SYSTEMS APPROACHES AND ECOLOGICAL MODERNISATION OF HORTICULTURAL PRODUCTION SYSTEMS

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Keywords: research paradigms, methodology, research prioritisation

Abstract

During the last decades horticultural science started a transition from an empirical, trial and error based science into a scientific discipline which is based on understanding and process knowledge. In the same period, society began to re-assess the role of horticulture using a much wider range of criteria than the traditional achievements of amount of physical product or production value. For horticultural science to contribute to these issues old paradigms need to be replaced by new concepts. In this paper the new challenges and perspectives are described and it is shown how renewal of agricultural and horticultural sciences will enable them to contribute to a new mission in a dynamic society.

1. Introduction

Horticultural science is confronted with a new mission: contributing to ecological modernisation of horticultural production systems. Ecological modernisation may be interpreted as the development of food production systems designed to maintain renewable resources, use non-renewable resources with foresight and recognise the intrinsic value of the environment while providing a decent living for farm families and satisfying the increasing demand for agricultural products (Rabbinge, 1997). The new mission is multidimensional. The old mission, in contrast, emphasised amount of physical product and production value. This new mission takes horticultural science into new domains of knowledge and calls for re-thinking of traditional ways of generating and disseminating information. There are ample opportunities. In this contribution we will explore the changing role of agriculture and horticulture in society, and investigate changes in horticultural research and practice that are needed in response. We will outline traditional concepts in agricultural and horticultural sciences and introduce their successors, radically different concepts, such as used in production ecology, based on systems thinking. Such re-orientation will not only lead to more effective understanding of biological phenomena, but also to better targeting of research at the relevant scales, field, farm and region, as well as at the relevant partners, students, growers and policy makers.

We expect the role of systems approaches in this renewal process to be considerable as they combine a holistic perspective with the power of the reductionistic analysis.

Proc. 5th Int. Symp. on Comp. Mod.
Eds. Wagenmakers, Van der Werf and Blaise
Acta Hort. 499, ISHS 1999 - IOBC/WPRS Bulletin

Examples of exploratory, predictive and explanatory studies based on a systems approach will be presented to provide underpinning. The lessons learned from these studies help in setting the research agenda in such a way as to affect the policy agenda in which explorative studies play an important role.

2. Old methodologies and new challenges

Methodologies in agricultural and horticultural science have been inspired upon the successes of farmers and growers who experimented by applying different treatments to their crops and comparing results, primarily crop yield. Until far into the twentieth century agricultural research built upon this approach and focused on 'dose-response' (or, treatment-yield) relations by experimentation at the field level only. Statistics provided a sophisticated toolkit for experimental design and enabled widely applicable recommendations with given confidence limits to be inferred from a limited set of experiments. Discoveries in biological and technical sciences were taken up by agricultural scientists and turned into new opportunities through field experimentation by disciplines such as plant breeding, engineering or crop protection. Key words in this approach were decision, action and recommendation orientation. How much nitrogen to apply, what pest and disease control measures to take, when and how to carry out land preparation, how to prune most timely and most effectively in fruit orchards, when and how to irrigate, what characteristics of new varieties or cultivars were most promising? These were questions, which were addressed with studies and experiments at the field level alone. The success of this approach is apparent from productivity increases in many products and regions all over the world.

The emphasis in agricultural research on widely applicable relations by studying responses at the system (=field) level only, has results in a number of undesirable simplifications: 1., ignoring heterogeneity, 2., ignoring *increasing* returns to *combinations* of inputs and, 3., ignoring integration levels other than the field. The aim of drawing general recommendations from a limited set of experiments at the system level caused heterogeneity in soil, crops or management to be considered a liability. The paradigm of the average reigned. Homogeneity was pursued by stimulating land development, propagating genetically uniform crops, and generic recommendations on uniform, high levels of fertiliser or pesticide supply.

When the response of crop growth to different levels of a *single* input is studied, the result is decreasing input productivity at increasing levels of input. This result, the so called law of diminishing returns, is valid only when one factor is changed under the ceteris paribus assumption that other factors remain constant. In practical agriculture, such conditions are usually not fulfilled in the longer term because investments in one production factor, e.g. improved plant nutrition, will only be made in conjunction with investments in other production factors, e.g. improved water availability or drainage, resulting in synergy between production factors and increasing productivity at increasing levels of input. The law of diminishing returns is a typical example of the field-oriented, statistical approach. Due to this dose-response approach this law of diminishing returns has been over-emphasised at the expense of the phenomenon of increasing returns which constitute an important and fundamental trait of dynamic agricultural production systems. Ignoring this trait constitutes a second serious limitation of the traditional research approach.

The third caveat of the traditional field-oriented approach in agricultural science is the lack of attention for integration levels other than the field. Studies that describe phenomena at the field level in terms of their (cor-)relation to other phenomena at the same level are descriptive in nature and fail to explain causes of observations. As a result, these studies do not offer much more than an analysis of the status quo. Similarly, upscaling to the farm or regional level is usually not pursued, leaving integration of the fragmented information to the farmer or policy maker.

These old concepts are challenged by new approaches. Through better understanding of basic physical, bio-chemical, physiological and ecological processes in plants it becomes possible to base interventions at the system level on insights at process level. The scientific challenge is not only to generate insights at process level, but, particularly, to integrate or synthesize such reductionistic knowledge to the system level. Examples of such integration are found in modern plant breeding which utilizes biotechnology and functional genomics. Processes that have been identified as having a major effect on a crop's field performance are traced to their genetic 'roots' using new molecular and statistical methods such as QTL mapping (Jansen, 1995). Also, behaviour of crops under different climatic conditions, e.g. in other parts of the world or even conditions that are projected to prevail in the future such as increased CO_2 levels, may be inferred from responses of constituent processes. Thus, understanding of functioning of the 'system', whether a plant, a crop or a cropping system, provides a rational basis for predicting system behaviour under new conditions.

Heterogeneity as a liability may be replaced by heterogeneity as an asset when spatially explicit information at the field level can be combined with process-based knowledge. Local fine-tuning of measures, such as timing of harvest or fertilizer and pesticide application, will improve the response at the larger spatial scales. A valuable concept in designing better crop management systems is the target-oriented approach. In this approach, target yield levels are defined on basis of the production situation, i.e. the prevailing conditions for crop growth that can not be changed within one growing cycle, and the ambition level of the grower, in our terminology the production orientation (Rabbinge and Van Ittersum, 1997). These target yields are used to derive the optimal mix of required inputs. Thus, output determines inputs. Usually, a range of output levels is defined in this way. The concept of production situation refers to biophysical factors which cannot be controlled by the grower in the short term but which affect the efficiency of interventions. In poor production situations, e.g. due to adverse climate or poor drainage, input efficiencies per unit product and per unit area will be negatively affected compared to good production situations (Van Ittersum and Rabbinge, 1997). Distinction of yield defining, limiting and reducing factors helps to prioritize crop growth factors and further structures thinking about the impact of interventions (Fig. 1). Target oriented approaches are becoming increasingly possible as the understanding of basic processes increases. They have already proved their usefulness in integrating information and designing new production systems (Rossing *et al.*, 1997b). Scientific problems to be addressed concern the upscaling and downscaling from process to systems level and the other way around. Thus, interventions and improvements based on insight and knowledge may be developed in an iterative and interactive way. The heuristic value of this approach is considerable (Rossing *et al.*, 1997a; Roetter *et al.*, 1998).

3. Society, horticulture and production ecology

The horticultural sector can no longer justify its existence solely by pointing out its achievements in terms of amount of physical product or production value. Society also expects top achievements with regards to external and internal product quality and quality of the production system and its ecology. These quality goals have operational definitions that differ among countries. Whatever form they take, these goals dictate the constraints and limitations within which horticulture has to operate. The renewed mission of horticulture is therefore the development of agro-ecosystems that are productive, efficient and effective in bio-technical, environmental and economic sense and utilize the options and possibilities at crop, farming (cropping) system and eco-regional levels. We have called this new mission 'ecological modernisation'.

To remain relevant for horticulture, horticultural science has broadened its knowledge domain considerably. Research projects dealing with production volume and product quality are supplemented with studies related to resource use: water and pest resistance conservation along with minimisation of external inputs per unit product and unit area. As we argued in the previous section, integrated evaluation of different options in relation to a range of goals has received little attention to date, particularly at integration levels above individual crop production systems. Important unused opportunities for development of modern horticultural systems exist at the farm and eco-regional levels and can be identified through land use studies. Such land use studies put into perspective current comparative advantages of a region, identify limits to achievement of goals and reveal constraints for improvement.

Today, horticultural science still is a discipline-oriented science. The types of studies we advocate typically require synthesis of information as is done when adopting a systems approach. To draw together agronomic, biological and technical knowledge and design new horticultural systems requires unifying concepts, such as the notions of production situation, production orientation and production level described above or the concept of target oriented approaches. We have found these concepts developed in production ecology to be highly valuable for organizing thinking about production systems, for prioritizing process-oriented research and for structuring information from very different disciplinary backgrounds, such as genetics, ecology, plant nutrition, biophysics and molecular biology (Rabbinge, 1993; Rossing and Heong, 1994; Van Ittersum and Rabbinge, 1997).

4. To explain, to predict and to explore using systems approaches

Systems approaches may be used for three purposes: explanation, prediction and exploration. In explanatory studies, systems analysis and simulation are used to gain understanding of the functioning of systems. Integration of basic knowledge and prioritisation of process studies are powerful features of this approach. A structured approach in explanatory studies comprises various phases and steps (Fig. 2). An interactive process of problem identification is followed by phases of quantitative systems modelling and systems design & management. In each of the phases various steps may be distinguished that have been described in detail elsewhere (Rabbinge *et al.*, 1989).

The tools used for analysing system behaviour in explanatory studies, usually simulation models, are often not suitable for the purpose of prediction. The amount of detail needed to explain system behaviour becomes a burden when prediction is the aim because of propagation of errors and input requirements. As a result, predictive (decision support) systems that make use of explanatory models are rare. Nevertheless, systems approaches may contribute to predictive models in two ways. First of all, knowledge of processes determining systems behaviour may lead to informed construction of regression models. Rather than establishing statistical correlation between variables and crop yield or other variables to be predicted in a purely trial and error manner, regression equations may be based on crop ecologically plausible predictors. Alternatively, explanatory simulation models may be used to generate information on systems behaviour under a wide range of external conditions *in lieu* of field experiments. Results may be summarised by regression for use in decision support systems.

Where predictions aim at probable futures, explorative studies sketch possible futures (Rabbinge *et al.*, 1998). In explorations, biophysical limits to horticultural production are confronted with goals and constraints imposed by politics, value systems or individual preferences. Thus, consequences of subjective choices are made visible and trade-offs between objectives or sociological constraints are shown. Options, utopia and dystopia may be made visible and the playing field can be identified. Examples of such studies exist at the level of farms (e.g. flower bulb production systems, Rossing *et al.*, 1997b) and regions (e.g. agricultural production in Europe, Rabbinge *et al.*, 1994). Below we will illustrate the various purposes of systems analysis in case studies.

5. Case studies

5.1. Explanatory studies

To understand the population dynamics in acarine systems, various process and system studies have been done (see e.g. Helle and Sabelis, 1985; Hardman *et al.*, this volume). In an early population dynamical study, Rabbinge (1976) analysed life cycle and interaction in the mite : predator system, *Phytoseiulus persimilis* and *Amblyseius potentillae,* in apple in the Netherlands. Empirical evidence had indicated that the native phytoseiid predators were able to control the phytophagous mite species, but no information was available on the robustness of biocontrol. Measurements on life table parameters were collated in simulation models of population dynamics of pest and predator. Predation was analysed in terms of predator satiation, 'hungry' predators being more voracious than predators with higher degrees of gut filling. The model was tested successfully with experiments on single trees in greenhouses and experiments in an orchard. Based on this understanding of the dynamics of the system, it was demonstrated that biological control could be expected for a wide range of predator-prey ratios, thus corroborating the empirical trust in the self-cleansing potential of the system.

5.2. Predictive studies

To help sugar companies plan their harvest campaign, predictive models of regional sugar yield have been developed (Vandendriessche and Van Ittersum, 1995). The models are usually based on regression of crop yield on one or more environmental variables. The availability of large databases enables evaluation of any combination of regressors with respect to predictive power of the regression equation. However, knowledge of crop growth processes may help to speed up the identification of useful regression models. For predicting the date of full ground cover, Spitters *et al.* (1990) took into account that rates of plant emergence and leaf appearance and leaf area expansion are nearly linearly related to temperature until the stage that plants start to compete for light. The length of the period between sowing and full ground cover was on average 75 days, with a coefficient of variation of 11%. When using the temperature sum approach, variation could be reduced to 5%. To describe production of sugar these authors used a regression model based on intercepted radiation, with radiation use efficiencies calibrated per region. For the major production regions, 77% of the variation in sugar yield between years was explained. The model is proposed as a tool in forecasting sugar beet yields. Results of periodic harvests can be used to update current model predictions.

A methodologically different approach was taken by Rossing (1991) to predict yield losses by cereal aphids in winter wheat. He developed an explanatory simulation model of winter wheat growth and included the major damage mechanisms of cereal aphids, reduction of leaf photosynthesis parameters and uptake of assimilates containing both carbon and nitrogen. The model was found to perform satisfactorily when evaluated using field data from specifically designed experiments. Next, damage by cereal aphids was calculated assuming a hypothetical 'representative' aphid infestation and running the model with different initial crop conditions to create yield levels ranging between 3 and 10 ton/ha. These 'artificial' data were used in regression equations to calculated yield loss per aphid-day (the entomological analogue of degree-day). Compared with other, empirical, damage models, the accuracy of these simulation-based regression equations was found to be similar to the best empirical model when evaluated with 21 sets of field data from different locations.

5.3. Explorative studies

In apple and pear production systems, planting systems were known to affect fruit growth and fruit quality (Wagenmakers, 1991a). Some multi-row systems performed better than single row systems, while the performance of others was inferior to single row systems. The causes of these results were poorly understood and, because of the multitude of interacting factors, hard to approach purely experimentally. In addition, an experimental result at the field level would not yield conclusive insight into the causes of variation between planting systems. Wagenmakers (1991b) used a systems approach to develop a 3-D simulation model of light interception and distribution, which explained performance of orchards differing in tree shape, planting density and planting system. The model was validated with light measurements in different apple and pear planting systems for a range of planting densities and pruning regimes. Deviations between model results and experimental findings were less than 10%. When used to explore various planting designs, the model showed so-called full-field systems with a low rectangularity of planting (ratio of between-row and within-row spacing) to have superior performance. Reasons included the high efficiency of light interception per unit ground area and the advantageous distribution of light inside the canopy. However, current mechanisation is not suited to full-field systems, which do not have tractor alleys, and even multi-row systems are currently under debate because they do not allow use of tunnel sprayers. As a next best solution, the model showed that single rows may perform as good as the theoretical, full-field optimum on the condition of an adapted (larger) tree height. Roughly, single-row trees should be 0.5 m taller than trees in multi-row systems to achieve similar light interception at a given planting density. The model illustrated further that trees planted in a triangular design would require very strong reductions, not only in tree height but in diameter as well, to allow for a light climate comparable to the full-field planting systems. Without these alterations, substantial shading in the centre of these systems would cause serious reductions in fruit growth and aspects of quality. This case study illustrates the role of a quantitative systems approach in testing hypotheses, and using the insights for defining ideotypes of planting systems as well as tree shapes. It was felt that the study increased research efficiency considerably, by greatly reducing the need for field experiments on planting systems and tree shapes, and by providing a tool to organise future thinking about strategic decision making.

An example from a different field, pest management, stems from Van der Werf *et al.* (1996). In a small, illustrative study of crop response to feeding injury by two-spotted spider mite (*Tetranychus urticae*) in cucumber, these authors combined detailed measurements of the effect of the pest on leaf photosynthesis parameters with different scenarios on mite injury distribution over the canopy profile. Specific aim of the study was to investigate the importance of vertical distribution of the pest for designing sampling plans with the purpose of estimating the relationship between injury and damage. The well tested, process-based crop growth model ASKAM (Gijzen, 1992) was used. Total mite injury of 25% of leaf area was distributed over the canopy profile according to 5 different patterns (Fig. 3) and gross photosynthesis and maintenance respiration was calculated for a crop with leaf area index 3, for high and low light intensities. The highest reduction of photosynthesis occurred when injury was concentrated in the top of the canopy. In practice, injury by *T. urticae* will commonly be concentrated in lower leaf layers, or be distributed more or less evenly throughout the canopy. The simulations indicated that for these cases, the shape of the injury profile only marginally affects the relationship between injury and photosynthesis. This suggested that precise observations on the vertical distribution of injury will not be necessary to calculate damage. The simulations also indicated that injury levels up to 40% result in only marginal reduction of crop photosynthesis, provided injury is in lower layers and LAI is not less than 3.

6. Outlook

In this paper we have argued the position that changes in the role of horticulture in society call for renewal of horticultural sciences. Possibilities for such renewal exist and we have outlined the changes in research aims and methodologies needed. In summary, the new research approach can be described as an HRH sandwich at different integration levels (Bouma, 1997), where HRH stands for Holistic - Reductionistic - Holistic. Reductionistic, disciplinary work will help to amplify the scientific basis of horticulture and open up new avenues for development. Explanatory studies, prediction and exploration each have their own role in further developing horticulture and stimulating informed decision making by growers and policy makers.

Renewal of horticultural science will also require scientists with new skills. Disciplinary depth is a necessary but no longer sufficient qualification for horticulturists. There is an urgent need for scientists with T-shaped skills. Familiarity with cutting edge reductionist science in a particular field alongside the capacity to integrate and use information in a larger setting. Context knowledge and understanding of problem identification through interaction with stakeholders are necessary skills of these systems oriented horticultural scientists. There are ample opportunities and rewards for these transitions. There is a demand in society, science becomes more rewarding and the broadening of horizons is stimulating. The opportunities are here to exploit, thus starting a new era of horticulture science in the next century.

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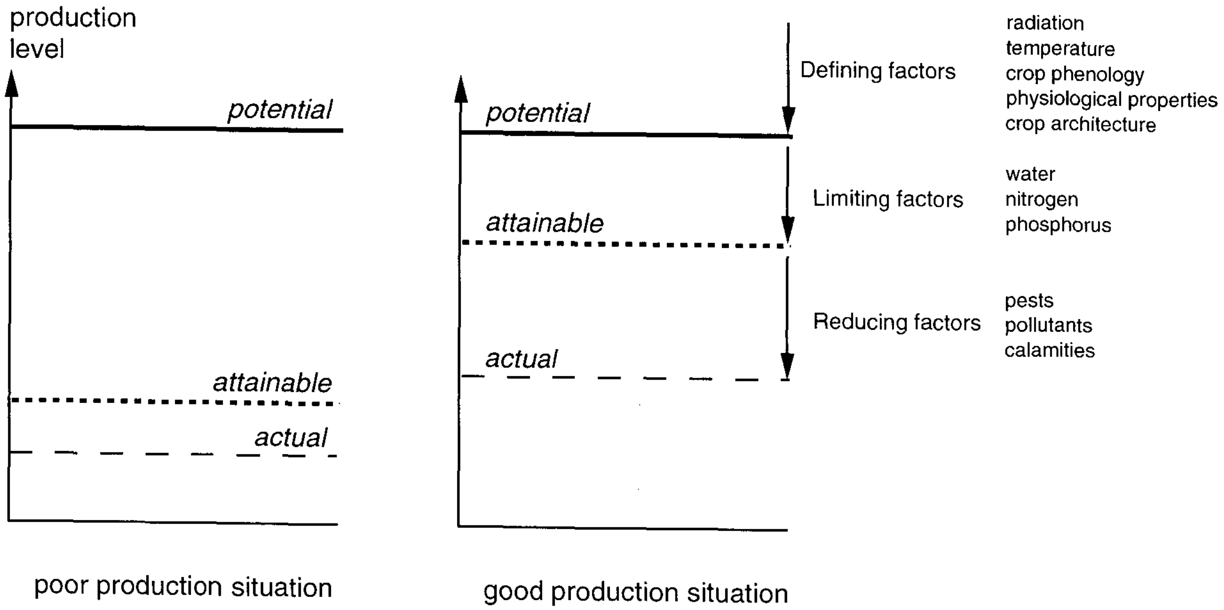

Figure 1 - Production situations, production levels and associated growth factors (from Rabbinge, 1993).

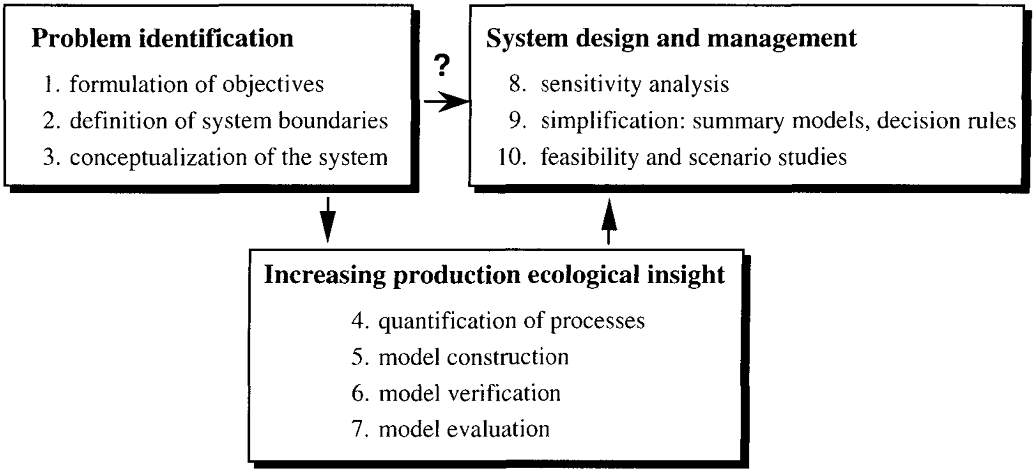

Figure 2 - Developmental phases in systems research (from Rossing and Heong, 1997).

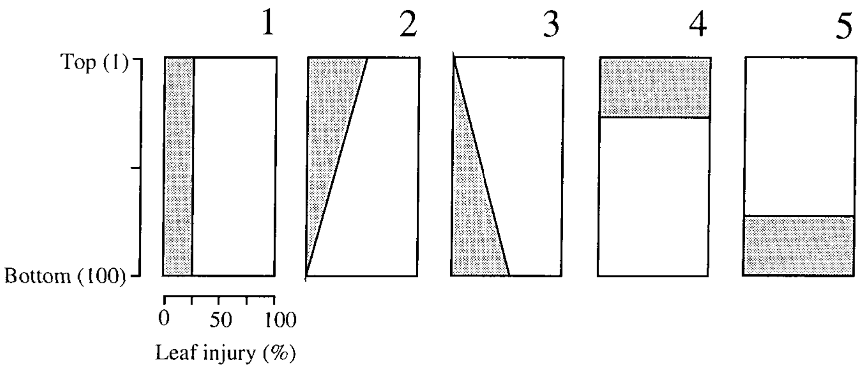

Figure 3 - Five injury profiles used in the simulations of the effect of mite injury on crop photosynthesis of cucumber. Here, the profiles represent a total injury of 25% leaf area.