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Impact of Climate Change on Agricultural Productivity in Asia

Katsuo Okamoto
National Institute for Agro-Environmental Sciences, 3-1-3 Kannon-dai, Tsukuba, Ibaraki, 305-8604 Japan

Abstract: Will Asian people have sufficient food in the 21st century? In this paper, predicting long-term (the time scale of 50 to 100 years) crop yield of major crops (rice, wheat and maize) were focused on. First, a general view of changes in the area and distribution of agricultural land in the past and climate change in the future was provided. Second, results of studies on change in the area for cultivating crops and yield in accordance with climate change were presented. The sizes of suitable and potential regions for cultivating major crops will remain in the status quo or expand. The yield per unit area will increase in accordance with the increase in climatology-based potential productivity. Climate change is not an event on the scale of a few years but on the scale of 50 to 100 years. Therefore, we have sufficient time to develop a new variety suitable for changed environments. Consequently, even if the global climate will change, the amount of food produced will meet the demands in Asia.

Key words: Agricultural productivity, Asia, climate change, major crops, potential regions for cultivation.

Idso *et al.* (1977) wrote, "The politics of food will become the central issue of every government. Agricultural research has become one of our most important national assets, exerting a two-pronged attack upon the problem. First, a variety of approaches to yield betterment are being studied and perfected; and second, new techniques for rapid and reliable assessment of global crop yields – to help us determine how best to match supply with demand – are being developed". It has been predicted that now and in the future the world population will increase and the food demand will also rise (Kawashima and Kubota, 1996; Lutz *et al.*, 1997; Rosenzweig and Parry, 1994). In developed countries, the increase in population is slowing down or the population is beginning to decrease, while the increase in population in most developing countries will continue in the next 10 or 20 years. Generally, the yield per unit area is smaller in developing countries than in developed countries. Therefore, in developing countries, the first approach pointed by Idso *et al.* (1977), that is, developing a high-yielding variety, will be more important.

In the book "Global Climate Change and Agricultural Production", Sombroek and Gommes (1996) reported that the risks associated with climate change lie in the interaction of several systems with many variables that must be collectively considered. Agriculture can be defined as one of such systems, and climate the other. They also said that climate affects agriculture, the source of all food consumed by human beings and domestic animals. Rosenzweig *et al.* (2008) reported that significant changes in physical and biological systems were occurring on all continents and in most oceans, with the available data concentrated in Europe and North America. Most of these changes are associated with warming temperature. Moreover, they concluded that anthropogenic climate change was having a significant impact on physical and biological systems globally and in some continents. For example, Guo *et al.* (2008) described an overall warming and drying trend of the climate and a common degradation tendency of the ecosystem in the source region of the Yellow River, China, in 1990-2000. The consequent decrease in the amount of growing season precipitation mainly affects ecosystems with low precipitation and poor vegetation condition, and superimposes the effects of increasing average growing season temperature, which further degrade the climate of these ecosystems. Stone *et al.* (1996) pointed out the relationship between El Niño/Southern Oscillation (ENSO) and rainfall all over the world. Rosenzweig (1994) reported the relationship between ENSO and the maize yield in many parts of the world. An extreme event associated with climate change is a phenomenon on a global scale. It has been reported that extreme events tend to occur frequently in the process of climate change (Japan Meteorological Agency, 1994). Under such conditions, the second purpose of agricultural research, namely, developing new techniques for the rapid and reliable assessment of global crop yield, will be more important for food-importing countries such as Japan.

For the stable food supply in Asia, governments in Asian countries must estimate the annual crop production (short- term crop) in Asia and other regions as soon as possible. Since the short-term crop yield can be estimated from the size of the annual planted area and the yield per unit area, an objective short-term crop yield can be predicted accurately and rapidly using satellite remote sensing. In developing countries in particular, statistical data may have poor reliability and the damage caused by natural disasters may not have been surveyed in the field. Satellite remote sensing has been found useful under such conditions, e.g. flood damage to rice crop (Okamoto *et al.*, 1998). Furthermore, to prepare for stable food supply in the future, governments in Asian countries must predict changes in the size of the planted area and the yield per unit area in the time scale of 50 to 100 years (long-term crop), in accordance with climate change.

In this paper, I focus on predicting long-term crop yield (changes in the size of the planted area and yield per unit area in the time scale of 50-100 years) of major crops (rice, wheat, maize and soybean). First, a general view of changes in the area and distribution of agricultural land in the past and climate change in the future is provided. Second, results of studies on changes in the area and yield of crops with climate change are presented. Finally, future food production and related problems in Asia are discussed.

Past Changes in Area and Distribution of Arable Land and Future Estimated Climate Change

Changes in area and distribution of available land in the past

The population in the eastern part of Asia (Pakistan and eastward) has continued to increase since 1961 (Fig. 1) and rice production has also increased in order to feed the population (Fig. 2). However, the amount of area for rice production increased

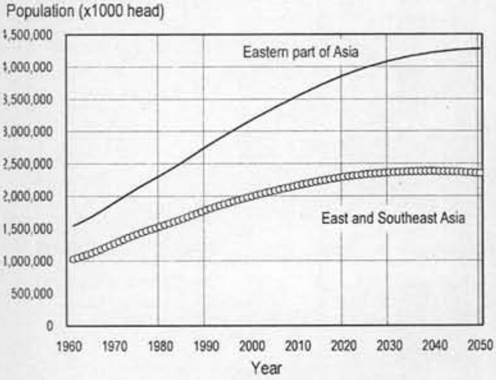

Fig. 1. Estimation and projection of population in the eastern part of Asia (Pakistan and eastward) and East and Southeast Asia (quoted from FAO Statistical Databases (FAO, 2009) and modified).

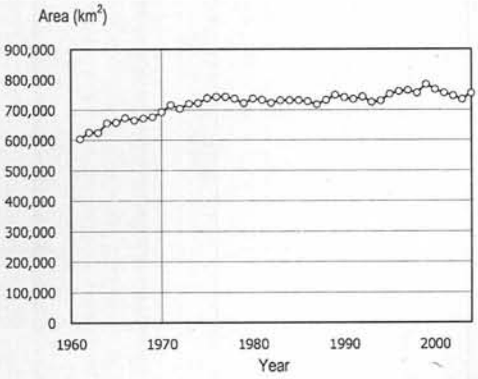

Fig. 3. Area planted with rice in the eastern part of Asia (Pakistan and eastward) (quoted from FAO Statistical Databases (FAO, 2009) and modified).

little during the same period (Fig. 3). The increase in the rice production during this period was due to an increase in the yield per unit area (Fig. 4). If so, did the amount of agricultural land not increase much before that, too? The answer is yes. Since the yield per unit area increased little before 1961, i.e., before the Green Revolution, the crop production was increased by extending the arable land in order to feed the increased population. Ramankutty and Foley (1999) used the land-use/land-cover map based on a 10-day composite vegetation index from satellite data in 1992 to estimate the cultivation intensity in proportion to statistical data, and generated the cultivation intensity maps from 1700 to 1992 year by year (Fig. 5). As shown in this figure, the cultivation

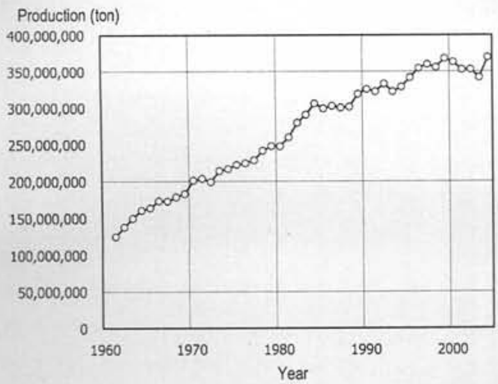

Fig. 2. Production of rice in the eastern part of Asia (Pakistan and eastward) (quoted from FAO Statistical Databases (FAO, 2009) and modified).

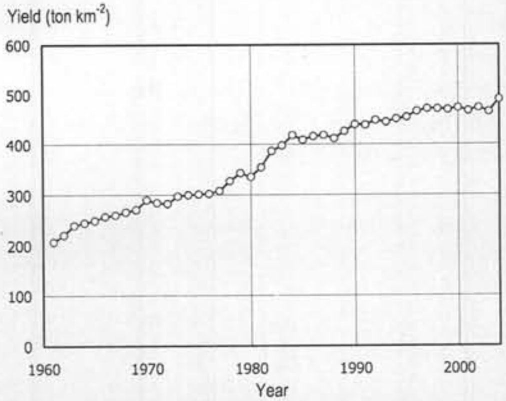

Fig. 4. Rice yield per unit area in the eastern part of Asia (Pakistan and eastward) (quoted from FAO Statistical Databases (FAO, 2009) and modified).

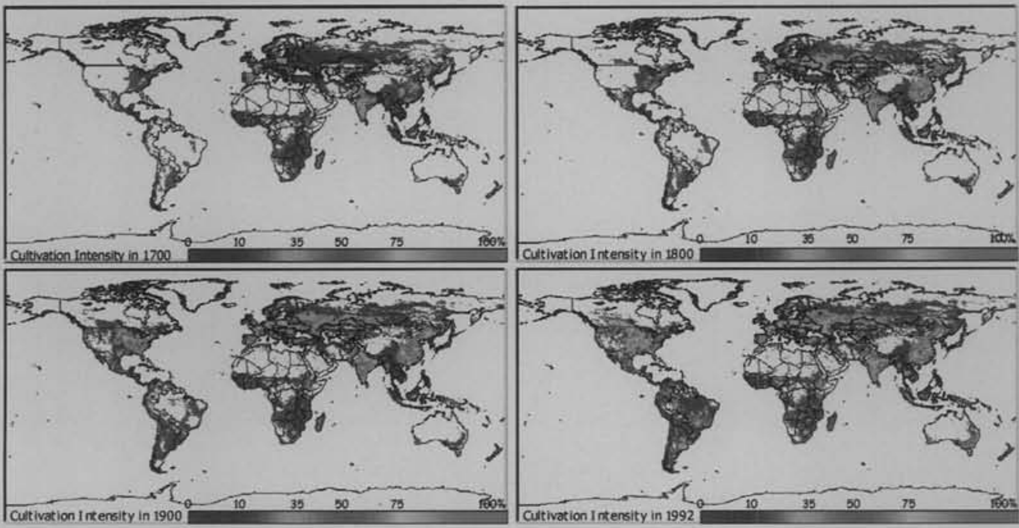

Fig. 5. Historical changes in cultivation intensity from 1700 to 1992. Colors indicate the percentage (%) of arable land area in a 0.5° grid (quoted from Ramankutty and Foley (1999) and colored).

intensity (fraction of area of arable land in a grid) has increased gradually. Many grids with more than 80% cultivation intensity in 1992 are distributed particularly in the USA and India. These grids in the USA are located in the Corn Belt and those in India in the basin of the Ganga River. In India, 54% of the total area was used as arable land in 2005 (FAO, 2009) and many grids with more than 35% cultivation intensity existed even in 1700.

Climate change in the past and the future

How did the global climate change in the past? Since 1985, the global surface mean air temperature rose gradually (Fig. 6). Battisti and Naylor (2009) reported that in future the high growing season temperatures can have considerable effects on agricultural productivity, farm incomes, and food security. They used observational data and output from 23 global climate models to show a high probability (90%) that growing season temperatures in the tropics and subtropics by the end of the 21st century would exceed the most extreme seasonal temperatures recorded from 1900 to 2006.

The results of simulation using global climate models (GCMs) under 6 socio-economic scenarios show that changes in global yearly mean air temperature vary widely (Fig. 7). Moreover, climate change differs with country and region. Let us examine the results from three GCMs (New *et al.*, 2002). The first scenario in 2001-2099 is the result from the GCM of the Hadley Centre, which indicates the middle rising curve of the mean air temperature; the second one is the result from the GCM of the Center for Climate System Research

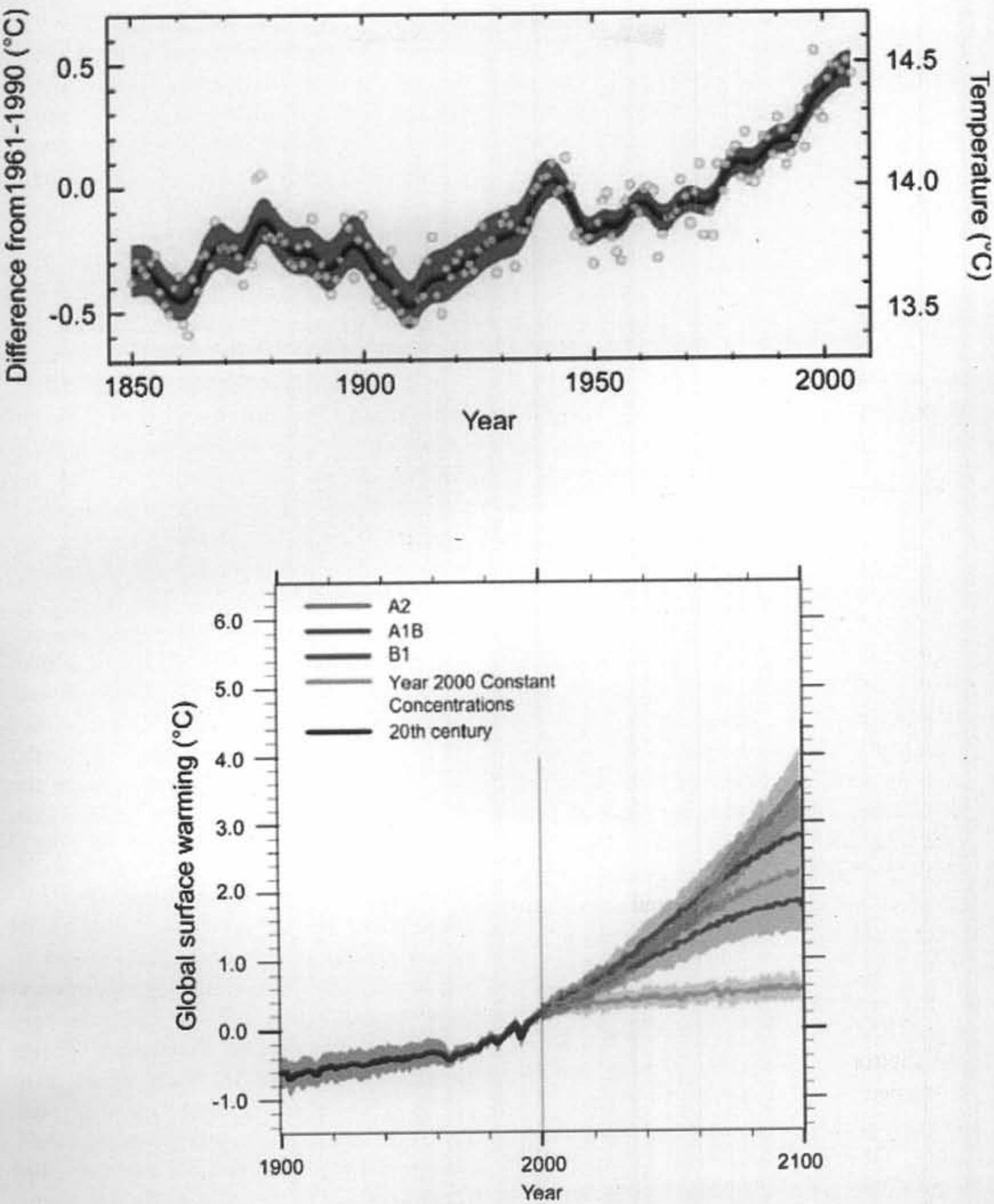

Fig. 7. Increase in global mean surface air temperature (quoted from IPCC (2007) and modified).

(CCSR, University of Tokyo)/National Institute for Environmental Studies (NIES, Japan), which indicates the highest rising curve of the mean air temperature; the third one is the result from the GCM of the Meteorological Research Institute (MRI, Japan), which indicates the lowest rising curve of the mean air temperature. The A2 economic scenario, which is region-oriented and pays more attention to economic growth, has been used in all these GCMs. The climate values for 1901-2000 are derived from the Climate Research Unit (CRU) (New *et al.*, 2002). The monthly mean air temperature and monthly precipitation were calculated by country or Chinese province.

Japan, located in the temperate zone of the middle latitudes, has large annual differences in the monthly mean air temperature. In all the results of simulation using GCMs, the monthly mean air temperatures vary seasonally and tend to rise slowly (Fig. 8). However, the monthly precipitation GCM-derived indicated a large value during the rainy season (June and July), but no clear trend. Only the result of simulation using the Hadley Centre GCM varied more widely than those using other GCMs.

Thailand, the top rice exporter in the world (FAO, 2009), is located in the tropical and subtropical zones. It has small annual differences in monthly mean air temperature. In all the results of simulations using GCMs, the monthly mean air temperatures vary up-and-down seasonally and tend to rise slowly, and the annual differences in monthly mean air temperature tend to decrease (Fig. 9). During the dry season, the monthly precipitation determined from simulations using GCMs does not differ from the actual monthly precipitation, while the monthly precipitation during the rainy season tends to increase gradually in all the GCMs.

Heilongjiang Province in China is the northernmost rice bowl in the world. The paddy field area and the rice production in Heilongjiang Province are almost the same as those in Japan (Heilongjiang Provincial Bureau of Statistics, 2004). Since Heilongjiang Province belongs to the cool temperate zone, it has large annual differences in the monthly mean air temperature. In all the results of simulations using GCMs, the monthly mean air temperatures vary up-and-down seasonally and tend to rise slowly (Fig. 10). Moreover, the differences in the monthly mean air temperature tend to widen gradually. There is no interannual trend in the monthly precipitation determined from simulations using GCMs, while the monthly precipitation determined from the simulation using the Hadley Centre GCM varies more widely than those using other GCMs.

India, whose population is predicted to exceed that of China in the 2040s and be the largest in the world (FAO, 2009), is a large country encompassing the tropical zone to the alpine tundra. The monthly mean air temperature determined from simulations using GCMs tends to rise here similarly to those of other countries and regions (Fig. 11). The monthly precipitations determined from simulations using Hadley Centre and CCSR/NIES GCMs are small and show no interannual trend. However, the monthly precipitations determined from the simulation using MRI GCM are

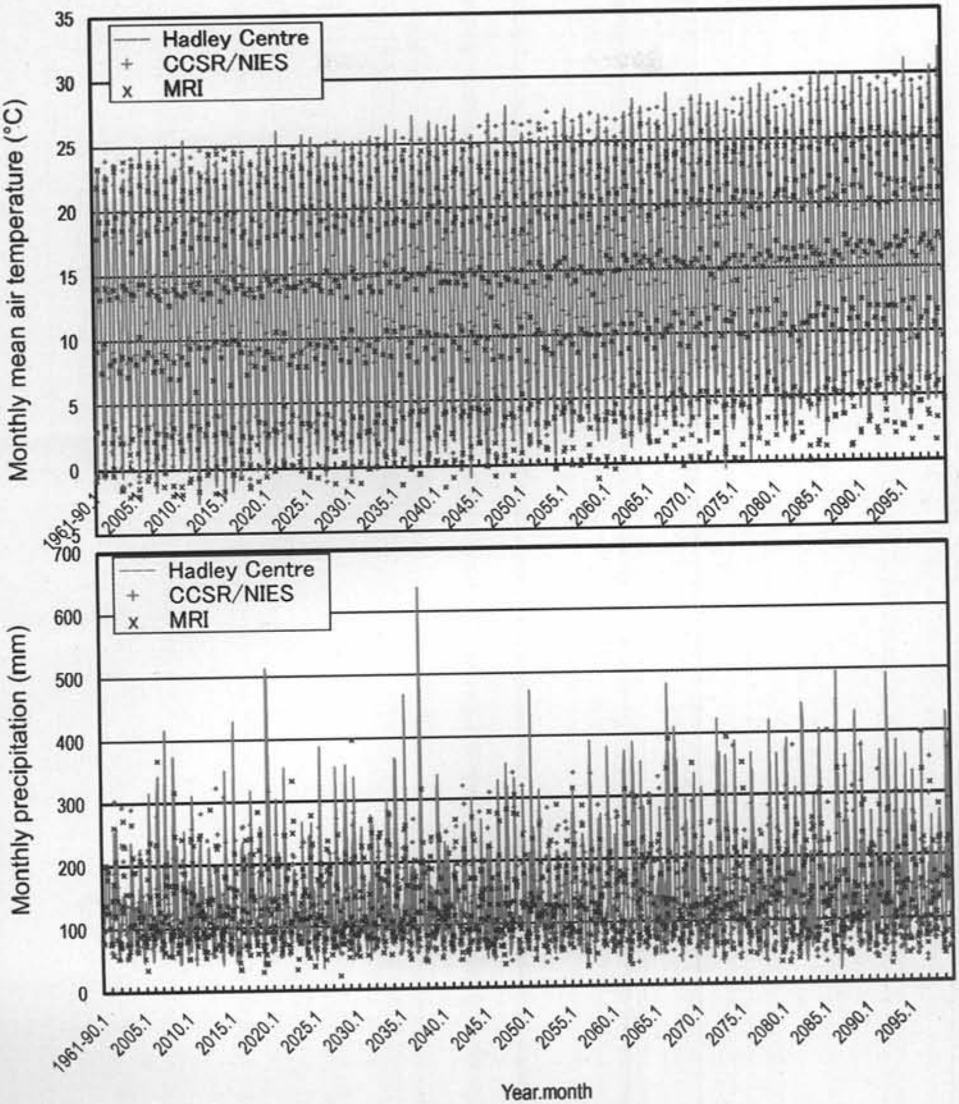

Fig. 8. Changes in (top) monthly mean air temperature (°C) and (bottom) monthly mean precipitation (mm) in Japan in average year (1961-1990 mean) and from 2000 to 2099: In both graphs, red lines indicate the results from Hadley Centre GCM, green plus signs indicate those from CCSR/NIES GCM, and blue X signs indicate those from MRI GCM (quoted from 0.5° grid data (New et al., 2002) and calculated by country).

markedly higher and vary more widely than those using other GCMs. MRI GCM may have a problem in estimating the effect of the monsoon.

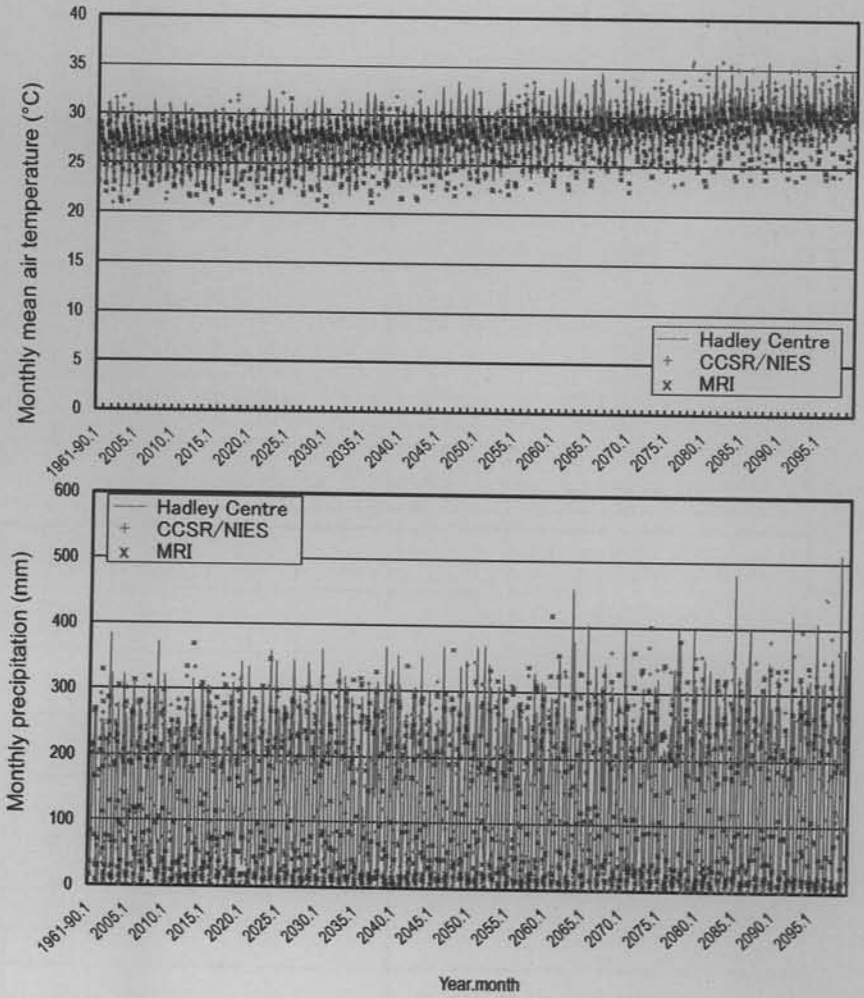

Fig. 9. Changes in (top) monthly mean air temperature (°C) and (bottom) monthly mean precipitation (mm) in Thailand in average year (1961-1990 mean) and from 2000 to 2099: In both graphs, red lines indicate the results from Hadley Centre GCM, green plus signs indicate those from CCSR/NIES GCM, and blue X signs indicate those from MRI GCM (quoted from 0.5° grid data (New et al., 2002) and calculated by country).

Positive and negative effects of climate change on major cereal cultivation

Climate change may be disadvantageous to agriculture in tropical and subtropical regions, while it may be advantageous in some temperate regions (Okamoto *et al*., 1997; Okamoto and Kawashima, 2000). The food demand in Asia will increase in the 21st century together with the population.

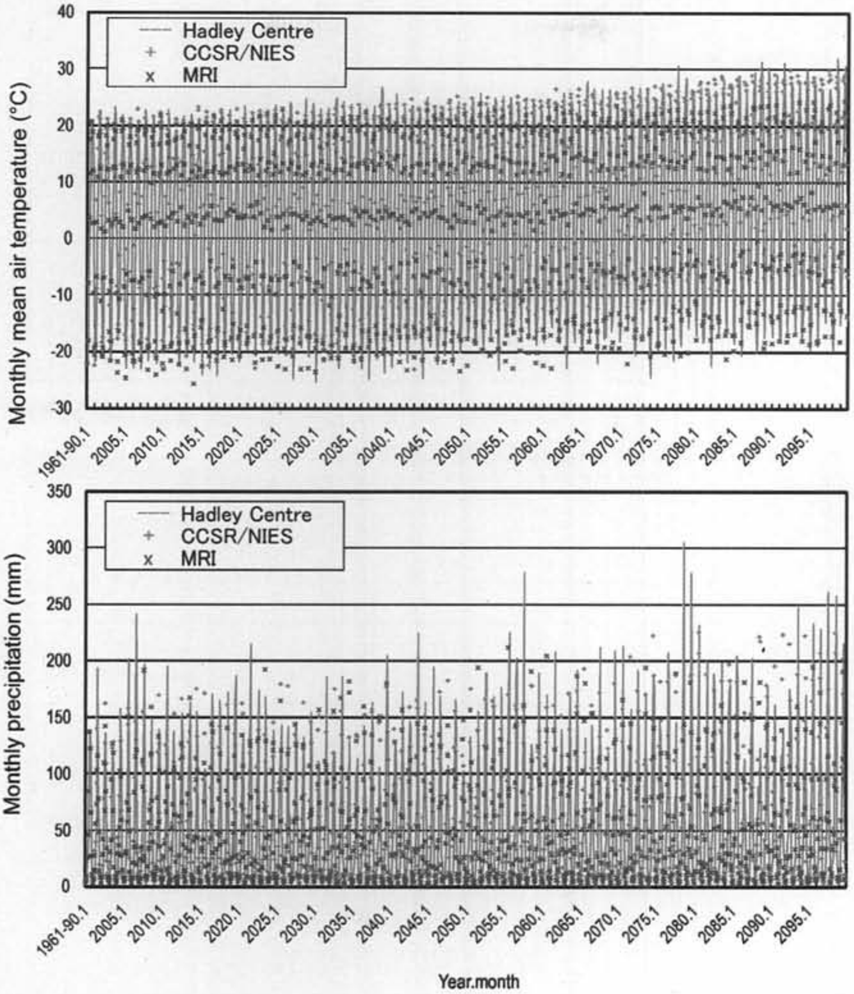

Fig. 10. Changes in (top) monthly mean air temperature (°C) and (bottom) monthly mean precipitation (mm) in Heilongjiang Province, China, in average year (1961-1990 mean) and from 2000 to 2099: In both graphs, red lines indicate the results from Hadley Centre GCM, green plus signs indicate those from CCSR/NIES GCM, and blue X signs indicate those from MRI GCM (quoted from 0.5° grid data (New et al., 2002) and calculated by Chinese Province).

Moreover, economic growth in Asian countries will also change the local diet. Climate change could vary the present cropping system. Major cereals in Asia are cultivated in regions with suitable temperature and precipitation. Climate change could cause the air temperature and precipitation to become unsuitable for major

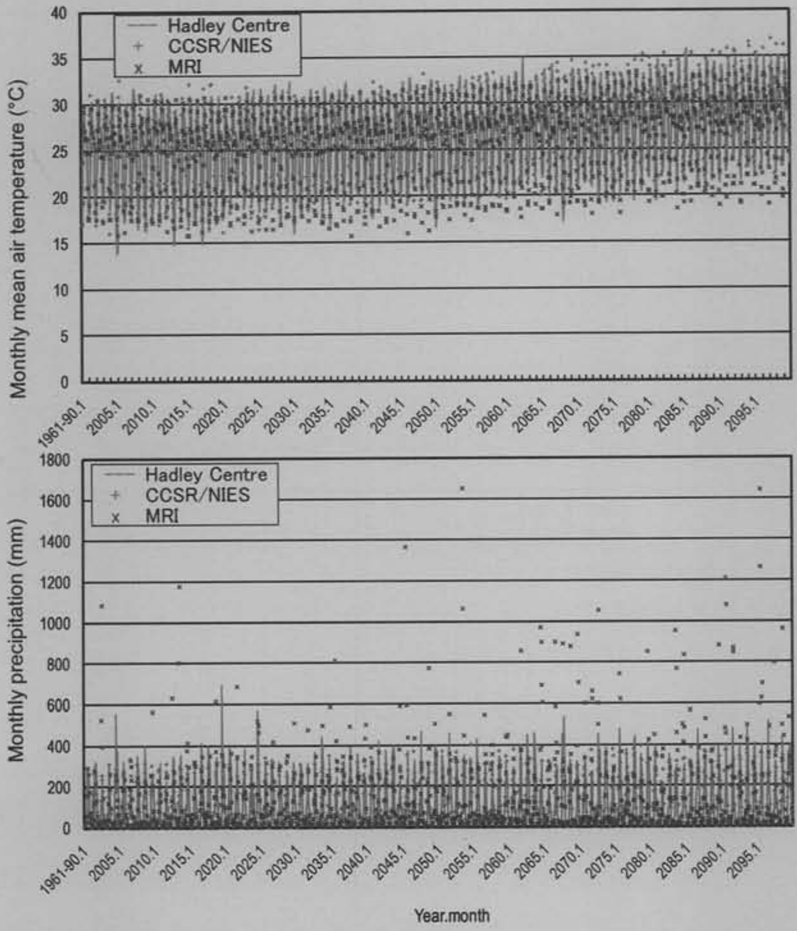

Fig. 11. Changes in (top) monthly mean air temperature (°C) and (bottom) monthly mean precipitation (mm) in India in average year (1961-1990 mean) and from 2000 to 2099: In both graphs, red lines indicate the results from Hadley Centre GCM, green plus signs indicate those from CCSR/NIES GCM, and blue X signs indicate those from MRI GCM (quoted from 0.5° grid data (New et al., 2002) and calculated by country).

cereal cultivation in Asia. To predict the effects of climate change on sustainable cropping and agricultural development, Okamoto *et al.* (2001) investigated the changes in air temperature and precipitation in the typical production regions of major cereals, i.e., rice, wheat and maize, in East through South Asia in different cropping seasons. The cumulative air temperature and precipitation in a typical rice-cropping season for each production region were calculated using the monthly mean air temperature and precipitation (New *et al.*, 1999).

The effects of climate change have two sides: positive and negative. The air temperature increase has positive impact in rice-cropping areas during the cool season. The air temperature in double-crop rice-cropping areas, i.e., north of Hefei and west of Guangzhou, during the second (cool) season will reach the potential limit for cultivating rice (Fig. 12).

The air temperature increase will have negative impact in wheat-cropping areas. Currently the air temperature is suitable to cultivate winter wheat to the south of Faisalabad, Uttar Pradesh (Allahabad), the northwest of Chongqing, the southwest of Hefei, Jinan, the north of Chongqing and the west of Faisalabad (Fig. 13). The air temperature increase will be disadvantageous for cultivating wheat because it will be above potential limit.

The precipitation increase will have positive effect in rice-cropping areas during the dry season and in dry wheat-cropping areas. It is dry in Dhaka during the second season (*Boro*) and to the south of Faisalabad (Fig. 14). It is also dry in Jinan during the wheat-cropping season (Fig. 13). The precipitation will be above the lower limit of the potential amount.

The precipitation increase will negatively impact the subtropical rice-cropping and wheat-cropping areas. The precipitation in the double-crop rice-cropping area of Punjab and in the rice- and wheat-cropping areas of Uttar Pradesh will increase rapidly (Figs. 12, 14). Punjab is located in the upper part of the Indo-Gangetic plains and Uttar Pradesh in the middle part. The lower reaches of the Ganges River are threatened by flooding during this season. Precautionary measures against flooding are required to strengthen infrastructures such as embankments and to set up drainage pumps.

Large quantities of irrigation water are consumed for cultivating rice. Hydrological conditions change in accordance with changes in water use in agriculture. Will Asian farmers always have sufficient water to cultivate rice? To answer this question, Okamoto *et al.* (2003) estimated the available water resources for cultivating rice in countries and regions from East to South Asia. They reported that most potential irrigation land areas are larger than the agricultural land areas, but that the river basins of the Ganges, Amur and the Huanghe have scarce water resources. Furthermore, they reported that in Southeast Asia, water resources are abundant in the first rice-cropping season but not in the second rice-cropping season. In other words, South Asia has scarce water resources.

Changes in Cropping Area: An Approach from Suitable and Potential Areas for Cultivation

Suitable and potential areas for cultivating crops

To predict changes in agricultural productivity in 50 to 100 years in accordance with climate change, changes in the extent of the planted area and the yield per unit area need to be predicted. If so, how can the extent of area for future crop cultivation be predicted? The area for actual crop cultivation does not depend only on the climate conditions. An increase in the population it expected to result in a higher cultivation intensity, but it is not necessarily true. Farm families employ strategies such as borrowing land or migrating temporarily or permanently. Population pressure does

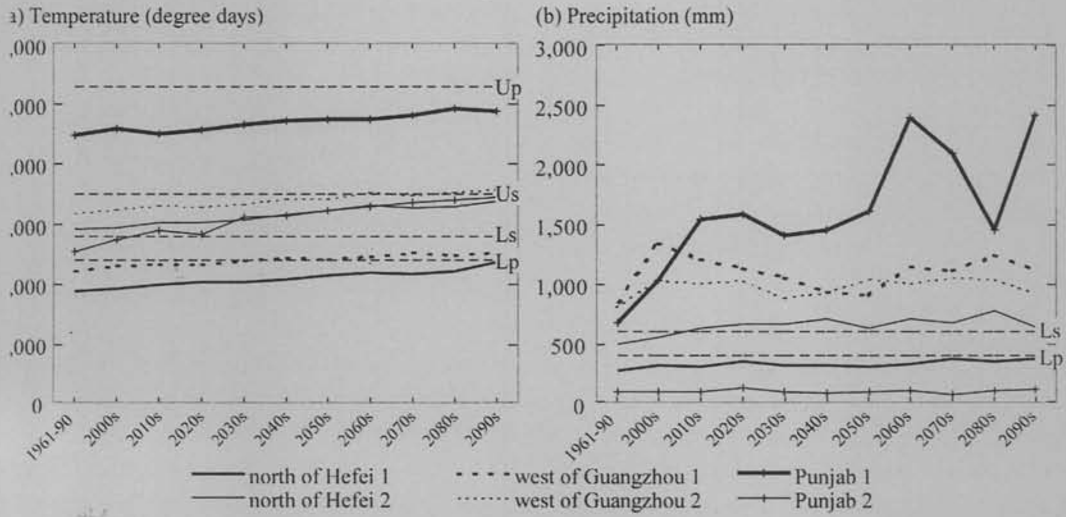

Fig. 12. Changes in (a) cumulative temperature (degree days) and (b) precipitation (mm) in double-crop rice-cropping areas. The number after the location name corresponds to the cropping season: 1 for the main season and 2 for the second season. Individual periods are listed in Table 1. Us in the graph indicates the upper limit of the suitable zone for cultivation, Up indicates that of the potential zone, Ls indicates the lower limit of the suitable zone, and Lp indicates that of the potential zone.

Table 1 Typical production regions of major cereals in East through South Asia. Information was obtained from Crop and Grassland Service (2000) and World Agricultural Outlook Board (1994) with modification

Cropping system	Main season	Second season	Country	Location
double-crop rice	Apr-Jun	Jul-Oct	China	N of Hefei
double-crop rice	Apr-Jun	Jul-Oct	China	W of Guangzhou
double-crop rice	Jun-Oct	Nov-Mar	India	Punjab (N of Delhi)
single-crop rice	Jun-Oct	Jan-Apr	Bangladesh	Dhaka
single-crop rice	Jun-Oct	Feb-May	Thailand	N of Bangkok
rice and wheat	Jun-Oct	Nov-Apr	Pakistan	S of Faisalabad
rice and wheat	Jun-Oct	Nov-Mar	India	Uttar Pradesh (Allahabad)
rice and wheat	Jun-Sep	Oct-May	China	NW of Chongqing
rice and wheat	Jun-Sep	Oct-May	China	SW of Hefei
rice and wheat	Jun-Sep	Oct-May	China	Jinan
winter wheat	Nov-Apr	–	Pakistan	W of Faisalabad
others and wheat	Jun-Sep	Oct-May	China	N of Chongqing
wheat or others	Apr-Jul	–	China	NW of Changchun
wheat or maize	May-Sep	–	China	Harbin

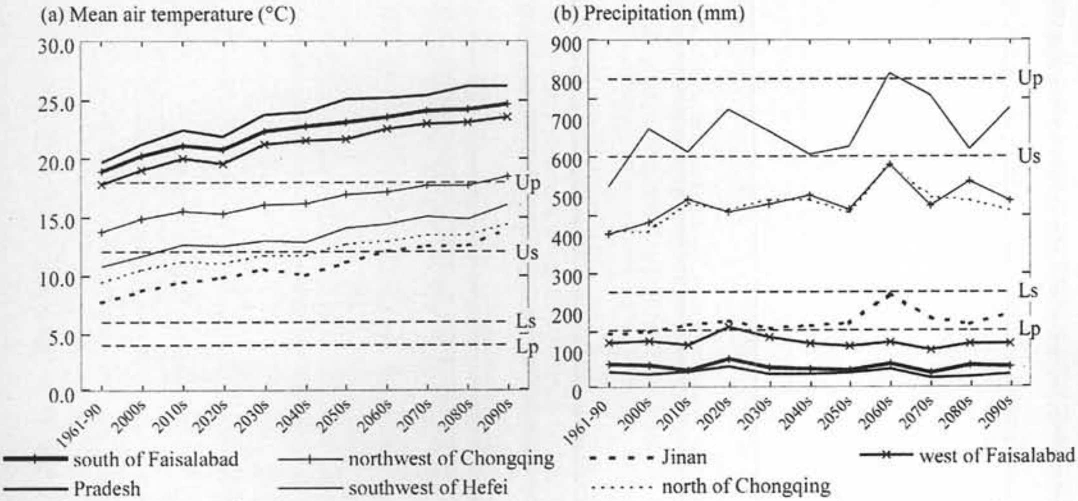

Fig. 13. Changes in (a) mean air temperature (°C) and (b) precipitation (mm) in rice and wheat-cropping areas during the second (wheat) season. Individual periods are listed in Table 1. Us in the graph indicates the upper limit of the suitable zone for cultivating winter wheat, Up indicates that of the potential zone, Ls indicates the lower limit of the suitable zone, and Lp indicates that of the potential zone.

not always lead to intensification; rather, it operates in conjunction with market and other social forces (Keys and McConnell 2005). Urbanization and income growth in rural areas cause people to change their taste (a shift in demand from grain to animal protein), while an aging society results in a decrease in the food demand (Honda *et al.*, 2008).

Because future socio-economic conditions except population growth are extremely difficult to predict, this paper deals with the maximum potential area for cultivation determined only under natural conditions, that is, the suitable and potential areas for crop cultivation. In this paper, a suitable area for crop cultivation is defined as a place suitable for crops to grow, or a place with natural conditions that make the yield per unit area maximum; a potential area for crop cultivation is defined as a place with natural conditions that are poorer than those of a suitable area but enable crop cultivation.

Identifying suitable areas for cultivating major crops is necessary to estimate appropriately the potential production of major crops. The growing environment of rice, which is the staple diet in many Asian countries, is separated into 5 rice ecosystems, such as irrigated field, rainfed lowland, upland, deep water and tidal wetland (IRRI, 1984). For extracting ecosystems/ subecosystems in which rainfed rice grows,

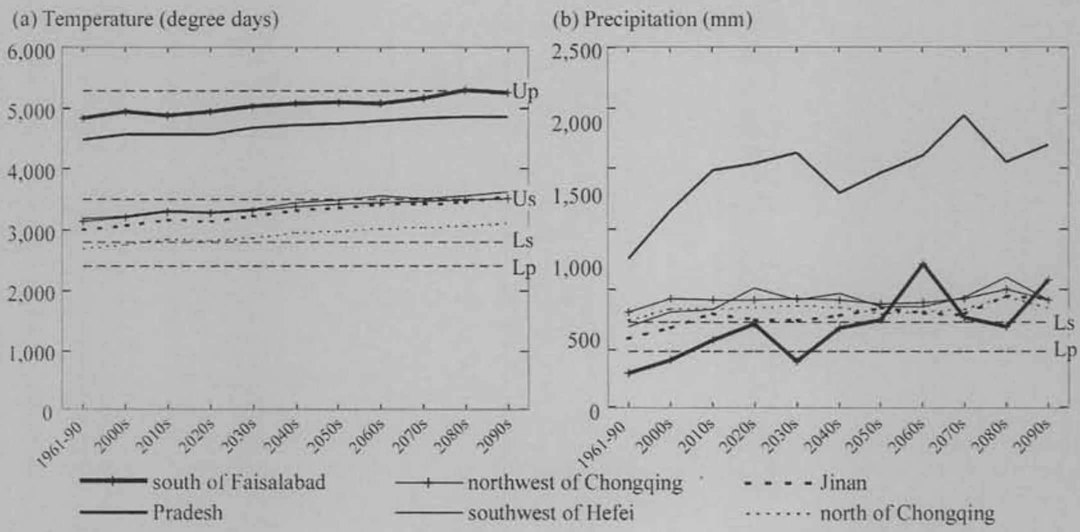

Fig. 14. Changes in (a) cumulative temperature (degree days) and (b) precipitation (mm) in rice and wheat-cropping areas during the main (rice) season. Individual periods are listed in Table 1. Us in the graph indicates the upper limit of the suitable zone for cultivating rice, Up indicates that of the potential zone, Ls indicates the lower limit of the suitable zone, and Lp indicates that of the potential zone.

Singh and Singh (1996) proposed criteria based on information of rational vegetation index (RVI), geographical features and meteorological data. They reported that these criteria are applicable to other cereals after modifying a part of the criteria. At the local level, new methods of identifying potential agricultural land have been attempted using climatic ecological zone. Maselli *et al.* (1996) classified ecosystems in Tuscany, Italy from an agricultural viewpoint, using the monthly maximum value of normalized difference vegetation index (NDVI) and surface temperature (ST) calculated from National Oceanic and Atmospheric Administration (NOAA) Advanced Very-High Resolution Radiometer (AVHRR) data.

The global distribution of cereal-growing areas generally depend on climate. To clarify changes in the distribution of potential areas for cultivating cereals and the production of cereals under the present and changed climate conditions, Leemans and Solomon (1993) developed a model to identify potential areas for cultivating cereals using daily air temperature, daily soil moisture and solar radiation data. On the basis of their study, at high latitudes, the growing period of cereals under changed climate conditions was predicted to be longer than those under the present climate conditions. On the other hand, Darwin *et al.* (1996) estimated the potential areas for cultivation on the basis of crop growing days only under the criterion of demand for temperature and water. Yokozawa *et al.* (2000) evaluated the impact of climate change on agriculture using the concept of climatic suitable zones (FAO, 1978), which is characterized by cumulative air temperature above 0°C and precipitation - potential evapotranspiration. They predicted that the favorable increase in the area of climatic suitable zones will occur in southern China and Southeast Asian countries, but that the climate of South Asian countries, particularly India, will be considerably affected by the variations of the Asian monsoon.

Suitable and potential regions for major cereal cultivation under changed climate conditions

Okamoto *et al.* (1997) considered that the present major crop-producing regions are the regions with suitable natural environments for cultivating crops. Then, they predicted suitable and potential regions for cultivating major crops under double the current CO_2 level (around the year 2050), seeking places with the same conditions as those of the present major crop-producing regions. They defined a suitable region for cultivation as a place with the same air temperature, precipitation and type of soil as those of the major crop-producing regions, and a potential region for cultivation as a place with the same air temperature and precipitation as those of the major crop-producing regions. Then, focusing on the current agricultural lands and grasslands in the world as subjects of analyses, they predicted changes in the suitable and potential regions for cultivating major crops in the current agricultural lands and grasslands, using the International Institute for Applied System Analysis (IIASA) climate data as the present climate value and the result of simulation using Geophysical Fluid Dynamics Laboratory (GFDL) GCM as the climate values of double the current CO_2 level (Fig. 15). They estimated the present area of suitable regions for major cereal cultivation to be 515 million ha. Under the condition of double the current CO_2 level, it was estimated that the area of suitable regions would be 279 million ha, which represents a decrease of 46%. They also identified potential regions for major cereal cultivation, which met the temperature and water requirements. The present area of potential regions for major cereal cultivation was estimated to be 1,333 million ha. They predicted that the area of potential regions under condition of double the current CO_2 level would be 1,378 million ha, representing an increase of 3%.

Okamoto and Kawashima (2000) estimated the suitable and potential regions for cultivating major crops, using the method of Okamoto *et al.* (1997), and compared the two. The results obtained by adopting some of the scenarios are shown in Table 2. The potential areas for cultivating major crops, which were calculated from the simulation results using GCMs were 71.8 to 123.2% of the current area (17.1 million km^2) (Table 3). The results are contradicting: the potential cultivation area increases in some scenarios, while it decreases in others. The result from HADCM2 gives the smallest global potential area among all the scenarios, while that from ECHAM4/OPYC3 gives the largest. The result from GFDL GCM gives an intermediate value. When we adopt

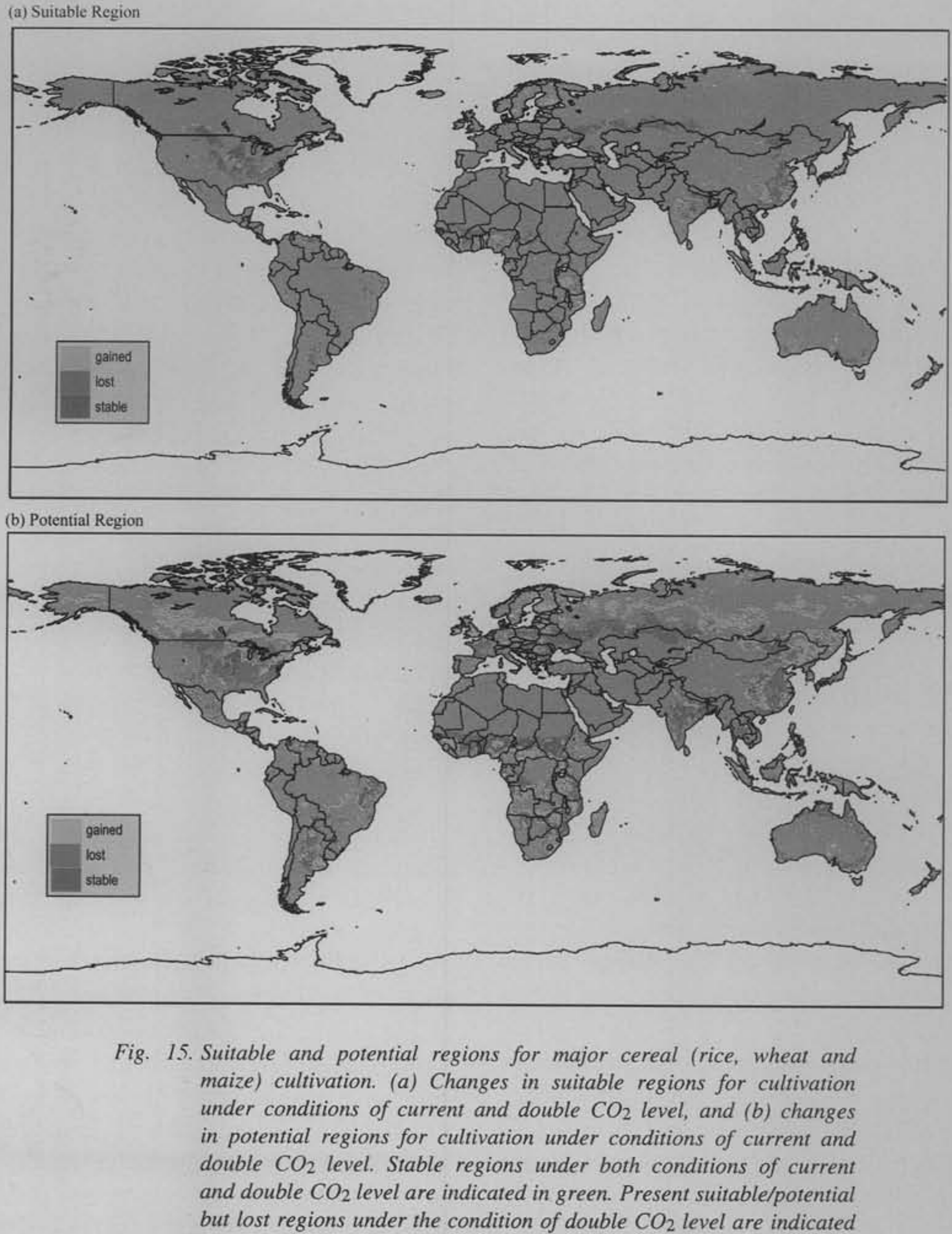

Fig. 15. Suitable and potential regions for major cereal (rice, wheat and maize) cultivation. (a) Changes in suitable regions for cultivation under conditions of current and double CO_2 level, and (b) changes in potential regions for cultivation under conditions of current and double CO_2 level. Stable regions under both conditions of current and double CO_2 level are indicated in green. Present suitable/potential but lost regions under the condition of double CO_2 level are indicated in red, and present unsuitable/impossible but gained regions under the condition of double CO_2 level are indicated in yellow.

the climate scenario from ECHAM4/OPYC3, the potential area increases by 23.2% compared with that under the present condition. Under this climate scenario, the potential area in all the continents except Oceania and South

Table 2. GCMs adopted for evaluation of future potential regions for major cereal cultivation. Integration indicates the year(s) in which atmospheric CO_2 concentration will double. For CGCM1, GFDL GCM, HADCM2 and ECHAM4/OPYC3, results from both simulation including and excluding the effects of sulfur compounds were used, while for MRI GCM, only the result from the simulation including the effects of sulfur compounds was used

Model	Laboratory	Sulfur effect	Integration
CGCM1*	Canadian Center for Climate Modeling and Analysis	exclusion	2060
		inclusion	2060
GFDL GCM*	Geophysical Fluid Dynamics Laboratory	exclusion	2050
		inclusion	2060
HADCM2*	Hadley Center for Climate Prediction and Research	exclusion	2060
		inclusion	2060
ECHAM4/ OPYC3*	Deutshes Klimarechenzentrum	exclusion	2060
		inclusion	2040
MRI GCM†	Meteorological Research Institute	inclusion	2056-2065

* Source: The IPCC Data Distribution Center (1998);
† Source: Tokioka *et al.* (1995).

America will increase. However, under the climate scenario from ECHAM4/OPYC3$_{+S}$, the potential area will decrease in all the continents except Europe and North America. If the scenario from HADCM2 is adopted, the potential area decreases by 28.2% compared with that under the present condition. Under this climate scenario, the potential area will decrease in all the continents. Comparison of the potential regions based on the results from ECHAM4/OPYC3, which gave the largest, with those from HADCM2, which gave the smallest, shows that the common potential regions based on these two GCMs were small (Fig. 16). The distribution and area shown above are only snapshots under the climate condition of double the current CO_2 level.

Changes in suitable and potential areas for cultivating rice in Asia under changing climate conditions

Since climate has been changing, the prediction easily became erroneous when it was obtained only from a simulation result at a point in time. If so, how continuous are the changes in suitable and potential regions for cultivating major crops in relation to climate change? Will climate change cause the air temperature and precipitation to become unsuitable for rice cultivation in Asia? First, climatically suitable/potential regions for rice cropping in the Eastern Asia (Japan to Pakistan) were estimated under three climate change scenarios in 2001-2099. The first scenario in 2001-2099 was the result from the Hadley Centre GCM, which indicates the middle rising curve of the mean air temperature; the second one was the result from the CCSR/NIES GCM, which indicates the highest rising curve of the mean air temperature; the third one was the result from the MRI GCM, which indicates the lowest rising curve of the mean air temperature. The A2 economic scenario, which was region-oriented and paid more attention to the economic growth, was used in all these GCMs. The climate values in 1901-2000 (New *et al.*, 2002) were derived

Table 3 Ratio between areas under conditions of current and double CO_2 level. The upper value on each row is the extent of area ($x10^6$ km^2) and the lower value in parenthesis is the percentage variation of the future potential area relative to the present one. In the table, +S indicates the inclusion of the effect of sulfur compounds

GCM	Africa	Asia	Europe	North * America	Oceania	South America	World
CGCM1	5.16 (+8.1)	4.66 (+20.1)	3.49 (+41.8)	4.11 (+30.0)	0.30 (-66.2)	2.75 (+39.6)	20.47 (+19.5)
$CGCM1_{+S}$	7.02 (+47.3)	*3.43* (-11.8)	3.05 *(+24.1)*	3.56 (+12.4)	0.34 (-61.4)	2.70 (+37.0)	20.10 (+17.3)
GFDL GCM	6.26 (+31.3)	*2.83* *(-27.1)*	2.19 (-10.8)	2.77 (-12.4)	1.05 (+18.5)	2.07 (+5.1)	17.18 (+0.3)
GFDL GCM_{+S}	5.94 (+24.7)	*3.32* *(-14.6)*	2.51 (+2.2)	2.84 (-10.1)	1.08 (+21.1)	2.12 (+7.4)	17.81 (+4.0)
HADCM2	4.21 *(-11.7)*	2.36 (-39.2)	2.22 (-9.6)	1.77 (-44.0)	0.29 (-67.9)	1.46 (-26.1)	12.31 (-28.2)
$HADCM2_{+S}$	5.19 (+8.8)	*3.60* *(-7.3)*	1.58 (-35.7)	1.98 (-37.3)	0.28 (-68.6)	1.34 (-31.9)	13.97 (-18.5)
ECHAM4/OPY C3	6.35 (+33.1)	3.89 (+0.1)	5.07 (+106.0)	3.41 (+7.9)	*0.48* *(-45.8)*	1.91 (-3.0)	21.11 (+23.2)
ECHAM4/OPY $C3_{+S}$	4.46 *(-6.5)*	2.80 (-27.9)	3.34 (+35.7)	3.60 (+13.7)	0.47 (-47.6)	1.79 (-9.3)	16.44 (-4.0)
MRI GCM_{+S}	8.20 (+71.9)	*3.82* *(-1.7)*	1.60 (-35.3)	1.53 (-51.5)	0.88 (-1.0)	3.53 (+78.8)	19.54 (+14.1)
GCMs Average	5.86 (+23.0)	*3.41* *(-12.1)*	2.78 (+13.2)	2.84 (-10.1)	0.57 (-35.4)	2.19 (+10.9)	17.66 (+3.1)

* *Central America is included.*

from the CRU. The climate conditions in Eastern Asia were examined in terms of whether the cumulative temperature in the cropping periods for each country and Chinese province was suitable (Ts), potential (Tp) or impossible (Ti) for rice cropping, and whether the cumulative precipitation was suitable (Ps), potential (Pp) or impossible (Pi). For cultivating rice, the suitable cumulative air temperature Ts is in the range of 2400-3500 degree day and the potential one Tp is in the range of 2000-2400 or 3500-5800 degree day; the suitable precipitation Ps is 600 mm or more and the potential one Pp is in the range of 400-600 mm. The suitable and potential limits of the air temperature and precipitation for rice cropping were determined, in reference to the literature on crop climate (Cui, 1994). Cropping periods were determined, in reference to Country Rice Facts (Crop and Grassland Service, 2000) and Major World Crop Areas and Climatic Profiles (World Agricultural Outlook Board, 1994). Then, the suitable and potential zones for rice cropping in 2001-2099 under three climate change scenarios were identified.

The distribution maps of suitable and potential regions for cultivating main/first-crop rice under the present climate conditions (1961-1990 mean) and those in 2099 are shown in Fig. 17. In all land areas, places

Fig. 16. Potential regions for major cereal cultivation: differences in potential regions between results of ECHAM4/OPYC3 and HADCM2 under the condition of double CO_2 level.

with suitable and potential climate conditions for cultivating rice are colored. These maps are snapshots of suitable and potential regions for rice cultivation at present and in 2099, and these depend on GCMs as shown in Fig. 17.

What is an interannual change? The suitable and potential areas for cultivating main/first-crop rice based on the simulation results using Hadley Centre GCM are shown in Fig. 18. I summed up the suitable and potential areas for cultivating main/first- crop rice, which is the total area with suitable air temperature and suitable precipitation (Ts and Ps), suitable air temperature and potential precipitation (Ts and Pp), potential air temperature and suitable precipitation (Tp and Ps), and potential air temperature and potential precipitation (Tp and Pp). These total areas in the eastern part of Asia (Pakistan and eastward) tended to increase slowly. In 2001-2099, these total areas will increase by 17% of the present (1961-1990 mean) area (10.0 million km^2). The predictions on suitable and potential areas based on the simulation results using CCSR/NIES and MRI GCMs were similar to those using Hadley Centre GCM. On the basis of these three predictions, the suitable and potential areas for cultivating main/first-crop rice in 2099 are predicted to increase by 10 to 20%.

So what did the suitable and potential areas for cultivating main/first-crop rice change in the 20^{th} century? Using the above-mentioned method, I estimated the suitable and potential areas for cultivating main/first-crop rice from 1901 to 2000. The suitable and potential areas were estimated to increase by 4% in 100 years of the 20^{th} century (Fig. 19). In accordance with these estimations, the suitable and potential areas for cultivating main/ first-crop rice for 100 years of the 21^{st} century will show a 3- to 5-fold increase over those of the 20^{th} century.

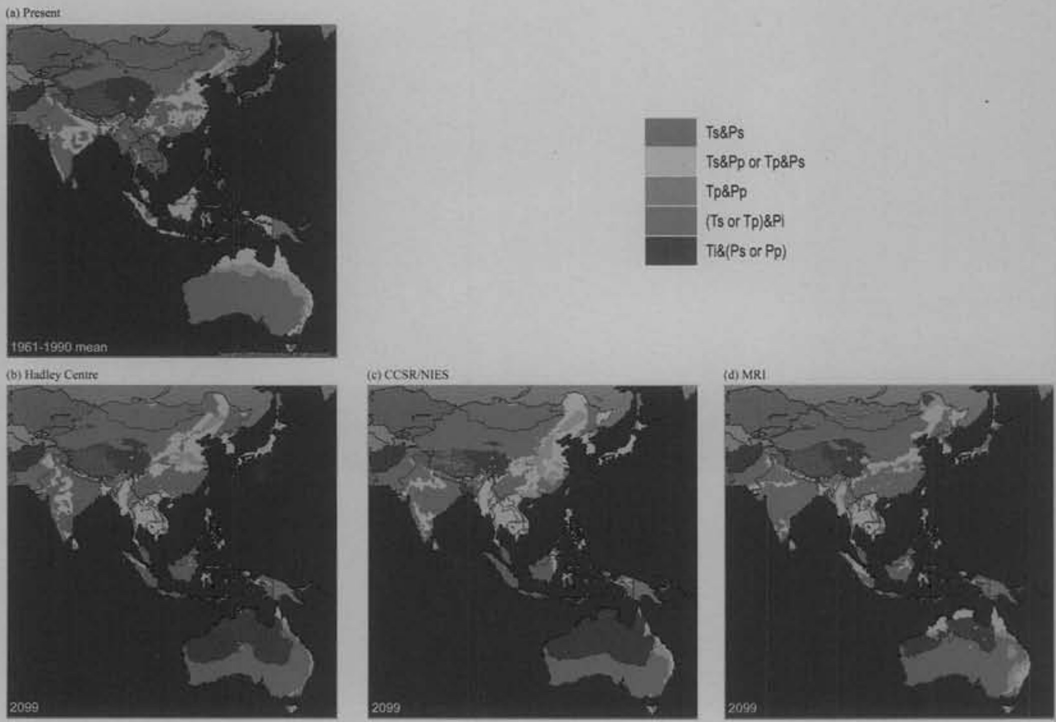

Fig. 17. Suitable and potential regions for cultivating main/first-crop rice under the current climate conditions ((a) 1961-1990 mean) and those in 2099 ((b) Hadley Centre GCM, (c) CCSR/NIES GCM, and (d) MRI GCM), based on the air temperature and precipitation, which are of the current growing period for each country or region. For cultivating rice, the suitable cumulative air temperature Ts is in the range of 2400-3500 degree day and the potential one Tp is in the range of 2000-2400 or 3500-5800 degree day; the suitable precipitation Ps is 600 mm or more and the potential one Pp is in the range of 400-600 mm; Ti indicates outside the range of suitable and potential cumulative air temperature and Pi indicates outside the range of suitable and potential precipitation.

Changes in suitable and potential areas for cultivating wheat and maize in Asia under changing climate conditions

How will suitable and potential areas for cultivating wheat and maize change? For cultivating winter wheat, the suitable mean air temperature Ts is in the range of 6-12°C and the potential one Tp is in the range of 4-6 or 12-18°C; the suitable precipitation Ps is in the range of 250-600 mm and the potential one Pp is in the range of 150-250 or 600-800 mm. The suitable and potential limits of the air

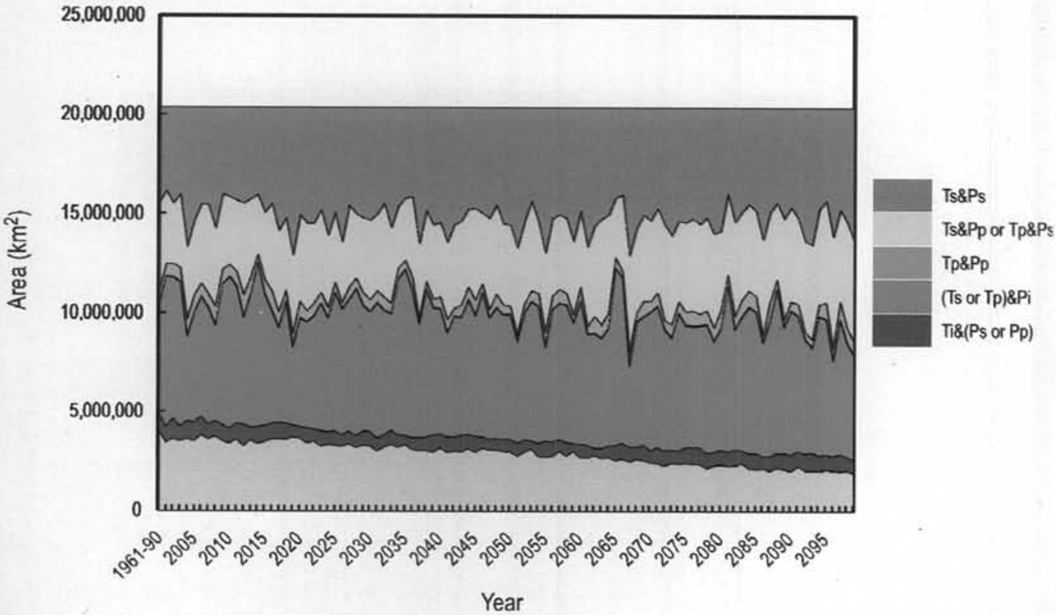

Fig. 18. Changes in suitable and potential areas for cultivating main/first-crop rice under the climate conditions of the present (1961-1990 mean) to 2099 simulated using Hadley Centre GCM, based on the air temperature and precipitation, which are of the current growing period for each country or region. For cultivating rice, the suitable cumulative air temperature Ts is in the range of 2400-3500 degree day and the potential one Tp is in the range of 2000-2400 or 3500-5800 degree day; the suitable precipitation Ps is 600 mm or more and the potential one Pp is in the range of 400-600 mm; Ti indicates outside the range of suitable and potential cumulative air temperature and Pi indicates outside the range of suitable and potential precipitation.

temperature and precipitation for winter wheat cropping were determined, in reference to the literature on crop climate (Cui, 1994). Cropping periods were determined, in reference to Major World Crop Areas and Climatic Profiles (World Agricultural Outlook Board, 1994).

Winter wheat prefers cool and dry climate in comparison to rice. I summed up the suitable and potential areas for cultivating winter wheat, which is the total area with suitable air temperature and suitable precipitation (Ts and Ps), suitable air temperature and potential precipitation (Ts and Pp), potential air temperature and suitable precipitation (Tp and Ps), and potential air temperature and potential precipitation (Tp and Pp). These total areas in the eastern part of Asia (Pakistan and eastward) tended to decrease slowly. In 2001-2099, these total areas decreased by 0-15% of the present (1961-1990 mean) area (2.2 million km^2).

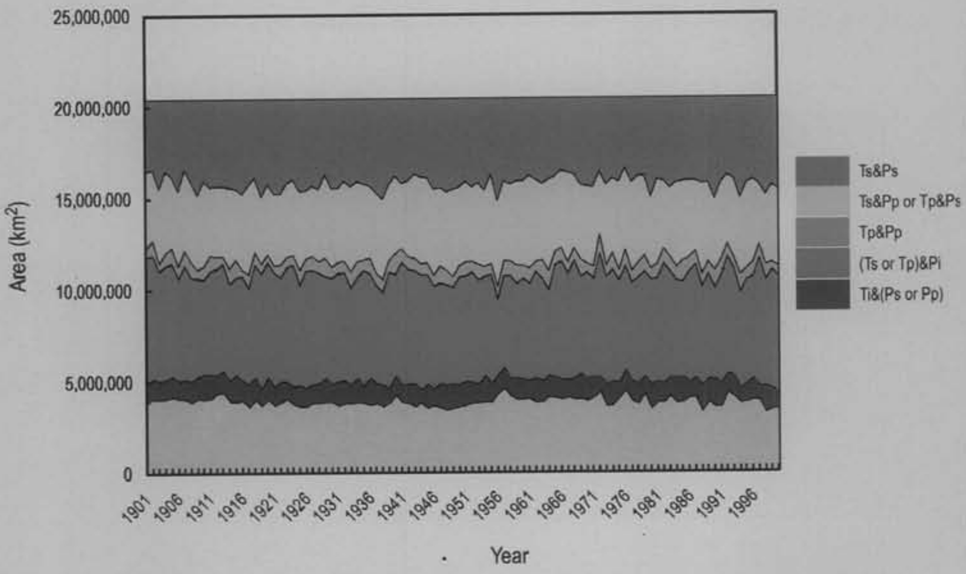

Fig. 19. Changes in suitable and potential areas for cultivating main/first-crop rice under the climate conditions from 1901 to 2000 (New et al., 2002), based on the air temperature and precipitation, which are of the current growing period for each country or region. For cultivating rice, the suitable cumulative air temperature Ts is in the range of 2400-3500 degree day and the potential one Tp is in the range of 2000-2400 or 3500-5800 degree day; the suitable precipitation Ps is 600 mm or more and the potential one Pp is in the range of 400-600 mm; Ti indicates outside the range of suitable and potential cumulative air temperature and Pi indicates outside the range of suitable and potential precipitation.

On the other hand, the suitable and potential areas for cultivating winter wheat from1901 to 2000 were estimated to increase by 10% in 100 years of the 20th century. In the total area of five major countries (USA, Canada, Brazil, Australia and Russia) producing winter wheat in the world, the suitable and potential areas in 2001-2099 were predicted to vary widely and increase by more than 20% of the present (1961-1990 mean) area.

For cultivating spring wheat, the suitable mean air temperature Ts is in the range of 15-18°C and the potential one Tp is in the range of 13-15 or 18-20°C; the suitable precipitation Ps is in the range of 200-500 mm and the potential one Pp is in the range of 100-200 or 500-700 mm (Cui, 1994; World Agricultural Outlook Board, 1994).

Spring wheat prefers cool and dry climate in comparison to rice. I summed up the suitable and potential areas for cultivating spring wheat. These total areas in the eastern part of Asia (Pakistan and eastward) depended on GCMs. In 2001-2099, these total areas were predicted to vary in the range of -75 to + 30% of the present (1961-1990 mean) area (1.7 million km^2). On the other hand, the suitable and potential areas for cultivating spring wheat from1901 to 2000 were estimated to increase by 15% in 100 years of the 20^{th} century. In the total area of the five countries mentioned above, the suitable and potential areas in 2001-2099 were predicted to vary in the range of -20 to +25% of the present (1961-1990 mean) area.

For cultivating main/early-crop maize, the suitable mean air temperature Ts is in the range of 20-25°C and the potential one Tp is in the range of 16-20 or 25-29°C; the suitable precipitation Ps is in the range of 400-800 mm and the potential one Pp is in the range of 250-500 or 800-1,000 mm (Cui, 1994; World Agricultural Outlook Board, 1994).

Main/early-crop maize prefers warm climate, the same as rice. I summed up the suitable and potential areas for cultivating main/early-crop maize. These total areas in the eastern part of Asia (Pakistan and eastward) tended to decrease slowly. In 2001-2099, these total areas were predicted to decrease by 10-30% of the present (1961-1990 mean) area (6.8 million km^2). On the other hand, the suitable and potential areas for cultivating main/early-crop maize from 1901 to 2000 were estimated to remain at almost the same level in 100 years of the 20^{th} century. In the total area of four major countries (USA, Canada, Brazil and Russia) producing main/early-crop maize in the world, the suitable and potential areas in 2001-2099 were predicted to increase by more than 50% of the present (1961-1990 mean) area.

Changes in Yield Per Unit Area: An Approach from Biomass Productivity

Agricultural productivity and climate change

Bhatti *et al.* (1991) estimated the productivity of agricultural land from the relationship between soil fertility and wheat yield per unit area, using the geostatistics method and the Landsat Thematic Mapper (TM) data. Saito *et al.* (1994) estimated the productivity of agricultural land using geographical information such as a soil fertility map and a land slope map, and thematic maps such as a vegetation index map and a soil organic matter map based on satellite remote sensing data.

To clarify changes in production in potential regions for cultivating cereals under the present climate conditions and after climate change, Leemans and Solomon (1993) developed a model to detect potential regions for cereal cultivation based on the daily air temperature, daily soil moisture and solar radiation. They predicted that in the higher latitudes, climate change would cause an increase in the production owing to a longer growing period, but in the middle to lower latitudes, the production would remain at the same level or decrease.

On the basis of global environmental change, it is predicted that the amplitude of climate change, particularly daily difference, will become wide (Easterling *et al.*, 1997). Estimating how climate change will affect the cereal production is very important to predict the food supply in the future. Mearns *et al.* (1996) examined the impact of daily and yearly change in air temperature and precipitation on the wheat production using the wheat growth model, CERES-Wheat, for the Great Plains, USA. They reported that a large change in the air temperature caused a change in production mainly because of a decrease in the mean yield per unit area; the mean yield in the regions with limited soil moisture increased. Moreover, they pointed out that considering the daily (and yearly) climate change was important to analyze the impact of climate change on the crop yield per unit area. For four test sites from north to south in the central part of the USA, Rosenzweig and Tubiello (1996) used CERES-Wheat to estimate changes in the wheat yield per unit area under the conditions of current CO_2 level (330 ppm) and high CO_2 level (500 ppm), and an air temperature increase of 1-4°C. Their results showed that the wheat yield per unit area decreased under the conditions of current CO_2 level and high air temperature; under the conditions of high CO_2 level and high air temperature, the wheat yield per unit area increased in some cases but decreased in other cases. Moreover, the decrease in the yield per unit area was larger in southern test sites than in northern test sites. This result provided evidence to support the prediction by Leemans and Solomon (1993). A similar prediction was also made by Fischer *et al.* (1995).

The report in which Tucker *et al.* (1985) estimated the net primary productivity (NPP) on the basis of the fraction of absorbed photosynthetic available radiation (fAPAR) calculated from vegetation index is the primary reference for estimating the terrestrial productivity of a country to the entire Earth using satellite remote sensing data. Many studies on the extension of this idea have been conducted. Sims *et al.* (2008) proposed a new model to estimate the gross primary productivity based solely on the enhanced vegetation index and land surface temperature from satellite data. Blackard *et al.* (2008) estimated biomass using satellite data and inventory data, such as topographic variables, and monthly and annual climate parameters. Nagai *et al.* (2007) clarified the relationship between biomass production and meteorological parameters (air temperature and precipitation) caused by El Niño- Southern Oscillation (ENSO), by analyzing meteorological parameters and satellite data in 1981 to 2000. Jeyaseelan *et al.* (2007) reported that changes in air temperature and precipitation affected the biomass production of India from 1982 to 2003. Tan (2007) conducted a similar study for the Great Plains, USA from 1982 to 2001. Myneni *et al.* (1997) showed that the level of terrestrial photosynthesis increased in the world from 1981 to 1991, using satellite remote sensing data. This was also supported by a report on an increase in the wheat yield per unit area in Australia (Nicholls, 1997). Moreover, Prasad *et al.* (2007) reported a correlation coefficient of $R^2>0.90$ between meteorological parameters and crop yield, by analyzing soil moisture, surface temperature and rainfall data and the normalized difference vegetation index (NDVI) calculated from satellite remote sensing data for India from 1984 to 1999.

Climatology-based potential productivity in Asia

Approaches to crop growth models are very effective for estimating the crop yield per unit area. Generally, these models require many input parameters (for example, a crop model by IBSNAT (1995) requires at least 23 input parameters of meteorology, soil, management and experimental location, and the input parameters required by these models are not available worldwide, but only for a limited region. Moreover, it is very difficult to predict future changes in land-use/land-cover and the actual cultivated crops in the world.

Approaches to process models using satellite remote sensing are also very effective for estimating the NPP. However, satellite remote sensing data cannot be used to predict something in the future because remote sensing data exist only from the past to the present.

Because of the reasons mentioned above, Okamoto and Yokozawa (1999) used only climate data to estimate the potential NPP, and then considered changes in the yield per unit area (vegetative productivity). They analyzed changes in the productivity in arable land and country as a whole for East and South Asia, such as Bangladesh, Cambodia, China (mainland), Indonesia, India, Japan, North and South Korea, Laos, Mongolia, Myanmar, Malaysia, Philippines, Thailand and Vietnam. The productivity was considered using the NPP (dry weight) as an index. However, the NPP depends on the model used (Bondeau *et al.*, 1999). Okamoto and Yokozawa (1999) used the Miami model (Lieth, 1973), in which the NPP was calculated only from air temperature and precipitation. For the current climate data, the monthly mean air temperature and precipitation from the database of the International Institute for Applied System Analysis (IIASA) (Cramer, 1996) were used. For the monthly mean air temperature and precipitation under the condition of double the current CO_2 level, the results from simulation using the world major GCMs were used (Table 2 except MRI). Okamoto *et al.* (2000) reported the prediction using the result from MRI and including Pakistan. For the land cover data, the global 1 km land-cover data set DISCover (Belward *et al.*, 1999) from the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) office was used. The Dryland Cropland and Pasture, Irrigated Cropland and Pasture, Mixed Dryland/Irrigated Cropland and Pasture, Cropland/Grassland Mosaic, Cropland/Woodland Mosaic in the DISCover were defined as current arable land.

According to the report by Okamoto and Yokozawa (1999), in East and South Asia (15 countries), the terrestrial NPP increased by 7 to 36% of the current one (22.2×10^{12} kg yr^{-1}) under the condition of double the current CO_2 level. The NPP in arable land increased by 4 to 21% of the current one (10.8×10^{12} kg yr^{-1}) under the condition of double the current CO_2 level, but the rate of increase was smaller than that all over the land (Table 4). The NPP based on the results from $HADCM2_{+S}$ increased by 7% of the current one in the land and by 4% of the current one in the arable land. Both rates of increase were small. The NPP based on the results from CGCM1 increased by 36% of the current one in the land and by 21% of the current one in the arable land. Both rates of increase were large. On the other hand, the NPP based on the results from $CGCM1_{+S}$ increased by 23% of the current one in the land but slightly by 5% of the current one in the arable land.

Table 4. Changes in NPP (a) all over the country and (b) in the current arable land in East and South Asia (India and eastward). The current arable land consists of Dryland Cropland and Pasture, Irrigated Cropland and Pasture, Mixed Dryland/Irrigated Cropland and Pasture, Cropland/Grassland Mosaic, Cropland/Woodland Mosaic. NPP is defined as dry weight and its unit is shown in 10^9 kg yr^{-1}. Subscript +S of the GCM name indicates the result from simulation including the effects of sulfur compounds

Country	IIASA2	CGCM1	CG CM1$_{+S}$	GFDL GCM	GFDL GCM$_{+S}$	HADC M2	HADC M2$_{+S}$	ECHA M4/ OPYC3	ECHAM4/ OPYC3$_{+S}$
(a) Land									
Bangladesh	285	278	264	278	217	173	125	263	253
Cambodia	361	457	427	427	387	378	323	344	359
China	5,811	10,351	8,836	9,549	9,511	7,618	6,760	7,312	6,952
Indonesia	3,323	3,222	3,380	3,593	3,904	4,226	4,196	4,120	4,490
India	4,359	5,327	4,446	3,785	4,006	3,909	3,850	4,119	3,628
Japan	375	502	401	567	536	620	589	593	623
Korea D P Rp	129	139	110	183	145	136	117	108	109
Korea Rep	120	98	103	125	118	119	82	147	123
Laos	448	488	486	544	454	442	321	502	430
Mongolia	412	911	1,029	725	1,064	597	487	439	486
Myanmar	1,301	1,528	1,419	1,479	1,250	1,379	1,116	1,341	1,115
Malaysia	687	665	676	746	748	784	756	784	766
Philippines	395	650	649	624	652	692	668	651	672
Thailand	895	1,196	1,138	1,239	1,045	1,118	931	1,037	919
Viet Nam	550	625	641	736	656	627	511	615	587
Total	19,450	26,437	24,006	24,601	24,693	22,817	20,831	22,376	21,512
Ratio to present	100.0	135.9	123.4	126.5	127.0	117.3	107.1	115.0	110.6
Ratio to Asia (%)	87.7	81.4	82.6	83.5	82.8	89.6	88.9	87.1	89.0
Asia	22,171	32,493	29,072	29,462	29,825	25,473	23,419	25,676	24,183
Ratio to World (%)	18.9	20.6	18.8	19.5	19.2	20.9	19.1	18.1	18.1
World total	102,918	128,403	127,797	125,860	128,831	109,335	109,003	123,687	118,923
(b) Current arable land									
Bangladesh	216	208	201	211	165	127	93	197	187
Cambodia	202	253	236	237	215	209	178	190	199
China	3,260	3,996	3,139	3,811	3,851	3,782	3,552	3,692	3,582
Indonesia	977	884	926	984	1,122	1,321	1,277	1,176	1,322
India	3,151	3,879	3,253	2,677	2,859	2,787	2,775	2,947	2,610
Japan	104	147	116	169	159	181	170	171	181

cont....

Table 4. contd.....

country	IIASA2	CGCM1	CGCM1+s	GFDL GCM	GFDL GCM+s	HAD CM2	HAD CM2+s	ECHAM4/OPYC3	ECHAM4/OPYC3+s
Korea D P Rp	81	87	67	111	88	84	70	70	65
Korea Rep	81	67	70	86	81	80	55	100	84
Laos	75	80	73	85	71	69	54	77	71
Mongolia	13	29	32	18	25	20	16	13	15
Myanmar	300	378	357	369	298	352	298	328	272
Malaysia	294	295	301	323	322	350	334	352	347
Philippines	335	562	560	539	563	598	576	563	581
Thailand	538	743	699	771	646	683	569	635	574
Viet Nam	293	363	361	420	380	362	297	345	338
Total	9,921	11,970	10,392	10,811	10,846	11,003	10,316	10,856	10,428
Ratio to present	100.0	120.7	104.8	109.0	109.3	110.9	104.0	109.4	105.1
Ratio to Asia (%)	91.6	89.8	89.4	91.7	90.7	92.2	92.3	90.6	92.2
Asia	10,836	13,326	11,621	11,783	11,960	11,940	11,178	11,976	11,307
Ratio to World (%)	34.2	35.8	31.7	35.2	34.8	36.1	34.1	33.2	33.2
World total	29,019	33,429	32,824	30,678	31,143	30,447	30,265	32,707	31,363

Changes in the potential yield per unit area under changing climate conditions

Okamoto *et al.* (2004) predicted changes in the yield per unit area for five major Asian countries, namely, Bangladesh, India, China, Japan and South Korea, on an extension of NPP estimated by Okamoto and Yokozawa (1999).

Changes in NPPs are shown in Table 4. The NPP of the total land area of China in the mid-21st century was estimated to increase by 1.2-1.8 times the present level, while the NPP of its cropland area in the mid-21st century was estimated to be 1.0-1.2 times the present level. The NPPs of the cropland and total land areas of Japan in the mid-21st century were estimated to increase by 1.1-1.7 times the present level. The NPPs of the cropland and total land areas of South Korea in the mid-21st century were estimated to be 0.7-1.2 times the present level. In the case of India, the NPPs of the cropland and total land areas in the mid-21st century were estimated to be 0.8-1.2 times the present NPPs. Moreover, in the case of Bangladesh, the NPPs of the cropland and total land areas in the mid-21st century were estimated to decrease to 0.4-1.0 times the present NPPs. The NPPs of the cropland and total land areas in the mid-21st century were generally estimated to be higher than the present NPPs for East Asian countries, viz., China, Japan and South Korea. The rate of increase in the NPP of the cropland area differed from that of the total land area for China, whereas the rates of increase in the NPP of the cropland area were the same as those of the total land area for Japan and South Korea. The NPPs of Central, Northern and Northeastern China will increase owing to increases in air temperature and precipitation, while those of Southern China will remain constant owing to surplus precipitation. The NPPs of Western China will decrease owing to a decrease in precipitation. Desertification will be a problem in these regions. The NPPs of the cropland and total land areas were generally estimated to be lower than the present NPPs for South Asian countries, viz., India and Bangladesh. This is considered to be due to the uneven distribution of rainfall.

Three scenarios for projections of cereal yields and changes in NPPs were constructed: first, an optimistic scenario of the highest growth rate of cereal yield, in which the cereal yield in the 21st century will be an extension of the second-order regression curve of 1961-1999 cereal yields:

$$Yield_{op} = a*yr^2 + b*yr + c, \quad .....(1)$$

where a, b and c are coefficients and yr is the year to be estimated; second, a moderate scenario, in which the cereal yield in the 21st century will be an extension of the regression line of 1961-1999 cereal yields:

$$Yield_{mod} = a*yr + b, \quad .....(2)$$

where a and b are coefficients and yr is the year to be estimated; and lastly, a pessimistic scenario of no growth rate of cereal yield, in which the cereal yield in the 21st century will remain the same as that in 1999:

$$Yield_{pes} = Yield_{1999}. \quad ....(3)$$

There are also three possible scenarios for projecting changes in NPPs: first, an optimistic scenario, in which the maximum outputs of GCMs are used as the NPPs in the mid-21st century; second, a moderate scenario, in which the mean outputs of GCMs are used as the NPPs in the mid-21st century; and lastly, a pessimistic scenario, in which the minimum outputs of GCMs are used as the NPPs in the mid-21st century.

Projected cereal yields in the mid-21st century were adjusted according to the ratio of the NPP in the mid-21st century to the present NPP, ΔNPP. We used both moderate scenarios for projections of cereal yields (equation 2) and changes in NPPs to evaluate the socio-economic impacts of NPP change, since the continuity of the recent trend is the natural course of events. By using ΔNPP and the results of regression analyses of the 1961-1999 statistics of cereal yields (FAO, 2009), the coefficients of the estimation equation of cereal yield for test sites were

$$\text{China:} Yield_{yr} = 12.9*yr - 25298.1, \quad .....(4)$$

$$\text{Japan:} Yield_{yr} = 15.9*yr - 31204.5, \quad .....(5)$$

$$\text{South Korea:} Yield_{yr} = 10.1*yr - 19522.3, \quad .....(6)$$

$$\text{India:} Yield_{yr} = 3.2*yr - 6251.6, \text{ and} \quad .....(7)$$

$$\text{Bangladesh:} Yield_{yr} = 1.5*yr - 2780.8 \quad ......(8)$$

Here, $Yield_{yr}$ is the estimated cereal yield in units of $x10^3$ kg km^{-2} in yr.

The 1961-2000 statistics of cereal yield (FAO, 2009) were summarized and cereal yields under the above-mentioned scenarios were predicted (Fig. 20). The cereal yield of China in 2050 was estimated to increase to 9.5 times that in 1961 and 2.3 times that in 1999, in accordance with the above-mentioned scenarios, viz., a regression line

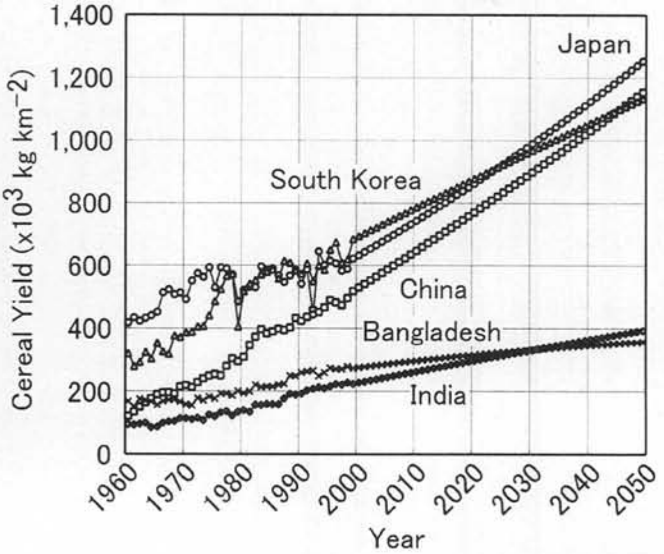

Fig. 20. History and prediction of cereal yield [$x10^3$ kg km^{-2}]. Both moderate scenarios for projections of cereal yields and changes in NPPs were used. Projected cereal yields were adjusted according to the ratio of the NPP in the mid-21st century to the present NPP. The cereal yields from 1961 to 1999 were derived from available statistics (FAO, 2009).

of 1961-1999 cereal yields and an increase in NPP. The cereal yield of Japan in 2050 was estimated to increase to 3.0 times that in 1961 and 2.1 times that in 1999. The cereal yield of South Korea in 2050 was estimated to increase to 3.5 times that in 1961 and 1.8 times that in 1999. The cereal yield of India in 2050 was estimated to increase to 4.1 times that in 1961 and 1.7 times that in 1999. The cereal yield of Bangladesh in 2050 was estimated to increase to 2.1 times that in 1961 and 1.3 times that in 1999.

Will Asian People have Sufficient Food in the Future?

As shown in a recent study, Battisti and Naylor (2009) said, "The food crisis of 2006-2008 demonstrates the fragile nature of feeding the world's human population. Rapid growth in demand for food, animal feed, and biofuels, coupled with disruptions in agricultural supplies caused by poor weather, crop disease, and export restrictions in key countries like India and Argentina, have created chaos in international markets".

However, the sizes of suitable and potential regions for cultivating major crops (rice, wheat and maize) would remain in the status quo or would expand. Then, we showed that the yield per unit area would increase in accordance with the increase in climatology-based potential productivity.

Actually, will Asian people have sufficient food in the 21st century? To answer this question, we must consider not only changes in natural conditions, but also changes in socio-economic conditions. Okamoto *et al.* (2004) predicted changes in the food supply and demand in five major Asian countries, on the basis of NPP estimation (Okamoto and Yokozawa, 1999) and population projection. The cereal demand was evaluated using cereal supply per capita as an index. The 2000-2050 population projections (FAO, 2009) were used to calculate cereal supply per capita. The 1961-2000 and 2001-2050 population projections (FAO, 2009) were also summarized (Fig. 21).

The population of China in 2050 is projected to increase to 2.2 times that in 1961 and 1.2 times that in 1999. Comparison of the 1961 cereal yield and population of China with the 2050 projections shows that the rate of increase in cereal yield is far higher than the population growth rate, which means that the Chinese people will have double the amount of cereals in 2050 than they have at present, if the area of arable land remains constant.

The population of Japan in 2050 is projected to increase to 1.1 times that in 1961 and 0.8 times that in 1999. That is, the population of Japan in 2050 will be lower than the present value. Comparison of the 1961 cereal yield and population of Japan with those of 2050 shows that the rate of increase in cereal yield is far higher than the population growth rate, which means that the level of self- sufficiency in food in Japan will possibly be higher in 2050 than it is at present if the area of arable land and food trade remain unchanged.

The population of South Korea in 2050 is projected to increase by 2.0 times that in 1961 and 1.1 times that in 1999. Comparison of the 1961 cereal yield and population of South Korea with the 2050 values shows that the rate of increase in cereal yield will be higher than the population growth rate, which means that the South Korean people will have a larger amount of cereal, or the same amount, in 2050 as that of the present, provided the area of arable land and food trade remain unchanged.

The population of India in 2050 is projected to increase by 3.4 times that in 1961 and 1.5 times that in 1999. Comparison of the 1961 cereal yield and population of India with the 2050 values shows that the rate of increase in cereal yield is almost the same as the population growth rate, which means that the Indian people will have almost the same amount of cereals in 2050 as they have at present, provided the area of arable land and food trade remain unchanged.

The population of Bangladesh in 2050 is projected to increase by 4.0 times that in 1961 and 1.7 times that in 1999. Bangladesh is the only country among the test sites that exhibits a smaller rate of increase in cereal yield than the population growth rate, as shown in the comparison between the 1961 values with the 2050 values, which means that the Bangladeshi people will have a smaller amount of cereals, or the same amount, in 2050 as they have at present, if the area of arable land and food trade remain unchanged. Bangladesh has 56.2% arable land area and 62.8% agricultural area, as a proportion of its total land area (FAO, 2009). It is difficult for Bangladesh to expand its arable land area to increase cereal production.

The cereal yields of East Asian countries in 2050 were estimated to be higher than

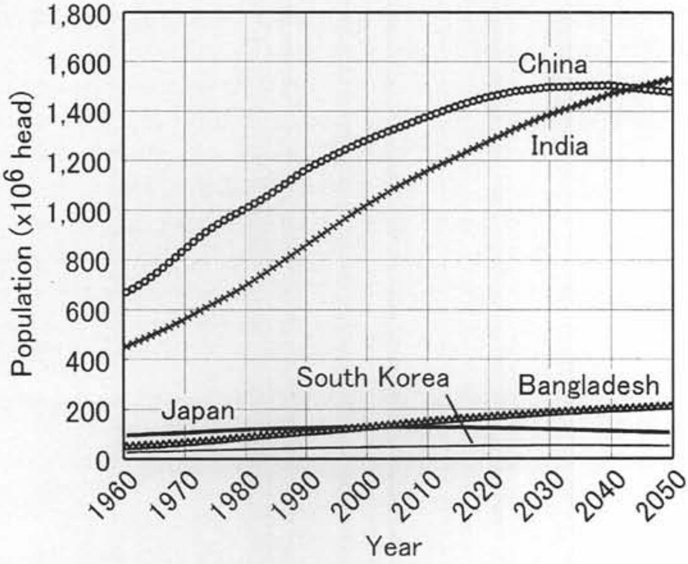

Fig. 21. History and projection of population [x10^6 head]. Estimation and projection of population were based on available statistics (FAO, 2009).

the present levels. China has 12.9% arable land area, as a proportion of its total land area and a large potential arable land area for cultivating cereals since its agricultural area is 55.8% of its total land area. Japan and South Korea are mountainous, Japan having 11.9% arable land area and 14.0% agricultural area and South Korea having 17.1% arable land and 19.7% agricultural area, as a proportion of their total land areas. The cereal yields of South Asian countries in 2050 were estimated to be lower than or equal to the present yields. India has 49.2% arable land area and 54.9% agricultural area, as a proportion of its total land area. These values are broadly similar to those of Bangladesh. It can be stated that the uneven distribution of NPP in South Asian countries will possibly cause regional differences in predicted cereal yields and socio-economic impacts.

In a study based on analyses of published statistics and prediction data, Kawashima and Okamoto (1999) predicted that economic growth would cause a decrease in the food production in Asia, and that free trade would result in further concentration of the major food-producing regions to North and South America and Australia.

In addition to the above-mentioned study, econometrics approaches to the analysis of the relationship between climate change and agricultural production have been conducted. Kumar and Parikh (2001) estimated the functional relationship between farm-level net revenue and climate variables, introduced through linear, quadratic and interaction terms, to understand the climate sensitivity of Indian agriculture. They concluded that the impacts that they estimated were smaller than those estimated using crop simulation model. To adopt the impacts of climate change, Chien *et al*. (2006) modified the global model on rice supply and demand to parameterize climatic factors. They simulated the rice supply and demand under the conditions based on the results from three GCMs, such as Hadley Centre, CCSR/NIES and MRI models. From their results, they concluded that a gap between supply and demand on rice would likely expand in China, Indonesia, Malaysia, Philippines and Bangladesh. According to their prediction, the main rice exporters, Thailand and Vietnam, will be very likely to oversupply under the changed climate, and there is a possibility that India will be a promising rice exporter. However, it was predicted that the impacts of climate change are mostly disadvantageous to these countries.

There is also a group of skeptical environmentalists on climate change. Lomborg (2001) started from asking if the global environment is really going from bad to worse, and investigated no less than 2000 papers and materials on the environment. Showing reliable evidence, such as the food production rate exceeding the world population growth rate, he pointed out that some environmental scientists made people worry about the global environment in the future. The author agrees with many of Lomborg's opinions.

Kawashima (2008) carefully analyzed the published statistics and predictions. As shown in his report, there is a possibility that the mean cereal yield per unit area in the world in 2050 will increase by 6.9 t/ha of the current level in West Europe. If so, because the increase in population will reach a peak except in Africa, agricultural surpluses will occur. In other words, this implies that an enormous surplus of arable land will be available in the world. A phenomenon of the increase in the cereal price caused by producing ethanol from biomass was observed from 2007 to 2008. In connection with this, Kawashima (2008) predicted that the production of ethanol from biomass would barely increase rapidly if the crude oil price is less than US$ 100 per barrel, because the cost of ethanol production from biomass is high in the USA. He also predicted that palm oil, which is a raw material for biodiesel, would be used as edible oil from the ethical viewpoint.

This prediction by Kawashima (2008) would be the most rational among the predictions on food production in the 21st century, because it takes an objective view. It does not mean that climate change will cause the conversion of the current arable land to wasteland. Moreover, climate change is not an event on the scale of a few years but on the scale of 50 to 100 years. Therefore, we have sufficient time to develop a new variety suitable for changed environments. Moreover, farmers will be able to select suitable crops for changed environments. Consequently, even if the global climate will change, the amount of food produced will meet the demands in Asia and the world, but it will not be equally distributed in the world.

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