Dealing with Climate Change and Food Security through Systems Analysis and Simulation

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ABSTRACT

In the next 30 years, the world must produce twice as much food to feed a population that is likely to double in the next three to four decades. It will be challenging enough just to double production, but henceforth, farmers everywhere must learn to produce more on less land and do so without compromising the productivity, stability and resiliency of the world's land, air, water and genetic resources. To complicate matters even more, the future is now blurred by the specter of climate change and the uncertainty it adds to the planning and decision-making process.

It is not likely that traditional research methods based on trial-and-error field experimentation can keep pace with future information needs. A substantial fraction of the information required to support global and site-specific decision-making will have to be generated trough systems simulation of agricultural options. This method provides a faster and more convenient and cost-effective way to study and improve agricultural systems than to experiment with the system itself.

Although there are many modelers and modelling groups throughout the world, most lack the critical mass of resources and technical skills to assemble and distribute validated simulation models for widespread adoption and use. This deficiency can be rectified by establishing an international collaborative research network for systems simulation in agriculture. Such a network may be able to produce the information generating tools the world will need to cope with systems problems stemming from a combination of heightened food demand, increased stress on our natural resource base and uncertain future climates.

INTRODUCTION

The first underlying thesis of systems analysis and simulation is that the workings of complex systems can not be understood by breaking them down and studying the components in isolation. By studying components separately, we miss the all-important emergent properties that make the whole larger than the sum of its parts. The second thesis of systems analysis and simulation is that it is often more convenient to study a system using models than to experiment with the system itself. In fact, models are turning out to be, not merely a convenience, but essential tools for investigating future consequences of current practices and policies. This symposium, for example, is based on simulated future climates associated with human activity on this planet. While there is considerable uncertainty about the nature and magnitude of change that is likely to occur on a site-specific basis, prudent leaders are investing in research that will enable their constituents to adapt to rapid changes that take unexpected direction. The purpose of this paper is to describe how systems analysis and simulation might be applied to help agricultural producers and policy makers cope with climate change and its uncertainty.

AGROECOSYSTEMS ANALYSIS

The system of interest in this paper is the agricultural system which we will henceforth refer to as the agroecosystem. Its analysis will follow procedures outlined by Conway (1982, 1984, 1985, 1987). Conway's analysis is based on the assumption that each distinct agroecosystem has a characteristic behavior that can be described by four interconnected systems properties. These properties which emerge from human interactions with the environment are (1) productivity, (2) stability, (3) sustainability and (4) equitability. Conway defines productivity as yield or income per unit input of land, labor or capital; stability as the constancy of production over time; sustainability as the ability of a system to maintain productivity when stressed or perturbed, and equitability as the fair sharing of the benefits derived from the system.

Today, the term sustainability is used in a broader sense and includes productivity, stability and equitability. For the purpose of this paper we shall use the broader definition of the term and substitute resiliency for Conway's sustainability. Thus, the four emergent properties of agroecosystems are productivity, stability, resiliency and equitability, and all four interconnected properties along with their interactions constitute sustainability.

Conway assumes that a limited number of key functional relationships and management decisions determine the system properties so that significant improvements in a specified agroecosystem require that their relationships and decisions are identified and understood. An example would be the relationship between variety or planting date with productivity or stability, and the consequence of decisions to change variety or planting date on productivity or stability of the agroecosystems. In practical terms, this means that the analyst must define and answer a limited number of key questions. These key questions relate to decisions and how decisions affect systems properties and performance.

The third of Conway's assumption is that these key questions are best identified and defined by an interdisciplinary group of experienced individuals spanning the natural and social sciences. These individuals analyze agroecosystems in terms of four basic patterns of space, time, flows and decisions which underlie the systems properties.

AGROECOSYSTEMS ANALYSIS AND SIMULATION

The bringing together of an interdisciplinary group of experienced individuals to undertake agroecosystems analysis is a luxury few can now afford and will become markedly more so in the future. At the same time, the need for interdisciplinary efforts will increase as the intensity of human interactions with the environment increases. This means that key questions and their answers will have to be identified and generated by some other means, of which systems analysis and simulation is one.

Conway (1977, 1986) acknowledged the potential value of simulation models in agroecosystems analysis, but chose to develop procedures without them. His justification for doing so was based on a desire not to exclude individuals from the analysis because of their unfamiliarity with models, and also because large scale modeling exercises have tended in the past to obscure key issues and questions by preoccupation with the details of model construction. While there is still considerable truth to Conway's concerns about simulation models, those in use today are much improved and will continue to be improved with time. But more importantly, it is unlikely that agroecosystem analysis can be undertaken, particularly under situations of changing climates, without simulation models. What makes Conway's approach to agroecosystems analysis so attractive is that it readily accommodates modelling. We shall endeavor to show how agroecosystem analysis can be facilitated by simulation models.

SPACE, TIME, FLOWS AND DECISIONS

Agroecosystems are analyzed in terms of four basic patterns of space, time, flows and decisions. In Conway's original approach pattern analysis was undertaken by using maps, transects, graphs, and flow and bar diagrams and decision trees. The objective of pattern analysis is to try to identify key processes that give the system its distinctive behavior and properties, and to identify those management decisions which are the key to improving systems performance (Conway, 1985).

Sound management decisions require that the decision makers have access to information that enables them to match the biological requirements of crops to the physical characteristics of land to meet specified objectives. Matching of crops to land is not easy because crop requirements vary with crop species and varieties, and land characteristics change over space with soil type and over time with seasons. Even today this matching process is mainly achieved by years and even decades of trial-and-error experimentation. In traditional pattern analysis, trial-and-error experimentation is replaced by the collective knowledge of an interdisciplinary team of experienced individuals. But anyone who has tried to form interdisciplinary team knows that only a small number of scientists in the research community is willing or able to work effectively in a team. For most researchers, it is still easier to exploit the reward system by publishing research results in one's own field of specialization. Unfortunately, the problem the world faces are not disciplinary problems, but systems problems that require the collective knowledge and integrated action of many individuals from many disciplines and professions.

Given the difficulty of forming effective interdisciplinary teams on the one hand and the need for so many of them on the other, it does not appear likely that the multitude of problems requiring systems analysis will receive timely attention by the type of interdisciplinary teams envisioned by Conway. This means that Conway's approach to problem solving must be captured and organized in a generic way so that others may use it to analyze patterns of space, time, flows and decisions for diagnosing and solving problems on a site- and situation-specific basis anywhere in the world.

In the final analysis, decisions are made on the basis of knowledge of flows of energy, material and information over space and time. We can illustrate this by following the fate of fertilizer nitrogen from the moment it is added to a soil to its appearance in the grain of a food crop at harvest time. It is clear from Figure 1 that nitrogen is involved in numerous interaction within the soil-plant-atmosphere continuum and the proportion of added nitrogen that eventually appears in the grain depends as much on factors such as weather over which humans have virtually no control as on manageable factors such as the timing, amount and type of nitrogen fertilizer to apply. It should also be evident that the fate of nitrogen in the environment varies with soil, time of year, cropping pattern and management options so that the same practice repeated on the same location will produce different results every year. It is only after many years of observations that a mental picture of expected outcomes emerges in the form of a probability distribution with a mean and a variance.

Decisions are made on the basis of expectations drawn from such probability distributions generated from years of observed outcomes. The mean and variance of the probability distribution are respectively related to the agroecosystem's productivity and stability. High means correspond to high productivity and low variances correspond to high stability and low risk. This is true if yield and yield stability were the main human goals of systems analysis. If we re-examine Figure 1, we see that nitrogen flows in several directions including downward into the ground water and upwards into the atmosphere. In the past, these losses were compensated by applying more nitrogen. Today nitrate contamination of ground water and additions of greenhouse gases to the atmosphere compel farmers to factor these side-effects into their management planning. We need probability distributions of nitrate leaching and greenhouse gas emissions from agricultural practices but cannot wait another 25 years to generate whole probability distributions to support decision making. The information the world will need to double food production without compromising environmental quality in the face of changing global climate will have to be generated in a different way. Information will have to be generated by those who need it to identify new practices and policies to improve agroecosystem performance. Since sustained performance is the aggregate of four systems properties including productivity, stability, resiliency and equitability, we want to be able to evaluate these four properties in ways that allow us to see how changes in one property affects all other properties.

PRODUCTIVITY

Defined as income or yield per unit input of land, labor, or capital, productivity has received the greatest attention by agricultural scientists. The green revolution symbolized huge gains in productivity, but with little regard for other systems properties. Rapid gains in productivity following the establishment of the first International Agricultural Research Center made it unnecessary to seek alternative ways to study and analyze agroecosystem performance. Early efforts to use models to simulate crop performance were not especially successful and Passioura (1973) caught the attention of the crop modelling community with an eloquent paper on the futility of modelling biological processes as complex as growth and development. Productivity is also unique among the four systems properties in that unlike the others, it is the one most sensitive to management factors such as irrigation, fertilization, crop protection and varietal selection. Human manipulation of these factors resulted in rapid and sometimes spectacular yield gains, but closer scrutiny by social scientists revealed inequities in the way productivity gains were being shared. There were clear evidence that the rich were benefiting from productivity gains at the expense of the poor.

EQUITABILITY

Judged on productivity alone, agroecosystems seem to be improving at a rapid pace, but when productivity gains were combined with equity losses, systems performance did not appear as healthy as the public had been led to believe. In response to the issue of equitability, many national and international agricultural research centers added a farming systems and research component to their programs. For the first time, the opportunity to analyze productivity and equitability simultaneously was presented to the agricultural research centers. But owing to the entrenched disciplinary structure of the centers, farming system research was not fully integrated with other disciplines and essentially operated as independent and separate units. If those involved in productivity research were not ready for modeling, the social scientists doing farming systems research were even less ready to consider modeling as an aid to systems analysis.

STABILITY

Climate and weather were two factors humans found difficult to control. And yet climate and weather often had more to do with agricultural outcomes than anything humans could do. Humans appear to be in control only because they operate within the limits of what climate and weather allow them to do. So long as the farming requirements matched climate and weather characteristics, the probability of harvesting a reasonable crop was high. But as soon as the farm objectives changed, some means of matching the new requirements of the new objectives to farm characteristics had to be undertaken. This matching process was achieved by slow and costly trial-and-error experimentation. A good match was needed to achieve high productivity at low risk. For risk averse farmers it was often more important to obtain low but dependable yields than to have high average yields at the expense of occasional crop failures. The reluctance to adopt new technologies on the part of risk-averse farmers was largely a reluctance to gamble with nature and destabilize an already shaky agroecosystems.

Events and outcomes that cannot be predicted or controlled compels humans to look beyond ordinary means to seek answers to problems that trouble them. Climate and weather were factors that were crying out be factored into the stability and productivity equation, and we can credit agroclimatologist for initiating efforts to model the relationships between crop performance and weather. In fact if we follow the progress of crop modelling we find, as van Keulen et. al. (1987) have described, a development path that involve taking into account four hierarchically ordered production situations. These four ordered situations are:

1. All production factors including water, nutrients, and pests are non-limiting and crop performance is determined by type of crop and weather.

2. Crop performance is determined by conditions of water, crop and weather.

3. Crop performance is determined by nutrients, water, crop and weather.

4. Crop performance is dictated by all factors that limit growth.

The extent to which crop simulations models have succeeded in taking into account the key factors that determine crop performance can be judged by the number of publication appearing in the scientific literature. Two relevant reports are Climate Risks in Crop Production (Muchow and Bellamy, 1991) and Systems Approaches for Agricultural Development (Penning de Vries et. al., 1993). In the past, model use was limited by the quality of the models themselves, but today their use is more limited by the shortage of site-specific soil and weather data, and cultivar-specific crop data needed to operate the models.

RESILIENCY

Resiliency refers to the capacity of agroecosystems to recover from imposed stresses and perturbations. This property is currently receiving a great deal of attention owing to the belief that human interactions with the environment are causing irreversible harm to the agroecosystem. It is clear that as we try to double food production in the next 30 to 40 years, we will subject the agroecosystem to even greater stresses. The objective therefore is to evaluate alternative strategies that enable food production to be increased without subjecting the agroecosystem to undue stress. For example, doubling food production will require heavier application of nitrogen fertilizer which will in turn increase the likelihood of groundwater contamination with nitrate nitrogen. If there is a way to apply more nitrogen to achieve higher yields without endangering the water supply, it is not going to be discovered by conducting field experiments. A more reasonable way is to produce the required information by *ex ante* means using models so that the results can be obtained in a timely and cost-effective manner without endangering the environment. Whether it be ground water pollution, soil erosion, water logging, salinization, desertification, pest infestation, or soil impoverishment, the strategy should be one of prevention rather than cure, and models are well suited to examine alternative ways to avoid subjecting the agroecosystem to unnecessary stresses.

SUSTAINABILITY

If productivity were the only systems property agricultural researchers were required to maintain at adequate levels, systems modelling would probably not be necessary. But productivity is no longer the only issue researchers and farmers will be asked to contend with. Henceforth, the goal is to achieve a state of sustainability requiring high productivity, consistent yields, adoption of ecologically sound practices, and equitable sharing of the benefits derived from farming. Efforts to make adjustments in one system property will surely result in adjustments in the others so that multicriteria analysis will be required to assess trade-offs among properties. Thus a systems approach must replace the discipline-oriented one that prevails in most research institutions. It is highly unlikely that the goals of sustainable agriculture can be attained without this change.

AGROECOSYSTEM MODELLING

The principal aim of agroecosystem modelling is to foster greater self-reliance in a critical number of the world's people. To be self-reliant, individuals need sound information with which to make timely decisions for themselves and society. Figure 2 illustrates one way to evaluate alternative strategies for increasing productivity. Since productivity varies from year to year owing to fluctuations in weather and other uncontrollable factors, strategies for increasing yields or profit must be repeated over many years. For illustrative purposes only two strategies are compared by plotting cumulative probability against yield or profit. The strategy on the right is stochastically dominant (Anderson, 1974) and is the preferred one if increasing yield or profit is the primary goal. The strategies might involve comparing new varieties, planting dates, plant populations, modes of irrigation, frequency of fertilization, or pest control practices.

Models have the capacity to generate information quickly and cost-effectively thereby allowing many alternatives to be compared. It would be prohibitively expensive and slow to even begin to generate the same information by field experimentation.

Models can also be used to assess stabilities of alternative strategies. In Figure 3, two strategies with identical means, but differing variances are shown. Most farmers prefer strategies that result in low year to year variability in yield or profit. Here again, it would be virtually impossible to search for stable strategies by means of trial-and-error field experimentation.

Resiliency can also be modelled provided the stresses causing productivity to decline is known. The EPIC model (Sharpley and Williams, 1990) for example relates productivity to erosion losses. Diminished resiliency lowers sustainability but does not necessarily result in lower yields. Use of nitrogen fertilizes, for example, may increase yield, but may contaminate ground water. Models are especially useful for screening strategies that minimize unwanted side-effects such as ground water pollution.

The fourth property of agroecosystem, equitability, is not subject to modelling and simulation, but can be helped by systems simulation of productivity, stability and resilience. Dent (1993) makes the point that the driving force for farming system change is social and cultural. He believes that if a modelling approach is to assist the process of technology development, adoption and change, then work must include, but extend beyond the use of crop models. He goes on to provide the format for a whole farm model in which farmers themselves are part of the process of technology choice and development. The critical element that makes self-reliance and choice possible is accessibility to the right kinds of information at the right time. Models are useful only in so far as they can generate needed information on an equitable basis.

GLOBAL CLIMATE CHANGE

The task of doubling agriculture production in a sustainable way would have been difficult enough even without global climate change. If climate undergoes change as indicated by a number of General Circulation Models, the results could have serious consequences for some and probably most people in the world. How well we cope with climate change will depend on (1) global solidarity for control of human action that contribute to climate change and (2) the human capacity to diagnose the nature and magnitude of change and prescribe alternative actions for circumventing unwanted consequences of change.

One beneficial consequence of anticipated climate change is that it promotes the development and use of models to help policy makers explore the future. Since there is considerable uncertainty as to what future climates will be like, crop-climate simulation models should be able to simulate alternative sustainable futures for any climate, now or future. To illustrate how far modelling has progressed, the U.S. Environmental Protection Agency, for example, has used crop models to assess the impact of global climate change on world food production and international trade (Rosenzweig, et.al., 1993). The models were first used to estimate yields under current climate, and subsequently for future climates predicted by three differing General Circulation Models. In addition the crop models were used to find alternative ways to circumvent the negative effects of climate change by altering varieties, planting dates, plant populations and nutrient and water supply. The models were modified to accommodate increased CO_2 concentrations and were run at CO_2 levels at 330 and 555 ppm. The knowledge for making the models respond properly to increased CO_2 levels was incomplete at that time so that there is little way of knowing how well the simulated outcomes for the high CO_2 level will hold up. Intensified efforts to study processes and outcomes of raised CO_2 levels, such as the FACE or free-air CO_2 enrichment experiments (Hendrey, 1993) will answer that question sometime in the future. Climate change is already having a profound effect on the way research is conducted. An increasing fraction of the research budget will go to support process-oriented research for model development at the expense of trial-and-error field experiments designed to study productivity, stability, resiliency and equitability of agroecosystems.

CONCLUSIONS

Systems simulation in agriculture may replace field trials as the primary means to generate information with which to identify new practices and policies for change. This approach will result in fewer trial-and-error field experiments and more process-oriented experiments to generate data for developing user-friendly simulation models. In order to produce effective models people will use, the users should be involved in the design of models from the beginning, and in addition every effort should be made to involve scientists from as many institutions and nations as possible to develop and test a standardized system that operates on a common, minimum data set. Models, however accurate and powerful, serve no useful purpose if they are not used by people to make better choices. A model that can be used only by individuals fluent in English, is not user-friendly. Several versions prepared in different language and tailored for specific user groups need to be produced. At the same time, it is better for the community of nations to join forces to develop a common model or set of models rather than for each country or institution to attempt to build its own. The slow pace of model development can be accelerated by an integrated effort mounted on an international scale. This is not to say that everyone should conform to the dictates of a single group. We need to avoid conformity and regimentation on the one hand, and fragmented modelling efforts lacking critical mass on the other. The Pacific Rim group can serve as the catalyst to initiate the integration of effort that is so critically needed for global agroecosystems modelling.

REFERENCES

Anderson, J.R. 1974. Risk efficiency in the Interpretation of Agricultural Production Research. Review of Marketing and Agricultural Research. 42: 131 - 184.

Conway, G.R. 1982. A Guide to Agroecosystems Analysis. In Tambon and Village Agricultural Systems in Northwest Thailand. Khon Kaen, Thailand: KKU-Ford Cropping Systems Project, Faculty of Agriculture, Khon Kaen University.

Conway, G.R. 1984. Rural resource conflicts in the UK and the Third World - Issues for research policy. In Science Technology and Public Policy. No. 6 London: Imperial College of Science and Technology.

Conway, G.R. 1985a. Agroecosystem Analysis. Agricultural Administration 20: 32-55.

Conway, G.R. 1987. Rapid rural appraisal and agroecosystem analysis: A case study from Northern Pakistan. In proceedings of the 1985 International Conference on Rapid Rural Appraisal. Khon Kaen, Thailand: Rural Systems Research and Farming Systems Research Projects. Khon Kaln University.

Conway, G.R. 1977. Mathematical models in applied ecology. Nature 269: 291-297.

Conway, G.R. 1985b. Analysis of tidal swampland agroecosystem. In KEPAS 1985. Tidal Swamp Agroecosystems of Southern Kalimantan: Workshop Report on the Sustainable Intensification of Tidal Swampland. In Indonesia, held at Banjarmasin, South Kalimantan, July 18-24, 1983. Jakarta, Indonesia. Kelompok Pnelitaian Agro-ecosystem, Agency for Agricultural Research and Development.

Dent. J.B. 1993. Potential for Systems Simulation in Farming Systems Research. In F. Penning de Vries, P. Teng and K. metselaar (eds.) Systems Approaches for Agricultural Development. Kluwer Academic Publishers. Pages 325 - 339.

Godwin, D.C. and P.L. G. Vlek. 1985. Simulation of nitrogen dynamics in wheat cropping systems. In: W. Day and R.K. Atkin (eds.), Wheat Growth and Modelling. Penum Publishing, New York, pp. 311-332.

Hendrey, G. R. (eds.). 1993. FACE: Free-Air CO_2 Enrichment for Plant Research in the Field.

Muchow, R.C. and J.A. Bellamy. 1991. Climate Risk in Crop Production. C.A.B. International.

Passioura, J.B. 1973. Sense and nonsense in crop simulation. J. Aust. Inst. Agric. Sci. 39.

Penning de Vries, F.; P. Teng and K. Metselaar. 1993. Systems Approaches for Agricultural Development. Kluwer Academic Publishers.

Sharpley, A.N., and J.R. Williams (eds.). 1990. EPIC--Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Department of Agriculture Technical Bulletin No. 1768.

van Kuelen, H., J.A.A. Bezkhout, C.A. van Diepen, H.D.J. van Heemist, B.H. Janssen, C. Rappoldt and J. Wolf. 1987. Quantitative land evaluation for Agro-ecological characterization. In A.H. Bunting (ed.), Agricultural Environments. C-A-B International.

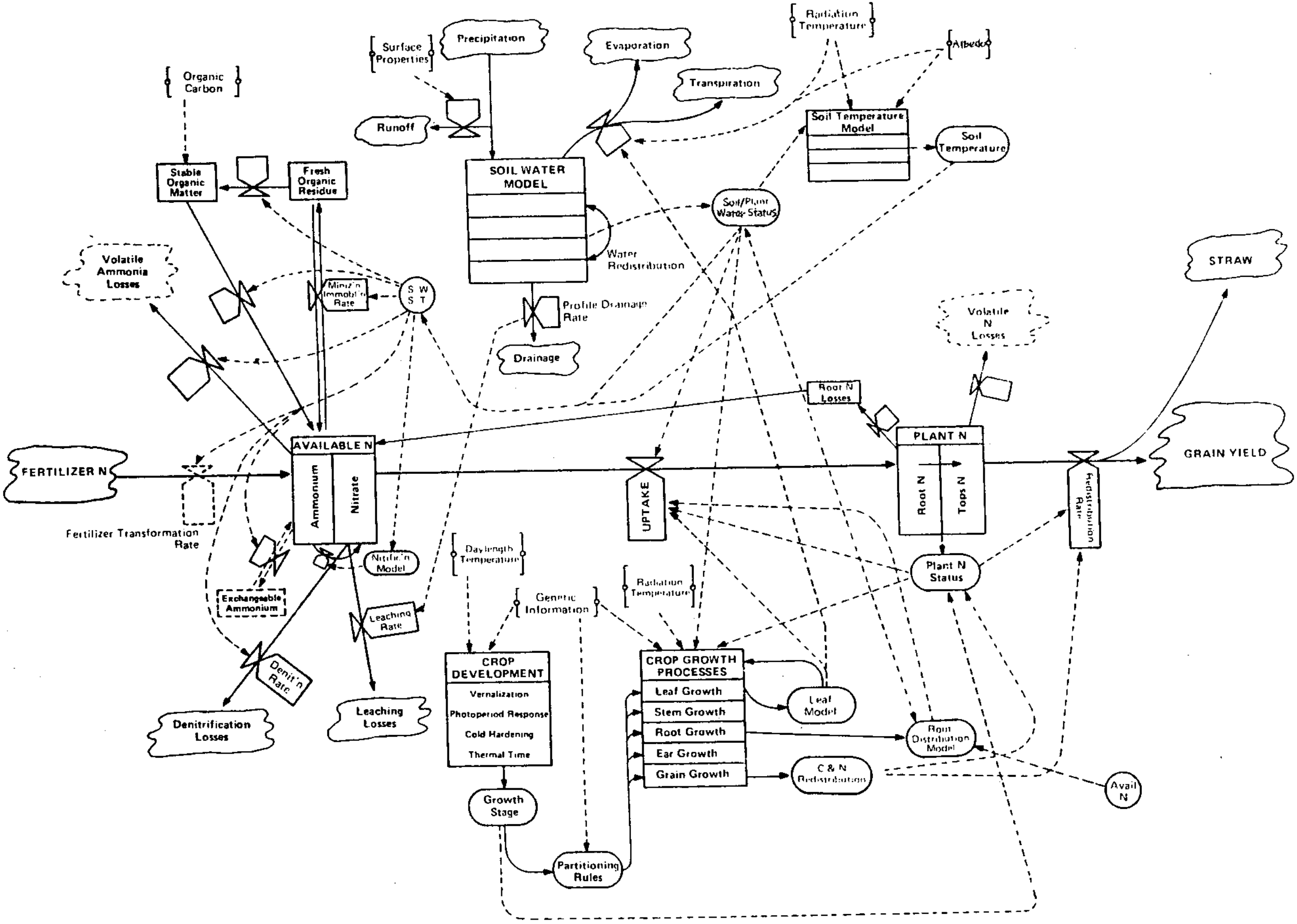

Figure 1 Nitrogen flow in the soil-plant-atmosphere continuum (Source: Godwin and Vlek, 1985).

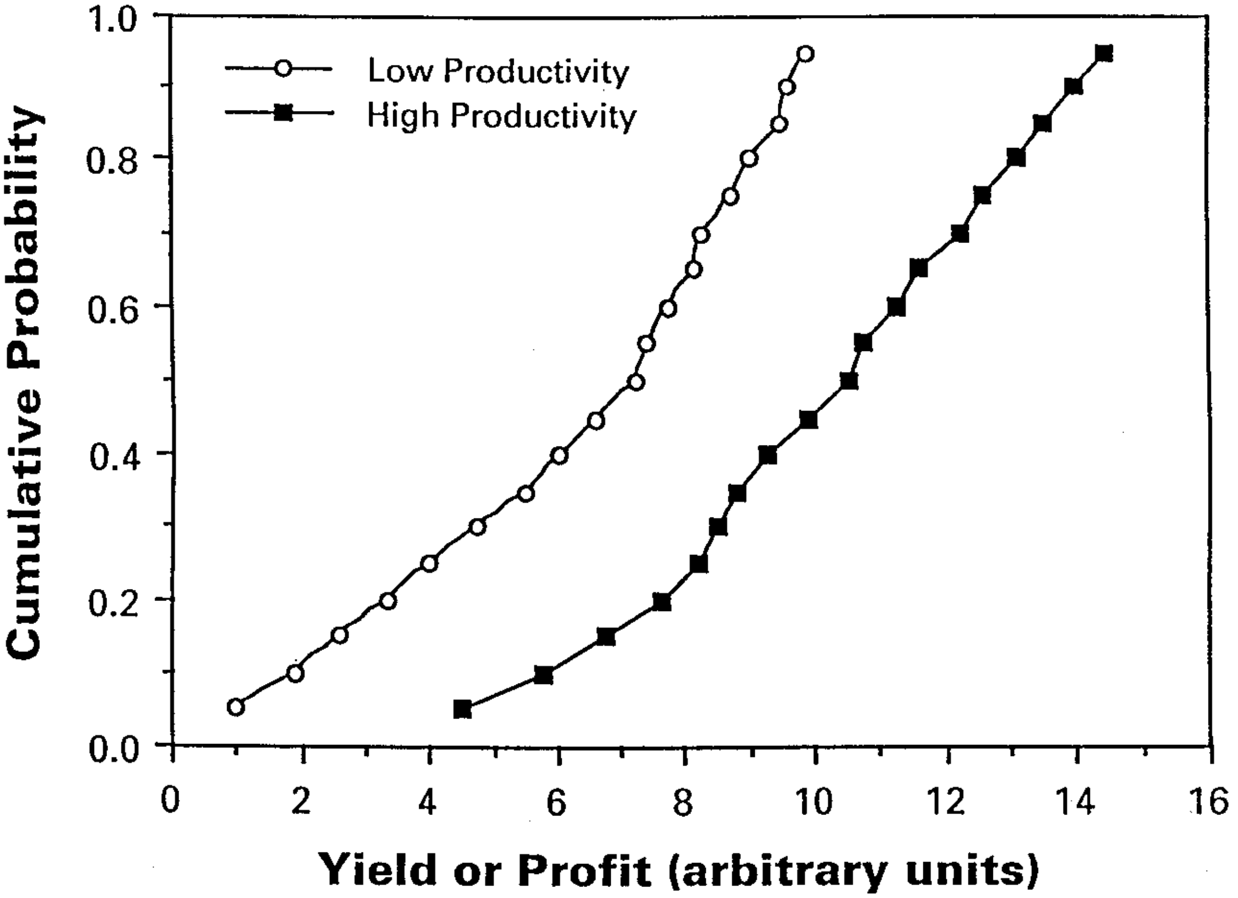

Figure 2. Cumulative probability versus yield (or profit) curves for low and high productivity strategies. Each point represents the outcome for a particular year. A comparison of the strategies for 19 consecutive years demonstrates that the curve on the right is more productive.

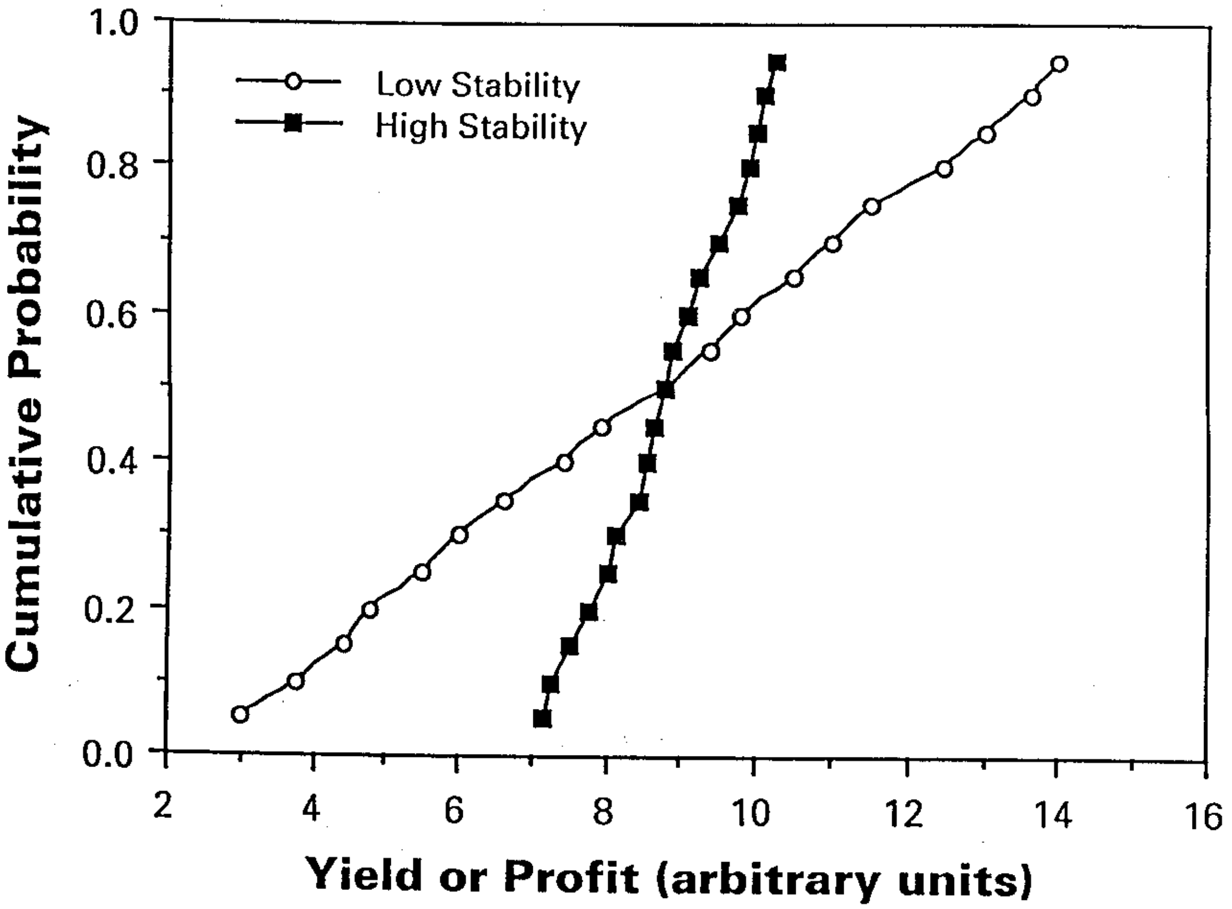

Figure 3. Cumulative probability versus yield (or profit) curves for loss and high stability strategies. Each point represents the outcome for a particular year. A comparison of the strategies for 19 consecutive years demonstrates that the curve with the lower variance (steeper slope) is more stable.