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CLIMATE CHANGE IMPACT ON GLOBAL CROP PRODUCTION

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Abstract

Climate change impact on crop production may be one of the most serious problems in the next century. In order to evaluate this problem, we estimated potential crop productivity with a model based on local climatic, hydrological and soil characteristics. The model consists of three submodules: climate module, crop growth module and soil constraints module. The first module processes inputted climate data to generate the information required in the following submodules. At the second module, the number of days suitable for crop cultivation is counted and crop growth during the period is biophisically simulated according to the growth characteristic parameters of each crop. The third module considers the effects of soil characteristics, and estimates potential crop productivity. According to the estimation, potential crop productivity of winter wheat in 2100 will decrease 7.41∼16.82%, while that of maize for tropical cultivation and rice will increase 4.70∼8.36%, 2.71∼6.79%, respectively, under the assumption of medium GHGs emission scenario (IS92a) and medium climatic sensitivity (2.5°C).

KEYWORDS: *Global Environment, Climate Change, Crop Production, Potential Productivity*

1. Introduction

The Intergovernmental Panel on Climatic Change published its second assessment report on climatic change December 1995 after 3 years' intensive review of the scientific knowledge of global warming issues. Working group II has confirmed that the historical record of climate shows some sort of symptom of global warming, and that the global warming will have a significant impact on the natural resources, society and economy of the world's countries (IPCC, 1995).

The impact on agricultural resources is one of them. Since the change of agricultural resources will , in a chain reaction, cause a change of the world trade balance of both agricultural and other commodities among nations, world food securities will also be affected. The objective of our study is to comprehensively estimate the climatic change impact on agriculture in support of decision makings against these uncertain future potential problems.

In this paper we evaluate the climatic change impact on the production of five crops (rice, winter wheat, spring wheat, maize for tropical cultivation and maize for temperate cultivation)

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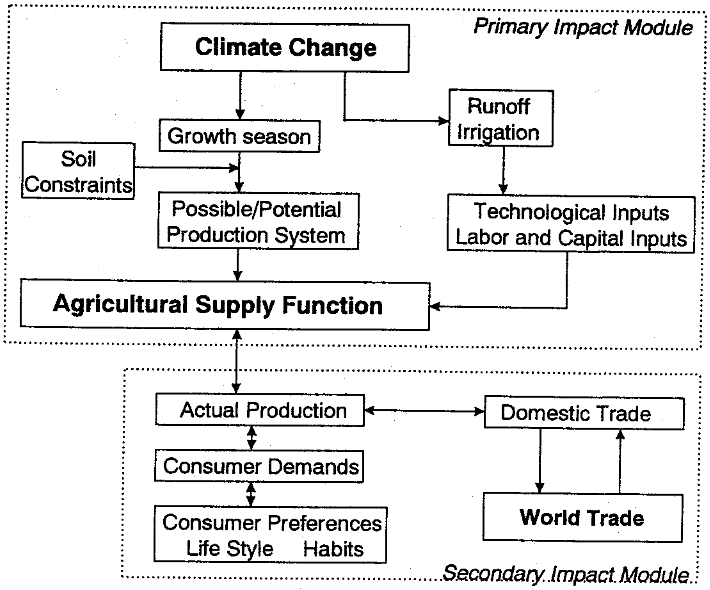

Figure 1. The framework for an estimation of climatic change impact on agriculture

through the quantitative estimation of potential crop productivity under changed climate. The method of potential productivity estimation is mainly based on the study by the Food and Agriculture Organization (FAO, 1978-1981). This method enables us to calculate crops yield under the constant level of agricultural inputs (potential productivity) from temperature, precipitation, solar radiation and soil conditions. The direct impact of CO_2 concentration on crop growth (CO_2 fertilization) is not considered in this study. Though a lot of similar studies have been done, most of them focused on local issues. However, we need to obtain an assessment of future agriculture from the point of view of global environment change. From this point of view, the target area of this study is the entire world, and the end of the next century is selected as the target year.

2. Framework of Agricultural Impact Study

In order to evaluate the impact of climatic changes on agriculture, we need to proceed the study based on a framework which can provide a step-by-step evaluation of the direct and indirect effects of such changes. Fig. 1 shows one example of such a framework approach. The basic assumptions of this figure are that (1) climatic change will directly affect land and water resources, and (2) changes in land and water resources will affect economic activities.

The upper part of this figure is an attempt to estimate the potential productivity of each crop under the climate and the land resources in the future. Potential productivity is calculated by a spot estimation of such productivity at selected representative points or by a spatial estimation which calculates it comprehensively with the help of a geographical information system (GIS). In many studies, yields are estimated using simulation models, which calculate daily crop growth in line with the plans of crop cultivation, *i.e.*, the crop calendars. The input factors of these simulation models are:

- climate conditions such as surface air temperature, precipitation, soil moisture and solar radiation
- physical and chemical soil characteristics such as soil unit and soil phase
- artificial agricultural inputs such as irrigation, fertilizer application and mechanization

Several points are controversial, *i.e.*, the effect of CO_2 fertilization, the changes in water use efficiency, soil degradation and the irrigation scenario. Table 1 shows examples of crop production simulation models which were used to evaluate climate impact on agriculture. All models in this table are classified as the primary impact module, as shown in the upper part of Fig. 1. The secondary impact consists of the change of commodity prices, balance of demand and supply, trade balance of agricultural commodities, and so on. Many studies on this secondary impact have used the existing world agriculture economic models. Applications of BLS (Fischer *et al.*, 1994), SWOPSIM (Kane *et al.*, 1992) and FARM (Darwin *et al.*, 1994) are well known. The crop productivity estimated in the upper part of Fig. 1 is systematically organized to form one agricultural supply function, which constitutes the basic production function of global/domestic agro-economic systems. In Kane's study, they divided the world into 13 regions and treated 20 commodities using a partial equilibrium model. According to their results, though some areas will suffer from serious production decreases due to climatic change, the worldwide economic impact will be alleviated by trade among regions, and the total change of GDP in world will be -0.17~0.09%. To advance this kind of analysis, deeper study of the direct impacts on a world scale is necessary, which often requires large capabilities of data management, computer resources and human resources. Moreover, there are many controversial and difficult points which should be taken into account by the model formulae and the scenarios which reflect the real world: transitive changes in cultivated crop species and cultivation methods, distinction of impact processes between domestic commodities and tradable commodities, changes of agricultural policy in each country. Consideration of strategic mitigation and adaptation is also very important in the secondary impact assessment. As for mitigation and adaptation, mainly there are two paths: the agro-ecological path and the economic path. The former includes physical efforts such as modification of cultivation schedules, change of planted species, development of new irrigation systems and more intensive fertilization. The latter includes maximization of financial profit (minimization of financial damage) expected with changes of planted crop species, production amounts and production methods. Fischer *et al.* (1994) reported the result of a climatic impact assessment on the world food supply considering adaptation and mitigation in conjunction with BLS (Fischer *et al.*, 1988), the general equilibrium model of world food trades developed by IIASA/FAP, and IBSNAT model (IBSNAT, 1989), the crop model developed by International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). According to their results, without mitigation and adaptation, world crop production will decrease 1~8%, and crop prices will increase 24~145% by 2060, compared with the base scenario assuming no climatic change. On the other hand, if appropriate mitigation and adaptation are adopted at the individual farmer's level, world crop production and crop prices will change -2.5~1% and -5~35%, respectively, by 2060.

3. Model Description

3.1 GIS potential crop productivity model

In this paper we focus the attention on the direct impact of climate change on food production, as shown in the upper part of Fig. 1. To evaluate the impact, we developed a GIS-based

Table 1. Simulation models used for the estimation of climate impact on agriculture (U.S. Country Studies Program, 1994)

Crop Name	Model Name	Developer/User
Alfalfa	ALSIM	Fick (1981)
	ALFALFA	Dennison and Loomis (1989)
Barley	CERES-Barley	Ritchie et al. (1989)
Cotton	GOSSYM	Baker et al. (1983)
	COTCROP	Brown et al. (1985)
	COTTAM	Jackson et al. (1988)
Beans	BEANGRO	Hoogenboom et al. (1989)
Maize	CERES-Maize	Jones and Kiniry (1986); Ritchie et al. (1989)
		Seino (1995)
	-	Stockle and Campbell (1985)
	CORNF	Stapper and Arkin (1980)
	SIMAIZ	Duncan (1975)
	CORNGRO	Childs et al. (1977)
	CORNMOD	Baker and Horrocks (1976); Morgan et al. (1980)
	-	Morgan et al. (1980)
	VT-Maize	Newkirk et al. (1989)
	GAPS	Buttler (1989)
	CUPID	Norman and Campbell (1983)
Peanuts	PNUTGRO	Boote et al. (1989)
	-	Young et al. (1979)
Millet	CERES-Millet	Ritchie and Alagarswamy (1989)
	RESCAP	Monteith et al. (1989)
White Potato	-	Ng and Loomis (1984)
	SUBSTOR	Griffin et al. (1993)
Rice	CERES-Rice	Godwin et al. (1990); Seino (1995)
	-	Aggarwal and Penning de Vries (1989)
	SIMRIW	Horie (1988)
Sorghum	SORGF	Arkin et al. (1976)
	CERES-Sorghum	Ritchie and Alagarswamy (1989)
	SORKAM	Rosenthal et al. (1989)
	RESCAP	Monteith et al. (1989)
Soybean	SOYGRO	Wilkerson et al. (1983); Jones et al. (1989)
	GLYCIM	Acock et al. (1983)
	SOYMOD	Curry et al. (1975)
Sugarcane	CANEMOD	Inman-Bamber (1991)
	-	Yoshino and Urushihara (1991)
Wheat	CERES-Wheat	Ritchie (1985); Godwin et al. (1985); Seino (1995)
	-	Stockle and Campbell (1989)
	TAMW	Maas and Arkin (1980)
	-	van Keulen and Seligman (1987)
	SIMTAG	Stapper (1984)
General	EPIC	Willams et al. (1984)

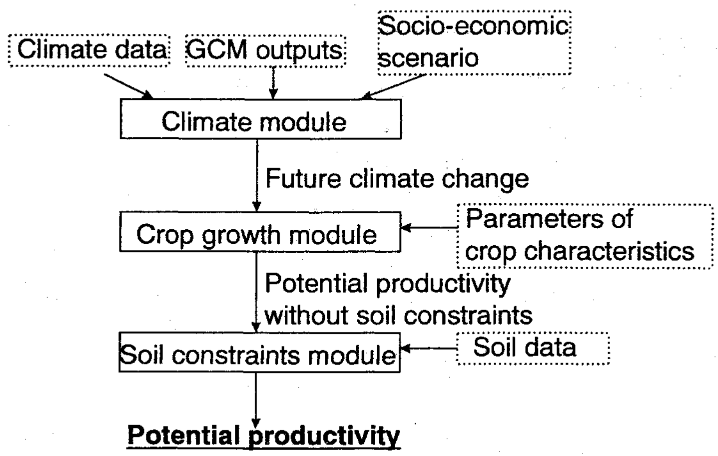

Figure 2. GIS potential crop productivity model

potential crop productivity model. Potential productivity is defined as crop yield under a fixed level of agricultural input. This model enabled us to calculate potential productivity under rainfed cultivation at each grid and to evaluate the climate impact on crop production quantitatively in various spatial aggregations. It also made it possible to investigate the change in arable land by graphical interpretation of the simulated result.

Until now, many agriculture models are used to evaluate the direct climatic impacts on food production (Table 1). Some of them have taken account of daily agricultural inputs such as fertilizer and irrigation water at the individual farmer's level. We, however, judged that those elaborate models which require detailed local and site-specific information were not appropriate for our study because of their complexity. The target area of our research is the whole world and the time scale is very large, for example the end of next century. Therefore we decided to adopt a model with medium complexity which can accommodate the global estimation. Though this approach is not better in accuracy than the more elaborate approaches, we judged it is applicable not only for a global estimation but also for a more local one such as a national-level study.

Fig. 2 shows the framework of this model. This model consists of three modules. The first one is the climate module. Here inputted climate data such as temperature, precipitation and cloudiness are processed to produce the information required to assess the feasibility of crop growth and to estimate crop growth rate. Outputs of this submodule are climatic factors which are concerned with crop growth such as potential evapotranspiration and solar radiation.

The second module is a crop growth simulation module. Here days suitable for crop cultivation (growing period) are counted using the information produced in the previous module, then the crop growth during the growing period is biophisically simulated according to the growth characteristic parameters of each crop. Adjusting these parameters, we can consider the differences of growth characteristics among species and varieties. In this module, potential crop productivity is evaluated only from climatic conditions.

In the third module, we consider the effects of four soil characteristics with data provided by the Soil Map of the World, *i.e.*, soil unit, soil phase, soil texture and slope. These effects are incorporated into the model as decrement factors of potential productivity calculated at the

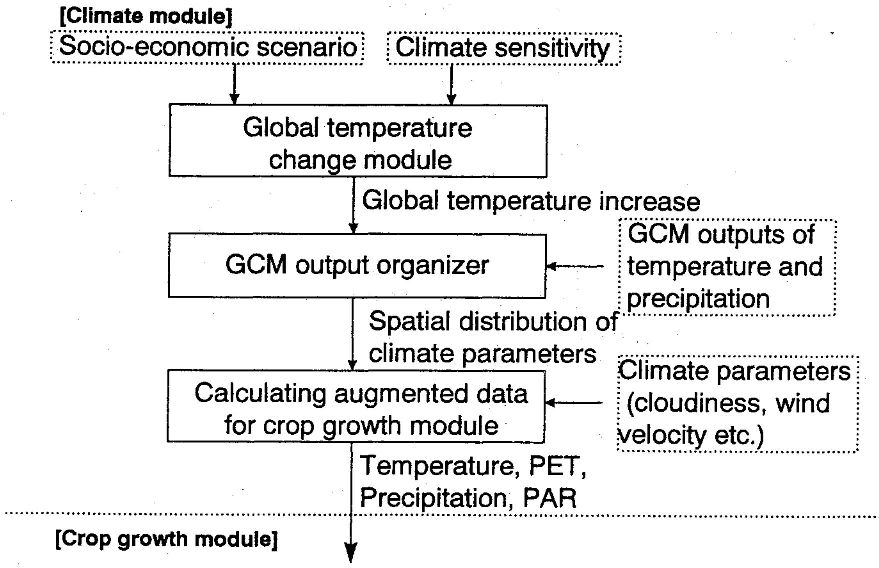

Figure 3. Calculation flow of the climate module

previous crop growth module. In the following chapter, we will illustrate these three modules one by one.

3.2 Climate module

This module consists of: the global temperature change part, the GCM output organizing part, and the calculation of data required in the crop growth module. The flow of this module is illustrated in Fig. 3.

The temperature change part calculates global annual mean temperature increases from GHGs emission scenarios. We used the global temperature increase model developed by AIM (Matsuoka *et al.*, 1995).

To consider the spatial distribution of climate data, we use the outputs of a climate model which was calculated by various General Circulation Models (GCMs). Since spatial resolution of GCM outputs is not fine enough for the use of impact studies, the GCM output organizing part interpolates the GCM outputs spatially by the methods appropriate for each climate parameter and generates future climate data with the global mean temperature increases calculated at the previous step. As for temperature, the spline interpolation method was used. The $1/r^2$-weighted interpolation method (r: radius) was used for precipitation. After the interpolation of GCM outputs, the following formula are used to calculate future climate data in each grid for each month.

For temperature,

$$T(t) = T(1990) + (T(2 \times CO_2) - T(1 \times CO_2)) \times \frac{T_{mean}(t) - T_{mean}(1990)}{\Delta T} \quad (1)$$

For precipitation

$$P(t) = P(1990) + P(1990) \times \left\{ \frac{P(2 \times CO_2)}{P(1 \times CO_2)} - 1 \right\} \times \frac{T_{mean}(t) - T_{mean}(1990)}{\Delta T} \tag{2}$$

Here, $T(t)$ [°C] and $P(t)$ [mm/month] are the temperature and the precipitation in year t, respectively. $T(2\times CO_2) - T(1\times CO_2)$ [°C] is the temperature difference and $P(2\times CO_2)/P(1\times CO_2)$ [-] is the precipitation ratio between $2\times CO_2$ and $1\times CO_2$ at the grid, which are calculated by GCMs. ΔT [°C] is the equilibrium surface temperature change on $2 \times CO_2$ (Table 6, later). $T_{mean}(t) - T_{mean}(1990)$ [°C] is the global annual mean temperature increase between the base year, 1990, and year t, which is calculated in the global temperature change part.

The crop growth module requires mean temperature, mean daytime temperature, precipitation, PET (potential evapotranspiration) and photosynthetically active radiation to estimate the suitability of cultivation and to estimate crop growth potential. PET was defined as the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation (Penman, 1948). Although temperature and precipitation are observed in many stations, PET and radiation are seldom observed. To estimate these data, solar radiation is estimated from cloudiness which is more often observed at many stations.

Regarding PET, we prepared modules based on the FAO24 method (FAO, 1992) and Thornthewaite method to estimate it in our model, and the choice depends on the data availability. The FAO24 method is one of the varieties of Penman's and requires more data than Thornthewaite method which expresses PET simply as a function of mean air temperature and day-length. On the other hand, Penman devised a more complex but more comprehensive set of formulae which involved saturation deficit, temperature, wind speed, net radiation, and so on.

3.3 Crop growth module

Using the results calculated with the climate module, the crop growth module calculates potential crop productivity without considering soil constraints. The calculating flow of this module is shown in Fig. 4, and the model parameters which represent crop characteristics are shown in Table 2.

To determine the days suitable for crop growth, the concept of a growing period is used. A growing period is defined as the period when available water and temperature regimes permit crop growth. If the growing period is longer than the growing period normally required for maturation (NGP, in Table 2), crops are expected to grow enough to reach maturation with achievement of a maximum LAI (LAI_{max}). LAI (leaf area index) is the area of all leaves (only one surface is counted) per unit area of ground (Loomis and Connor, 1992). If the growing period is less than the NGP, the growth rate of the crop is estimated to be slower because LAI_{max} cannot be achieved and not enough photosynthesis occurs. If the growing period is much less than the required days (less than GP_{min}), the crop is judged inappropriate for cultivation.

The growing period is calculated as the number of days which satisfy the following requirements.

- Water requirement: The amount of precipitation exceeds half of the PET or the water which plants can utilize remains in the soil.
- Temperature requirement: The daily average temperature is in the range appropriate for crop growth.

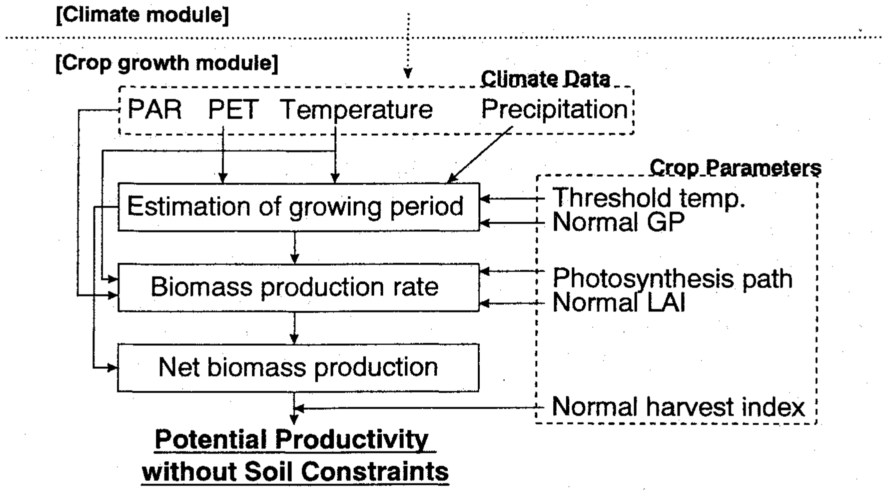

Figure 4. Crop growth module

Table 2. Model parameters of crop characteristics

Crop Name	Rice	Winter Wheat	Spring Wheat	Maize (tropical)	Maize (temperate)
Crop group	II	I	I	III	IV
Photosynthesis path	C3	C3	C3	C4	C4
Normal GP (*NGP*), days	130	150	100(*)	120	110(*)
Minimum GP (GP_{min}), days	100	120	100	90	110
Yield formation period (*YP*), days	30	30	-	30	-
Maximum LAI (LAI_{max})	5	5	5	4	4
Normal harvest index (NH_i)	0.3	0.4	0.4	0.35	0.35
Minimum allowable temperature (T_{min}), °C	13	5	5	12	12
Maximum allowable temperature(T_{max}), °C	36	25	25	40	40

(*) Normal growing period (*NGP*) of spring wheat and maize (temperate) changes depending on the GP-averaged daily mean temperature. *NGP* of spring wheat in the table, 100 days, is the *NGP* for 20°C. As the temperature decreases by 0.5°C, *NGP* extends 6 days. For example, *NGP* of spring wheat at 18°C GP-averaged daily mean temperature is 100 + 6*(20 - 18) /0.5 = 124 days. The upper limit of extended *NGP* is 190 days. In the same way, for maize (temperate), *NGP* extension is 40 days per 1°C decrease from 20°C, and the upper limit of NGP is 310 days.

To calculate the growing period, both the maximum allowable temperature (T_{max}) and the minimum allowable temperature (T_{min}) are set for each crop in our study. Information from ECOCROP1 (FAO, 1994) was used to estimate these temperature boundaries. Those values are also shown in Table 2. The maximum water amount which soils can store (field capacity) was assumed to be 100 mm.

Net biomass (dry matter) production is calculated as the difference between the gross biomass production by a photosynthesis process and the biomass lost by a respiration process.

$$B_n = B_g - R \tag{3}$$

Here, B_n[kg/ha] is the net biomass production, B_g[kg/ha] is the gross biomass production, and R[kg/ha] is the respiration loss. The rate of the net biomass production is deduced from eq.(3).

$$b_n = \frac{dB_n}{dt} = b_g - r \tag{4}$$

Here, b_n[kg/(ha·day)] is the rate of the net biomass production, b_g[kg/(ha·day)] is the rate of the gross biomass production, and r[kg/(ha·day)] is the rate of the respiration loss.

Potential crop productivity without taking account of soil constraint is the economically useful part of this net biomass. This fraction of the useful part is called the harvest index and is crop-specific.

$$B_y = B_n \times H_i \tag{5}$$

Here, B_y[kg/ha] is the potential productivity without taking account of soil constraints, and H_i[-] is the harvest index.

The growth rate of dry biomass weight added by photosynthesis process (b_g) is determined by the daytime mean temperature, photosynthetically active radiation (PAR), leaf area index (LAI), and photosynthesis path. Photosynthetically active radiation (PAR) is the radiation which plants can utilize for photosynthesis. The amount of PAR on a perfectly clear day at different latitudes has been given by an experimental formula and, on a totally overcast day, is assumed to be 20% of that on clear day. To calculate b_g, we used experimental formula which was introduced in FAO/AEZ Method (FAO(1978-1981), pp.66).

The rate of respiration loss (r[kg/(ha·day)]) is made of maintenance respiration (linear function of the net biomass production, B_n) and growth respiration (linear function of the rate of gross biomass production, b_g). According to McCree (1974), the respiration rate is

$$r = 0.28 \times b_g + c(T) \times B_n \tag{6}$$

$$c(T) = 0.0108 \times (0.044 + 0.0019T + 0.001T^2) \tag{7}$$

Here, T[°C] is the 24-hour average temperature.

In order to calculate crop growth simply, the following assumptions were adopted.

- Climate parameters for crop growth are averaged ones during the growing period.
- Cumulative crop growth is assumed to show a sigmoid curve. (Fig. 5)
- The average rate of net biomass production during the growing period is half of the maximum crop growth rate.

Under these assumptions, the net biomass growth is described in the following formula.

$$B_n = \begin{cases} 0 & GP \leq GP_{min} \\ 0.5 \times b_{nm} \times GP & GP_{min} < GP < NGP \\ 0.5 \times b_{nm} \times NGP & NGP \leq GP \end{cases} \tag{8}$$

Here, B_n[kg/ha] is the net biomass production during the growing period (in eq.(3)), b_{nm} [kg/(ha·day)] is the maximum rate of net biomass production, and GP [days] is the growing period. GP_{min} [days] and NGP [days] are the minimum growing period and the required growing period, respectively, in Table 2.

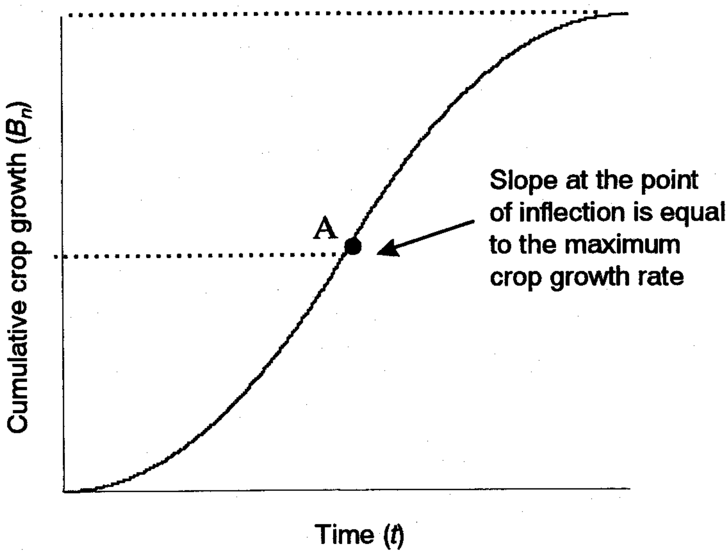

Figure 5. Assumed characteristics of crop growth

Since cumulative crop growth is assumed to show a sigmoid curve, the maximum net biomass growth rate b_{nm} is achieved at the middle of the growing period (the reflection point A in Fig. 5) and the cumulative biomass production at the point (B_{nm}) is equal to half the net biomass that would be accumulated at the end of the crop's life. From eqs.(4), (6) and (8), b_{nm} is represented as a function of the rate of gross biomass production (b_{gm}) and growing period GP .

$$\begin{aligned} b_{nm} &= b_{gm} - r_m \\ &= b_{gm} - (0.28 b_{gm} + c(T) \times B_{nm}) \\ &= 0.72 b_{gm} - c(T) \times 0.5 \times 0.5 b_{nm} \times GP \quad (\text{ if } \; GP_{min} < GP < NGP) \\ b_{nm} &= \frac{0.72 b_{gm}}{1 + 0.25 c(T) \cdot GP} \end{aligned} \tag{9}$$

From eqs. (8) and (9),

$$B_n = \begin{cases} 0 & GP \leq GP_{min} \\ \dfrac{0.36 b_{gm} \times GP}{1 + 0.25 c(T) \cdot GP} & GP_{min} < GP < NGP \\ \dfrac{0.36 b_{gm} \times NGP}{1 + 0.25 c(T) \cdot NGP} & NGP \leq GP \end{cases} \tag{10}$$

As mentioned before, b_{gm} is calculated by the average mean temperature and average daytime mean temperature during the growing period, average photosynthetically active radiation during the growing period, and the crop characteristics parameters in Table 2 . The discount of the growth rate caused by incomplete LAI (failure in formulation of leaves) due to the short growing period is also considered here.

The harvest index H_i is estimated in the following equation.

$$H_i = \begin{cases} NH_i \times (GP - GP_{min})/YP & GP_{min} < GP < NGP \\ NH_i & NGP \leq GP \end{cases} \quad (11)$$

Here H_i [-] is the harvest index in eq.(5), NH_i [-] is the normal harvest index in Table 2, and YP [days] is the yield formation period. From eqs. (5), (10) and (11),

$$B_y = \begin{cases} 0 & GP \leq GP_{min} \\ \dfrac{0.36b_{gm} \times GP}{1 + 0.25c(T) \cdot GP} \times NH_i \times (GP - GP_{min})/YP & GP_{min} < GP < NGP \\ \dfrac{0.36b_{gm} \times NGP}{1 + 0.25c(T) \cdot NGP} \times NH_i & NGP \leq GP \end{cases} \quad (12)$$

3.4 Soil constraints module

Four kind of soil characteristics are considered. These correspond to the soil inventory made by the Soil Map of the World: 106 soil units, 12 phases, 3 slopes and 3 textures. To reflect the differences of soil constraints depending on agricultural input levels, two input levels, high and low, are considered. We assume high input as the cultivation with mechanization and high fertilizer input, and low input as non-mechanization and low fertilizer input.

For each soil constraint, the reduction rate of potential productivity is assumed, according to the experience by FAO (FAO, 1978-1981). Based on these results, the suitability of soil units classification for each crop cultivation was divided into four ranks :suitable (S1), marginally suitable (S2), not suitable but with a possibility of improvement through major land improvements (N1), and not suitable (N2). To calculate potential crop productivity under the soil constraints quantitatively, we replaced these suitability ranks with numerical reduction factors. We considered S1 as denoting no constraint from soil condition (soil unit constraint factor $f_{su} = 1.0$), S2 as a 50% reduction ($f_{su} = 0.5$), and both N1 and N2 as a 100% reduction ($f_{su} = 0$). In the same way, the soil phase constraint factor (f_{sp}), soil texture constraint factor (f_{st}) and slope constraint factor (f_{slp}) were prepared. The values of f_{sp}, f_{st} and f_{slp} for each crop and agricultural input are shown in Table 3, Table 4, and Table 5, respectively.

For the GIS calculation, the Digital Soil Map of the World (FAO/Unesco, 1994), which was distributed in the vector format , was converted to the 5-minute grid raster. Since each grid contains multiple soil units, we calculated crop productivity, considering the soil constraints as follows.

$$B_{ys} = B_y \times f_{sp} \times f_{st} \times f_{slp} \times \sum_{unt} (f_{su}(unt) \times urat(unt)) \quad (13)$$

Here, B_{ys} [kg/ha] is crop productivity considering soil constraints, B_y [kg/ha] is crop productivity without soil constraints in eq.(5), and $urat(unt)$ [-] is the area ratio of the soil unit unt in the grid.

4. Model Experiment

4.1 Input data and assumptions of the experiment

Using the model described in the previous section, we estimated potential crop productivity under the changed climate conditions in 2100, and compared it with potential productivity under current climate conditions. Five crops were the focus of in this paper: rice, winter wheat,

Table 3. Constraint factors by soil phase (f_{sp})

CROP / PHASE	Rice Low	Rice High	Wheat Low	Wheat High	Maize Low	Maize High
Stony	0%	0%	50%	0%	50%	0%
Lithic	0%	0%	25%	25%	25%	25%
Petric	50%	0%	75%	75%	75%	75%
Petrocalcic	25%	25%	50%	25%	25%	25%
Petrogypsic	0%	0%	25%	0%	0%	0%
Petroferric	25%	0%	25%	0%	25%	0%
Phraetic	100%	100%	100%	100%	100%	100%
Fragipan	100%	100%	100%	75%	100%	75%
Duripan	100%	100%	75%	75%	75%	75%
Saline	0%	0%	25%	25%	0%	0%
Sodic	0%	0%	0%	0%	0%	0%
Cerrado	100%	100%	100%	100%	100%	100%

Table 4. Constraint factors by soil texture (f_{st})

TEXTURE	SOIL UNIT	f_{st}
Coarse	Qc, Ql, Qf, Tv, Po,Pl, Pf, Ph, Pp, Pg, Fx	100%
Coarse	Other units	50%
Medium	Every unit	100%
Fine	Every unit	100%

Table 5. Constraint factors by slope (f_{slp})

SLOPE LEVEL	INPUT	f_{slp}
a (0-8%)	Low	100%
a (0-8%)	High	100%
b (8-30%)	Low	50%
b (8-30%)	High	33%
c (30% -)	Low	7.50%
c (30% -)	High	5%

(*)For Rice, the f_{slp} is 0% under b or c slope.

Table 6. GCM outputs used for the experiment (IPCC, 1990)

Climate Model	Calculated Date	lat x long(°)	Δ T (°C)	Reference
CCC	Nov-89	3.75x3.75	3.5	Boer et al., 1989
GISS	1982	7.83x10.0	4.2	Hansen et al., 1984
GFDL	1984-85	4.44x7.50	4.0	Wetherald & Manabe, 1986
GFDL R30	May-89	2.22x3.75	4.0	Wetherald & Manabe
GFDL Q-flux	Feb-88	4.44x7.50	4.0	Wetherald & Manabe, 1988
OSU	1984-85	4.00x5.00	2.8	Schlesinger & Zhao, 1989
UKmet	Jun-86	5.00x7.50	5.2	Wilson & Mitchell, 1987

Δ T =Equilibrium surface temperature change on doubling CO_2

spring wheat, maize (tropical) and maize (temperate). The following data and scenarios were used for this model experiment.

- Current climate data
  - Temperature: Monthly mean temperature (Legates and Willmott, 1990a)
  - Precipitation: Monthly mean precipitation (Legates and Willmott, 1990b)
  - Cloudiness: Monthly mean cloudiness (Leemans and Cramer, 1992)
  - Range of diurnal temperature change: Monthly mean range of diurnal temperature change
- Soil data
  - Soil unit, phase, texture and slope: Digital Soil Map of the World and derived soil properties (FAO/Unesco, 1994)
- Future climate scenarios
  - GHGs emission scenario: IS92a (IPCC, 1992)
  - Climate sensitivity: 2.5°C at $2\times CO_2$
  - Soil characteristics will not change
  - Spatial patterns of climatic change: 7 GCMs shown in Table 6

The resolution of the calculation was a 0.5-degree grid for the climate module and the crop growth module, and a 5-minute grid for the soil constraints module. As for the PET calculation, we chose the Thornthewaite method for this experiment because of the data restriction.

4.2 Results

With the simplified climate model (Matsuoka *et al.*, 1995), the global annual mean temperature increase between 1990 and 2100 was estimated as 2.49°C under the emission scenario IS92a (IPCC, 1992).

Here the results of potential crop productivity estimations are aggregated globally as well as nationally and their increase is discussed. Table 7 shows the percentage increase of global potential productivity. Table 8 shows the increase of potential productivity considering soil constraints with the assumption of high agricultural inputs in some countries (the median of the results with seven GCM outputs).

As shown in Table 7, the potential productivity of rice will increase with all GCM outputs, and the mean value is a 5.88% increase. Based on Table 8 which shows the impacts on a national level, remarkable increases can be found in Canada and the former USSR. The increases in

Table 7. Changes of crop productivity aggregated in the world between 1990 and 2100 (%)

	Rice		Winter Wheat		Spring Wheat		Maize (tropical)		Maize(temperate)	
	free	high	free	high	free	high	free	high	free	high
CCC	9.42	4.30	-18.39	-16.82	-1.24	-9.40	11.39	5.61	2.85	-10.57
GISS	9.22	6.56	-11.11	-7.41	7.43	0.92	11.56	8.36	3.29	-6.50
GFDL	9.68	5.20	-12.38	-13.20	3.93	-5.28	10.82	5.84	12.38	2.44
GFDL-R30	11.92	6.33	-8.54	-8.50	8.94	-1.15	13.70	8.25	13.47	0.00
Q-FLUX	9.83	6.79	-10.79	-8.14	5.28	-1.15	10.68	7.33	8.54	-1.22
OSU	8.71	2.71	-16.01	-15.01	-0.54	-8.26	10.05	4.70	4.05	-8.94
UK-MET	11.87	5.88	-14.27	-13.20	3.61	-5.05	13.22	7.45	15.99	0.81
min	8.71	2.71	-18.39	-16.82	-1.24	-9.40	10.05	4.70	2.85	-10.57
max	11.92	6.79	-8.54	-7.41	8.94	0.92	13.70	8.36	15.99	2.44
median	9.68	5.88	-12.38	-13.20	3.93	-5.05	11.39	7.33	8.54	-1.22

free: without soil constraints

high: considering soil constraints, assuming high agricultural input

Table 8. Changes of crop productivity aggregated by country between 1990 and 2100 (%)(Considering soil constraint, assuming high agricultural input, median of the results with 7 GCMs)

	Rice	Winter Wheat	Spring Wheat	Maize (tropical)	Maize (temperate)
Argentina	-7	-8	-24	1	-60
Bangladesh	1	-88	---	0	---
Brazil	-3	-42	-48	-2	-73
Canada	204	14	19	95	166
China	7	-10	-13	0	-31
France	1	-5	-4	-5	78
India	-10	-60	---	0	---
Italy	1	-10	-4	-3	29
Japan	3	3	-5	-5	-51
Nigeria	-4	-55	---	-1	---
Thailand	-4	---	---	5	---
USA	1	-4	0	4	-36
USSR	151	13	8	35	130
Vietnam	-2	-58	---	-3	---

these two big countries contribute to the global total increase. In East and South-East Asia, where people eat rice as their main food, smaller changes can be found; 3%, a slight increase, in Japan, and a 7% increase in China because the northern limit of cultivation moves to a higher latitude under the warmer climate.

As for wheat, the world potential productivity of winter wheat and spring wheat decreases 13.2% and 5.05%, respectively. In South Asia, India and Nepal, the potential productivity will decrease 50~60%. Since the results with all GCM outputs show the same trend, the remarkable decrease in the potential productivity of winter wheat in this region can be considered highly probable. In Argentina, France, China and Italy, which now constitute major wheat production areas, each potential productivity of winter wheat decreases about 10%. In these countries, estimations with any GCM output predict potential productivity decreases, though there are some differences depending on the GCM output. No big change of potential productivity is observed in USA and Canada from Table 8. Through the graphical interpretation of the result, however, the land which has greater potential for cultivation is found to move north. E.g., in the northern part of Europe, the increase is observed.

Regarding maize, Table 7 shows a 7.33% increase of tropical maize and a 1.22% decrease of temperate maize. Reliability of the estimated value for temperate maize is, however, rather low judged from the variances among the different GCM outputs. As for tropical maize, the increase of potential productivity is observed at the high latitudes, with no big changes found in the low-latitude countries. As a result, world potential productivity increases. Significant changes are observed such as a 95% increase in Canada and a 35% increase in the former USSR. Tropical maize can be considered as a crop which fits the climatic change because it adds arable land in the high-latitude countries without diminishing the current arable land. Also from the graphical interpretation, some areas currently suitable for temperate maize are found to become suitable for tropical maize due to climatic changes in South America.

5. Discussion

To evaluate the climatic change impact on agriculture, crop potential productivity is estimated on a large scale both temporally and spatially. Based on the simulated results, we will discuss the climatic change impact on agriculture in this section.

As the results in the previous section show, no critical impact on agriculture was expected except the slight decrease of potential productivity of wheat when viewed through global aggregation under the assumption of medium GHGs emission scenario (IS92a) and medium climatic sensitivity (2.5°C). Nevertheless, this does not mean that the climatic impact on agriculture is proved to be either negative or positive. In fact, we can observe that areas which have high potential productivity currently will alter their status in the future due to climatic changes. To evaluate the impact related with changes in arable area, we need to take into account more complicated higher order effects, such as the change of trade among countries and the change of consumer demand. An equal decrease of potential productivity in two places does not mean equal damage. For example, the decrease of potential crop productivity should be considered as more serious problem in the countries where shortage of crops caused by climate change cannot be made up through the international trade or where a future explosive population increase is projected.

In fact, it is possible that many developing countries face such a difficult situation. In our results, for instance, the remarkable decrease of potential productivity of winter wheat in India should be more carefully studied, and we must not neglect discussing future strategies in the region. The environmental impact of deforestation caused by the displacement of cultivated areas is also one of the potentially severe problems which must be studied intensively. To evaluate these impacts comprehensively, we urgently need to develop impact estimation methods which can deal with the economic aspects of agriculture, linked with the potential crops productivity model already developed.

Now we must monitor the various environments which impact agriculture and the world food supply. There are many other factors as well as the climatic change which affect the future of world agriculture. The estimation reported by the International Food Policy Research Institute (IFPRI) gives the optimistic projection that the food supply will exceed the total world demand, and that the prices of agricultural commodities will decrease for the next several decades (Islam, 1995). On the other hand, there are also many pessimistic estimations which take a serious view of the decelerating increase of irrigated areas and crop yields. There are two ways to increase total agricultural production. One way is expanding cultivated area by land transformation: expansion, and the other is increasing production per acre through more intensified use of land with fertilizer :intensification. Though the total area which has potential for agriculture in the world is much larger than the current cultivated area, the cost of conversion to agricultural use is often very expensive. As for intensification, the limit of increasing yield is near in some countries (for example, rice in China and wheat in U.S.), and land degradation caused by intensification is also a matter of concern. Irrigation has also contributed to the increase of agricultural productivity. The share of irrigated acreage is 17% in the total agricultural area, and the production in the irrigated acreage is more than 30%. Though it is possible to expand the cultivated area under irrigation, this is also expensive. It is important to remember that the climatic change impact might occur in conjunction with these various serious factors.

This study made it possible to evaluate climatic change impact on agriculture using the idea of potential crop productivity. However, it has not yet succeeded in suggesting ways in which we might cope with potential agricultural problems in the future because it does not take into account higher order impacts or the relationship between climatic change and other future environmental changes influencing crop production. More studies on these future steps are urgently necessary.

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