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Systems approaches for the design of sustainable agro-ecosystems

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Abstract

The complexity of agricultural systems and the need to fulfil multiple objectives in sustainable agro-ecosystems call for interdisciplinary analyzes and input from a wide variety of disciplines in order to better understand the complete agronomic production system. Systems approaches have been developed to support these interdisciplinary studies; their development and use have increased strongly in the past decades. Agronomic systems have pronounced spatial and temporal dimensions. Spatial aspects can be distinguished at crop, field, farm, regional and higher levels while processes at each spatial level have characteristic temporal components. Systems analysis in agronomic systems implies the use of various types of knowledge, such as expert knowledge including stakeholder expertise and knowledge derived from scientific measurements and model-simulations. The latter two can be derived from different types of studies: simple, rapid and cheap procedures, which are often relatively unreliable, at one end of the scale and complex, cumbersome and expensive data-intensive procedures at the other end. Selection of proper procedures for specific issues, both in terms of measurements and in applying simulation models, needs attention. Each problem requires its own research approach. Based on the output requirements and data availability, the proper systems approach has to be selected. Examples of these different procedures are given in this paper. Considering the type of problems to be studied in agronomic systems, different procedures can be followed to address the issues raised at a specific scale. These procedures start with a proper analysis of the system followed by studies that are projectory, exploratory, predictive, or are focused on decision support. Examples will be provided. Increasingly,

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systems approaches include stakeholders to fine-tune problem definition, the research itself, and the implementation of results. Stakeholders are farmers and citizens on farm and community levels and policy makers and planners at higher levels of aggregation. A comprehensive interdisciplinary analysis of agricultural production systems is seen as a necessary condition for the development of innovative, sustainable systems for the future. Systems for improving crop production systems are presented in this paper as well as applications of systems approaches at the farm and regional levels with emphasis on selecting the right approach.

Keywords: Crop modelling; Agronomy; Crop protection; IPM; Crop management; Farming systems; Ecological studies; Climatic impact

1. Introduction

Agronomic research contributed to the tremendous increase in agricultural production during the second half of this century. This production increase was largely a consequence of improved crop varieties in combination with improved management using external inputs and driven by the enormous increase in food demand as a result of population growth from 1.6 billion around 1900 to over 6 billion today. The supply of food has evolved into a complex system of production activities, land use needs, industrial processes, trade, market and price mechanisms, and national and international policies. The increased production per unit of land area by increased external inputs such as fertilizers and biocides and often large-scale reconstruction in regions with an agricultural function have led to irreversible changes in the landscape, diversity of the environment and the quality of natural resources. World-wide this has resulted in major questions in relation to the sustainability of agricultural production systems. Especially in the highly industrialized countries such as countries in the EU, there is a large call for organic farming systems without chemical inputs. To meet the challenges of increased food production, ways have to be found to improve the productivity, profitability, and sustainability of agricultural production systems. In large parts of the world where the food demand increases are highest such as in Asia, this production increase has to be achieved on less land with less labour, water, and pesticides, and it must be sustainable through conserving scarce natural resources.

For a long time, agronomic research focused on monodisciplinary studies in the field of plant breeding, plant nutrition, physiology of plant growth and development and crop protection with pesticides. Dose–effect relations were determined in the field to derive optimal fertilization rates, irrigation rates and effects of agrochemicals when combating pests and diseases. However, it has been shown that single factor efficiency is strongly affected by other production factors making an integrated approach necessary. Also, stronger emphasis is given to the analysis of entire agronomic production systems to support the need to design agro-ecosystems that increasingly have to fulfil multiple objectives. Such interdisciplinary analyzes need input from a wide variety of disciplines which, in turn, are used to better define and understand the complete agronomic production system. Systems approaches have been developed to support these interdisciplinary studies. The systems approach can be described as the systematic and quantitative analysis of agricultural systems, and the synthesis of comprehensive, functional concepts of them. The systems approach uses many specific techniques, such as simulation modelling, expert systems, data bases, linear programming, and geographic information systems (GIS). Systems research employs systems approaches and the techniques appropriate for its purposes.

Science-based mathematical models and computer simulation provide objective tools to determine biophysical consequences of resource management options at field, farm and regional scales. For a true systems analysis, such biophysical assessments need to be complimented by socio-economic analyzes before they will result in benefits at any scale. This requires a link between biophysical sciences and the social sciences when dealing with issues at the regional, farm and field level. Systems approaches have definitely moved beyond the research mode into the application mode. This is evident from the large number and quality of interdisciplinary research teams in different parts of the globe.

At the field level, the optimization of resource use is a key issue to achieve the different goals with respect to food supply, income, and protection of the environment. That requires the understanding of genotype $\times$ environment $\times$ management interactions to better adjust genotype selection and management options to specific local conditions and objectives. Systems approaches are now being used to increase the efficiency of breeding efforts, to determine yield potential in different environments, to optimize water and N use at the field level and to improve crop protection (through prevention and the use of natural enemies to minimize pesticide requirements; Kropff et al., 1997c).

Research on water and nutrient management has conceptually changed in the past decade because of environmental problems with, for example, nitrates in groundwater and the competition for water resources among sectors in the society such as industry, households and agriculture. Much research is geared towards matching the seasonal pattern of supply to the demand of the crop at each stage of development to achieve maximum resource-use efficiency and to minimize, for example, nutrient losses to the environment. Optimization of resource use, therefore, often serves different objectives that seem to be contradictory.

Concepts in crop protection have changed in recent decades from exclusion or destruction of pests to integrated pest management. Serious problems with pesticides, like the sometimes very fast development of pest resistance, environmental effects of pesticides and high costs, have triggered the development of new systems approaches and techniques in pest management. These are based on improved knowledge of pest dynamics and their natural enemies and the interaction between the pest and the crop. An improved understanding of the system will help to identify new control techniques by indicating intervention points and can be useful in decision making in pest management.

At the farm level, many decisions need to consider the trade-offs between different biophysical and socio-economic objectives. Integrated approaches for farm-level decision support have been developed that consider both biophysical approaches with socio-economic approaches (e.g. Rossing et al., 1997; Vereijken, 1997).

At the regional level, systems approaches have made eco-regional studies possible where new tools such as GIS can help to organize and utilize huge data bases that can be made more valuable through the use of systems models for interpretation. Scaling issues play a role here and novel approaches are being developed (Teng et al., 1997).

In this paper we will review developments in agricultural systems research at the different levels of integration and will indicate directions for further developments with special emphasis on the role that an international consortium such as ICASA can play.

2. Systems approaches for improving crop production systems at the field level

Traditionally, field experimentation at 'representative sites' was used to evaluate genotypic performance and to identify opportunities to improve production efficiency. Then results were extrapolated to other sites sharing similar characteristics (Nix, 1984). In climatically variable regions, such experimentation (following the so-called 'white peg agronomy' approach; Nix, personal communication) is costly and time consuming because of the need to sample sufficient numbers of seasons, cultivars, soil types and management scenarios. In the last few decades, agronomic research has been changing towards a knowledge based, systems focused approach. Simulation tools are needed to facilitate evaluation and extrapolation of management options. As a result, systems approaches have become important tools in agricultural research for breeding (e.g. Cooper and Hammer, 1996) and for general crop management and planning (Kropff et al., 1994a, 1997c; Teng et al., 1997). With respect to specific applications in breeding we refer to Boote et al. (2001). Here we will focus more on general applications.

The central question to be addressed at the field level today is how genotype $\times$environment$\times$management interactions can be optimized given the objectives set by farmer and society (economic, environmental and socio-economic). Systems approaches can quantify achievable yields of a specific genotype at different input levels in different environments. The simplest case is crop production at the potential production level, which is solely determined by the key growth-determining factors genotype, radiation and temperature. Adding the effects of water, nutrients, pests, diseases and weeds progressively increase the system's complexity. Potential production can be simulated based on historical weather data for yield gap analyzes (benchmarking). Including the effects of water, nutrients and management in the simulation studies facilitate decision support and analysis of management options for specific target yields and other (environmental) objectives. Models that link crop growth to pest, disease and weed population models can be helpful to develop for instance management scenarios, risk analyzes, and plant type design for host plant resistance. A primary function of these models, however, remains the integration of scientific understanding of physiological processes to analyze and understand the system holistically and the setting of priorities for process-related research. Here we will discuss recent advances at the different levels.

2.1. Yield potential as a reference point for yield improvement and breeding

Potential production is rarely achieved in field crops. Generally, only a fraction of calculated potential production is obtained, ranging from less than 5% up to 60% for country average yields (Oerke et al., 1994). Potential productivity is defined as the yield where only growth and yield determining factors play a role. It varies across agro-ecologies in response to solar radiation and temperature. Muchow and Kropff (1997) described in detail, the role of field experimentation and crop simulation modelling in assessing potential production in different systems, highlighting that good models for potential production require sound experimentation for parameterization and model evaluation.

Crop production can be quantified based on the capture and use of solar radiation. For many crop species, biomass production under potential growing conditions has been shown to be linearly related to the amount of radiation intercepted (captured) by the crop canopy (Williams et al., 1965; Monteith, 1977). The slope of the linear relationship is the radiation use efficiency (RUE) defines the efficiency of energy-to-biomass conversion. Sinclair (1997) and Muchow and Kropff (1997) concluded from literature data that there is little scope to improve in maximum RUE. The maintenance of high rates of carbon assimilation throughout the growing season has shown to be more important. This is particularly so during grain-filling, where a decline in carbon assimilation is often related to inadequate nitrogen supply (Kropff et al., 1993; Muchow and Sinclair, 1994).

Both temperature and solar radiation influence the variation in benchmark potential yields in contrasting environments (Kropff et al., 1997b). Using examples for maize, rice and wheat, Muchow and Kropff (1997) showed a wide variation in potential yield, with low yields in tropical environments and high yields in temperate environments at higher latitude (and altitude). In a study by Kropff et al. (1995b), it was found that the variability in potential rice yield ranged from 6 t ha^{-1} in tropical environments (wet season, Los Baños, Philippines) to 15 t ha^{-1} at higher latitudes (Yanco, Australia). The primary influence of temperature was on growth duration, with lower temperature increasing the time that the crop can intercept radiation. Potential biomass accumulation was directly proportional to the amount of radiation intercepted. Grain yield was directly proportional to biomass for a given harvest index. As a result, high yield was associated with low temperature and high solar radiation within the range of environments studied. For maize a simple mechanistic model accurately simulated yields ranging from 9.5 to 17.1 t ha^{-1} and it was shown that the main reason was the difference in growth duration (from 84 to 153 days) as a result of temperature differences (from 28.7 to 18°C; Muchow and Kropff, 1997). These analyzes indicate that the solar radiation and temperature regime set a limit to potential yield of grain crops in a given environment.

Although it seems that potential productivity can be simulated easily, there are large pitfalls. As was shown at the GCTE modelling group where 12 wheat models were evaluated for their capacity to simulate potential yields in different environments, many models may contain inherent factors that are calibrated for non-optimum conditions. Using the same weather data as input, a wide range of potential yields was simulated for The Netherlands where measured yield was about 12 t ha^{-1}. Simulated yields varied from 4.2 to 12.5 t ha^{-1} using models ranging in complexity from extremely detailed to relatively simplistic (Goudriaan, 1996). Apparently, the models were developed and calibrated for completely different environments and not necessarily for potential production situations. As a result, effects of growth-limiting and -reducing factors were inadvertently incorporated in the model structure and species parameters. For rice, however, a similar exercise yielded sound results using five different models (Kropff et al., 1995b). All models were evaluated and parameterized with data from irrigated, well-managed rice experiments and were able to simulate the yield variation of 6–15 t ha^{-1} accurately.

A very important application of these potential production models is the determination of the yield that can be achieved with current varieties in a specific environment (benchmark). An essential characteristic of yield gap analysis studies is to determine opportunities for yield improvement in well managed systems where additional inputs can be applied. This is the case in many parts of the developed world and in parts of the developing world (e.g. in irrigated rice ecosystems). In low yielding systems, this benchmark yield is not obtainable; approaches are needed that simulate yields under those conditions by taking other factors into account.

However, applications of these models go beyond straightforward yield potential predictions. The models can be very useful for plant-type design, such as was done at IRRI to design plant types with increased yield potential (Kropff et al., 1994b). Aggarwal et al. (1997) refined the simulation models for high-yielding rice varieties and evaluated the opportunities for improved varieties based on single traits and combinations of traits in environments with different levels of fertility. They found that higher-yielding varieties can only be selected based on better performance in enriched N environments and that only varieties with both improved sink and source traits can result in increased yield potential (up to 30% compared to the current varieties). Although new plant types have been developed since 1995 based on increased sink and source capacities, no reports of increased yield potential have been published yet. This may be due to sensitivity to pests under field conditions and because the required longer grain filling duration cannot be realized by the new plant types with bigger panicles and less tillers. However, these lines have a larger grain number per m^2 which may indicate an increased yield potential.

Boote and Tollenaar (1994) also used modelling to study the combination of genetic traits for maximizing soybean yield in two locations in the USA. They used the SOYGRO soybean model (Wilkerson et al., 1983; Jones et al., 1989) to vary traits related to carbon assimilation, seed filling duration, N concentration in leaves, and degree of determinacy within ranges that have been reported in the literature. Weather data from Wooster, Ohio (1988) and Gainesville, Florida (1984) were used, and it was assumed that the plants were grown under potential yield conditions (adequate water and nutrients and no losses due to pests or weeds). Row spacing was assumed to be 18 cm for these studies. They found that increases in the effective seed filling period by 10 days and increasing leaf photosynthesis from 1.05 to 1.39 mg CO_2 m^{-2} s^{-1} would produce a yield of 4870 kg ha^{-1} in Florida. Using these changes in traits to the cultivar grown in Ohio and making it more determinate resulted in a yield potential of 5760 kg ha^{-1} in Ohio. These simulated results were consistent with reported yields from maximum yield trials in Ohio. Differences in yield potential between Ohio and Florida were considered realistic by the authors because of the warmer temperatures in Florida. They concluded that these simulated yields represented current yield potential at these two locations within the current range of germplasm.

In a more detailed analysis, Boote et al. (1999) and Batchelor et al. (1998) reported on studies of new and old soybean varieties grown over multiple locations in the Midwest USA for 2 years (1997–1998). They determined how this crop achieves high yields, if growth patterns differ between older and newer genetics, and whether there is a linkage between genetics and yield response to stresses. New varieties yielded higher than older ones, by 17–20% at a location in Iowa. The CROPGRO-Soybean model was used to analyze growth analysis data collected in the field to determine which traits were different between old and new varieties. They found that the yield increases of new varieties were due to earlier pod formation, more determinacy, longer duration of the seed filling period, and higher photosynthesis rates. These differences resulted in more partitioning of growth into grain and higher harvest index for the new soybean varieties, which explained the higher yields.

In conclusion, modelling potential yield is achievable, but sound parameterization of the models for specific varieties is needed. Also, robust mathematical representations of physiological processes are crucial for accurate yield potential prediction. That requires a good interaction between modellers and experimentalists. A detailed discussion on advances in the use of models in plant breeding is given by Boote et al. (2001).

2.2. Optimizing water and nutrient management

Shortage in water and/or nutrients may reduce radiation capture. The availability of water and nutrients determines the level of stress resulting in a reduction of the development of early leaf area, the maximum Leaf Area Index, and the increase of the rate of leaf senescence (Kropff et al., 1994b; Muchow, 1994). Radiation use efficiency is also decreased by water and nitrogen shortage (Muchow, 1989, 1994). Climatic variability has a major impact on attainable yield under rainfed conditions. In the semiarid tropics and subtropics, rainfall is highly variable, both within and among seasons, and among locations. Hence it is difficult to determine attainable yields for using conventional field experimentation. Muchow et al. (1991) analyzed the variation in maize and sorghum yield in semi-arid tropical Australia using crop simulation models coupled to historical climatic data. Yields were highly variable from year to year, and while, on average, maize yielded more than sorghum, the coefficient of variation was less for sorghum (Muchow et al., 1991). The choice of crop to sow and the inputs to be used would depend on the level of risk aversion by the farmer. Knowledge of the yield gap between rainfed and potential yields is important for strategic decision making, such as investment in irrigation where water resources are available. Crop simulation is a powerful tool to assess temporal and spatial variation in water requirement.

In the past decade, our thinking about water and nutrient management has conceptually changed because of environmental problems. Examples include nitrogen pollution of groundwater and the competition for water resources among sectors in society such as industry, households and agriculture (WRR, 1995). Nitrogen is mobile in the soil and with the required high rates of nitrogen application for high yields in these environments in which water is not limited, the possibility exists for N losses (e.g. leaching and volatilization), and negative environmental impact. In rice, it appeared essential to match the seasonal pattern of N supply to the N demand of the crop at each stage of development to achieve full yield potential, but also to minimize N losses to the environment (Cassman et al., 1993; Ten Berge et al., 1994). Optimization of resource use, therefore, often serves different objectives that may seem to be in conflict. Generally, resource use efficiency increases with production level so that reduced nutrient losses to the environment can be achieved at near optimum yield levels.

In many intensively managed agricultural systems, nutrient supply still strongly affects attainable yields, in spite of recommendations based on half a century of intensive fertilizer research in many crops. In the past, many fertilizer trials were conducted without a systems approach. This provided general fertilizer recommendations which sometimes resulted in excessive fertilizer (e.g. grassland in The Netherlands or in suboptimal fertilizer recommendations for rice, resulting in yield levels of 7 t ha^{-1} whereas more than 9 t ha^{-1} were attainable with adequate N fertilizer (Cassman et al., 1993; Kropff et al., 1994b). Systems models are now being used for decision support providing the appropriate broad scope for advice.

Techniques are being developed to integrate spatial data from precision agricultural fields for using agronomic models and systems approaches. Paz et al. (1998, 1999) used soybean and maize crop models to analyze reasons for spatial variability of a highly productive field in Iowa, USA. Their approach was first to diagnose reasons for yield variability, then to use the model to determine ways to increase yield and profits via spatially variable management. They found that 70% of the yield variability of soybean over 3 years was accounted for by differences in soil water holding characteristics, but these differences in soil characteristics could not be inferred from existing soil maps. For maize, they found that soil water availability accounted for about 57% of the spatial yield variability. By using yield map data along with existing soil maps, they refined soil parameter estimates over the field and used these to determine optimal rates of nitrogen application rates. They showed that yield and profit could be increased using variable N rates and that lower amounts of N were needed for the field, thereby reducing risks of N leaching to groundwater.

One good example of the use of a systems analysis of nitrogen management in low input agriculture was described by Keating et al. (1991). They first conducted field studies in semiarid Kenya to determine the accuracy of CERES-Maize model in describing maize yields under different combinations of water and N availability.

They made adjustments to the model so that it would more accurately simulate yield responses to severe limitations of water and N. They then simulated various management strategies, using long-term weather data, to quantify the economic risks to small changes in current practices related to crop residue management, plant population, and N application. They showed that small changes in these basic management factors could result in greater earnings in most years, even though there was a risk of crop failure in some years due to drought. A similar evaluation and application was done for Malawi by Singh et al. (1993). They evaluated maize management options for increasing yield and decreasing nitrate leaching, and showed how soil and weather variations across time and space affected yield and risk to the environment.

These examples show that decision-support systems based on the use of data and models can help to improve resource use efficiency and to address environmental objectives at the same time to improve agro-ecological production systems.

2.3. Crop protection

Pests, diseases and weeds affect crop growth in spite of intensive crop protection measures taken world-wide. Oerke et al. (1994) estimated crop losses for eight major crops by pests (insects, diseases and weeds) in spite of all control measures taken. Worldwide this would add up to about 40% loss due to the three components.

Linked pest and crop models provide tools to explore the dynamics of the interactions and to optimize pest management strategies (Kropff et al., 1995a). Models at different levels of detail have been developed to quantify pest damage ranging from empirical functions to mechanistic simulation models. Empirical approaches are often used to quantify economic threshold levels in decision-support systems for pest management. These empirical damage functions are generally derived by regression analysis relating a measure of pest severity at a given crop stage to yield loss. These functions have been useful because of their relative simplicity, but they ignore the dynamics of crop–pest interactions and their value is generally limited to the specific conditions at which the measurements were taken. More insight can be obtained by linking pest–crop models (review by Kropff et al., 1995a). Coupling points are located at the level of resource capture (light, water, nutrients), at the process level (photosynthesis, respiration, translocation) or at the state variable level (consumption of assimilates, biomass, leaf area). Different categories of damage mechanisms can be distinguished (Boote et al., 1983; Rabbinge et al., 1994): competition for resources, plant killing, reduction of assimilation rate, effects on respiration, tissue necrosis and interception of light, tissue consumption, assimilate consumption, hampering of water uptake and induction of hormonal effects on stomatal regulation and deformations.

In the recent decades, concepts in crop protection in intensive agricultural production systems have changed from exclusion or destruction of pests to pest management. Serious problems with pesticides like the sometimes very fast development of pest resistance, environmental effects of pesticides and the cost have triggered the development of new approaches and techniques in pest management based on improved knowledge of pest dynamics and their natural enemies and the interaction between the pest and the crop (Kropff et al., 1995a). An improved understanding of the system will help to identify new control techniques by indicating intervention points and can be useful in decision making in pest management (reviews by Boote et al., 1993; Rabbinge et al., 1989; Pinnschmidt et al., 1994).

Since the early eighties, computer-based decision-support systems have been developed that range from simple decision rules to complex multiple-criteria optimization software. In its simplest form, a decision-support tool could be a threshold pest infestation level calculated from empirical relations based on field data. Empirical models and thresholds have been developed for many pests in the recent decades (Zadoks, 1985). Successful decision-support systems have been developed based on these relationships (e.g. EPIPRE; Rabbinge and Rijsdijk, 1984; Rijsdijk et al., 1989). This kept the number of sprayings in wheat in the Netherlands down to 2.5 compared to 8.5 in the UK and 7 in Germany (Rabbinge, 1988). The possibility of linking pest–crop models opens new options to improve decision making in pest management in intensive agricultural production systems which are designed to serve multiple objectives: the analysis of risk and uncertainty associated with alternative decisions and strategies for pest management with minimum environmental impact from pesticides.

Recently, several early warning systems with online weather recording units on the farm have been developed for the prediction of the need to spray for late blight (*Phythopthora infestans*) in potatoes, but other applications are being investigated as well. Such modern information networks for farmers put the farmer at the centre of agricultural and scientific developments (Fig. 1). In this network, the information obtained at the farm is stored in a large data base. Such a data base serves as the tool for the farmer to decide upon the use of pesticides. At this stage, the network as

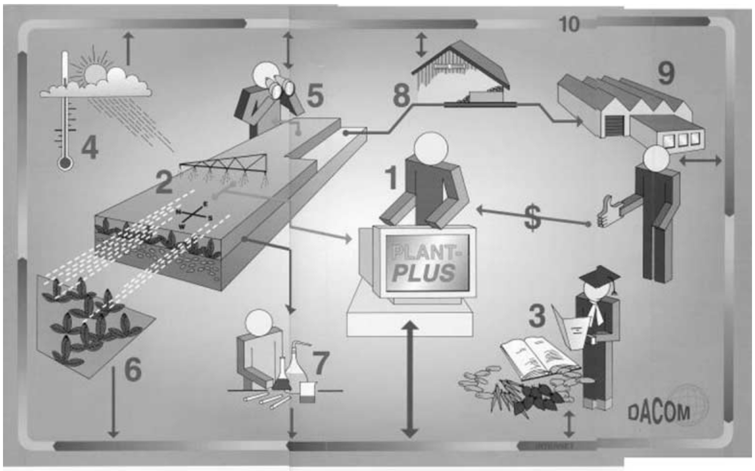

Fig. 1. The place of the farmer (1) between his field (2), scientific developments (3) and weather (4), with scouting and crop advice (5) on sources of diseases (6) and laboratories (7), storage (8) and processing and payment (9), all integrated in a single data base (10) (Scheme produced by DACOM).

maintained by DACOM (The Netherlands; www.dacom.nl) links to 2500 farmers, distributed throughout The Netherlands. Other organizations, such as DLV (Dutch Extension Service), are also maintaining and expanding such networks.

For weeds, an increased interest in the development of integrated weed management systems (IWM) has evolved. Rather than trying to eradicate weeds from a field, emphasis is on the management of weed populations (Cousens, 1987). Three aspects of IWM systems can be distinguished: decision making, prevention and weed-control technology (Kropff et al., 1997a). In order to answer this type of question, quantitative insight into crop–weed interactions and dynamics of weed populations in space and time are highly relevant. Irrespective of the time dimension of the analysis, it is clear that attempts to reduce the present dependency on herbicides should focus on prevention. This can be based on cultural measures that favour the crop or through the use of more competitive varieties, on the development of better curative control techniques and on better long- and short-term decision making. Quantitative insight into both crop–weed interactions and the dynamics of weed populations in space and in time forms the basis for such explorations of opportunities to improve weed management. Modelling approaches for weed population dynamics and crop–weed interactions were reviewed by Kropff et al. (1996). They indicated that using systems approaches changed the focus of weed ecological research from pure competition studies on the effect of weeds on the crop to population dynamics studies on long-term development of weed populations, as the latter determines farmers' decision making. Competition studies now focus on the effect of the crop on the weed (seed production).

A major application of the models is to define optimal control that fits the needs of the farmer and to evaluate scenarios for different control strategies such as the use of preventive measures, the use of thresholds, a critical kill rate or the use of HT (transgenic herbicide resistant) crops.

The development of weed suppressing varieties of crops without trade-offs with yield may be one of the options for preventive weed management. Insight in processes related to crop–weed interactions and weed population dynamics might help in the development of such preventive measures. The eco-physiological simulation model (INTERCOM; Kropff and Van Laar, 1993) for crop–weed interactions explained the experimentally determined large differences in competitive ability between rice cultivars accurately (Bastiaans et al., 1997). The model showed that competition for light is mainly determined by morphological characteristics of which early relative leaf area growth rate, early relative height growth rate and maximum plant height were found to be the most important. The ability of the model to identify key traits with respect to competitive ability makes it a useful tool for designing ideotypes. The systems approach provides guidelines for the design of weed suppressing varieties with minimum trade-offs with yield.

Kropff et al. (1997a) determined whether the introduction of cultivars with an increased competitive ability would reduce the seed production of weeds (in this case *Agrostemma githago* L. in wheat). In a preliminary analysis it was found that the critical kill rate to maintain the population of weeds at a low density was very sensitive to competition by the crop. Large differences in competitive ability between genotypes have been demonstrated (e.g. for rice by Kropff and Van Laar, 1993). Especially, the seed production of late-emerging weeds or weeds that survive control measures can be strongly reduced by using competitive varieties. In addition, this component could be used in herbicide resistant crops to reduce population development of relatively insensitive weeds. Effects of other preventive measures can be evaluated using the models as well.

Wallinga (1998) used density-based population models to determine the influence of the threshold level on the frequency of herbicide applications. The simulations resulted in an oscillation of weed density in a periodic fashion around the threshold, with a frequency that seemed to be independent of the threshold value. He concluded that the weed control threshold as a tool to base control frequency on economic considerations loses meaning when it is applied to the long term. These are very important findings to take into account when applying these threshold approaches in herbicide resistant crops for the late-emerging weeds and surviving weeds. The above studies resulted in a shift of interest in weed science from yield loss studies to studies on weed population dynamics and effects of the crop on the weeds for strategic management.

In general, the use of systems approaches has helped crop protection research to evolve from empirical site specific studies to the development of decision-support system based on insight in the crop–pest system.

2.4. Other factors affecting yield

Other factors that result in reduced yields are factors such as waterlogging, lodging, biomass loss and seed shattering. These are factors that are difficult to control, even under potential growth conditions. In modern, semi-dwarf rice varieties, lodging is often a constraint to potential yield when N supply is high (Setter et al., 1994). The breeding of semi-dwarf soybeans to overcome the lodging barrier to yield, combined with modified crop management, has led to higher yield potential in soybean in high-yielding environments (Cooper, 1985). In high-yielding sugarcane, Muchow et al. (1994) identified an early yield plateau well before scheduled crop harvest when climatic conditions and resource supply were favourable for continued crop growth. Stalk death and subsequent loss of biomass associated with lodging and smothering were significant contributors to the cessation in yield accumulation, with consequent poor efficiency of utilization of radiation, water and nutrients due to poor late growth in these crops. Opportunities for genetic and management manipulations to improve radiation utilization in these circumstances need to be sought (Kropff et al., 1997b).

2.5. Systems for agronomic research and decision support at the field scale

There are three notable examples of systems models designed specifically for agronomic research and decision support at the field scale developed within the ICASA framework. The first is the decision support system for agro-technology transfer (DSSAT; IBSNAT, 1993; Jones et al., 1998; Uehara and Tsuji, 1998). It contains crop–soil simulation models, data bases for weather, soil, and crops, and strategy evaluation programmes integrated with a user-friendly interface on micro-computers. It was designed for users to create 'experiments' to simulate outcomes of the complex interactions between various agricultural practices, soil, and weather conditions and to suggest appropriate solutions to site specific problems. It has functions for users to (1) input, organize, and store data on crops, soils, and weather; (2) retrieve, analyze and display data; (3) validate and calibrate crop growth models; and (4) evaluate different management practices at a site. In adapting and applying DSSAT, users typically use the following procedures (Uehara, 1989; Jones et al., 1998):

- Conduct field experiments on one or more crops, and collect a minimum data set (MDS) required for validating a crop model (Hunt and Boote, 1998). Run the model to evaluate the ability of the model to predict performance of crops in the region of interest, using new and existing data.
- Enter other soil data for the region and historical weather data for sites in the region. Conduct sensitivity analysis on the crop model(s) to get an overview of the response of the model to alternative practices and weather conditions.
- Select a set of management practices and simulate each of these over a number of years to predict performance and uncertainty associated with each practice.
- Compare alternative practices using means, variances, and cumulative probability distributions of simulated yield, water use, season length, nitrogen uptake, net profit and other responses (Thornton et al., 1994). Make decisions and recommendations.

The second system is the Agricultural Production System Simulator (McCown et al., 1996). This system was designed for use in agronomic research to simulate crop production in specific soil, weather, and management situations, similar to the DSSAT. However, a new modular structure was developed specifically to provide flexibility to researchers in the application to different problems requiring different components. This structure allows the selection of the desired components and therefore provides a means for selecting the appropriate level of complexity for the task. It greatly enhances code maintenance and flexibility. Improvements and new features to the system are much more practical using such modular design. APSIM has modules for a number of crops, and it has been used for various applications in various countries (Hammer et al., 1999). Modularization of agronomic system models is a high priority for ICASA, and is essential for more effective progress in agronomic systems approaches (Jones et al., 2001).

The third ICASA set of systems analytical tools is developed by the Wageningen group. A novel example of the use of models for water and nutrient management is provided by precision agriculture. A decision-support systems for arable farming systems in the Netherlands is being developed with a primary focus on operational decisions and soil related variability. Bouma et al. (1999) are developing a forward looking approach for N fertilization allowing farmers to respond pro-actively to N deficiencies that can be expected in the production systems as well as to the exceeding of environmental threshold values for groundwater pollution (see also: Van

Uffelen et al., 1997; Van Alphen and Stoorvogel, 2001). The system consists of several components:

1. *Soil data base*. From soil sampling observations in the field in a grid pattern a data base can be constructed that has value for the longer term. The grid density depends on the spatial variability in the field which can be determined by remotely sensed information, yield maps, soil surveys etc. (e.g. Verhagen et al., 1995). Primary data are stored in the data base (e.g. layer structure, bulk density, organic matter content) and secondary data such as hydraulic characteristics are derived using so-called pedo-transfer functions (e.g. Wösten, 1997).
2. *Management units*. The spatial resolution at which precision agriculture is implemented varies significantly and equipment is currently being developed for precision at the sub-meter level (Robert et al., 1994; Stafford, 1997). However, the proper scale depends on the level of spatial detail of the basic data base (unless on-the-go measurements are made such as in urine spot detection). Models can be used to distinguish between land units that significantly differ in soil moisture regimes and nitrate leaching.
3. *Real time simulation*. Real-time simulations can be performed using the proper site-specific input data in terms of soil and weather data up to the moment of running the real-time model. Today, weather data are available online for many Dutch farms that use early warning systems. Real time simulations can indicate the need for fertilizer and irrigation. If the models are not well calibrated, soil and plant measurements may be needed. An example is given by Booltink et al. (2001) where the real time simulation of N recommendations for wheat are given (1998 data). Simulations indicate that applications are needed much later than commonly practiced. With historical weather data yield predictions can be made as well (e.g. Booltink and Verhagen, 1997). The fertilizer level can be adjusted to that target yield. Similar procedures can be used for pests and disease early warning systems (e.g. Boesten and Gottesburen, 2000).

2.6. Challenges for crop modelling at the field level

In general, process modelling needs improvements to better simulate genotype $\times$ environment $\times$ management interactions. The main processes that need further quantitative study are related to: morphology, phenology, source-sink, nutrient effects, pest, disease and weed effects, management effects. Species characteristics need to be as genotypic as possible and not, as in many cases, based on a large environmental component (such as Specific Leaf Area). The identification of these genotypic characteristics creates new challenges for the future to predict yields of different genotypes based on genetic marker analyzes (e.g. Yin et al., 1999). In a recent study, Mavromatis et al. (2001) and Irmak et al. (2000) reported on research to determine whether typical soybean yield trials, conducted by plant breeders, could be used to estimate genotype characteristics for the CROPGRO-Soybean model. They found that data taken over a range of locations (5–7), planting dates (up to two per year), and years (3–7 for each cultivar) could be used effectively to determine the characteristics required by this model. In addition, they showed that this process could successfully reproduce the G $\times$ E interactions observed in the variety trials under some situations.

Besides improved process knowledge, better data bases with crop data for model evaluation are needed. In the IBSNAT project (Hunt and Boote, 1998) minimum data sets were defined. Standard formats and data structures were defined to facilitate the documentation of experiments, to allow easy sharing of data in electronic formats, and to use as inputs to crop simulation models. ICASA developed a new data and file structure system that can be widely advocated to crop modellers and to experimentalists (ICASA v1.0 data standards; Hunt et al., 2001). One major advantage of these file and data structures is that they are text files and are thus easily exchanged and read or edited by many software packages. These text files also have limitations for some applications, however, so we envisage an evolution of other accepted data standards with software tools for translation. However, advanced data base systems such as commercially available relational data base management systems can form a next step in modelling agronomic systems, as was shown by Van Evert et al. (1999a, 1999b). They developed CropSyst, which is a collection of object-oriented simulation models of agricultural systems in conjunction with a relational data base (Van Evert and Campbell, 1994; Van Evert et al., 1999a, 1999b).

The basis of these models is climatic and soils data. Radiation data are available for relatively few stations in major regions in the world. A very important initiative of ICASA could be to establish a data base using existing data bases of the international institutions like IRRI, CYMMIT and ICRISAT and national research institutions as well as sound calibrated models for yield potential of the different crops. Free access to such data and tools to facilitate their uses would be great assets for effective use of simulation models in the coming decades.

Another future activity that is very important is joint module development. Crop models should be modular so that new components can be added, modified, and maintained with minimal effort. This would greatly facilitate our ability to integrate knowledge from different disciplines and move models toward predicting actual as opposed to potential yields. It will help model developers add new components to models to include new factors, such as pests and diseases, with minimal changes to existing model code. This ability is urgently needed to allow easy substitution of components for evaluating alternate model formulations. It will allow model developers to update documentation and to maintain code much more effectively. Several groups in ICASA are currently investigating alternative approaches (Jones et al., 2001).

In general, we need a system in which data bases, model concepts and information and communication technology (ICT) are interlinked in a modern and flexible way that allows modellers and model users to apply the tools effectively (Fig. 2). Finally, the operationalization of the models for real world applications needs further developments such as real time simulations for decision making. ICASA will focus on joint development of such a toolbox in the coming decade.

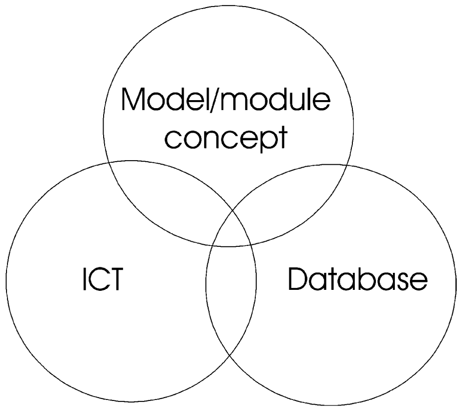

Fig. 2. An integrated model environment that has to be based on the latest model concepts, an information and communication technology (ICT) resulting in modular systems and data base management systems.

3. Systems approaches at farm and regional levels

Systems approaches in agronomic systems at higher scales require different types of systems models. With respect to land use changes, three different approaches can be distinguished for application at different hierarchical scales:

1. The prediction of future land use based on extrapolation of existing trends. The past is used as a measure for the future; optimization of future land use, considering trade-offs between conflicting objectives, is not possible and land use changes may be predicted that are not feasible from a biophysical point of view, especially when applied at a regional level (Veldkamp and Fresco, 1996). Moreover, the deviations from the regressions between factors and land use are taken as opportunity for change, whereas they may just reflect deviations that cannot be explained by the factors taken into account in the model.
2. The exploratory approach that defines a number of realistic land use options for the area to be considered. These studies use biophysical insight in the system as a starting point (often using MGLP); optimization of land use can be evaluated based on different sets of objectives. This makes the analysis of trade-offs between objectives possible. The stakeholder makes the decision. The exploratory approach does not predict but explores the window of opportunities. Criticism is focused on the fact that agro-ecological opportunities may never be realistic because socio-economic factors play a major role (FAO, 1976; Van Latesteijn, 1995). However, several studies have demonstrated the usefulness of this approach for policy-making (Van Ittersum et al., 1998).
3. Identification of policy instruments to realize particular land use options. An example for the farm level was reported by Kruseman et al. (1995).

All three approaches can be used in several ways. However, an integrated approach in which the stakeholders participate may be the most feasible approach to address the objectives of the stakeholders in the most effective way (Teng et al., 1997). This will lead to effective decision-support systems (Bouma, 1997).

To obtain generic knowledge on the opportunities for development of intensive agricultural production systems, interdisciplinary studies are needed in which models and experimentation are integrated. Such models can be used to design agricultural systems that serve multiple objectives by interactive multiple goal optimization. In the Netherlands, such an approach (Approach 2: exploratory) has been developed and tested for several case studies by the Wageningen Agricultural University and the Research Institute for Agrobiology and Soil Fertility (AB-DLO) and the Scientific Council for Government Policy (WRR; WRR 1992, 1995; Jansma et al., 1994; Habekotté and Schans, 1996). In this approach, opportunities to achieve multiple goals with respect to profitability and environmental issues can be explored. For arable farming systems, profitability of different farming systems was determined at different maximum levels of N emission to the environment and pesticide use (Habekotté and Schans, 1996). In the model, a wide range of production technologies was generated with varying input–output relationships and different use of N fertilizers or manure and pesticides with the help of crop simulation models and expert knowledge. The model optimizes income at different levels of constraints with respect to N emission and pesticide use by selecting the most profitable combination of crops in the rotation. A wide range of N emission and pesticide use, appeared to be possible at the same level of income. Rotation systems change dramatically when the maximum N loss was set to 70 kg ha^{-1}, as no manure was used in the systems. Because of the manure surplus in The Netherlands an objective was to maximize manure application. In that case, 15 t ha^{-1} manure was used at a cost of Dfl 1000 per ha. This clearly shows the strength of the approach to explore options and the exchange of different objectives. However, it only serves as a tool to explore the possible range of options for agricultural development. Socio-economic studies are needed to determine the possibilities to implement such systems. For example, market issues would be needed to determine the need for diverse farming systems.

Systems approaches to optimize farming systems with respect to multiple objectives, based on a comprehensive scientific analysis may help to identify options for sustainable agricultural development. The implementation and practical development of options can be realized using the prototyping concept developed by Vereijken (1997). In this approach, the scientist designs and evaluates the farming system with a network of farmers based on quantitative indicators of systems performance.

The sustainability of farming systems is influenced by many biophysical, economic, social and political factors. As such, it is difficult to study the sustainability of farms through a forward-looking process. However, Hansen and Jones (1996) proposed a systems approach for characterizing farm sustainability that provides probabilities of farms being able to continue to operate when faced with threshold levels of income, food, or other indicators of the economic, environmental quality, and productivity of the farm. Below these thresholds, the farm was assumed to fail. Long-term stochastic simulation of a farm system model was used to quantify sustainability of a rice farm in Texas, demonstrating how crop rotations and land tenure contribute to expected sustainability. In addition, Hansen (1996) used the approach to compare the effects of weather variability on farm income and sustainability for a small farm in the hillsides of Colombia with the effects of price variability. This work showed that price variability in this region poses a greater threat to farms than weather variability when there was a minimum income requirement. This approach integrates information and responses at the farm scale to support decision making.

Agriculture is highly affected by year-to-year climate variability. If farmers had predictions of climate 3–6 months ahead of time, it may be possible to modify decisions to decrease unwanted impacts and to take advantage of expected favourable conditions. Recent scientific advances have led to capabilities for predicting climate variations with useful skill several months ahead of time in many parts of the world (Barnston et al., 1994; National Research Council, 1996; Hammer et al., 2000). Most current climate forecasts are based in some way on the El Niño-Southern Oscillation (ENSO). ENSO refers to shifts in surface temperatures (SST) in the eastern equatorial Pacific and related shifts in barometric pressure gradients and wind patterns in the tropical Pacific (the Southern Oscillation). ENSO activity is characterized by warm (El Niño), neutral, or cool (La Niña) phases identified by SST anomalies.

Because farmers might change the proportion of crops they plant depending on ENSO phase, Messina et al. (1999) used crop simulation linked to an economic optimization model to explore the potential benefits of tailoring farm-scale crop mix to ENSO phases for two location in the Pampas of Argentina. The model identifies the crop mix that maximizes expected utility of wealth at the end of a 1-year planning period for given expected weather conditions, prices, risk preferences, and simulated crop yields. They found that the economic value of modifying crop mix was between 10 and $15 per ha in Pergamino and about $35 per ha in Pilar, a location with lower rainfall amounts. Expected forecast values depended on several factors, including current prices, the preceding crop, ENSO phase, and farmers' risk aversion. These studies suggest that the potential value for climate prediction application to agriculture in the Pampas region of Argentina is indeed very high. In 1998–1999, about 11.1 million ha of land was used to produce soybean and maize. If one assumes an average value of only $15 per ha by using climate forecasts to modify crop mix, crop management, or both for these two crops alone, the expected potential value would be about $166 million per year in this region. Although the regional value of climate forecasts will depend on many factors not yet analyzed, this extrapolation provides a rough estimate of the order of magnitude of potential value. Research is still on going to determine how farmers respond to this information and whether the potential can actually be realized.

Meinke and Hochman (2000) demonstrated how ENSO related information is actually used by making crop management decisions. Physiologically based crop simulation models were used to quantify the relationship between crop performance and phases of the Southern Oscillation Index. Farmers are adopting the approach to improve their farm management.

Explorative land use studies are highly useful in the development of efficient and effective production systems at higher levels of integration.

Beinroth et al. (1998) described studies in which crop models were integrated with GIS to evaluate different agricultural uses of land as well as climate change effects on regional crop productivity. In one study, Hansen et al. (1998) analyzed the trade-offs between agricultural production and environmental risk for a small watershed in Puerto Rico. Sugarcane had been grown in this watershed, but due to low international prices for sugar and increasing costs of production, farmers had to search for new options. Candidate crops were tomato, maize, bean, soybean, sorghum, and sugarcane. They showed that most crops would increase risks of soil erosion and chemical leaching relative to sugarcane, but that double cropping tomato with cereal crops provided the greatest profits and lowest risks of erosion and chemical contamination among all other combinations of crops analyzed in the study.

4. Selecting the right methodology

Scientists have to select methodologies in a specific project, which requires a thorough analysis of the type of problem to be studied, costs/benefits and the degree of accuracy needed considering the demands. Very often not enough time is spent on the selection of methods as scientists are inclined to apply their favourite model or expert system. Bouma (1997) has analyzed this problem for a study on soil acidification in Europe. He distinguished four methods to be applied at different scale levels, at the European level, the site level and the molecular level. The most complex and comprehensive method used detailed measurements of weathering rates in all 185 major soil types in Europe, as derived from the existing soil map. A simplified method was derived by using expert knowledge to select 35 aggregated soil units that were significantly different in terms of their weathering behaviour. Detailed measurements were used only to characterize these 35 units; results were again extrapolated to the soils map of Europe. A still simpler approach was derived by using a simple empirical model for predicting weathering rates for all soil units, thus avoiding detailed measurements. Finally, a very simple approach was obtained by asking experts to rank the different soil units in terms of their relative degree of weathering. Going from complex to simpler approaches, costs decrease and the time by which results are obtained is shortened. At the same time the reliability and accuracy decreases. Often, documentation of the accuracy is not provided, making selection of the most suitable method difficult. The first method is not necessarily the best: single measurements on a given spot may not be the most representative for the whole soil unit because of spatial variability in the map units. We, therefore, advocate comparison of different procedures for measurements before starting field work to obtain the most efficient procedure given the objectives of the study. The aspect of interdisciplinarity plays an important part here: when different disciplines work together it is not efficient to work in great detail in one discipline and in a very general way in the other (Bouma, 1997).

For all levels of integration a systems approach is needed, where the systems approach toolbox, data needs and data availability are linked in such a way that the research or application question can be addressed in the most effective and simple

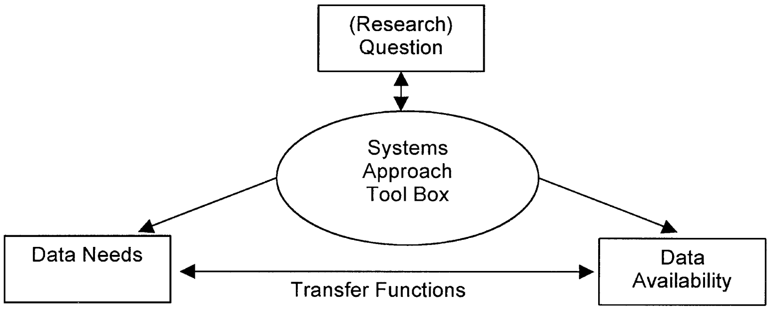

Fig. 3. Towards a flexible methodology for using systems approaches in agronomic systems.

way. This is illustrated in Fig. 3. If the data needed by the modules selected from the toolbox are not available, another module may be selected with other data needs, or transfer functions can be applied (e.g. pedo-transfer functions, Bouma, 1989).

5. Conclusion

Agronomic research has developed from empirical descriptive research to explanatory research that provides the basis for knowledge-based management options. Knowledge of physical, chemical, physiological and ecological processes that determine the behaviour of agro-ecosystems provides the foundation for a production ecological approach. This approach is based on the HRH approach: holistic observations at the systems level that lead to questions that need to be addressed by reductionistic approaches that after integration using systems models lead to options for improvements at the systems level.

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