Evaluation, Design and Control of Sustainable Horticultural Cropping Systems

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Keywords: environment, modelling, indicator, decision support system

Abstract

As all other human activities, horticulture is accountable for its impact on the resources available, now and in the future, to our societies. The problem is of particular importance in production systems that are often intensive and require high amounts of inputs. To fit with the increasing number of regulations and contracts growers have to respect, tools must be created to evaluate existing cropping systems and design and control original ones with respect to sustainability. Whatever the adopted technique, a systemic approach is required.

Evaluation is possible either beforehand or during the implementation of the sequence and spatial combination of crops and corresponding technical operations that constitute a cropping system. Sets of agro-ecological indicators have been designed to evaluate the fittingness to specifications of ecological sustainability of the various components of cropping systems. They can be used to assess the global environmental impact of cropping systems on environmental resources. Existing or novel management strategies can also be evaluated with simulation models.

Conception of crop management strategies consistent with objectives of sustainability has been made possible by the use of specific techniques belonging to the fields of linear programming and artificial intelligence. They make possible the generation of original crop successions and sequences of technical operations.

At last an on-line control of the cropping system is compulsory to keep it within the limits of the strategic plan. To this end, indicators can be organised in a control board, and combined to decision rules. Artificial intelligence provides a way of formalising decision rules based on either scientific or expert knowledge, and generate decisions at a tactical level.

Such examples show that indicators, models and decision support systems are relevant tools to assess the fittingness of horticultural cropping systems to the new standards of resource management.

INTRODUCTION

During the recent years, an increasing number of public regulations and private contracts have converged to orientate horticultural production towards a better control of the environmental impact of the cropping systems and an improvement of the quality and health value of their products. For example, through the Common Organisation of the agricultural Markets, the European Union supplies financial incentives to producers' organisations provided they achieve the objectives of the market organisation (improved productivity and marketing and greater attention to the environment). Specific regulations have been set up: e.g. the Nitrates Directive (1991) defines nitrate vulnerable zones in which action programmes aiming at limiting nitrate pollution must be carried out. Such regulations often converge with the contracts linking producers and their clients and defining not only the required properties of the products (for example specifications limiting the nitrate content of leafy vegetables) but also the characteristics of the

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Proc. XXVI IHC – Sustainability of Horticultural Systems
Eds. L. Bertschinger and J.D. Anderson
Acta Hort. 638, ISHS 2004
Publication supported by Can. Int. Dev. Agency (CIDA)

production process itself (for example specifications prescribing integrated protection and production).

In this changing social and economic context, new scientific concepts and methods are required in horticulture, based on systemic approaches (Rabbinge and Rossing, 2000). The concept of sustainability is multidimensional; it includes ecological, social and economic objectives. I will focus here on the ecological dimension of sustainability and present some examples of novel scientific approaches designed to face three major challenges for research in this field: (i) the fittingness of cropping systems to the specifications of sustainability must be evaluated, (ii) in many cases, innovative cropping systems must be designed and, (iii) a closer control of these systems is required.

EVALUATION OF THE ECOLOGICAL SUSTAINABILITY OF CROPPING SYSTEMS

Cropping systems can be evaluated with sets of indicators. Indicators can be defined as variables that provide information about a complex system for users to take appropriate decisions (Gras et al., 1989; Mitchell et al., 1995). Various indicator-based methods have recently been analysed and compared (van der Werf and Petit, 2002). They usually require input information that is easily available on farm. Among them, methods designed for industrial processes such as life cycle assessment are being introduced in agriculture and horticulture (Antón et al., 2002; Mempel and Meyer, 2002). Simulation models provide an alternative tool to predict the various outputs of a management strategy and the degree of realisation of the manager’s objectives. Their formalisms and parameters are more dependent on scientific knowledge.

Use of Agro-ecological Indicators: the Example of the Indigo Method

In the Indigo method, a set of agro-ecological indicators has been defined to evaluate the impact of various cultivation practices on a range of environmental variables (Bockstaller et al., 1997; Girardin et al., 1999). In contrast to other evaluation methods, Indigo indicators are based on the effects of cultivation practices on the environment rather than on cultivation practices as such (van der Werf and Petit, 2002). The Indigo method has been used for cereals and vineyards; specific features are in development for fruit production.

The major cultivation practices that have been analysed are related to the management of not only production factors (nitrogen and phosphorus fertilisation, use of pesticides, irrigation, use of energy, tillage, management of organic matter) but also other dimensions of the cropping system (crop diversity, soil cover, non productive components). The environmental variables that are considered are the surface and underground water quality, the air quality, the soil depth, structure and composition, the use of non-renewable resources, the biodiversity and the landscape quality. Each cultivation practice affects a particular set of environmental variables. For example, the use of pesticides is related to the quality of surface and underground water, to the quality of air, and to biodiversity whereas nitrogen fertilisation is mostly related to the quality of underground water and to the quality of air.

Quantitative as well as qualitative information can be used in the construction of an indicator. Simple models were used for nitrogen fertilisation and irrigation whereas an expert system was designed for the pesticide use. In the latter case, the risks for underground water, surface water, air and biodiversity linked to pesticide use have been rated. Rating results from the combination of several variables. For example, the risk for air quality depends on the volatility of the pesticide molecules, their half-life, the acceptable daily intake for humans, and the spraying conditions.

Different users may find interest in such an analysis. For example, growers willing to evaluate their strategy of plant protection would focus on the associated indicator whereas institutions or companies involved in the protection of water resources would integrate all the indicators linked with one component of the environmental impact, water quality. Growers willing to fit with specifications of e.g. integrated protection and protection should integrate several agro-ecological indicators and several variables of environment quality.

Use of Simulation Models: the Case of Nitrate Pollution in Vegetable Production

Nitrate pollution in vegetable production is related to the soil water and nitrogen balances that mainly depend on the time-courses of crop nitrogen demand, and water and nitrogen supply. In the specific case of lettuce production, the quality of products is linked to the environmental impact as nitrate may accumulate in leaves when nitrogen absorption is more active than its assimilation. As mechanistic models were available to simulate the soil and crop behaviour, model-based explorations could be carried out to evaluate vegetable cropping systems in terms of (i) nitrate pollution during the crop cycle, (ii) nitrate content of harvested lettuce, and (iii) fresh weight of harvested lettuce (de Tourdonnet, 1999; Figure 1). The soil submodel (Lafolie et al., 1991; Leenhardt et al., 1996) simulates the water, nitrogen and heat fluxes in the soil and the biochemical transformations of nitrogen. The lettuce crop model (de Tourdonnet, 1999) simulates the time-course of cover rate as a function of temperature and converts intercepted radiation into biomass, which in turn permits the calculation of nitrogen and water demand.

The analysis of the cropping system performance cannot be limited to the study of the behaviour of the biophysical system. The effect of cultivation techniques on the crop environment must also be formalised. In the particular case of lettuce crops grown under cover, de Tourdonnet et al. (2001) paid attention to the heterogeneity due to the uneven soil compaction during tillage, transmission of the plastic cover and distribution of water by sprinklers. This is of particular importance as, to satisfy their production objective, growers tend to over-irrigate and –fertilise in order to get all plants over the minimal size required by the market (included those plants grown in spots with less light or more soil compaction or less water).

The crop-soil model was spatialised so that the spatial organisation of the three main outputs (nitrate leaching, nitrate accumulation in leaves, plant growth) could be simulated. Model-based explorations could then be carried out to predict environmental and production variables important to the ecological and economical sustainability of vegetable cropping systems in a range of strategies of irrigation and fertilisation.

DESIGN OF SUSTAINABLE HORTICULTURAL CROPPING SYSTEMS

Agro-ecological indicators or simulators can be used for the evaluation of either existing or innovative candidate strategies of management of cropping systems. In this respect, these tools can contribute to the design of original cropping systems whose performances would fit the standards of sustainability (whatever their definition). However, some methods have recently been developed to directly identify or generate the appropriate strategies.

Rossing et al. (1997) have looked for the optimisation of flower bulb production systems within a group of growers. The objectives of sustainability were limited to three variables: farm gross margin (to maximise), pesticide input and nitrogen surplus (to minimise). By considering these objectives together with the characteristics of the existing farming systems and the socio-economic and agronomic constraints they have to respect, interactive multiple goal linear programming produced a set of optimal strategies (Figure 2). Those strategies included the crop rotations and the policies of pesticide and fertiliser use. Economic and environmental objectives could be conflicting. For different specific farming systems, a path of development could be analysed with, at each step, the corresponding reductions of pesticide input and nitrogen surplus and changes in gross margin.

This research permitted to assess deficiencies of knowledge about some features of the cropping systems under study: auto-intolerance of crops in a succession, soil-borne yield reducing factors, role of break crops… It stressed the usefulness of balancing strategic (organisation of crop successions) and tactical (management of growth factors) choices to improve the economic and ecological sustainability of cropping systems.

Another promising approach has recently been adopted by Loyce et al. (2002) for the management planning of winter wheat grown for ethanol production (Figure 3). The aim was again to design crop management strategies that would satisfy a set of requirements (about semi-net margin, production cost, environmental risk, number of technical operations…). A knowledge base was built to predict the behaviour of the system for various combinations of open strategic options. Possible (in the framework of a set of requirements) management plans were selected by resolving a CSP (constraint satisfaction problem). At last, these possible plans were sorted by a multiple criteria analysis based on the notions of agreement and discordance.

CONTROL OF THE ECOLOGICAL SUSTAINABILITY OF HORTICULTURAL CROPPING SYSTEMS

Once a general strategy has been designed to fit specifications of ecological sustainability, it should be implemented in the field and its effectiveness verified all along the production process. To this end, information about the system should be made available and put in a general framework to evaluate its status in relation to the final results aimed at. This information should be processed to take the proper tactical decisions. The first step is made possible by the design of "control boards"; the second needs the production of decision rules that can eventually be assembled in decision support systems.

An example of control board has recently been presented by Wery et al. (2000) for the management of the water and nitrogen supply of lettuce crops. In this example, production and environmental objectives were precisely defined by three actors: the land owner (a mineral spring company concerned by the underground water quality), the client (an organic food company requiring organic production, quality of product and timing of production), and the grower himself (aiming at a satisfying gross margin i.e. yield and product quality).

From a detailed analysis of the system, it appeared that indicators were needed (i) for the risks of water and nitrogen stresses in relation to the crop yield and quality (nitrate content in leaves), and (ii) for the risk of nitrate leaching in relation to the quality of underground water. To this end, Tensionic tensiometers (enabling the measurement of both the soil water potential and the nitrate concentration of the soil solution) were set in and below the root zone to calculate hydraulic gradients. An indicator of nitrate leaching risk was calculated (Cuny et al., 1998) which, together with the water potential and nitrate content in the zone, enabled the continuous tracking of the major control variables.

Decision rules connecting observed and reference values of indicators together with management decisions can be built. They can be gathered into a decision model. A promising example is the SERRISTE expert-system that has been designed to produce the optimal daily climatic set points (temperature and vapour pressure deficit) for a greenhouse tomato crop (Tchamitchian et al., 1997). Indicators of the greenhouse climate and crop status are input to the expert-system. For the crop, the vegetative vigour is characterised by the grower himself as "high", "OK" or "low" and the presence of grey mold (*Botrytis cinerea*) attacks is defined as "yes", "no" or "possible". A large range of decision rules define fuzzy intervals of acceptable climate conditions, and alterations of set points required to avoid crop stresses such as grey mold attacks, heat or water stresses or improve the crop vegetative vigour. The constraint solver embedded in SERRISTE returns all the combinations of values of variables that fit with the whole set of constraints. The fuzzy intervals of acceptability make it possible to determine the combinations that would satisfy only partially some constraints. At last, a multicriteria selection of the best solution is carried out, the risk of disease development and energy consumption being the most common criteria. This constraint satisfaction approach is open to the integration of a large range of conditions that should be satisfied for the grower to attain his objectives.

CONCLUSION

To face the new challenges of the evaluation, design and control of sustainable cropping systems, horticultural science must develop new concepts and methods (Rabbinge and Rossing, 2000). Sustainability is multidimensional, included when it is limited, as in this review, to its ecological component. Pieces of knowledge produced by different scientific disciplines must be integrated and the methodologies (based on models or knowledge bases) needed to carry out such an integration have become a key issue. How for example should a global indicator of sustainability be built from a set of agro-ecological indicators designed for each production factor? How to design a cropping system that would satisfy a large range of constraints on the different physical and biological inputs and outputs of the system? Significant advances in this field have recently been published in agronomy and horticulture.

Another source of complexity is spatial heterogeneity. In many cases, the environmental impact of a cropping system is linked to the treatment of heterogeneity. For example, when crops are sold by plant unit (e.g. lettuce), over nitrogen fertilisation can be a way to be sure that all plants, even grown in a heterogeneous environment, will reach the minimal size required by the market. In this case, a strategy of reduction of nutrient losses should go together with either a reduction of environmental heterogeneity or the introduction of a site specific management. A comparable example can be found in plant protection. The use of pesticides is reduced when integrated protection is adopted. Consequently, plant health becomes more dependent on local physical or biological conditions (Boulard et al., 2002).

At last, operationality benefits from early interaction with stakeholders (e.g. flower bulb producers and environmentalists in Rossing et al., 1997). This relation is useful for both the definition of the set of requirements the cropping system should satisfy and the identification of the good indicators of fittingness of the system outputs to these requirements. Indicators should be relevant and easy to use. Research is needed to link the state and flux variables of scientific models to integrative indicators end-users have adopted empirically (Navarrete et al., 1997). The SERRISTE example (Tchamitchian et al., 1997) shows that adopting these end-user indicators is a condition of success of a DSS. Consequently, modelling the decision system is as important as modelling the biophysical system (the crop and its environment).

Literature Cited

Antón, A., Montero, J.I. and Castells, F. 2002. Life cycle assessment: a tool to evaluate and improve the environmental impact of Mediterranean greenhouses. Acta Hort., in press.

Bockstaller, C., Girardin, P. and van der Werf, H.M.G. 1997. Use of agro-ecological indicators for the evaluation of farming systems. Eur. J. Agron. 7: 261-270.

Boulard, T., Mermier, M., Fargues, J., Smits, N., Rougier, M. and Roy, J.C. 2002. Tomato leaf boundary layer climate: implications for microbiological whitefly control in greenhouses. Agric. Forest Meteorol.. 110: 159-176.

Cuny, H., Wery, J. and Gaufres, F. 1998. A simple indicator for diagnosing nitrate leaching risk below the root zone using the Tensionic tensiometers. Agronomie. 18: 521-535.

de Tourdonnet, S., Meynard, J.M., Lafolie, F., Roger-Estrade, J., Lagier, J. and Sebillotte M. 2001. Non-uniformity of environmental conditions in greenhouse lettuce production increases the risk of N pollution and lower product quality. Agronomie 21: 297-309.

de Tourdonnet, S. 1999. Control of quality and N pollution in greenhouse lettuce production: a modelling study. Acta Hort. 507: 263–270.

Girardin, P., Bockstaller, C. and van der Werf, H. 1999. Indicators: tools to evaluate the environmental impacts of farming systems. J. Sustain. Agr. 13: 4, 5-21.

Gras, R., Benoît, M., Deffontaines, J.P., Duru, M., Lafarge, M., Langlet, A. and Osty, P.L., 1989. Le Fait Technique en Agronomie: Activité Agricole, Concepts et Méthodes d'Etude. L'Harmattan, Paris, France.

Lafolie, F., Bruckler, L. and Tardieu, F. 1991. Modeling root water potential and soil-root water transport: I- Model presentation. Soil Sci. Soc. Am. J. 55: 1203–1212.

Leenhardt, D., Bruckler, L. and Lafolie, F. 1996. Use of simulations to limit nitrate leaching under intensive irrigated lettuce. In: Proc. of the fourth ESA congress, Veldhoven – Wageningen (The Netherlands), pp. 356–357.

Loyce, C., Rellier, J.P. and Meynard, J.M. 2002. Management planning for winter wheat with multiple objectives (1): The BETHA system. Agr. Syst. 72: 9-31.

Mempel, H. and Meyer J. 2002. Environmental system analysis for horticultural crop production. Acta Hort. this issue.

Mitchell, G., May, A. and Mc Donald, A. 1995. PICABUE: a methodological framework for the development of indicators of sustainable development. Int. J. Sust. Dev. World 2: 104-123.

Navarrete, M., Jeannequin, B. and Sebillotte, M. 1997. Vigour of greenhouse tomato plants (*Lycopersicon esculentum* Mill.): analysis of the criteria used by growers and search for objective criteria. J. Hort. Sci. 72: 821-829.

Rabbinge, R. and Rossing, W.A.H. 2000. Meeting the demand for ecological modernization in horticulture: the role of systems approaches. Acta Hort. 525: 115-121.

Rossing, W.A.H., Jansma, J.E., Ruijter, F.J. and de Schans, J. 1997. Operationalizing sustainability: exploring options for environmentally friendly flower bulb production systems. Eur. J. Plant Pathol. 103: 3, 217-234.

Tchamitchian, M., Montbroussous, B., Jeannequin, B. and Martin-Clouaire, R. 1997. Serriste: daily greenhouse climate set-point determination for tomatoes. p. 25-30. In: A. Munack and H.J. Tantau (eds), Mathematical and control applications in agriculture and horticulture, Pergamon, Oxford.

van der Werf, H.M.G. and Petit, J. 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agr. Ecosyst. Environ., in press.

Figures

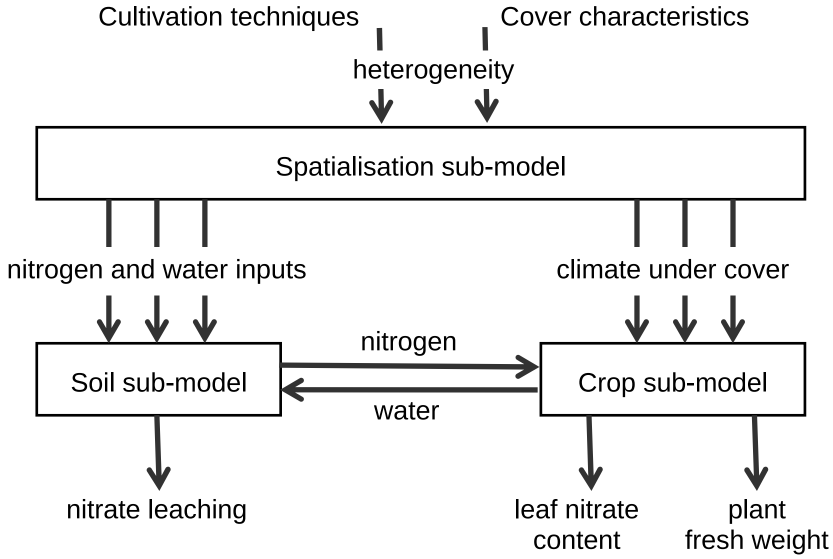

Fig. 1. Simulation model of the crop-soil system for lettuce grown under cover (redrawn from de Tourdonnet, 1999).

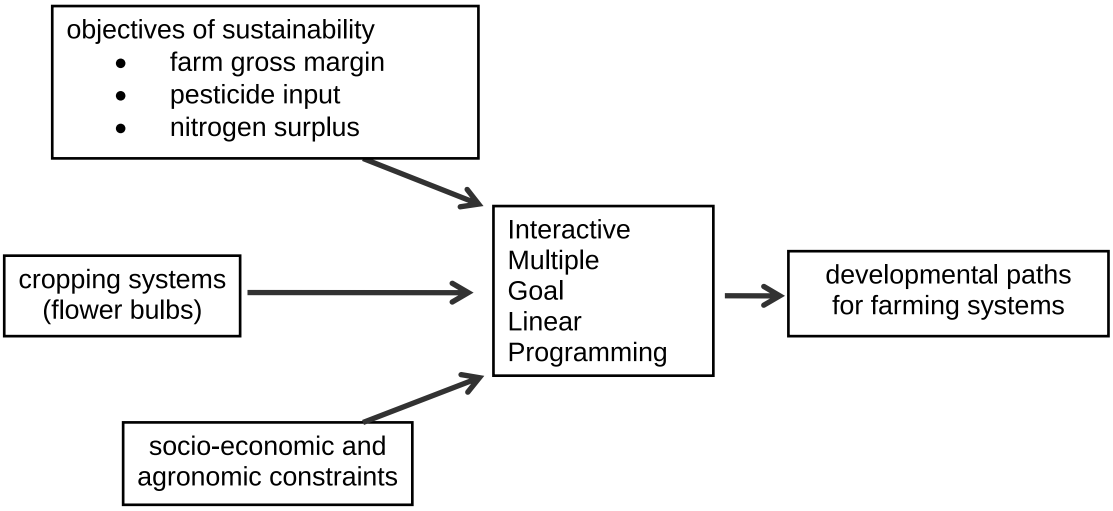

Fig. 2. Identification of sustainable flower bulb cropping systems (redrawn from Rossing et al., 1997).

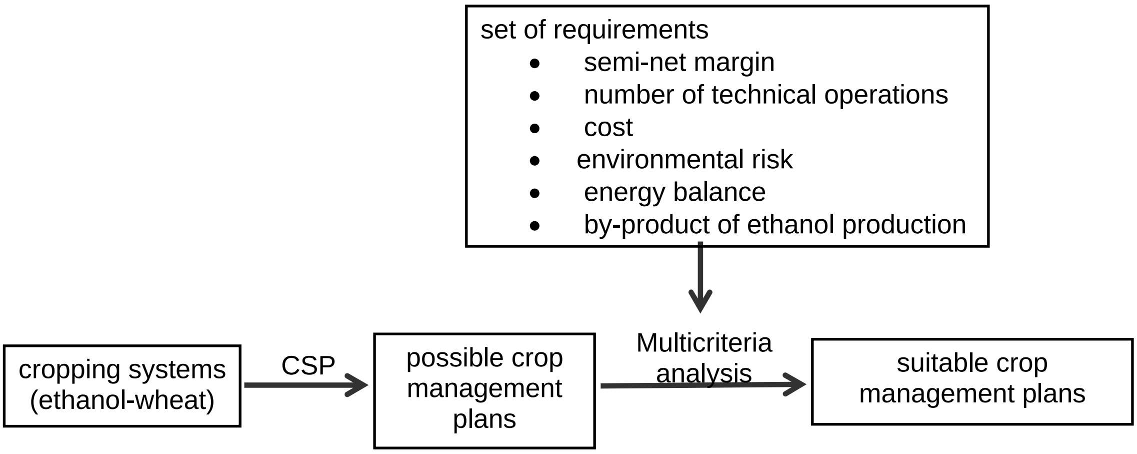

Fig. 3. Identification of sustainable ethanol-wheat cropping systems (redrawn from Loyce et al., 2002).