Article

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The Problem of Predicting Global Food Production

This paper examines the problem of the development of models capable of predicting the capacity of the global food production system. In particular, it identifies the various factors influencing the food production, and estimates their relative influence and predictability. The paper discusses also the problems connected with coupling of models representing the "driving" forces, the Earth system consisting of the atmosphere, the ocean and land surface, and food production. The overall conclusions drawn are: *i*) The time is not yet ripe for designing a comprehensive coupled model for predicting the global food production that takes into account all the factors having a significant influence; *ii*) the main difficulties are the modelling of the driving forces, e.g. socioeconomic and political factors, and *iii*) despite these problems, it is judged that results obtained with existing models are capable of providing concrete information for implementation of adaptation and mitigation measures.

INTRODUCTION

Although considerable progress has been made during the past few decades in augmenting food production, there are indications that we cannot take it for granted that this trend will continue. For example, based on recent projections to 2020, the International Food Policy Research Institute (IFPRI) raises serious concerns about whether the world food production system will be able to feed the expected world population, especially in the face of possibly stagnant, or even declining stock of natural resources (1). A similar opinion has been voiced by the World Resources Institute by stating that the challenge of meeting human needs seems destined to grow ever more difficult (2).

Concern has also been expressed by the UN Food and Agricultural Organization. According to their projections the increment in crop production in developing countries during the next 34 yrs (1995–1997 to 2030) will be 70%, as compared to 175% over the preceding 34-yr period (3).

Given this information, indicating a possible risk of insufficient availability of food, the need for reliable predictions of food production becomes more pronounced. Thus, one may ask:

- What are the problems encountered in designing models for predicting global food production?
- What are the prospects of making reliable predictions of future global food production?

In the following I will attempt to respond to these two questionsby:

a) Identifying the various factors having a significant influence on food production, and identify the ones that can be taken into account realistically at present.

b) Examine possibilities and limitations in taking into account various interactive processes by coupling models that represent the driving forces and the various influencing factors.

In this connection it must be understood that we are not concerned with the question about predicting what is theoretically possible, but rather what is most likely to happen. It appears that this important distinction is not always made.

ATTEMPTS TO MODEL THE GLOBAL FOOD PRODUCTION SYSTEM

There are reasons to be pessimistic about the possibility of developing realistic models for long-range prediction of global food production. Some of them are identified here, and different approaches taken in developing such models are examined.

Nature of the Prediction Problem

In order to understand the complexity and the difficulties in predicting future global food production we present the problem in the following way:

Suppose it realistic (which it is not) to assume that we have complete knowledge of:

i) The equations that govern the processes taking place within and between the various components of the Earth system (i.e. atmosphere, oceans, land surface, biosphere, and cryosphere).
ii) All the factors that have, or will have, an influence on global food production, including the driving forces and environmental factors.
iii) The state of all the quantities that are required to define the initial condition of the global food production system.

It might then be argued that the prediction problem we are concerned with can be treated as a standard initial-value problem.

However, it should then be recognized that experiences gained from similar, but considerably less complex prediction problems, have revealed that infinitesimal errors in the definition of the initial state do amplify steadily, and can after a comparatively short time dominate the solution, and thereby significantly reduce the predictability (4).

Problems Encountered

The problem of predicting future global food production is becoming more and more complex. In the past few decades the factors to be taken into account were fewer. To a large extent the production was determined by the demand determined by the growing world population. However, the opportunities to increase the production by improving the yield and expanding the cropland is slowly being exhausted, at the same time as environmental stresses are increasing. More specifically, the difficulties we are encountering may be characterized in the following way.

Many uncertain influencing factors. Practically none of the factors having an influence on food production can be specified with a high degree of accuracy, due to insufficient knowledge of the processes involved and/or lack of reliable data. Thus, there still prevails considerable uncertainty about the nature, extent, and significance of such key issues as soil degradation, scarcity of water resources, biodiversity loss and pesticide risks (5,6). It might very well be advisable to disregard certain influencing factors if it is judged they cannot be taken into account in a realistic way.

Simulating mixed human and nonhuman processes. Many of the influencing factors can be characterized as a mix of human and nonhuman processes, for example with regard to large-scale land-use changes. Attempts to take into account such factors by linking causal models of social processes (that have large uncertainties) with qualitatively different models of the Earth system, simulating nonhuman processes, can pose problems (7).

Unexpected rapid developments. Even small, gradual changes in the forcing conditions of the Earth system can, through complex nonlinear interactions and feedback processes, result in significant and rapid changes and surprises. As expressed by Canadell (8), linear thinking is very much entrenched in the way policy-makers perceive environmental change and, consequently, ways to manage it.

Model validation. In similarity with other models for long-range predictions there is a problem of assessing the reliability of the model (7). The reason is simply the absence of future observational data. There exist, however, possibilities to perform testing and validation of certain internal processes and parameterization procedures.

Types of Prediction Models

In the following I shall identify 4 different approaches taken in designing a model to predict future global food production. In doing so, I emphasize that the purpose has not been to try to judge whether one approach is better than another. Rather, the intention has been to demonstrate that the choice of approach to a large extent is determined by the type of prediction that is required, e.g. the length of prediction period and the level of detail required.

Nevertheless, the above does not exclude us from making some observations. For example, *it appears that there is an exaggerated optimism about our capabilities to predict economic factors and their impacts on the global food production* (9). It also seems that some modellers cannot resist the temptation to couple different types of models, representing the various parts of the global food production system. Experience has shown that this can lead to unexpected model behavior. At the same time it should be admitted that this is also a way to advance our understanding and capabilities to deal with the projections for the future.

World price-equilibrium model. Time horizon: 2015/2030. The World Food Model of the United Nations Food and Agricultural Organization (FAO) (10) is as typical example of such a model. It is being classified as a price-equilibrium, multi-commodity model, and it is designed to provide year-by-year world price equilibrium solutions for 40 agricultural products. Its main components are the supply equations, the demand equations and the market clearing mechanism.

The key explanatory variables in the equations are commodity prices, which are determined in the world market. Trade is mainly given as a residual by the supply-utilization balance equations. It consists of about 15 000 equations, both linear and nonlinear. These equations are simultaneously solved when world exports are equal to world imports.

Models in which physical factors dominate. Time horizon:2025/2050. The model developed at the Stockholm Environment Institute (9) is a representative of this kind of model**.** In designing this model, the use of economic models was ruled out due to data limitations. Instead, physical parameters such as tonnes of food produced or ha of cropland required were used. It is pointed out that an important consequence of using such a physical model is that agricultural demand and supply must in a formal sense be treated independently. These computations cover 11 agricultural products for 10 world regions.

Models dominated by economical-physical factors. Time horizon: 2025. A third approach may be defined as a combination of these two approaches. The models of this type may be represented by the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) developed at the International Food Policy Research Institute (11, 12).

This model is specified as a set of 36 country or regional models that determine supply, demand, and prices for 16 commodities. The factors taken into account include: population and income growth, the rates of growth in crop and livestock yield and production, feed ratios for livestock, agricultural research, irrigation and other investments, price policies for commodities, and elasticities of supply and demand. It also takes into account expert judgements.

Note that the results of this model have been compared with results from two other models presented by Alexandratos (13) and Mitchell and Ingco (14). According to the judgement of the author of this comparison, the assumptions and initial conditions have more influence on the results than the differences between the models (15).

Integrated assessment models. Time horizon: 2100. This approach can be used for combining knowledge from a variety of disciplines. A large number of such models have been developed, and an overview of these has been presented by Weyant (16). As an example of this type of model we can select the IMAGE 2.1 model developed at the National Institute of Public Health and the Environment (RIVM) in The Netherlands (17). It consists of three fully linked systems: *i*) the energy-industry system; *ii*) the atmosphere-ocean system; and *iii*) the terrestrial environment system.

The model is designed to serve many purposes, for example, to examine long-term changes in global land cover, and to assess climate change impacts on agriculture. The computations are carried out with a time horizon from 1970 to 2100 for 12 crops in 13 world regions. For some computations (e.g. climatic change) a grid with comparatively high horizontal resolution is used (0.5° x 0.5° latitude/longitude).

CATEGORIES OF INFLUENCING FACTORS

Table 1 identifies the factors that can be expected to have a significant influence on global food production. In addition, this table contains very subjective estimates of:

- The degree of influence of these factors on global food production.
- The present, and the likely future level of accuracy with which these factors can be predicted for a few decades.

The following section will examine briefly the present knowledge about these factors, and indicate how they are connected with each other (Fig. 1).

Driving Forces

The major external driving forces include: the expected growth of the world population, some aspects of the socioeconomic and technological developments, including the emission of greenhouse gases.

Population change

As seen in Table 2, the projections of the global population exhibit surprisingly wide ranges of uncertainties. The problem confronting us here is that we will then have a large percentage uncertainty with regard to the expected demand of food production (18, 19).

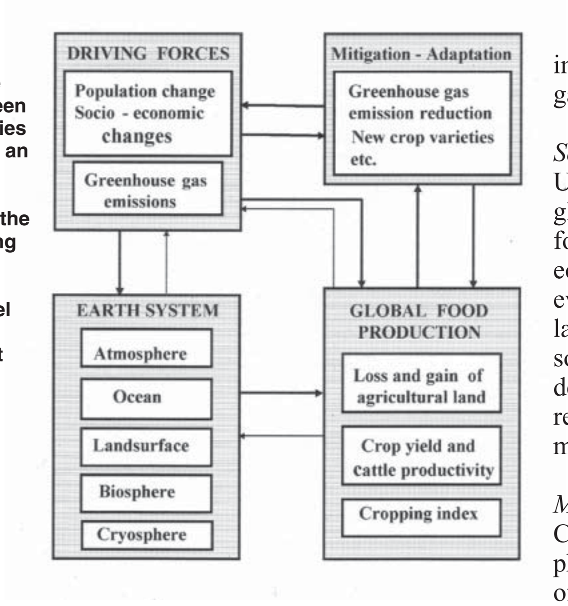

Figure 1. **A schematic illustration of the interaction between the main categories of factors having an impact on global food production. The character of the arrows connecting the different components indicates the level of importance to take into account the interactive processes.**

Table 1. Subjective estimates of the degree of influence of the socio-economic and environmental factors on the global food production during the next few decades. The table also contains subjective estimates of the present level of accuracy with which these factors can be predicted for such a length of time, and what can be expected to be possible.

Factors influencing the global food production	Degree of influence	Accuracy of prediction present level	Accuracy of prediction possible level
Driving forces			
• Population change	High	Medium	Medium
• Socio-economic developments	High	Low	Low
• Management, new technologies	High	Medium	Medium
• Greenhouse gas emissions	High	Medium	High
Climatic change/variability			
• Temperature	Medium	Medium	High
• Precipitation	High	Low	Medium
• Droughts, monsoon change	High	Low	Low
• Mitigation & adaptation	High	Medium	High
Yield & cropping index			
• Use of fertilisers	High	Medium	Medium
• Irrigation & salininization	High	Low	Medium
• Biotic stresses	High	Medium	Medium
• CO_2 "fertilisation effect"	Low	Low	Medium
Loss & gain of agricultural land			
• Competition for land	Medium	Medium	High
• Sea level rise	Low/Medium	Low	Medium
• Soil degradation, erosion	High	Low	Medium
• Use of land reserves	Medium	Medium	High
Natural disasters			
• Tropical cyclones	Low	Medium	Medium
• Earthquakes etc.	Low	Low	Low

Table 2. Long term global population projections made by the United Nations Population Division (in billions). Sources: (17, 18).

Projection to		Projections made by Pearl 1924	UN 1974	UN 1978	UN 1982	UN 1992	UN 1998
	High			6.5	6.4	6.4	
2000	**Medium**	**2.0**	**6.4**	**6.2**	**6.1**	**6.3**	
	Low			5.9	5.8	6.1	
	High			12.1	11.6	12.5	10.9
2050	**Medium**	**2.0**	**11.2**	**9.8**	**9.5**	**10.0**	**9.3**
	Low			8.0	7.7	7.8	7.9
	High			14.2	14.2	19.2	
2100	**Medium**	**2.0**	**12.3**	**10.5**	**10.2**	**11.2**	
	Low			8.0	7.5	6.0	

A large uncertainty in the projected global population will also imply an uncertainty with regard to the emission of greenhouse gases, and thereby also for the human-induced climatic change.

Socioeconomic developments

Undoubtedly, economic developments do have an impact on the global environment, and on the demand for and production of food. However, it has to be recognized that our ability to make economic predictions is very limited. One reason is that the relevant economic data for food production and/or consumption are lacking for many countries and large regions (9). Another reason is insufficient knowledge of the laws governing economic development. It is not foreseen that any model can provide more realistic predictions of sociological factors than do simple estimates based on present trends.

Management and new technologies

Considerable opportunities exist to improve the efficiency of all phases of the food production system, including the development of new crop varieties. However, the rate at which such improvements can be implemented in the less developed countries is comparatively slow due to limited economic resources (20).

Emissions and concentrations of greenhouse gases

The prediction of the future emission of greenhouse gases caused by human activities is based on numerous assumptions relating to population changes, economic development, implementation of new policies, etc. (21).

Given this information the future atmospheric concentration of these gases can be computed using models of the carbon cycle. It should then be realized that these calculations will result in additional uncertainties. With the aid of the computed concentrations, calculations for the resulting change of the planetary radiative forcing that drives the climatic change can be performed.

Climatic Change

A change in the climate will influence food production in many ways, both directly and indirectly. However before discussing this I will briefly examine the questions of climate predictability and the sensitivity of climate to anthropogenic influences.

Climate predictability

It is true that weather is not even potentially predictable beyond a period of about 1–2 weeks (4). However, this does not necessarily imply that climate is not predictable. It can be argued that climate is of a different character than weather. At the same time it has to be recognized that due to the presence of nonlinear processes in the climate system, deterministic projections of changes of the climate are inherently fraught with uncertainties (22, 23).

Climate Sensitivity

If we limit our interest to evaluating the sensitivity of the present climate to changes in influencing factors, then we have reason to believe that present Coupled General Circulation Models (CGCMs) are capable of simulating such changes fairly realistically (24).

However, it should be recognized that natural climate variations do occur simultaneously with human-induced changes, and that we only can distinguish between natural and human-induced climatic changes with great difficulty, and ascertain the causes of an observed climatic change (25, 26).

Climate variability

At present, it is not possible to predict to what extent an anthropogenically induced climatic change will be accompanied by a change in the variability of climate, e.g. the risk of an increased frequency of droughts and floodings. However, Sivakumar (27) notes that there now exist opportunities to help the agricultural world to cope better with climate variability.

Factors Mainly Influencing Yield and Cropping Index

According to recent projections by IFPRI, increases in cultivated area are expected to contribute only one-fifth of the increase in global cereal production needed to meet demand between 1995 and 2020. Therefore, improvements in crop yields will be required to bring about the necessary production increases, i.e. intensification rather than further extensification (28).

Use of fertilizers
In some climates, and where fertilizers already are applied copiously, applying more and more fertilizers increases yields very little (29). For example, on much of Asia's rice land applying more fertilizers has had little, if any, effect on the yield (30).

However, there are still substantial opportunities to improve the yield in many less-developed countries. Thus, it can be assumed that the increase in food production will follow a function that asymptotically approaches a maximum value more or less rapidly, depending on the economic development as illustrated in Figure 2 (31). As indicated in this figure, this maximum value might be decreasing with time due to harmful environmental effects caused by the fertilizers. Certainly, with proper administration of the fertilizer input, harmful effects can be reduced.

Irrigation and salinization
There are still opportunities to increase the food production through expansion of irrigated land. However, it is bound to be at a slower rate than before due to competing demands for water (32). Thus, as reported by Scherr (33), the projected annual growth rate of irrigated area in developing countries for the period 1993–2020 is expected to be only 0.7%, as compared to 1.7% during the period 1982–1993. The fact that irrigation implies a substantial loss of land due to soil salinization and waterlogging also needs to be taken into account.

The change in food production over time, due to irrigation can be expected to be of the same character as in the case of food production as a function of an increased use of fertilizers (Fig. 2).

Biotic stresses
Pests, diseases and weeds cause significant impacts on the world's food production under present climatic conditions. The current yield losses caused to the harvests of the world's four most important crops (maize, rice, wheat and potatoes) has been estimated to be 36% (34).

Carbon dioxide "fertilization effect"
From controlled experiments, with optimum environmental conditions, some knowledge has been gained about the increase of the yield of C_3 and C_4 plants with an increased atmospheric CO_2 concentration, the so called carbon dioxide "fertilization effect".

Initial results from free-air CO_2 enrichment experiments that attempt to create conditions close to those likely to be experienced in an open field, confirm the basic positive response of crops to elevated CO_2 (35).

Loss and Gain of Agricultural Land

Considerable areas of agricultural land are being lost each year due to various forms of soil degradation. In addition, substantial areas of agricultural land are each year lost in competition with other demands for land and the question is to what extent the loss of food production in these ways needs to be compensated by making use of land reserves, taking into account their quality and availability.

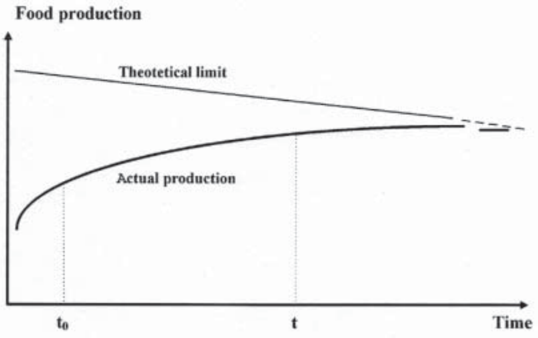

Figure 2. A schematic illustration of the expected change of the agricultural production by increasing the use of fertilizers, or by expansion of irrigated land. In both cases it can be expected that the production will approach asymptotically an upper limit, and that this upper limit is declining with time.

Soil degradation
Considerable areas of cropland are lost each year due to erosion together with physical and chemical soil degradation. According to calculations by the Global Assessment of Soil Degradation (GLASOD) 5–6 mill. ha yr^{-1} have been permanently lost since the mid-1940's through human-induced soil degradation (36). Based on these data, Crosson (37), assuming an accelerating future rate of degradation, calculated a 17% cumulative global production loss by the year 2030.

Competition for Land
Due to the growing world population and the ongoing migration of people from rural to urban areas, there is an increasing demand for areas for housing, industry, infrastructure, and recreation. As has been pointed out in several studies much of the land lost in this way can be expected to be prime agricultural land located in coastal plains and in river valleys. According to Döös and Shaw (31) 2 ± 1 mill. ha cropland will be taken out of production each year. Other studies have arrived at somewhat greater losses. For example Kendall and Pimentel (20) estimated the annual loss to be 2–4 mill. ha and Norse et al. (38) 4–10 mill. ha. Given the existing projections of the world population, this rate of loss will continue during the next few decades.

Sea-level rise
Estimates of the expected rise of the global sea level caused by an anthropologically induced climatic change are still very uncertain. Thus, according to Church and Gregory (39), during the period 1990–2100 it is projected to be within the range 8–88 cm. This is due primarily to thermal expansion of the oceans and contributions from glaciers and ice caps.

Thus, it cannot be considered likely that sea level rise will cause any severe loss of agricultural land until the second half of this century. However, this does not exclude the risk that it may contribute significantly to salinization in many coastal zones within the next few decades.

In some regions the land elevation is changing due to different types of processes, e.g. tectonic phenomena and compaction of underlying sediments. These processes can be of such a magnitude that they can significantly reinforce or compensate for the global sea level rise (40).

Use of land reserves
According to FAO (41), it is projected that 3.5 mill. ha of arable land needs to be added every year to the agricultural area of developing countries between 1995/1997 and 2030 against 5.1 mill. in the historical period.

Undoubtedly, considerable land reserves still exists in some regions of the world. In addition to the about 1 billion ha, the resource base includes an additional 1.8 billion ha. However, it should be recognized that:

- there is little left of the category of land that can be characterized as very suitable for agriculture;
- most reserves are currently under forest or permanent pastures, and the demand for both forests and pastures is growing (38);
- the availability of land reserves is smallest where they are most in demand. Thus, in the Near East/North Africa region, there is virtually no spare land available for agricultural expansion (42);
- the financial costs of bringing land reserves into production can be prohibitive in many developing countries.

Crude Estimates of the Future Global Food Production

A crude estimate of the future global food production can be obtained by: *i*) making use of available estimates of the rate of impact of the various influencing factors identified above; *ii*) disregarding the interactive processes that are taking place between the influencing factors.

Several such estimates have been undertaken, for example by Kendall and Pimentel (20) and Döös and Shaw (31). Clearly, such estimates of the future food production are bound to suffer from large uncertainties. The question is then: Will it be possible to achieve a more realistic prediction by developing a composite model that attempts to simulate the influences of the various factors, and also taking into account the interactions between them?

BASIC MODELLING SPECIFICATIONS

Depending on the type of prediction of the future global food production that is required, certain decisions have to be made with regard to the design of the model. In the following we will identify some of the most important ones.

Component Models Required

As is indicated in Figure 1. we are concerned with 4 categories of processes that have an influence on future food production. Briefly they can be characterized in the following way:

– *The driving forces.* In its most complete form this component consists of several interacting models for specifying the driving forces, e.g. the future world population, food demands, energy consumption, and emission of greenhouse gases. However, it should be recognized that the processes determining such quantities are basically governed by socioeconomic and political processes that have a low level of predictability. This implies that we are forced to reduce our ambition to perform so-called "predictions of the second kind" implying prediction of the food production based on pre-specified scenarios of the driving forces.

– *Earth system processes.* Given the specified driving forces, this component simulates the various physical, chemical and biological processes taking place in the Earth system, and provide projections of the factors, including climatic change, that have an influence on the food production.

– *Food production.* Based on the information obtained from the driving forces and Earth system model, the changes in yield, cropping index and land areas required for cropland and pasture are evaluated. Given this information, the future food production is computed. This component also includes an assessment to what extent the food production meets the food demand.

– *The Mitigation-Adaptation component.* Based on the output of the results obtained from the food model, this component identifies opportunities that are available for adapting the agricultural production to a changing climate. In addition, it identifies the need for implementation of mitigation actions.

Length of the Prediction Period

Clearly, there are different demands on the length of the predictions of global food production. However, here we will only be concerned with comparatively long-range predictions, say from about 3–4 decades up to a century.

The problem is not only that the number of influencing factors become numerous, but also that their range of predictability probably is shorter than the length of the attempted prediction of the food production.

Required Level of Resolution

In designing a model for prediction of the food production we are confronted with decisions relating to three types of resolution, namely with regard to: *i*) the number of food commodities or groups of commodities; *ii*) the number of countries or groups of countries; and *iii*) the horizontal and vertical resolution of the grid used by the Earth System Model.

With regard to the first 2 types of resolution, I note that the FAO World Food Model has a very high resolution both with regard to commodities and countries. No doubt, detail may very well be important for comparatively short prediction periods, and if the data can be considered to be reliable. However, for predictions over longer periods (4–5 decades) the demand for a high degree of detail can hardly be justified. Concerning the third type of resolution (the grid for computing climatic and land-use changes) an increased horizontal and vertical resolution usually has a beneficial effect (25, 43). However, in some cases the effect might be small, or even negative, if proper account is not taken to the grid and scale of the parameterizations of small-scale processes (44).

Complexity Versus Simplicity

In designing a model for prediction of the future state of a system the best result will not necessarily be obtained by including all the processes that take place, or by attempting to describe them in great detail. The inclusion of processes for which understanding is not complete can function as a serious source of error. Lorenz (23) notes that it is not always true that the more

Table 3. Categories of Earth System models with different spatial resolutions. Sources: (25, 45).

	Comprehensive 3-dimensional climate models (CGCMs)	Intermediate complexity, 2–2½ dimensional models (EMICs)	Simplified, 0–1–1½ dimensional conceptual models
Driving forces	E.g.: an enhanced atmospheric concentration of greenhouse gases	E.g.: population and economic development	Same as for EMICs
Components and subcomponents	Earth system: –Atmosphere –Hydrosphere –Cryosphere –Biosphere –Landsurface	Earth system (simplified) and other system components	Earth system (very simplified) and systems representing human activities
Processes	Detailed description of many processes	Less number of processes and less detailed descriptions	Fewer processes and more simplified descriptions
Time scale	10–100 years up to ~ 1000 y	Up to several millennia	A wide range of time scales
Computer time required	For equilibrium simul.: Long. For transient simul.: Extensive	For transient simulations: Less extensive	Comparatively short

equations you add to describe a system, the more accurate will be the eventual forecast.

There is also another reason for not using a comprehensive model. Despite the considerable capacity of present computers, the run-time required for such models can be prohibitive.

For these reasons, various models of less complexity than the most comprehensive 3-dimensional Earth system models have been developed. In a simplified way the characteristics of such a hierarchy of Earth system models is shown in Table 3 (45). The obvious advantage with the simpler models is that they require comparatively little computer time. They make it possible to quickly study the sensitivity of the climate to a particular process over a wide range of parameters (25).

It should also be mentioned that, in contrast to so-called "transient" simulations, extensive use has been made of the less realistic "equilibrium" method for sensitivity studies. It is based on the assumption that the Earth system is continually in balance with the external forcing. The advantage of this method is that it requires considerably less computer time.

As a final point on this issue, the philosophy of avoiding complexity should not be driven "in absurdum". This can prevent Opportunities to develop more realistic models.

COUPLING COMPONENT SYSTEMS

Because the various factors having a significant influence on the global food production (c.f. Fig. 1) do interact with each other, a logical approach in designing a model for the prediction of the future food production would undoubtedly be to design a comprehensive coupled model that takes into account all interactions. However, this has to be done with great care in order to avoid difficulties.

General Considerations

As has already been pointed out, our ability to specify the various processes that have an influence on the food production is still limited. It should also be emphasized that this is true also with regard to the interactive processes that take place between the different influencing factors.

Note that in developing a prediction model involving two or more subsystems interacting with each other, we are bound to be confronted with problems unless the component models are properly tuned to each other. This caused Fung et al. (46) to ask: How robust must our understanding be before coupling subsystem models reduces uncertainty inherent in the coupled system rather than increasing it?

Socioeconomy with Other Components

Human processes are critically linked to the Earth system and they are contributing to global change. For example, even if the relationship between population growth and environmental changes is indeed very complex, population growth contributes to a variety of environmental changes (47). However, casual models of social and economic processes have large uncertainties, and pose problems which may be of qualitatively different character than those associated with modelling nonhuman components (7). For these reasons, it seems advisable to avoid a close coupling of the "driving forces" with the Earth system and the global food production system. Actually, in some cases, the interaction is mainly one-way, i.e. there is little or no feedback to the driving forces.

Earth System Sub-components

Significant progress has been made in the development of climate models by coupling the various components of the climate system (24). However, it is still true that the coupling of models representing systems with significant time-scale separation often leads to unexpected model behavior. Also, as demonstrated by Lorenz (4), because of nonlinearity, the predictability of the climate system depends on the accuracy with which the initial state can be determined. For example, most climate models require especially designed initialization schemes to avoid imbalances in the model that can result in so-called "climate drifts" (25, 48).

Climatic Change and Food Production

In attempting to calculate the impact of a climatic change on food production by coupling a model of the climate system with a model of the food production system, we need to take into account that the change consist of 2 parts.

i) The change resulting from the climatic change: $\mathbf{\Delta P_c(t)}$.
This quantity is uncertain for two reasons:
- The climate prediction model is not perfect.
- The model for computing food production is not perfect.

ii) the change due to utilization of existing opportunities to adapt agriculture to a climatic change: $\mathbf{\Delta P_a(t)}$.
- Certain knowledge exists with regard to adjustment to a slowly changing climate.
- Considerably more difficult is the problem how to adjust to a change of the variability of the climate.
- Account also needs to be taken to the fact that the less-developed countries have limited financial resources to make use of existing opportunities to make use of existing adaptation methods.

Thus, we obtain the following expression for the resulting change in the food production:

$$\mathbf{DP(t) = DP_c(t) - DP_a(t)}$$

a quantity that cannot be determined very accurately since it is expressed as the difference between the 2 comparatively large, and uncertain quantities.

DEVELOPMENT OF RESPONSE MEASURES

Even in the absence of reliable predictions of future food production the efficiency of food production must be improved.

Weak Points in the Food Production System

Although existing models may not provide reliable predictions of future global food production, realistic model experiments can be conducted providing information about the sensitivity of food production to changes in the various influencing factors.

The results of such experiments can provide information about weak points in the global food production system. This in turn will make it possible to develop response measures for international agreement and implementation.

Figure 3 shows a typical outcome of such a sensitivity experiment, making it possible to achieve an early identification of the need for response measures.

This figure also demonstrates that widespread implementation of response measures aimed at reducing an environmental stress factor usually requires a considerable length of time ($\mathbf{t_i - t_0}$), and that there is long lead time ($\mathbf{t_e - t_i}$) before there is a noticeable effect (a decade or more). An example is the slow response of nations to reduce the emission of radiatively active gases.

Through the conduct of sensitivity experiments it may also be possible to establish criteria for the reduction of the environmental stresses that may cause sudden and unwelcome responses of the Earth life support system (8).

Mitigation and Adaptation

A wide range of opportunities do exist for reducing the negative effects of natural forces and human activities on food production, e.g. efforts aimed at minimizing the various forms of soil degradation and a slowing down of the ongoing man-induced climatic change by reducing the anthropogenic emissions of radiatively active gases (49). With regard to the latter problem, it may be noted that mitigation and adaptation measures are closely interlinked with each other. The more one succeeds in limiting climatic change, the easier it is to adapt to it.

According to recent observational studies, there is already evidence for a changing climate. For example, temperature changes have already affected physical and biological systems in many parts of the world (50).

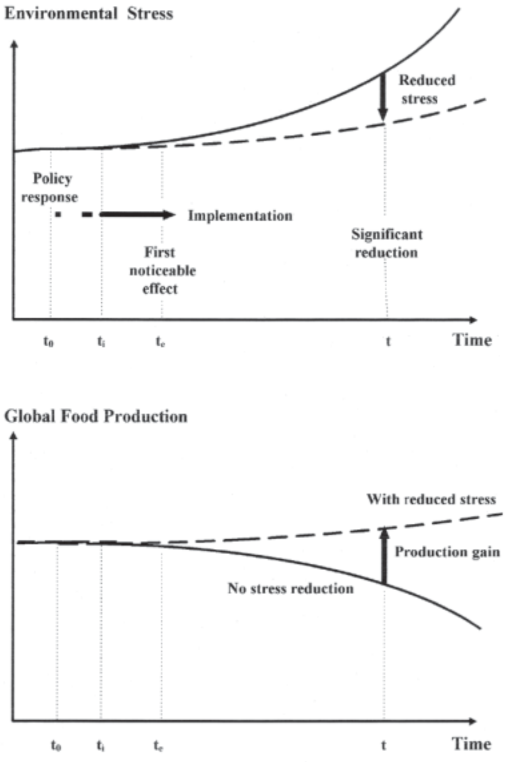

Figure 3. The upper figure illustrates schematically the reduction with time of a particular environmental stress factor following the implementation of response measures. The time t_i represents the time at which a comparatively widespread implementation of response measures has been achieved. The time t_e represents the time of the first noticeable effect. The lower figure shows the resulting augmentation of food production.

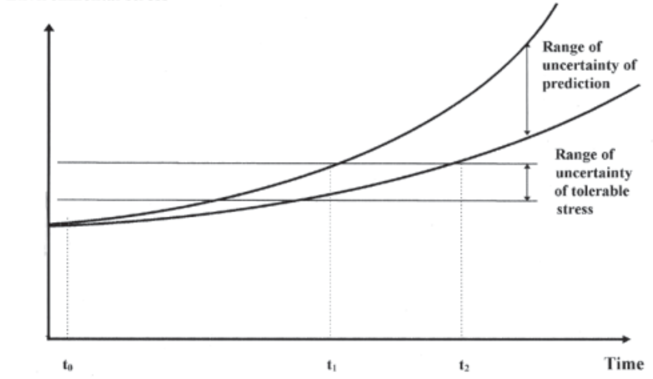

Figure 4. Schematic illustration of the predicted change of an environmental stress factor. Despite the comparatively large error of the predicted environmental quantity, it is clear that the maximum tolerable stress will be exceeded sooner or later. (Source; 51).

It can also be stated with confidence that considerable progress has been made in identifying opportunities for adapting agriculture to a slowly changing climate, i.e. to lessen the adverse effects and enhance beneficial effects. As already emphasized, adjustment to an increased variability of climate is more problematic.

In this context it should be emphasized that implementation of mitigation and adaptation measures often require financial investments that could imply serious problems for many developing countries. With regard to the industrial nations, it appears that some of them are reluctant to reduce their emissions, considering the cost to be prohibitive.

Timing of Response Measures

Even if the predicted environmental stresses are characterized by large uncertainties, this may not necessarily imply that the implementation of response measures is premature. As is illustrated in Figure 4, the environmental stress factor, despite even a large uncertainty, will eventually exceed the maximum tolerable stress — that has its own range of uncertainty.

CONCLUSIONS

As an overall conclusion it can be stated that: the time is not yet ripe for the design of a comprehensive coupled prediction model that takes into account all the factors having an influence on future global food production. The main reasons being:

- Present models of social and economic processes are not yet capable of making reliable predictions. Consequently, these 2 categories of factors, having a direct influence on changes in the Earth system and food production (the driving forces) cannot be determined with sufficient accuracy.
- The problem of predicting the change over time of the driving forces is further aggravated by the fact that they are influenced by political factors that indeed have a very low level of predictability; e.g. the willingness of nations to reduce greenhouse gas emissions.
- The negative impact of human-induced environmental stresses on food production are becoming increasingly important.

This implies we have to base the predictions of the Earth system and the global food production on certain scenarios of the basic driving forces, e.g. the future emission of greenhouse gases, the global food demand and technological developments.

Assuming now that these external (“human”) driving forces are known, the question is: Can the Earth system be predicted with a reasonable degree of accuracy? Taking into account the present positive trends in the development of coupled atmosphere-ocean-land surface models, it can be expected that within about a decade it will be possible to develop fully coupled dynamic (prognostic) models of the Earth system (7). This would imply that the Earth system model will be capable of providing realistic projections of the quantities the food production model requires for calculating such variables as yield, cropping index, and cropland area. In turn, this would enable the food prediction model to provide a feedback to the Earth system model making it possible to take into account more accurately the effects of changes in land surface.

Although the predictions of the food production obtained by prescribing the basic driving forces do not provide a “complete” forecast, they can provide useful information for planning purposes, including the identification and implementation of adaptation and mitigation measures. Thus, in this way there exists possibilities to provide concrete suggestions how the present driving forces need to be modified to ensure sustainable development.

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