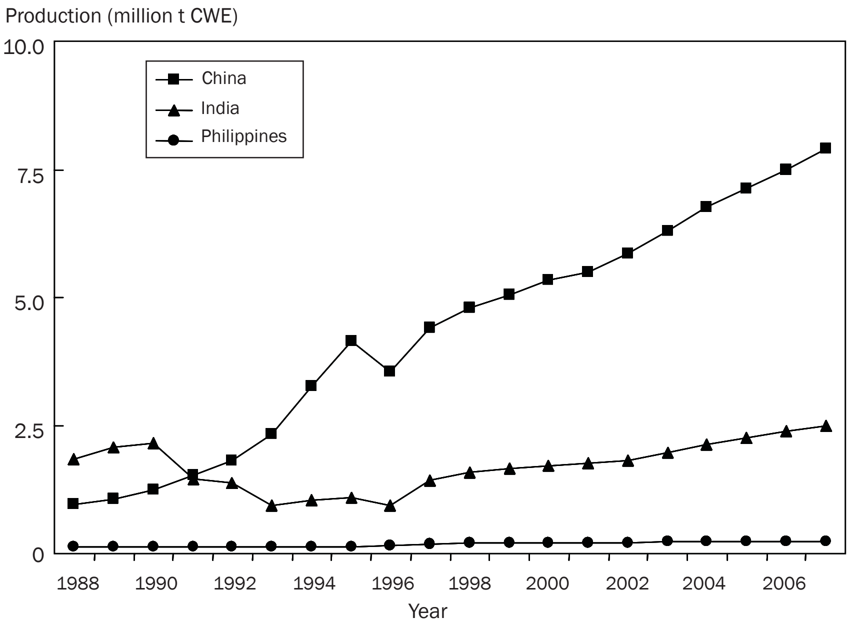

Fig. D.8. Trends in beef and veal production in three Asian countries (1988-2007).

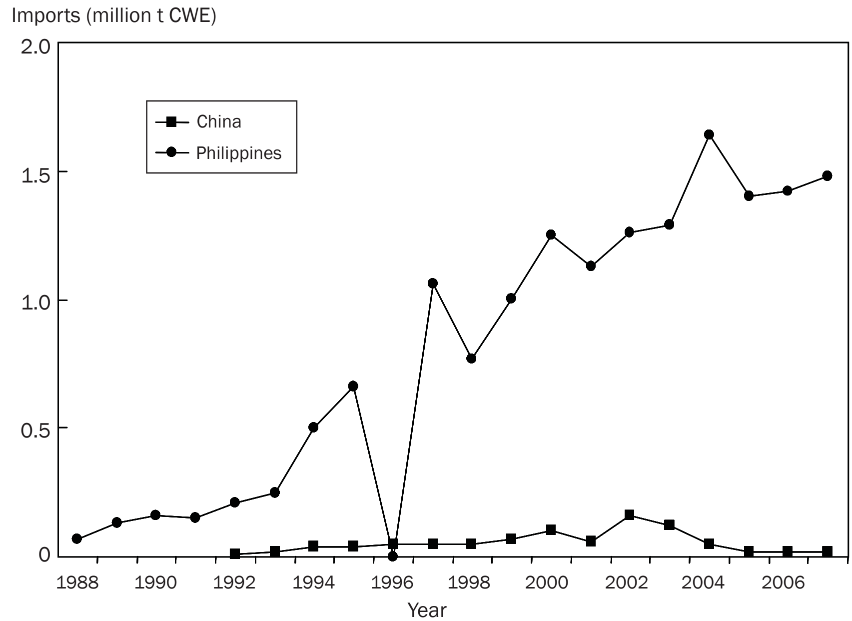

Fig. D.9. Trends in beef and veal importation in two Asian countries (1988-2007).

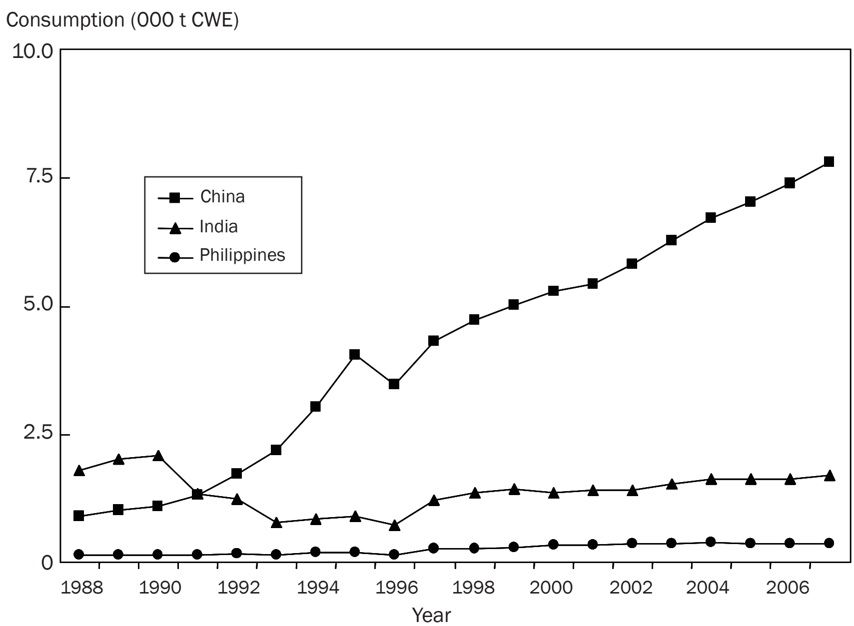

Fig. D.10. Trends in domestic consumption of beef and veal in three Asian countries (1988-2007).

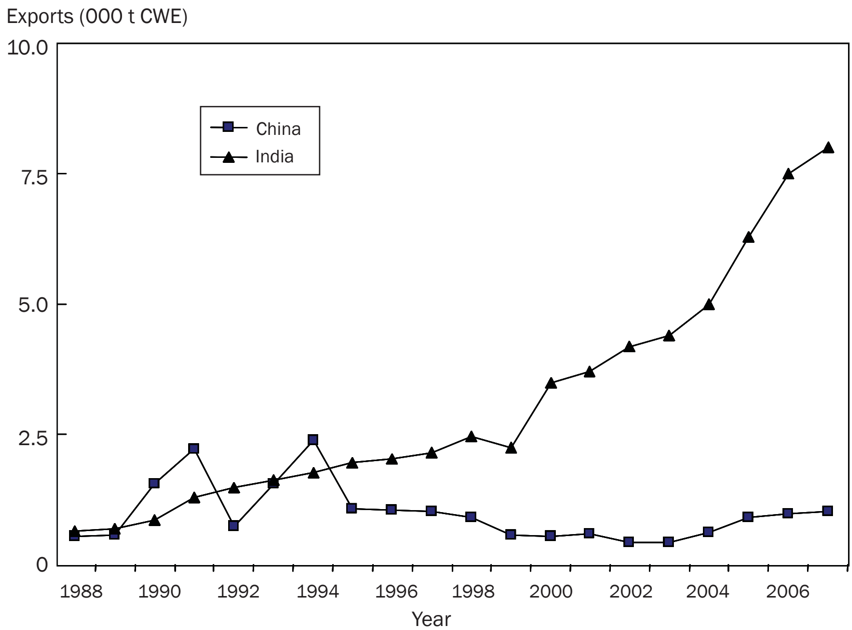

Fig. D.11. Trends in beef and veal exportation in two Asian countries (1988-2007).

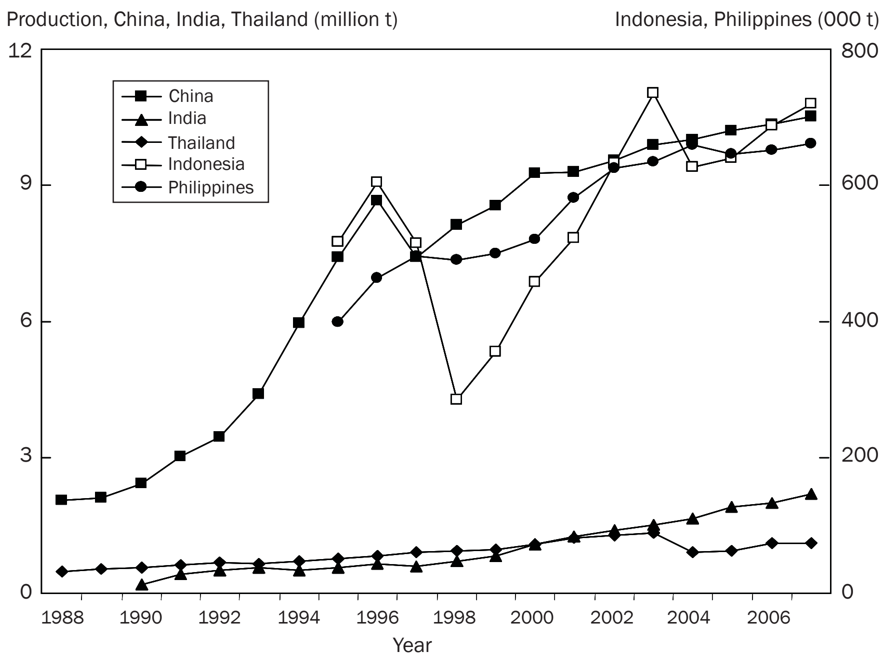

Fig. D.12. Trends in poultry meat production in five Asian countries (1988-2007).

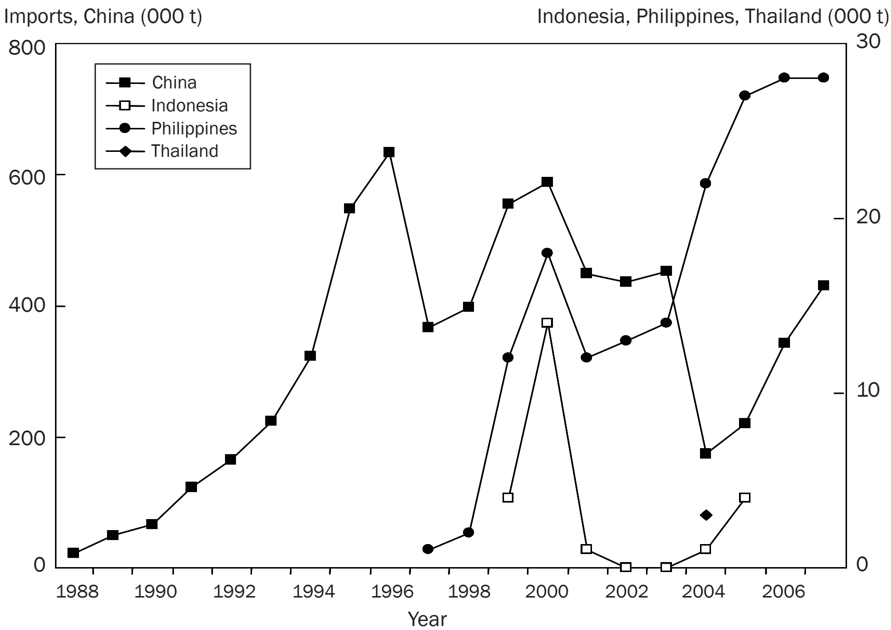

Fig. D.13. Trends in poultry meat importation in four Asian countries (1988-2007).

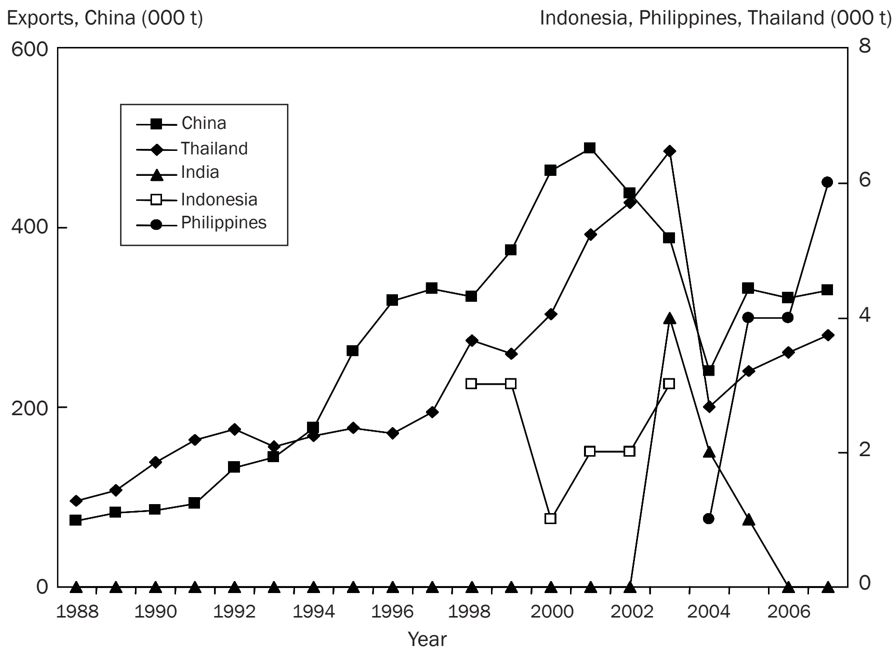

Fig. D.14. Trends in poultry meat exportation in five Asian countries (1988-2007).

Annex E
Demand projections for rice, wheat, and maize

Projections for rice, wheat, and maize for some periods in the future are reported on the basis of projections done by IFPRI and FAPRI. Figure E.1 provides IFPRI projections for rice, maize, poultry, pork, and milk for selected Asian countries for 2015 and 2030 (with 2000 as the base).

IFPRI projections

Based on the IMPACT-WATER model for the Reference Scenario of the International Assessment of Agricultural Science and Technology for Development (IAASTD), IFPRI has made projections on demand for rice, maize, beef, poultry, pork, lamb, and milk and eggs for South and Southeast Asian countries. In their projections, South Asian countries include Afghanistan, Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan, and Sri Lanka. Beef includes cattle and buffalo meat, while poultry meat includes only chicken. The projections show that, for South Asia, rice demand will increase from 130 million t in 2000 to 171 million t in 2030. This high demand from South Asia is reflected in India's high demand alone: from 80 million t in 2000 to 111 million t in 2030. For China, the increase in demand will be less: from 125 million t to 134 million t over the same period. For Indonesia, the demand will be greater: from 36 million to 47 million t (Fig. E.1). In 2030, the demand for maize will be almost double that in 2000 for South Asia (17.3–33.0 million t), China (115.6–222.6 million t), and India (12.9–24.5 million t). In Indonesia, however, there will be 50% more demand in 2030 (16.7 million t) compared with that in 2000 (11.5 million t).

The demand for poultry meat will increase by more than 300% in South Asia (from 1.8 million to 7.0 million t), 150% in China (from 13.5 million to 34.1 million t), and by 200% in Indonesia (from 0.8 million to 2.5 million t). Milk demand will also increase by 80–100% in all these countries in 2030 compared with 2000 demand. Pork demand in China will also increase by about 60% (from 42.5 million to 67.7 million t) over that period. Such a high demand for livestock products (meat and milk) will result in a high demand for feed grains, especially maize (Fig. E.1).

Other projections for 2020 based on 1997 projections by IFPRI (Rosegrant et al 2001) show that animal feed use, driven by rising meat demand, will be responsible for most of the increasing demand for maize in developing countries in general and in Asia in particular. Whereas feed accounted for 21% and food for 67% of total worldwide cereal demand in developing countries in 1997, feed will account for 35% and food for 53% of the cereal demand increase between 1997 and 2020. Cereal demand for feed is projected to grow by 2.5% per year in developing countries, accounting for total feed demand increases of 84% in the developing world. Maize demand for

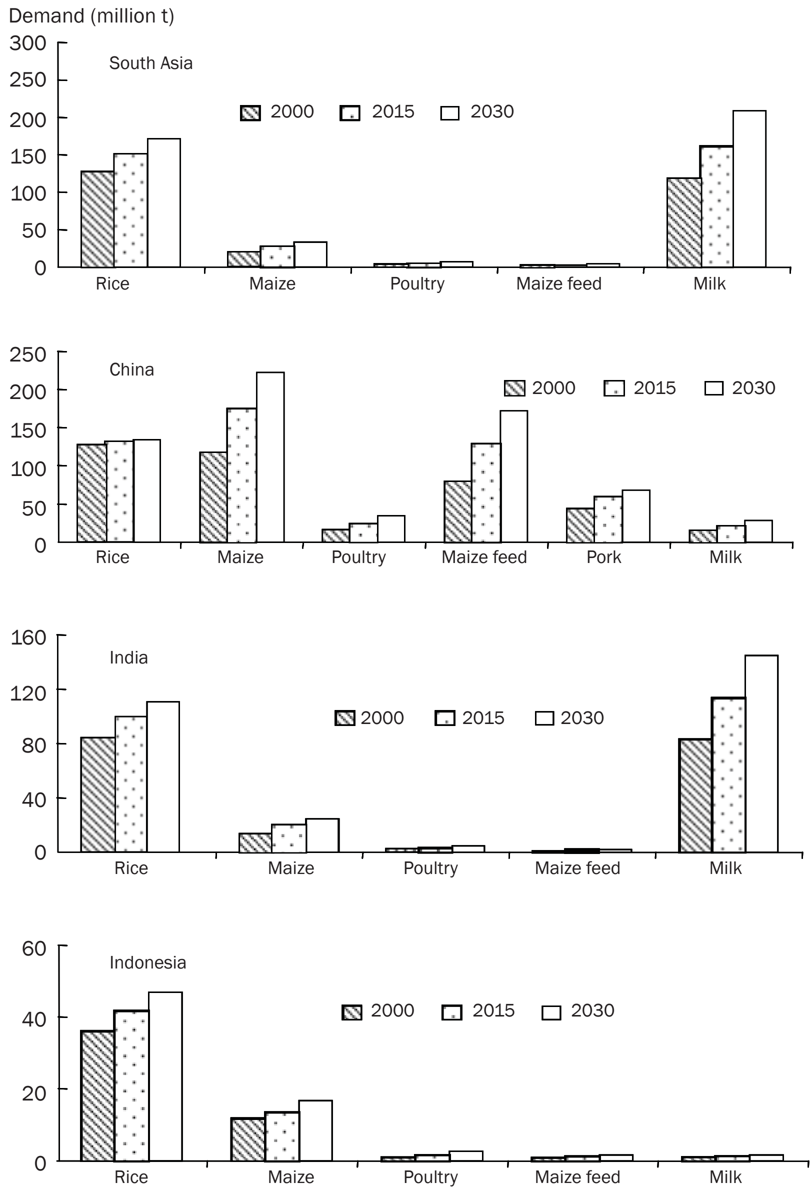

Fig. E.1. IFPRI demand projections for cereals, poultry, and milk for 2015 and 2030 for South Asia and Indonesia (S. Msangi, IFPRI, pers. commun.).

feed in the developing world will lead all other cereal crops, with a rate of increase of 2.9% annually and an even faster rate of increase (3.1% per year) in Asia.

Rising meat, egg, and milk demand will drive increased cereal feed demand. Global meat demand (208 million t in 1997) is projected to grow by 57% (118 million t) by 2020. Asia, led by China, will account for the major share of increase in meat demand in developing countries. China alone will account for 43% of additional meat demand worldwide between 1997 and 2020. India, due to traditionally low meat consumption, will account for only 4% of additional meat demand. The rest of Asia will account for 13% of the global increase (Rosegrant et al 2001). Recent projections (Msangi 2007, unpublished) show that pork demand in China will increase by about 60% (from 42.5 million to 67.7 million t), and that the demand for poultry meat will increase by more than 300% in South Asia (from 1.8 million to 7.0 million t), 150% in China (from 13.5 million to 34.1 million t), and 200% in Indonesia (from 0.8 million to 2.5 million t) from 2000 to 2030.

Egg demand in 2020 will grow faster in South Asia (by 113%) from admittedly low levels in 1997. China will continue to dominate egg consumption, with an increase from 16 to 19 kg per capita consumption. South Asia will continue to dominate milk consumption and production in the developing world, with demand increasing from 43% to 47% of the developing-world total and production increasing from 46% to 50%. Per capita demand for eggs in South Asia will grow at 2% annually. Recent projections show that milk demand will also increase by 80–100% in all South Asian countries and in China in 2030 as compared with that in 2000 (Msangi 2007, unpublished).

There is already, and will be, a shift in meat consumption pattern from pork to poultry and beef in China, and to poultry in the rest of Asia. Because of rising income, consumers prefer poultry to other kinds of meat in China. Such a high demand for livestock products (meat and milk) will mean a high demand for feed grains, especially maize, throughout Asia.

FAPRI projections

Table E.1 provides FAPRI projections for area, yield, production, net trade, and per capita consumption of wheat, maize, and rice for eight Asian countries for 2016-17 based on baseline data for 2006-07. In 2016-17, harvest area under wheat will decrease in China and Pakistan but will increase in India. There will be a slight increase in average yield per hectare in all three countries, but overall production will increase only in India and Pakistan and not in China. In 2006-07, China's net wheat exports were 1.8 million t because of expanded area and higher yield but they will decrease to 0.98 million t in 2016-17. Both India and Pakistan, however, will be net importers of wheat in 2016-17 to meet their domestic requirements. Per capita consumption of wheat will decrease in China, will remain the same in India, and will increase slightly in Pakistan.

Harvest area, yield, production, and per capita consumption of maize will increase in all countries in 2016-17 compared with 2006-07, except in the Philippines, where harvest area will decrease slightly. Consistent with other studies, FAPRI projec-

Table E.1. FAPRI projections for rice, wheat, and maize for different Asian countries for 2016-17.

Country	Wheat		Maize		Rice	
	2006-07	2016-17	2006-07	2016-17	2006-07	2016-17
China						
Area (000 ha)	23,400	22,484	27,000	27,684	29,200	26,360
Yield (t ha^{-1})	4.42	4.44	5.3	5.91	4.38	4.68
Production (000 t)	103,500	99,803	143,000	163,608	128,000	123,290
Net trade (000 t)	1,800	98	3,900	–1,922	251	–153
Per capita consumption (kg)	74	67	28.9	32.6	89	82.1
India						
Area (000 ha)	25,000	26,724	7,700	8,169	44,000	45,089
Yield (t ha^{-1})	2.72	3.11	1.88	2.11	2.07	2.27
Production (000 t)	68,000	82,998	14,500	17,264	91,000	102,226
Net trade (000 t)	–5,700	–2,685	200	234	3,846	6,226
Per capita consumption (kg)	65	66	8.1	8.12	79.1	74.2
Pakistan						
Area (000 ha)	8,300	8,227	900	909	2,650	2,660
Yield (t ha^{-1})	2.61	2.98	1.44	1.55	2.11	2.21
Production (000 t)	21,700	24,552	1,300	1,413	5,600	5,887
Net trade (000 t)	300	–2,489	0	0	2,935	2,835
Per capita consumption (kg)	130	133	5.4	5.6	15.4	15.2
Bangladesh						
Area (000 ha)					11,200	11,552
Yield (t ha^{-1})					2.6	2.99
Production (000 t)					29,100	34,492
Net trade (000 t)					–697	–479
Per capita consumption (kg)					203.3	196.3
Indonesia						
Area (000 ha)			3,250	3,330	11,500	11,768
Yield (t ha^{-1})			2.03	2.17	2.93	3.09
Production (000 t)			6,600	7,225	33,700	36,371
Net trade (000 t)			–1,250	–2,724	–1,758	–1,701
Per capita consumption (kg)			16.4	16.8	153.2	147.5

Philippines				
Area (000 ha)	2,500	2,486	4,140	4,236
Yield (t ha^{-1})	2.32	2.54	2.42	2.49
Production (000 t)	5,800	6,318	10,000	10,566
Net trade (000 t)	–50	–662	–1,319	–1,841
Per capita consumption (kg)	17.9	18.3	123.9	118.3
Thailand				
Area (000 ha)	1,130	1,161	10,250	10,229
Yield (t ha^{-1})	3.76	4.32	1.78	2
Production (000 t)	4,250	5,011	18,250	20,448
Net trade (000 t)	50	25	8,633	10,697
Per capita consumption (kg)	1.6	1.6	147.8	142.6
Vietnam				
Area (000 ha)	1,150	1,186	7,360	7,355
Yield (t ha^{-1})	3.8	3.97	3.06	3.39
Production (000 t)	4,370	4,712	22,536	24,961
Net trade (000 t)	–190	–167	4,877	4,916
Per capita consumption (kg)	11.9	13.2	217.4	215

tions show large demand for maize in all the Asian countries because of growth in the livestock industry and demand for feed. China exported about 3.9 million t of maize in 2006-07 but will import about 1.9 million t in 2016-17. India and Thailand will export very small quantities of maize in 2016-17, but all other countries will import maize to meet their livestock feed requirements.

Rice area in 2016-17 will decrease significantly in China, decrease slightly in Thailand and Vietnam, and will either remain unchanged or increase slightly in other countries. Average yield and total production of rice will increase in all countries, except in China, where production will decrease. A major proportion of the projected net growth in total rice production in 2016-17 will come from India, although Indonesia, Thailand, and Vietnam will also contribute to that. In 2006-07, Bangladesh, the Philippines, and Indonesia were net importers of rice, while all others were net exporters. In 2016-17, in addition to the three countries, China will become a net importer. India, Thailand, and Vietnam will increase rice trade, whereas Pakistan will try to maintain it. Per capita consumption of rice will decrease in all countries, except in Pakistan and Vietnam.

Projections for cattle and swine population and production, trade, and per capita consumption of beef, pork, and poultry for 2016 (based on 2006 baseline data) are presented in Table E.2. Cattle and swine population, and beef, pork, and poultry production, will all increase in 2016 compared with 2006 in the five countries for which projections are available. Increases are, however, more striking in China. Beef and poultry meat production will increase in all countries. Pork meat will also increase in all countries, except for India, where no data are available for swine population and production, consumption, and trade of pork. China was exporting beef and pork and importing a small amount of poultry meat in 2006. However, because of changes in dietary patterns and preferences toward meat, it will continue to import beef, pork, and poultry in large amounts in 2016. Because of a large proportion of vegetarians in India, the country will have surplus beef and will continue to export it. Likewise, because of overproduction, Thailand will continue to export poultry in 2016. Other countries, however, will continue to import beef, pork, and poultry at that time. Except

Table E.2. FAPRI projections for livestock and meat for 2016-17.

Country	Cattle/ beef	Swine/ pork	Poultry			
	2006	2016	2006	2016	2006	2016
China						
Population (million)	142	157	503	548		
Production (000 t, meat)	7,500	10,576	53,000	63,566	10,350	13,476
Net trade (000 t, meat)	87	–225	464	–117	–20	–555
Per capita consumption (kg)	5.6	7.7	40	45.4	7.9	10
India						
Population (million)	282	296				
Production (000 t)	2,375	2,885			2,000	2,567
Net trade (000 t, meat)	750	829			0	0
Per capita consumption (kg)	1.5	1.6			1.8	2
Indonesia						
Population (million)	11.3	16.6	6.6	7.7		
Production (000 t)	481	642	589	679	688	887
Net trade (000 t, meat)	–16	–27	0	0	0	–46
Per capita consumption (kg)	2.1	2.5	2.6	2.6	3	3.6
Philippines						
Population (million)	5.6	6	13	16.6		
Production (000 t)	224	229	1,215	1,440	651	801
Net trade (000 t, meat)	–142	–253	–25	–219	–24	–116
Per capita consumption (kg)	4.1	4.6	13.9	15.8	7.5	8.7
Thailand						
Population (million)	4.94	5.84	5.37	6.46		
Production (000 t)	115	136	688	828	1,050	1,470
Net trade (000 t, meat)	–1	–10	2	0	280	497
Per capita consumption (kg)	1.8	2.1	10.6	12.1	12.1	14.2

for India, per capita consumption of all kinds of meat will increase in 2016 compared with 2006. As a result, all these countries will have to import some meat, resulting in negative trade.

Annex F
International and producer prices of commodities

Between 1970 and 2000, real world wheat prices declined by 47%, rice prices by 59%, and maize prices by 61% (Rosegrant et al 2002). International prices of rice, wheat, and maize were highest around the mid-1970s and around early to mid-1990s; they then started to decline from the mid-1990s, becoming lowest around 2000 (Fig. F.1). The prices started to rise again in 2000 and reached their peak in 2007-08. Between 2001 and 2008, the international prices of rice, wheat, and maize rose by 143%, 209%, and 139%, respectively. The prices of all cereals rose drastically in the first quarter of 2008. The international prices of rice decreased from around \$360 t^{-1} (1994) to around \$173 t^{-1} (2001); they then again increased drastically to \$950 t^{-1} (April 2008). Wheat and maize prices have fluctuated over the years and have always remained much lower (\$89–165 t^{-1} for maize and \$111–207 t^{-1} for wheat) than the rice price (\$173–360 t^{-1}). Wheat prices are always slightly higher than maize prices. The nitrogen price decreased from \$460 t^{-1} in 1995 to \$169 t^{-1} in 1999 but increased thereafter to around \$750 t^{-1} in 2008.

Producer (or farm-gate) prices followed similar trends but were much lower than international prices. Producer prices of rice in all the countries were highest during 1995 and 1996 but have decreased since then. The differences in producer prices among countries were much greater in the earlier years than in the later years. The producer prices of rice have always been highest in the Philippines, followed by Indonesia and China. They were lowest in Nepal (Fig. F.2). In the Philippines, the producer price ranged from \$310 in 1996 to \$160 in 2001, whereas, in Nepal, the price ranged from \$105 to \$130 t^{-1} between 1994 and 2005. Producer prices of maize in all countries as well as differences in prices among these countries were also much greater in earlier years than in recent years. Among all countries, producer prices of maize were highest in the Philippines (\$188–244 t^{-1}) until 1997, but prices have remained highest in Bangladesh since 1998 (\$150–175 t^{-1}). Maize prices have been lowest for China and India (between \$100 and \$150 t^{-1}). In Indonesia, Nepal, and Thailand, maize prices have been quite variable (Fig. F.3). As for wheat, producer prices of wheat were highest during the mid-1990s and lowest during the early 2000s; they again increased in recent years. The prices fluctuated over the years in all countries but were relatively stable in India (Fig. F.4).

Table F.1 shows mean farm-gate prices for maize, rice, and wheat for eight Asian countries. Long-term farm-gate price means for these cereals were highest in Pakistan, the Philippines, and Bangladesh, respectively.

Table F.1. Mean (1994-2005) farm-gate prices (US$ t^{-1}) of three cereals for eight Asian countries.

Country	Maize	Rice	Wheat
Bangladesh	162.7	132.8	163.2
China	118.4	155.8	144.4
India	116.7	133.8	150.5
Indonesia	144.1	160.8	–
Nepal	128.2	122.6	128.3
Philippines	163.8	210.3	–
Thailand	115.9	147.5	–
Pakistan	173.2	175.5	160.2

Source: FAO (2007).

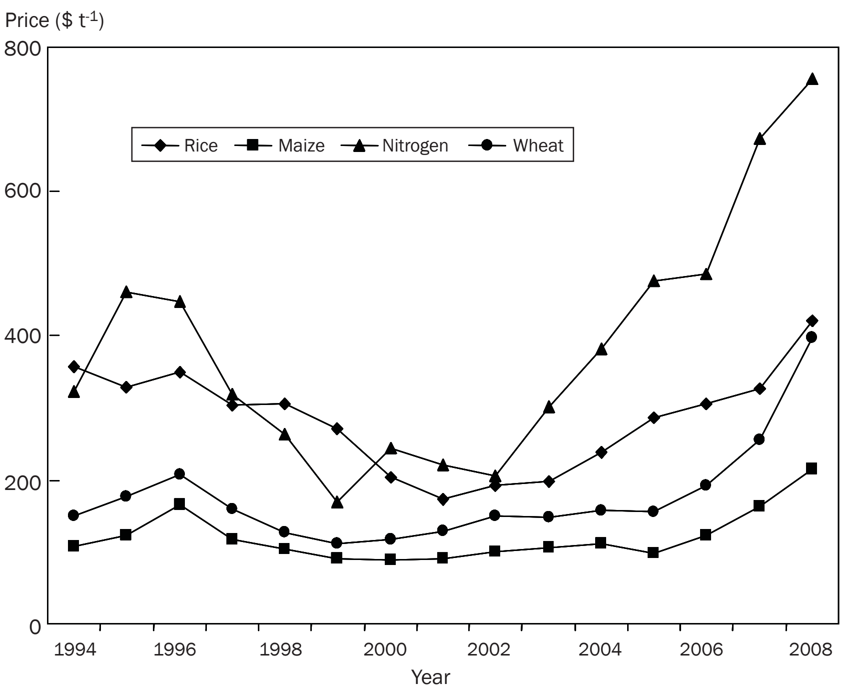

Fig. F.1. Trends in international prices of rice, maize, wheat, and nitrogen (1994-2007).

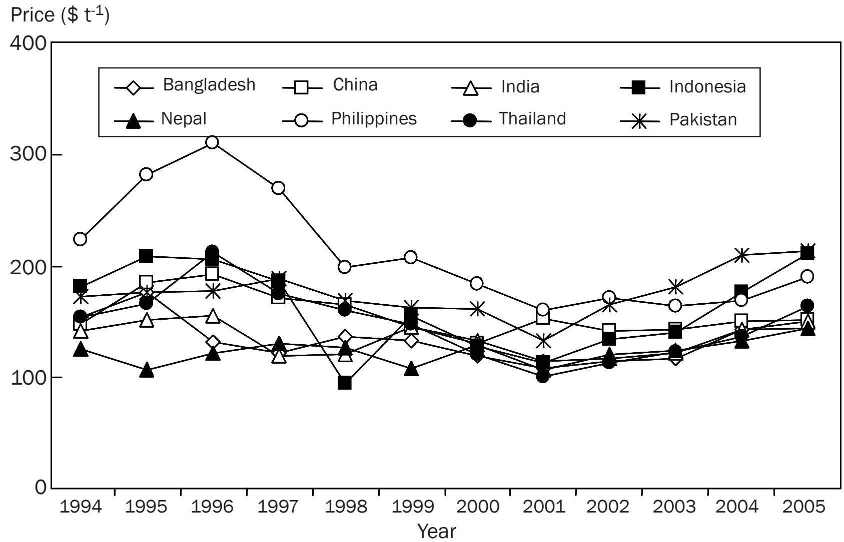

Fig. F.2. Trends in producer prices of rice in eight Asian countries, 1994-2005.

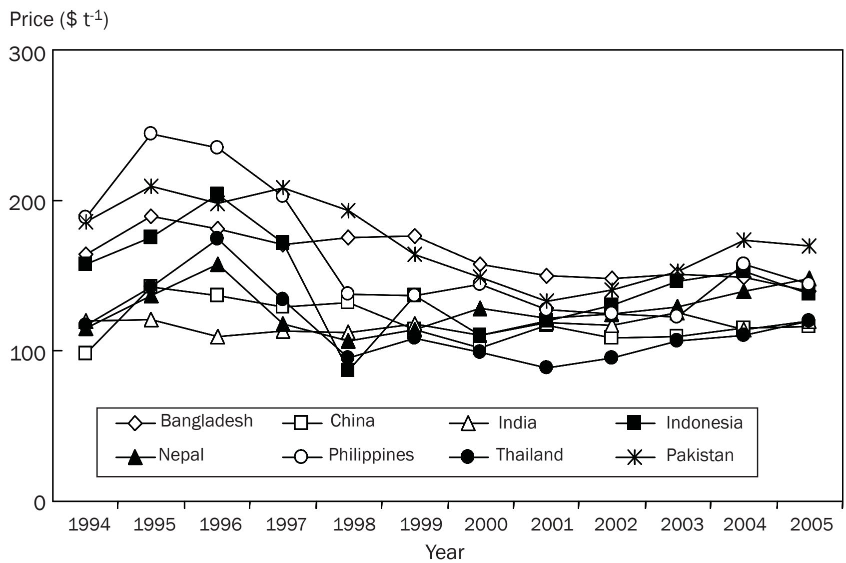

Fig. F.3. Trends in producer prices of maize in eight Asian countries (1994-2005).

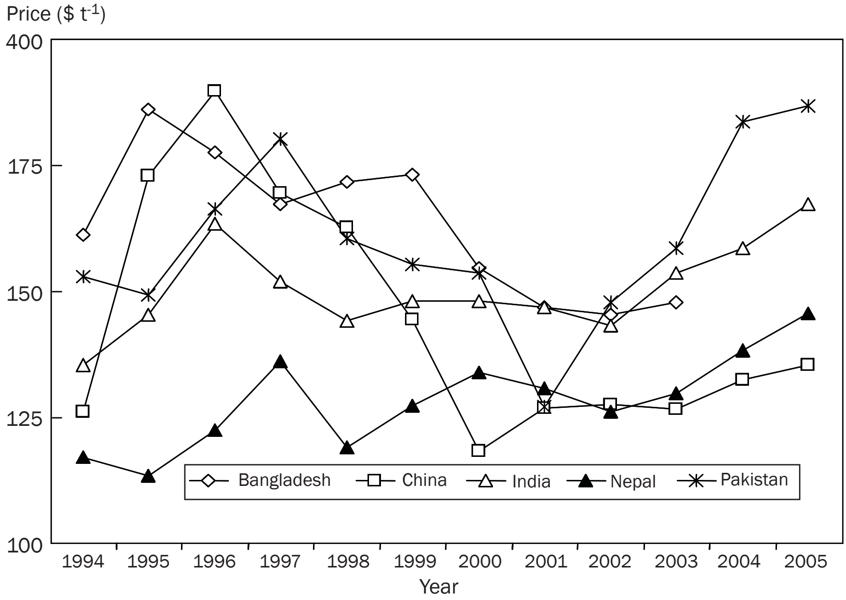

Fig. F.4. Trends in producer prices of wheat in five Asian countries (1994-2005).

Annex G
Projections for international prices of cereals

International prices of rice, wheat, and maize projected by FAPRI and OECD-FAO for 2017-18 (based on 2007-08) are presented in Table G.1. It can be noted that the baseline prices for all cereals for 2007-08 differed substantially for the two projections; as a result, the projections for 2017-18 also differed substantially.

Projections by FAPRI

International world grain prices rose sharply in 2007-08 because of weather-related shortfalls in production in the major grain-producing regions, resulting in a tightened supply on world markets, dwindling global stocks, and demand increases from biofuels. The projected recovery in wheat production and supply stabilizes the international price of wheat from the recent high of \$314 t^{-1} and it is expected to decline for U.S. f.o.b. Gulf wheat to \$264 t^{-1} in 2017-18 (Table G.1). The price of maize continues to increase in 2007-08, reaching \$198 t^{-1}, because of the high demand from the ethanol sector and the continuing growth of the livestock sector. Over the coming decade, the price tends to stabilize or there might be a slight decline to \$195 t^{-1} because of production increases. International prices of rice spiked in 2007 and early 2008 because of tightened exportable supplies, as India, Egypt, and Vietnam restricted their exports to control rising domestic prices. Driven by strong consumption and trade, and appreciation of the Thai baht, the export price of 100% milled rice continues to trend upward, reaching its peak in the first quarter of 2008; it will reach about \$450 t^{-1} by 2017. Thus, the FAPRI projections indicate a sharp decline in wheat price, steady or little decline in maize price, and some increase in rice price in 2017-18.

Projections by OECD-FAO

In the context of generally lower global stocks of cereals in recent years, this additional demand is expected to underpin prices and to lead to price levels that are, on average, higher than in past projections. They are, however, expected to decline toward the end of 2016 but will still stay substantially higher than prices observed over the past decade because of expanding food demand in developing countries as well as increasing demand for maize for ethanol production (Table G.1).

Table G.1. Projections for international prices of cereals (US\$ t^{-1}) based on FAPRI (2008) and OECD-FAO (2007).

Years	FAPRI[1]			OECD-FAO[2]		
	Wheat[a]	Maize[b]	Rice[c]	Wheat*	Maize**	Rice***
2007-08	314	198	397	204.5	158.9	352.1
2008-09	251	195	358	197.5	157.6	360.3
2009-10	248	194	382	191.8	147.1	347.8
2010-11	247	188	377	186.1	143.3	331.9
2011-12	250	191	398	184.6	144.0	331.0
2012-13	252	193	402	184.5	140.8	336.3
2013-14	257	196	425	183.1	138.4	336.3
2014-15	259	196	435	181.7	138.6	330.2
2015-16	261	197	439	182.4	139.5	326.2
2016-17	263	195	448	183.2	138.2	326.0
2017-18	264	195	450	–	–	–

[a]Wheat: U.S. f.o.b. Gulf. [b]Maize: f.o.b. Gulf. [c]Rice: Thai 100% Grade B.
*#2 hard red winter wheat, ordinary protein, USA f.o.b. Gulf ports (June/May).
**#2 yellow corn, U.S. f.o.b. Gulf ports (September/August).
*** milled 100%, Grade B, nominal price quote, f.o.b. Bangkok (August/July).
[1]FAPRI (2008).
[2]OECD/FAO (2007).