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Operationalizing sustainability: exploring options for environmentally friendly flower bulb production systems

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Abstract

Current production systems for flower bulbs in the Netherlands employ considerable quantities of pesticides and nutrients per unit area. In 1993, an association of growers and environmentalists set out to design new farming systems that meet environmental objectives in addition to economic objectives. To support the design process, an explorative study was carried out to bring together the fragmented agronomic information and to assess agro-technical options for sustainable flower bulb production with a time horizon of 10 to 15 years. Crop and inter-crop management systems representing the agro-technical components of sustainability at the farm level, were generated with a computer model by systematically varying four system characteristics, three of which represented strategic and tactical aspects of crop protection. Subjective components, one economic and two environmental objectives and various socio-economic constraints, were identified in interaction with the stakeholders. Interactive multiple goal linear programming was used to optimize the objectives at the farm level and determine the exchange value of the economic objective in terms of the environmental objectives. Calculations were carried out for two reference farm types. The results revealed that the negative impact of environment-oriented production systems on farm gross margin is importantly mitigated by strategic choices at the farm level, such as renting land and allowing a soil health improving crop, even though of low gross margin, into the rotation. In contrast, the *a priori* attention of the growers was focused on improving tactical pest and nutrient management at the crop level, the effect of which on farm gross margin is constrained by the strategic choices. Sensitivity analyses highlighted the need for more insight into the ecology of soil-borne growth reducing factors and their effect on crop yield. The paper describes the approach used, reports results and discusses the usefulness of the approach for the stakeholders and for disciplinary crop protection research.

Introduction

Flower bulb production in the Netherlands constitutes an economically successful activity. On approximately 17,000 ha (5% of the arable crop area) a yearly production value of over 1,000 million guilders is reached, increasing yearly by some 5%. Compared to production on farms with a broader range of arable crops, production value per hectare is 17 times higher for flower bulbs. Moreover, income is generated at the regional scale by the recreational value of flowering fields.

At the same time, production methods have been employed that rely heavily on external inputs. The level of pesticide input has been estimated to be 120 kg of active ingredient per hectare (Anon., 1991). Even on fore-runner farms, surpluses for nitrogen, phosphate and potassium on sandy soils have been estimated at 231 kg N per hectare, 106 kg P_2O_5 per hectare, and 171 kg K_2O per hectare, respectively (Weel et al., 1995), causing considerable contamination of surface and ground water.

Several causes can be mentioned for these input levels. High prices of suitable land, traditionally located in the most urbanized parts of the Netherlands, have stimulated adoption of intensive, bulb-dominated rotations that can only be maintained with major pesticide inputs. Costs of inputs are small relative to product value and relative to prices of the land. To prevent wind erosion on these alluvial sandy soils cattle and pig slurry have been used extensively until 1995, because of their low costs due to overproduction. Finally, adoption of alternative production methods is hampered by fragmented research results and relatively low level of formal training of the grower community.

Decreasing the side-effects of flower bulb production to levels which are considered acceptable, is addressed in the Dutch Multi-year Crop Protection Plan (Anon., 1991) and agreements between the government and the flower bulb industry. Targets have been established with respect to input of pesticides and (in)organic fertilizers, energy use and volume of production-related waste. This setting has stimulated the development of integrated production systems which, in addition to economic objectives, allow for objectives in areas of environment, public health, rural scenery and nature.

Explicit distinction between objectives of agricultural land use and agro-technical possibilities of land use has proved to be valuable in operationalizing the concept of sustainability in agriculture (WRR, 1992; WRR, 1994). This distinction is equivalent to separation of normative, policy-based aspects of sustainability that determine the objectives, from scientifically-objective components of sustainability that are subject of biological and agronomic research. Since objectives are at least partially conflicting, development of sustainable farming systems is equivalent with searching for acceptable compromises between objectives using all agro-technical possibilities available. Actors in this process are producers, consumers and the public sector. The challenge for agricultural research is to develop methodology to facilitate this process and help to develop technologies and systems that enable combination of, to date, conflicting objectives.

Sustainability issues may be addressed at different levels of aggregation; field, farm and region. Depending on the level of aggregation, objectives, constraints and agro-technical possibilities may differ. Opportunities for integrated pest and disease management at the field level are constrained by the choice of crops and their succession at the farm level, which in turn may be affected by regional or global market incentives. Currently, crop protection research has a disciplinary emphasis, focusing on the pathosystem and lower levels of biological organization. To effectively address sustainability issues integration of component knowledge is required at the levels of field, crop rotation, farm and region. Such integration will also highlight areas where knowledge availability is restrictive, providing a basis for strategic research prioritization. During the last decade, two promising integrative approaches have emerged, an empirical approach on experimental and commercial farms, and a model-based approach which is illustrated in this paper.

To demonstrate integrated flower bulb production in terms of both economic and environmental objectives, three experimental farms were created on which prototype farming systems have been tested and improved since 1990 (Raven and Stokkers, 1992). Drawbacks of this empirical approach are the small number of prototypes that can be evaluated and, as a result, the limited possibility to test designs which deviate importantly from current practices. Model-based explorations in which a broad range of options are evaluated with respect to their consequences for economic and environmental objectives, can remedy these drawbacks of the empirical approach, and represent an important complementary research and teaching tool in farming systems research and extension (Meynard and Rossing, 1997).

An association of progressive flower bulb producers and environmentalists in the main bulb growing areas of the Netherlands set out to design production systems which meet environmental objectives in addition to economic objectives and could be tried out on the participating farm enterprises. To support this design process, an explorative study was carried out in which fragmented agronomic information was synthesized and technical options for sustainable flower bulb production were investigated with a time horizon of 10 to 15 years (Jansma et al., 1994; De Ruijter and Jansma, 1994). This paper describes the method used, reports results and addresses the usefulness of the approach for the stakeholders and disciplinary crop protection research.

Methods

Approach

Throughout the paper, the term crop management system will be used to indicate agronomic as well as economic aspects of growing a single crop, inter-crop management system to refer to coherent activities between two successive main crops, cropping system to address all aspects of a rotation, while farming system refers to the farm context. The term production system is used to address any of the four systems.

The approach in the study (Figure 1) is based on the Interactive Multiple Goal Linear Programming (IMGLP) methodology, which has been applied for land use studies at the regional level (Ayyad and Van Keulen, 1987; De Wit et al., 1988; Veeneklaas, 1990; Rabbinge and Van Latesteijn, 1992; Van de Ven, 1994, 1996) and at the farm level (Schans, 1991; Van Rheenen, 1995). Essential to the approach is a distinction between objectives and agro-technical possibilities of land use. The objectives reflect normative choices of individuals or of society, whereas the agro-technical possibilities of agricultural land use are the subject of biological and agronomic research. IMGLP establishes the agro-technical possibilities that optimally satisfy the objectives, and demonstrates the consequences of different priorities that may be given to objectives. In this fashion, the procedure enables operationalizing sustainability.

Management systems for individual crops and for inter-crop activities are defined (Figure 1A), each characterized by technical coefficients which describe the inputs and outputs for the systems. In part, these technical coefficients represent the production system 'characteristics', the features by which management systems for a particular crop differ. The remaining technical coefficients are based on agronomic and farm economic information which is generally applicable to production systems of that particular crop. Input-output relations are derived from empirical information, expertise and production ecological theory (Van Ittersum and Rabbinge, 1996). The variety of systems depends on the time horizon of the study, larger time horizons enabling formulation of more 'futuristic' systems. Economic and environmental objectives are defined in terms of these inputs and outputs. Linear programming is used to combine the crop and inter-crop management systems to cropping systems and to optimize objectives at the farming system level (Figure 1B). First, each objective is optimized without restrictions on the others. The results delineate 'the playing field', the maximum and minimum values attainable for each of the objectives for the set of production systems. Next, a particular objective is optimized in successive iterations with stepwise increasing restrictions on the other objectives. The results, summarized as developmental paths, demonstrate the exchange value of one objective in terms of the other objectives, and show the associated change in farming systems.

Fundamental to the IMGLP approach is a distinction between subjective components and agro-technical components of sustainability. Subjective components comprise objectives of agricultural production and socio-economic constraints, and are usually identified from policy papers and by interacting with stakeholders. Agro-technical components are represented by the production systems. In defining production systems, level of knowledge, available farm equipment, layout and size of the parcels are assumed to present no limitations. In this way, a wide perspective of future options is obtained, consistent with the aim of an explorative study to reconnoiter the possible rather than the plausible (Schoonenboom, 1995). In the next sections, the approach will be applied to the flower bulb case.

Objectives and socio-economic constraints

Objectives

The subjective components of sustainability were established in two workshops with the association of flower bulb producers and environmentalists, the stakeholders in this study. Three objectives were agreed upon, one of a farm economic and two of an environmental nature (Table 1). Economic aspects of sustainable flower bulb production were expressed as farm gross margin. It is calculated as financial returns minus allocated costs of casual (unskilled) labour, crop protection agents, fertilizers, contractor and machine use, averaged over the cropped area, and expressed in an index. The index represents farm gross margin in Dutch guilders of a particular farming system, relative to maximum farm gross margin of the farming systems that satisfy the governmental environmental targets for 2000 (see below). The association opted for the index to avoid confusion over farm economic terminology.

The environmental objectives considered were pesticide input and nitrogen surplus. Pesticide input is calculated as the amount of active ingredient (a.i.) averaged over the cropped area and expressed in kg

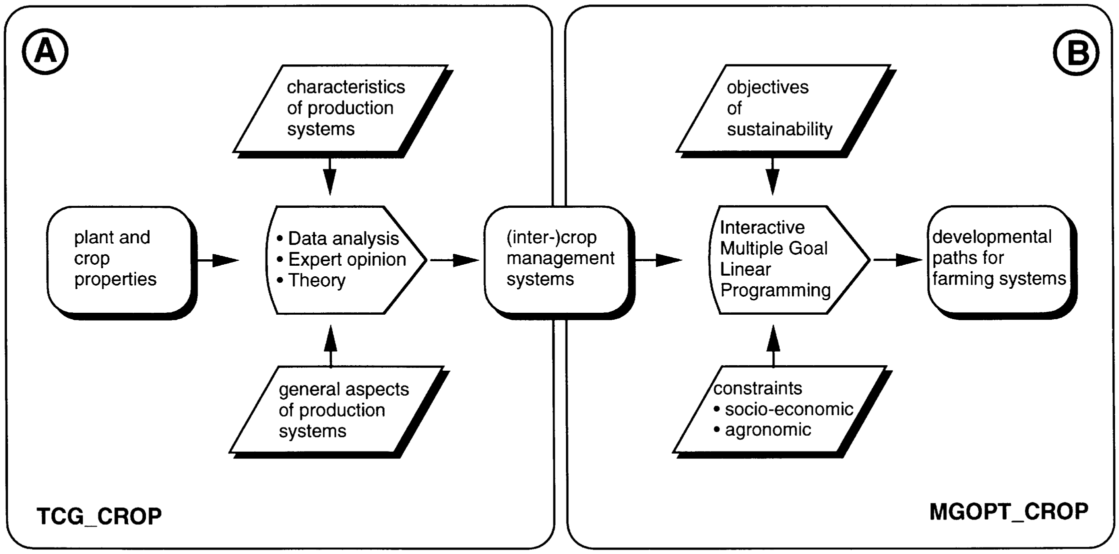

Figure 1. Schematic representation of the approach in the study.

Table 1. Objectives of sustainable flower bulb production, formulated interactively with an association of flower bulb growers and environmentalists

Problem area	Objective	Target	Unit
Farm economics	Farm gross margin	Maximize	index[a]
Crop protection	Average pesticide input	Minimize	kg a.i. ha^{-1}
Nutrient management	Average nitrogen surplus	Minimize	kg N ha^{-1}

[a] Ratio of farm gross margin (in Dutch guilders) of a particular system and maximum farm gross margin of the farming systems that satisfy the governmental environmental targets for 2000.

a.i. per hectare, consistent with the units used by the government. While the stakeholders expressed preference for units which account for toxicity, persistence and mobility of pesticides in addition to volume, none of the units available at the time was considered sufficiently comprehensive.

Nitrogen surplus is calculated as the amount of nitrogen which is not taken up by the crop or carried over to a subsequent crop, averaged over the cropped area, and expressed in kg N per ha. Sources of nitrogen comprise atmospheric deposition, previous crop residues and net mineralisation. Since in the model calculations nitrogen shortage is remedied by (artificial or organic) fertilizer input, nitrogen surplus is either zero or positive. Nitrogen, rather than phosphorus or potassium, was selected as nutrient related objective because of its mobility and the complexity of its management. Nitrogen surplus is not equivalent with nitrogen lost from the system, but was chosen to indicate potential losses. Input of phosphorus is limited to the legal maximum of 125 kg P_2O_5 per hectare.

Constraints

Socio-economic constraints that were formulated pertained to farm size, array of crops that may be grown, possibility to rent land in case of excess labour, and the minimum level of environmental goals to be attained.

Farm size is determined by both area and permanent labour force. Farm size determines type and area of crops that can be grown, and represents an important constraint in the study. Labour requirement is assessed per period of two months. Casual labour may be hired to supplement permanent staff. Two farm sizes were selected for analysis: 15 ha on sandy soils and 3 full-time labour equivalent (fle), and 25 ha on sandy soils and 4 fle. One fle is assumed to work 38 h per week. Selection of the farm sizes was based on what experts judged to be economically viable farm sizes for the next 10-15 years.

Five crops were selected for which production systems were formulated; tulip, narcissus, hyacinth, lily and winter wheat. The bulb species comprise currently major crops, while winter wheat was included as a break crop with positive effects on soil structure and soil health.

The option of renting land on clay soils was included to evaluate the current practice of growing bulb crops on land rented for one year from dairy or arable farmers. Soil structure and, especially, soil health of such land is conducive for bulb production due to the low bulb cropping frequency. Because skin quality in hyacinth and harvestability in lily are negatively affected, only tulip and narcissus can be grown on clay soils. Routine tasks on rented land are assumed to be carried out by contractors. Specialized tasks require input of permanent staff, the availability of which (including a fixed amount of traveling time) limits the area of rented land. In practice, rented land is pasture or part of a crop rotation of traditional arable crops. The input of pesticides and surplus of nitrogen in these systems may be much lower compared to specialized flower bulb production. To limit the extent of environmental burdening of the arable and dairy farming systems, the range of bulb crop management systems on clay soils was restricted in the model. On clay, maximum pesticide input was set to what was considered a moderate level, 12 kg a.i. per ha for tulip and 14 kg a.i. per ha for narcissus, while nitrogen input was restricted to result in at least 5% yield limitation.

The final category of constraints put forward by the stakeholders comprises the governmental targets for 2000 with respect to pesticide input and nutrient surplus. For pesticide input the targets for the flower bulb industry are a maximum total amount of, on average, 48 kg a.i. per ha (60% decrease compared to 1989), and soil fumigation with a maximum frequency of once every 5 year (Anon., 1991). For nitrogen, phosphorus and potassium, an equilibrium between nutrient availability and nutrient removal by the crop is aimed at, while allowing for unavoidable losses. At the time of the study, these unavoidable losses were not yet fixed. We assumed the levels to be 25 kg P_2O_5 per hectare for phosphorus, 50 kg K_2O per hectare for potassium, and 140 kg N per hectare for nitrogen, averaged over the cropped area. In the model, nutrient demand may be met by application of animal manure or artificial fertilizer.

Input-output relations of crop management systems

Starting point for quantification of crop management systems is the calculated actual production level *sensu* Rabbinge (1993), which depends on the production situation and the inputs of yield increasing and yield protecting measures. In the study, crop management systems are distinguished by four system characteristics: ‘soil type and soil health’, ‘cropping frequency’, ‘crop protection regime’ and ‘nitrogen regime’ (Figure 2). For each characteristic, several alternatives are defined. Characteristics and alternatives have been chosen such that crop management systems can be generated which differ distinctively in terms of the objectives, ranging from ‘nearly current’ to ‘futuristic’, consistent with the time horizon in the study of 10 to 15 years.

Actual marketable crop yield is calculated by correcting potential marketable crop yield for effects of soil type and soil health, cropping frequency, crop protection regime and nitrogen regime in a multiplicative fashion. Where interactions between production system characteristics are accounted for, these are indicated below. Calculated actual marketable crop yield is the output variable which determines those inputs and outputs that characterize the crop management system. The remainder are standard inputs and outputs which are specific to the crop species but independent of the crop management system, for instance the methods of planting, harvesting and post-harvest operations.

Quantification of inputs and outputs is based on results of the experimental prototypes (Stokkers, 1992; Stokkers and Van den Berg, 1993), practices currently applied in integrated production systems in other commodities, and standard agronomic information (Anon., 1992) supplemented with expert information where necessary. In calculating labour input, a distinction is made between specialized tasks and routine tasks. Specialized tasks, such as screening crops for diseases or disorders, can only be carried out by permanent staff. Routine tasks may be carried out by permanent or casual labour. Although one full-time labour equivalent (fle) is assumed to work 38 h per week, permanent staff may have additional organizational tasks. Labour input on clay soils includes the time spent traveling between the farm and the rented land, based on a distance of 70 km.

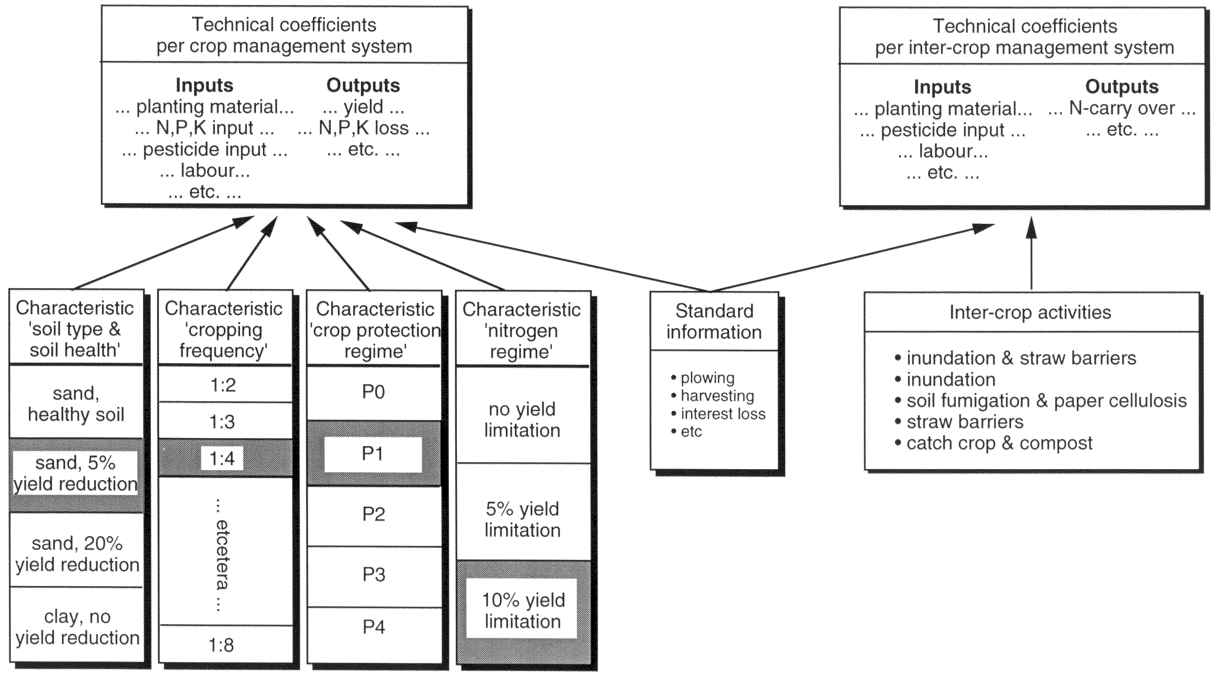

Figure 2. Schematic representation of structured description of crop and inter-crop management systems.

Potential marketable crop yield

Potential marketable crop yield is defined as the fresh weight of potential harvestable bulb yield minus losses during harvesting and sorting, and minus the weight of next year's planting material, when crop growth was not limited by lack or excess of water and nutrients, and pests, diseases and weeds were absent. In bulb crops, potential yield depends on the size of the bulbs planted, larger planting weight resulting in larger weight increases. In the study, size composition of the planted bulbs is assumed to reflect a constant weight distribution in time, similar to grower's practice.

Potential marketable crop yield (Table 2) has been quantified using standard agronomic information on potential harvestable yield (Anon., 1992) and subtracting losses (Meijles and Marcelis, 1990) and planting material. Crop growth simulation models constitute a more objective data source, but these are still in development for flower bulb crops.

Table 2. Components (ton ha^{-1} fresh weight) used to calculate potential marketable yield of the crops in the study, based on Anon. (1992), Meijles and Marcelis (1990) and Habekotté (1994)

Crop	Potential harvestable yield	Harvest losses	Seed weight	Potential marketable yield
Hyacinth	26.0	2.6	13.0	10.4
Lily	25.8	6.0	6.5	13.3
Narcissus	54.1	4.1	25.0	25.0
Tulip	26.5	4.0	10.0	12.5
Winter wheat	7.9	–	p.m.	7.9

Characteristic 'Soil type and soil health'

Modifications of marketable crop yield because of soil type and of level of soil-borne pests and diseases that are not crop-specific are described by the characteristic 'soil type and soil health'. Four alternatives are formulated, three for sandy soils and one for clay soils (Figure 2). On sandy soils, three levels of effect are distinguished, 0, 5 and 20% reduction of marketable crop yield, depending upon the stimulation of especially *Pythium* spp. and ecto-parasitic nematodes by the preceding crop (Table 3). Also, soil compaction due to the late harvest time of lily is accounted for. On clay soils no negative effects of the preceding crop occur. The classification is based on expert opinion since relevant experiments are lacking.

Effects on marketable yield by crops grown two years before are not taken into account since the necessary increase in model complexity cannot be supported

Table 3. Reduction of marketable yield (%) as a consequence of preceding crop on sandy soils. Agro-technically infeasible successions are indicated as ‘NF’. Continuous cultivation of the same crop is not considered (•)

Crop	Preceding crop				
	Tulip	Lily	Hyacinth	Narcissus	Winter wheat
Tulip	•	5	20	5	0
Lily	5	•	5	0	0
Hyacinth	20	NF	•	5	0
Narcissus	5	NF	5	•	0
Winter wheat	0	0	0	0	•

by empirical evidence. Negative effects of preceding crops described by the characteristic ‘soil type and soil health’ may be nullified by inter-crop management involving soil fumigation and inundation.

Characteristic ‘Cropping frequency’

Modifications of marketable crop yield due to auto-intolerance, including effects of crop-specific soil-borne pests and diseases, are described by the characteristic ‘cropping frequency’ (Figure 2). Quantification of effects is based on data for conventional arable crops (Habekotté, 1994) and expertise. The negative effect of auto-intolerance on marketable crop yield is assumed to decrease exponentially with time. The relative rate of decrease represents an indication of the level of auto-intolerance and allows classification of crops (Table 4). In the model, six alternatives of the characteristic ‘cropping frequency’ are described, ranging from once in 2 years to once in 8 years.

The level of auto-intolerance may be affected by pesticides, especially disinfection of planting material. In the model, relative rates of decrease of auto-intolerance are lower when no pesticides are used (Table 4). The effect of inter-crop management involving soil fumigation on auto-intolerance is ignored. When applied once every 5 years, the legal maximum frequency in 2000, its effect on auto-intolerance is small.

Characteristic ‘Crop protection regime’

The characteristic ‘crop protection regime’ modifies marketable crop yield depending on management of growth reducing factors: weeds, pests and diseases. Management includes chemical, mechanical and biological control in combination with cultivar resistance or tolerance. Four key-categories of growth reducing factors are distinguished: *Botrytis* spp., aphidious virus vectors, weeds, and seed-borne pests and pathogens. For each category, five management packages are defined (Figure 2), based upon practices developed at the experimental farming systems prototypes, practices in advanced management systems of other arable crops, and promising practices currently in a laboratory stage. Differences in treatment between young and marketable bulbs are taken into account. From the package P0, which comprises currently applicable methods (Anon., 1991), to the package P4, which comprises largely experimental and non-chemical methods, chemical inputs decrease (Table 5) while mechanical and biological methods increase along with the time spent weeding and scouting for diseased or infested plants. Cultivars used exhibit increasing levels of tolerance or resistance. As a general trait, methods become more knowledge-intensive, e.g. monitoring, prediction of disease, composting to remove inoculum from organic waste.

Some of the crop protection packages for the same crop on sand and clay differ slightly. On clay less weed control is needed because of absence of wheat volunteers originating from straw for wind erosion and frost protection. In addition heavier soils do not require treatment against ecto-parasitic nematodes.

Characteristic ‘Nitrogen regime’

Potential marketable crop yield may not be realized due to suboptimal supply of the yield limiting factor nitrogen. Nitrogen limitation is defined in terms of percentage yield decrease compared to yield at full satisfaction of crop nitrogen demand. Three levels of nitrogen limitation, 0, 5 and 10%, equivalent to three alternatives of the characteristic ‘nitrogen regime’ are distinguished (Figure 2). Major variables related to this characteristic are crop nitrogen demand, and soil nitrogen supply.

Table 4. Classification of crops in the study in terms of auto-intolerance and reduction of marketable yield (%). Continuous cultivation of the same crop is not considered

Category	b[a]	Crop	Cropping frequency				
			1:2	1:3	1:4	1:5	1:6
Chemical control (P0 to P3)							
1	1	hyacinth tulip	14	5	2	1	0
2	1.5	lily winter wheat	5	1	0	0	0
3	2	narcissus	2	0	0	0	0
No chemical control (P4)							
1	0.7	hyacinth tulip	25	12	6	3	0
2	1	lily winter wheat	14	5	2	1	0
3	1.5	narcissus	5	1	0	0	0

[a] Parameter value used to calculate yield relative to yield with no auto-intolerance, *y*, as a function of rotation length, *x*, in $y = 1–e^{-bx}$.

Table 5. Reduction of marketable yield (%), pesticide input (kg a.i. ha^{-1}) and specialized labour requirements (h ha^{-1}) of the crop protection regimes

Crop	Marketable yield reduction (%)					Pesticide input (kg a.i. ha^{-1})					Specialized labour input (h ha^{-1})				
	P0	P1	P2	P3	P4	P0	P1	P2	P3	P4	P0	P1	P2	P3	P4
Hyacinth	0	0	0	5	15	20	13	9	6	0	274	267	288	298	461
Lily[a]	0	0	10	15	25	104	86	50	13	0	163	156	166	169	170
Narcissus (sand)	0	0	0	0	8	22	15	14	11	0	150	140	175	177	217
Narcissus (clay)	–	–	0	–	–	–	–	14	–	–	–	–	188	–	–
Tulip (sand)	0	0	0	5	15	32	18	12	7	0	131	128	149	150	193
Tulip (clay)	–	–	0	–	–	–	–	12	–	–	–	–	175	–	–
Winter wheat	–	0	12.5	–	20	–	4	1	–	0	5	7	8	21	5

[a] Including mineral oil (full dose equivalent with 58 kg a.i. ha^{-1}).

Crop nitrogen demand is derived from actual marketable crop yield, using information on bulb dry matter content, average bulb nitrogen content, fraction of plant nitrogen in bulbs (N-harvest index) and fraction of available soil mineral nitrogen taken up (N-recovery). For each bulb species these factors are derived from two years' experimental data (Landman, personal communication) according to the approach of Schröder et al. (1993). Similar data for winter wheat are based on Habekotté (1994). Soil mineral nitrogen supply is calculated from information on atmospheric deposition and net mineralisation, modified according to the growing period of the crop (Smit and Van de Werf, 1992), and carry-over from previous (catch) crops. Soil organic matter is assumed to be not restrictive for mineralisation, but is not taken into account explicitly.

In the linear programming model, supply falling short of demand is supplemented by nitrogen input as mineral fertilizer, organic manure or a combination. Input of organic manure is restricted by the phosphorus and potassium demand of the crops in the rotation, after accounting for unavoidable losses. The amount of mineral nitrogen available from organic manure depends on the type of manure, the timing of application and the speed of incorporation into the soil. Quantification is based on Habekotté (1994).

Input-output relations of inter-crop management systems

Five inter-crop management systems have been formulated for flower bulb production on sandy soils (Figure 2). They include inundation with and without wind erosion control by straw barriers, soil fumigation with paper cellulosis to seal the soil and prevent wind erosion, wind erosion control by straw barriers, and cultivation of a catch crop in combination with application of household compost. The systems have been selected such that wind erosion is prevented, the level of soil-borne pests and diseases is not increased, nitrogen loss is prevented and soil organic matter content is at least maintained. Inundation and soil fumigation nullify any negative effect of the preceding crop on succeeding crop yield. The suitability of an inter-crop activity to preceed or succeed a particular crop has been taken into account. Quantification of inputs and outputs has been based on practices at the experimental prototypes and standard agronomic information.

Scenario's and developmental paths

Based on the socio-economic constraints formulated by the association of growers and environmentalists, two reference farms were formulated. The first farm ('reference farm type 1') comprises 15 ha sandy soils with a permanent labour force of 3 fle. On this farm, winter wheat may be grown in addition to the four flower bulb species considered in the study, and healthy land on clay soils may be rented. In practice, this farming style which utilizes an external, arable crops-dominated rotation in addition to the traditional bulb-dominated rotation, is increasing in prevalence and is expected to become even more important in the future. On the second farm ('reference farm type 2'), the four species of bulbs may be grown on 25 ha sandy soils with 4 fle permanent labour input. Choice of crops is limited to flower bulbs, winter wheat as a break crop is not considered. The growers considered this farm idiotypic for a traditional farming style, prevalent in the older bulb producing areas of the Netherlands. Both farm sizes are well above the current average of 9 ha.

For each farm type developmental paths were constructed by optimizing the economic objective in successive iterations with stepwise increasing restrictions on the environmental objectives. In this way, the exchange value of the economic objective is expressed in terms of the environmental objectives.

Prices of bulbs and winter wheat were based on information of 1993/94. No differentiation was assumed for prices of susceptible/intolerant and resistant/tolerant cultivars, or for prices of bulbs grown with and without pesticides. Prices of production factors were based on standard agronomic information (Anon., 1992; Anon., 1993). Casual labour was assumed available at a price of 15 Dutch florins per hour.

Implementation

Crop management systems were generated by the model TCG_CROP (Technical Coefficients Generator for Crops; Figure 1A), which combines alternatives of the four characteristics and calculates the associated technical coefficients. The output of TCG_CROP also contains the standard technical coefficients of the various crops. TCG_CROP is designed as a generic technical coefficient generator to be used for IMGLP applications at the farm level (Habekotté, 1994; De Ruijter and Jansma, 1994). The software is programmed in standard Fortran-77 and utilizes the Fortran Utility Library of Rappoldt and Van Kraalingen (1990).

Farming systems are evaluated in the linear programming model MGOPT_CROP (Multiple Goal OPTimization for CROP rotations; Figure 1B), using technical coefficients of crop management systems generated by TCG_CROP, technical coefficients of inter-crop management systems, prices of inputs, and socio-economic constraints. Implementation of the linear programming model is currently in SCICONICS (EDS-Scicon, 1992, 1993). The linear programming framework is described in detail by Schans (1996).

TCG_CROP and MGOPT_CROP have been developed as a generic framework for evaluation of farming systems. In addition to flower bulb systems, they have been used in a study of options for integrated arable farming systems in the Netherlands (Habekotté and Schans, 1996).

Results

Optimization of single objectives – the corners of the playing field

In the first optimization round, each objective is optimized without restrictions on the others. The resulting

Table 6. Values of economic and environmental objectives at the optimization of each objective without restrictions on the others, for reference farm type 1. On clay soils, only a single level of pesticide and nitrogen input is allowed in the model

Objective optimized	Values of objectives				
	Farm gross margin (index[a])	Pesticide input (kg a.i. ha^{-1})		Nitrogen surplus (kg N ha^{-1})	
		sand	clay	sand	clay
Farm gross margin [max.]	**104**	73	12	195	134
Pesticide input [min.]	–4	**0**	12	169	134
Nitrogen surplus [min.]	2	8	12	**55**	134

[a] Index value 100 corresponds to a farm gross margin of 205,000 Dfl.

Table 7. Values of economic and environmental objectives at the optimization of each objective without restrictions on the others, for reference farm type 2

Objective optimized	Values of objectives		
	Farm gross margin (index[a])	Pesticide input (kg a.i. ha^{-1})	Nitrogen surplus (kg N ha^{-1})
Farm gross margin [max.]	**142**	110	199
Pesticide input [min.]	–132	**0**	169
Nitrogen surplus [min.]	–82	11	**81**

[a] Index value 100 corresponds to a farm gross margin of 265,000 Dfl.

corners of the playing field, the maximum and minimum values attainable for each of the objectives, are shown in Table 6 for reference farm type 1. Maximum index value for farm gross margin is 104, with associated pesticide input and nitrogen surplus averaged over the sandy soils of the farm of 73 kg a.i. ha^{-1} and 195 kg N ha^{-1}, respectively. The index value of 104 implies that maximum farm gross margin is 4% above the farm gross margin of the economically most attractive system that satisfies the governmental environmental requirements for 2000. In a three year crop rotation lily, tulip and winter wheat are grown. Preceding lily, the legal maximum of 3 ha of land is fumigated, the remaining 2 ha before lily are inundated. Pesticide input is at the P1-level and nitrogen is applied to allow unrestricted growth in all crops. On approximately 11 ha rented land, tulip is grown with pesticide input and N-surplus amounting to 12 kg a.i. $ha^{-1}$and 134 kg N ha^{-1}, respectively. On average 1.5 fle of the 3 fle available is used for specialized work. Full utilization of permanent labour only occurs in the period May-June. Activities during this period comprise disease scouting and spraying in lily and tulip, and harvesting of tulip.

The other corners of the playing field are represented by the minimum values for pesticide input, 0 kg a.i. ha^{-1}, and nitrogen surplus, 55 kg N ha^{-1} (Table 6). For both environmental variables the optimal rotation includes narcissus and winter wheat, and tulip is grown on rented land. Farm gross margin is around zero.

Maximum farm gross margin for reference farm type 2 is 142, coupled to pesticide input of 110 kg a.i. ha^{-1} and nitrogen surplus of 199 kg N ha^{-1} (Table 7). Since farm gross margin of the economically most attractive system that meets the governmental environmental targets for 2000 is equated with index value 100, farm type 2 will have to make greater economic sacrifices than farm type 1, having maximum farm gross margin 104. The optimal rotation includes hyacinth and narcissus in a 6-year rotation, in combination with lily and tulip in a 3-year rotation. Soil fumigation precedes hyacinth and part of lily. The remaining lily area and the area allocated to narcissus is inundated. Pesticide input is according to the P1-regime and nitrogen is applied to allow unrestricted crop growth. On average 50% of the available 4 fle is used for specialized work. Maximum utilization of specialized labour is 78%.

Pesticide input can be reduced to 0 kg a.i. ha^{-1} and nitrogen surplus can be minimized to 81 kg N ha^{-1} (Table 7). At minimum levels of both pesticide input and nitrogen surplus farm gross margin is dramatically negative.

In conclusion, when trying to meet the governmental environmental targets for 2000, the decrease of farm gross margin will be greater in farm type 2, the ideotype of the traditional bulb production system on sandy soils, as compared to farm type 1 which utilizes a soil health improving crop and allocates excess specialized labour to bulb production on rented land. The reasons for this difference in what *a priori* were considered economically equally viable systems, will be elucidated in the next sections.

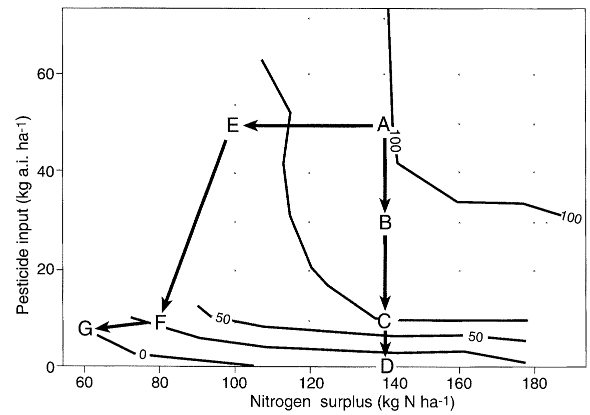

Figure 3. Iso-lines of calculated maximum farm gross margin (index) associated with different levels of pesticide input (kg a.i. ha^{-1}) and nitrogen surplus (kg N ha^{-1}) for reference farm type 1. Letters in the graph indicate the developmental paths for pesticide input (A-B-C-D) and nitrogen surplus (A-E-F-G). The small x-es represent calculated points, the iso-lines are interpolations.

Environmentally restricted optimization of farm gross margin

Developmental paths farm type 1

The results of unrestricted optimization of single objectives showed conflicts to exist between the economic and the environmental objectives. The next step in the analysis is to investigate the degree of conflict, in terms of trade-off between objectives and associated production systems. Figure 3 shows iso-lines of maximum achievable farm gross margin associated with particular levels of pesticide input and nitrogen surplus for reference farm type 1. Within this playing field, for each environmental objective a possible developmental path is distinguished to allow more detailed analysis.

Starting point for the developmental paths are the anticipated governmental environmental targets for 2000, represented by point A in Figure 3. In Table 8 the points on each path are characterized in terms of objectives, area fumigated and utilization of permanent labour for specialized tasks. Figure 4 represents the associated rotations, and the regimes of crop protection and nitrogen for each crop in the rotation.

Reducing pesticide input from point A to point B on the developmental path initially is possible with marginal loss of farm gross margin. From A to B, a decrease in pesticide input from 50 to 30 kg a.i. ha^{-1} requires giving up only 3 index points of farm gross margin (Table 8). The reduction of pesticide input is realized by abolishing soil fumigation in favour of slightly more expensive inundation, by adopting crop protection regime P3 in a part of lily and by adopting regime P2 in tulip (Figure 4B). In lily, the P3-regime involves only half of the number of sprays against *Botrytis* spp. because of supervised control, no use of mineral oil (approximately 60 kg a.i. ha^{-1} in P1), and weed control using reduced dosage in combination with row application. As a consequence, lily yield is 15% lower compared to a P1-regime. Compared to the P1-regime in tulip, soil treatment with systemic fungicides is abolished in the P2-regime and a high dose fungicide for *Botrytis* spp. control (chlorothalonil/prochloraz) is replaced by a low dose fungicide (fluazinam) without any negative effect on yield. Further reduction from 30 kg a.i. ha^{-1} in point B to 10 kg a.i. ha^{-1} in point C is associated with a decrease of the economic objective of 20 units, mainly because of yield loss in lily associated with implementation of the P3-regime on a larger area. Because supervised control in the P3-regime increases the demand for specialized labour, the area rented land is limited to 9 ha (Figure 4A). Bulb production without pesticides (point D) results in slightly negative farm gross margins, not taking into account the higher prices for these ‘green’ bulbs. Decreases in pesticide input from A to C are accomplished without changes in crop rotation, and only marginal changes in the area rented land. Only in point D, the crop rotation changes, from the three-year rotation lily – winter wheat – tulip to a two-year rotation of narcissus and winter wheat. The area rented land is 12 ha (Figure 4A).

Reducing nitrogen surplus from point A along the developmental path is relatively more costly than

Table 8. Characteristics of the optimal farming systems on the developmental paths for pesticide input (A-B-C-D) and nitrogen surplus (A-E-F-G), reference farm type 1. The points on the developmental paths correspond to the points in Figure 3

	Pesticide input reduction			**Starting point**	Nitrogen surplus reduction		
	D	C	B	**A**	E	F	G
Farm gross margin index	–4	77	97	**100**	62	38	2
Pesticide input on sand (kg a.i. ha^{-1})	0	10	30	**50**	50	9	8
Nitrogen surplus on sand (kg N ha^{-1})	140	140	140	**140**	100	90	50
Soil fumigation (ha)	0	0	0	**1.2**	2.2	0	0
Minimum utilization of fle (%)	2[a]	2[a]	2[a]	**2[a]**	2[a]	2[a]	2[a]
Maximum utilization of fle (%)	100[b]	100[b]	100[b]	**100[b]**	100[b]	100[b]	100[b]

[a] During the period January–February.
[b] During the period May–June.

Table 9. Characteristics of the optimal farming systems on the developmental paths for pesticide input (A-B-C-D) and nitrogen surplus (A-E-F-G), reference farm type 2

	Pesticide input reduction			**Starting point**	Nitrogen surplus reduction		
	D	C	B	**A**	E	F	G
Farm gross margin index	–137	41	87	**100**	3	–41	–82
Pesticide input on sand (kg a.i. ha^{-1})	0	10	30	**40**	50	50	11
Nitrogen surplus on sand (kg N ha^{-1})	140	140	140	**140**	110	90	81
Soil fumigation (ha)	0	0	0	**0**	3.4	4.9	0
Minimum utilization of fle (%)	0[a]	1[a]	1[a]	**1[a]**	1[a]	1[a]	0[a]
Maximum utilization of fle (%)	88[b]	100[c]	62[b]	**62[b]**	83[c]	71[d]	72[d]

[a] During the period January–February.
[b] During the period September–October.
[c] During the period May–June.
[d] During the period July–August.

reducing pesticide input (Table 8). From A to E, a decrease of nitrogen surplus from 140 to 100 kg N ha^{-1} requires giving up 38 index points of farm gross margin. The reduction of nitrogen surplus is realized by changes in crop rotation as well as nitrogen regime (Figure 4C). The least efficient crop with respect to nitrogen, lily, is partially replaced by the most efficient bulb crop narcissus. Since lily is also the crop with the highest financial value per unit N-input, its nitrogen regime is geared towards maximum yield, while in tulip, narcissus and wheat nitrogen limitations on yield are allowed from 5 to 10%. In the next step, resulting in point F, lily is excluded from the rotation, and nitrogen inputs to tulip are further reduced. As a consequence a further 24 farm gross margin units are lost. In the step from F to G, narcissus and winter wheat are grown at the lowest nitrogen input possible in the model. Because of the low labour demand by these crops, the area rented land on which tulips are grown increases to 13 ha, maintaining farm gross margin just above zero.

Maximum utilization of specialized labour is 100% in all farming systems of farm type 1.

Developmental paths farm type 2

In the starting point A of the developmental paths for reference farm type 2 (Table 9), narcissus, lily and tulip are grown at maximum supply of nitrogen. Although input of pesticides in all three crops is according to high-input regime P1, total pesticide input is below the threshold of 50 kg a.i. ha^{-1}.

From point A to point B reduction of pesticide input by 10 kg a.i. ha^{-1} is associated with a reduction of farm gross margin index of 13 points. Both in tulip and lily less pesticide is used, for lily resulting in lower yields. Further reduction to 10 kg a.i. ha^{-1} of pesticide input causes hyacinth to be included into the rotation. Yield losses due to pests, diseases and weeds occur

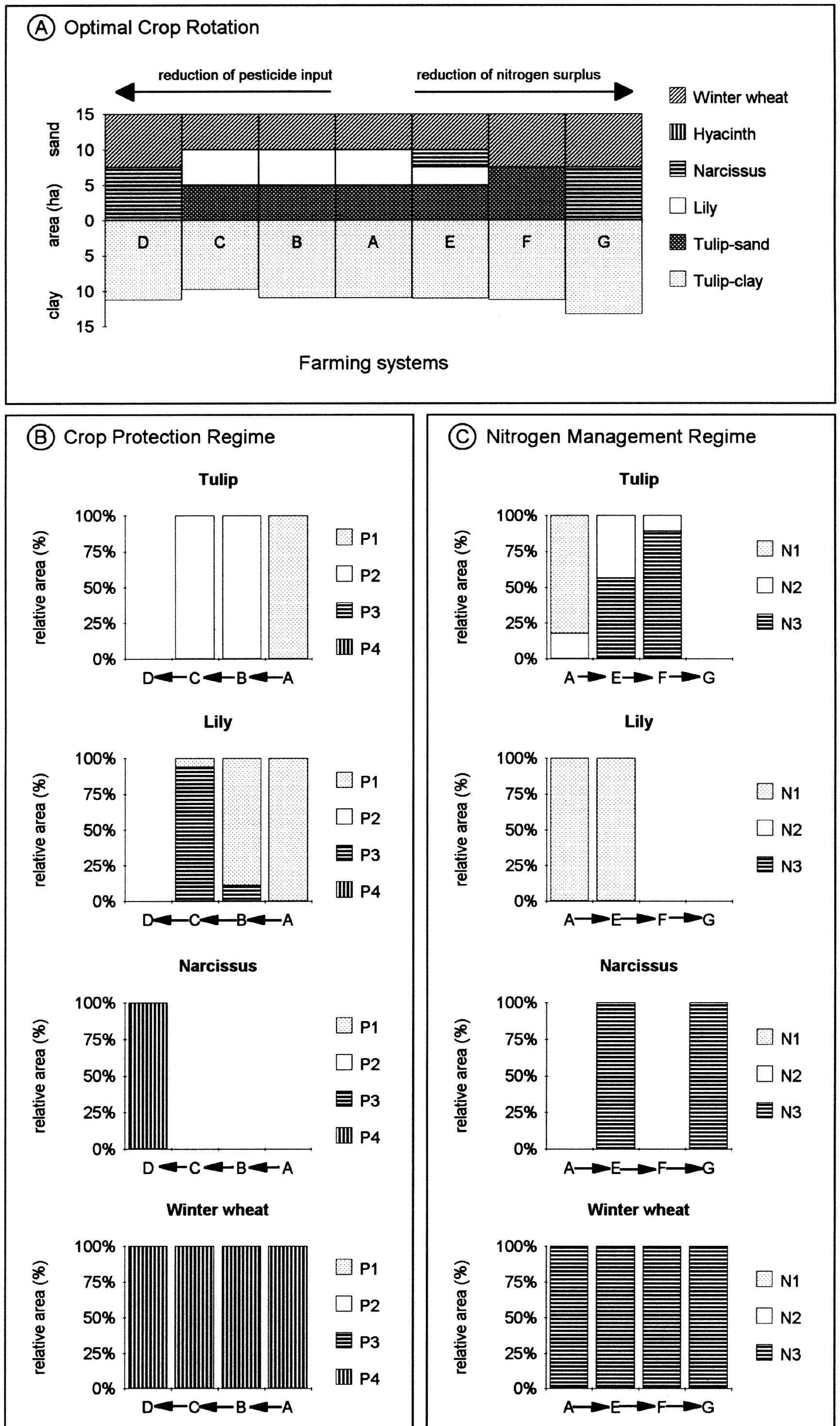

Figure 4. Development paths for reference farm type 1. Letters refer to farming systems distinguished in Figure 3. Figure 4A: Optimal crop rotations on sandy soils, and area rented land on clay soils; Figure 4B: pesticide regimes per crop for the development path aimed at reduction of pesticide input; Figure 4C: nitrogen regimes per crop for the development path aimed at reduction of nitrogen surplus. Areas in Figure 4B and Figure 4C are expressed relative to the area under the particular crop as shown in Figure 4A.

in all crops. The step to zero pesticide input results in negative farm gross margin associated with a rotation of narcissus, lily and tulip.

Reduction of nitrogen surplus by 30 kg N ha^{-1} from point A to point E requires giving up 67 index points of farm gross margin. The decrease in farm gross margin is caused by a change in crop rotation, half of the lily area being replaced by hyacinth, and 5 to 10% yield reductions in tulip and narcissus due to nitrogen limitation. Further decrease of nitrogen surplus by 20 kg N ha^{-1} from point E to point F causes farm gross margin to become negative. The high-value crops lily and hyacinth are no longer grown, the rotation comprising tulip and narcissus. The final development step from point F to point G involves a reduction of nitrogen surplus by only 9 kg N ha^{-1} at the expense of 41 index points of farm gross margin.

Maximum utilization of specialized labour is low for most farming systems of farm type 2, varying between 62% and 88% in points A and D, respectively, and reaching 100% only in point C.

Comparison at the farm level

The results confirm the earlier findings that for reference farm type 2 the conflict between economic and environmental objectives is more pronounced than for farm type 1. In addition, the permanent labour force is not utilized as effectively as in farm type 1. The major differences between the two farm types are of a strategic nature: the options of growing winter wheat and renting land.

When in a sensitivity analysis, winter wheat is allowed to be grown on farm type 2 without renting additional land, farm gross margin in point A increases from 100 to 156. Crop rotation includes lily, winter wheat and tulip. The positive effect of winter wheat replacing narcissus is caused by direct and indirect effects. Directly, winter wheat has a positive effect on soil health, causing less yield loss in the subsequent tulip crop. Indirectly, winter wheat enables higher nitrogen and pesticide inputs into the other crops of the rotation since winter wheat is grown at the lowest levels of nitrogen and pesticide input possible in the model. Compared to the rotation without winter wheat, nitrogen limitation in tulip is alleviated and yield reduction due to soil-borne pests and diseases in lily is nullified by soil fumigation. Moreover, the level of nitrogen utilization of winter wheat is high and comparable to narcissus. Finally, labour requirements in winter wheat are low, resulting in lower costs for casual labour because of increased availability of permanent labour.

By introducing winter wheat, but not renting additional land, in farm type 2 farm gross margin can be improved. Nevertheless, utilization of specialized labour is still only 58% in peak periods, while in farm type 1 full utilization is achieved. The difference is caused by the possibility in farm type 1 to rent land, which represents an additional cause of higher farm gross margins in this farm type.

Comparison at the crop level

An emergent property of the approach is an assessment of crop management systems in terms of their contribution to each of the objectives and in terms of limiting constraints. As an illustration, the crop production systems in which effects by growth limiting or reducing factors are excluded, are ranked according to a number of aspects (Table 10). When growth limitation or yield reduction do occur, rankings may be different.

In Table 10, extreme positions are taken by winter wheat, lily, hyacinth and narcissus. Winter wheat combines low gross margins with low pesticide input, high nitrogen recovery and low labour requirements. For lily, almost the complete opposite is true. This crop combines high gross margins with high pesticide input, low nitrogen recovery and medium (specialized) to high (routine) labour requirements. Because of the high scouting intensity, hyacinth cultivation has the highest labour requirement of the crops in the study. Although environmentally attractive for its high nitrogen use efficiency, narcissus is economically the least attractive of the bulb crops considered in this study, with a gross margin comparable to winter wheat.

Discussion

Research prioritization

Development of the technical coefficients generator showed that current agro-technical information on integrated and ecological flower bulb production is to a large extent based on expertise, rather than empiricism. The approach in this study enables assessment of the importance of deficiencies in knowledge relative to the problem at hand, design of sustainable farming systems. Knowledge deficiencies occur in two categories: phytopathological knowledge, and technological know-how. An example of the first category, lack

Table 10. Ranking of production systems on sandy soils according to aspects at the crop level. In the crop production systems growth limiting or growth reducing factors are excluded. Per aspect, the target level is indicated between brackets. High ranks imply better performance

Crop	Aspect				
	Gross margin (Dfl ha^{-1}) [maximum]	Pesticide input[a] (kg a.i. ha^{-1}) [minimum]	Nitrogen recovery (kg kg^{-1}) [minimum]	Labour (h ha^{-1}) [minimum]	
				specialist	routine
Hyacinth	4	4	3	1	3
Lily	5	1	1	3	1
Narcissus	2	3	5	2	2
Tulip	3	2	2	4	4
Winter wheat	1	5	4	5	5

[a] excluding soil fumigation which is an inter-crop activity.

of phytopathological knowledge on input-output relations, is quantification of carry-over effects between crops. Sensitivity analyses showed that changes in the classification of the auto-intolerance of crops (Table 4) result in major changes in farm gross margin and associated optimal crop rotations. More insight into the ecology of soil-borne yield reducing factors and their behaviour under different inter-crop management is urgently needed. In contrast, changing the yield loss associated with hyacinth preceding or succeeding tulip (Table 3) did not result in any changes in the optimal solution, because of the restrictive labour demand of hyacinth. This result emphasizes the need for an integrative framework to analyze research prioritization in the proper context.

The category of deficiencies in technological know-how comprises components of systems which can be described in functional terms, but, as yet, lack a real-world technology. Illustrations pertain to nitrogen utilization and to the role of a break crop. The results of the study indicate that reducing pesticide input requires less economic sacrifice than reducing nitrogen surplus (Figure 3). Cause of this differential effect on farm gross margin are opportunities for substitution. Non-chemical methods of pest management can substitute pesticides to a certain degree without major negative effects on yield. In contrast, substitution opportunities in nutrient management are limited to the choice between artificial fertilizer and animal manure. However, with the current technologies the latter always contribute more to nitrogen surplus at the farm and field levels. To alleviate the conflict between maximizing farm gross margin and minimizing nitrogen surplus, technologies are needed that improve nitrogen utilization through placement and timing of nutrients, for example animal manure applied in combination with drip irrigation.

The second illustration of lack of technological know-how pertains to the role of a break crop. In the study, winter wheat emerged as an important break crop in flower bulb dominated rotations. Four attributes contribute to this status: restoration of soil health, high nitrogen recovery, tolerance to pests, diseases and weeds, and low labour requirement. Counter-intuitively, the low crop gross margin was found to be of little importance for farm gross margin provided that labour may be allocated to high-profit activities. Such functional specifications guide the search for crop management systems that may act as break crops. In this way the approach directs the design of crop management systems that are geared to improving the performance of the design at the next higher level of aggregation, the farming system level.

Contribution to design process

Both the explorative process and its results have proven useful for the aim of the study, to support the design process of sustainable flower bulb production systems by an association of flower bulb growers and environmental lobbyists. Two essential elements in the approach met with much appreciation and resulted in bridging the gap between the two polarized parties involved. First, by separating objectives and agro-technical options it became clear that polarization was caused by divergent views on poorly defined objectives, rather than by disagreement on agro-technical relations. Subsequently, the quantitative perspective on the trade-off between economic and environmental objectives enabled a transparent discussion on preferred developmental pathways. Second, current constraints concerning farm size and distribution, and farm management quality were deliberately ignored. As a result opportunities were identified which led to re-adjustment of perceptions and represented challenges for further development. In contrast, a predictive approach which focuses on finding *plausible* futures (Schoonenboom, 1994) would have been less successful in the present context, since plausibility assumes consensus on possibilities.

The results highlight the importance of strategic choices at the farm level over tactical choices at the crop level. Renting land and including a break crop such as winter wheat in the rotation proved to be crucial factors for mitigating the negative impact of environment-oriented production systems on farm gross margin. In contrast, the *a priori* attention of the growers was focused on improving management of growth reducing factors and nutrients for crops or for inter-crop activities. The results of the study challenged this perception and stimulated critical reflection on agronomic and farm economic causes.

Complementary studies at the regional or sectoral level would be useful to put the results at the farm level further in perspective. Because flower bulbs produced in the Netherlands constitute a major share of the world market, changes in production area and associated supply are reflected in changes in price. Studies at the regional and sectoral levels would be needed to investigate the possibilities for maintaining national production of flower bulbs at current levels.

Some agronomic relations in the study were questioned, and the farmers took action to stimulate relevant research by the experimental station. Nevertheless, the results were considered sufficiently robust to be tried out on commercial farms. A project was formulated to this end and discussed with all major actors in the flower bulb industry. In the project, anticipated to start in 1997, continuous training of selected farmers and extensionists is an important component to support testing and improving of prototypes.

Perspective

Current attention in research and practice for ecological farming systems (Vereijken, 1992) requires new objectives as well as new constraints to be formulated. Production systems conducive to novel objectives, such as maximizing recreational and natural value of the farming system (Vereijken, 1994, 1995), will need to be defined. Objectives of integrated systems become constraints during design of ecological farming systems, such as the zero-input level of pesticides. New constraints include balances for soil organic matter and weed seed bank, and restrictions with respect to use of organic manure. Operationalizing yield stability of production systems represents another major challenge.

The usefulness of the approach for targeting disciplinary crop protection research is twofold. First, component knowledge is scaled up to answer questions on sustainability at the relevant level of the farming system. The approach shows to which extent environmental and economic objectives can be met using the current level of phytopathological knowledge and technological know-how. Second, sensitivity analyses indicate the need for increasing insight into the ecology of soil-borne yield reducing factors and their behaviour under different inter-crop management. In combination with information on effects on crop yield, such studies will enable more detailed assessment of soil health related aspects of farming systems.

Much of the interaction in this study between the research group and the association of farmers and environmentalists can in retrospect be characterized as learning processes. It has been recognized before that learning constitutes an essential element in development of integrated and ecological farming systems (Röling, 1994). Therefore, the aspect of learning during systems design should be enhanced. The project formulated by the association provides an excellent opportunity to gain experience with application of exploratory models for educational purposes at the farming systems level.

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References

Anonymus (1991) [Multi-year Crop Protection Plan: Governmental Decision.] Ministry of Agriculture, Nature Conservation and Fisheries. Staatsdrukkerij Uitgeverij, The Hague. In Dutch

Anonymus (1992) [Quantitative information, flower bulbs and bulb flowers.] IKC-AT, Lisse. In Dutch

Anonymus (1993) [Quantitative information for arable farming and field production of vegetables.] Publication nr. 69, IKC-AT, Lelystad. In Dutch

Ayyad MA and Van Keulen H (1987) The ‘Mariut’ project. Final report submitted to Directorate General for International Cooperation (DGIS), Part 3, CABO, Wageningen

De Ruijter FJ and Jansma JE (1994) [Bulbs in numbers]. Report 17, AB-DLO and Wageningen Agricultural University. In Dutch

De Wit CT, Van Keulen H, Seligman NG and Spharim I (1988) Application of interactive multiple goal programming techniques for analysis and planning of regional agricultural development. Agricultural Systems 26: 211–230

EDS-Scicon (1992) MGG User guide, Version 3.20. EDS-Scicon, Wavendon Tower, Wavendon, Milton Keynes, England

EDS-Scicon (1993) SCICONIC User guide, Version 2.30. EDS-Scicon, Wavendon Tower, Wavendon, Milton Keynes, England

Habekotté B (1994) [TCG_CROP, a model for calculation of production and environmental variables of various crops.] Simulation Reports CABO-TT, nr. 35, Wageningen. In Dutch

Habekotté B and Schans J (1996) [Model-based exploration of options for integrated arable farming.] Report 64, AB-DLO, Wageningen. In Dutch

Jansma JE, Rossing WAH, De Ruijter FJ and Schans J (1994) [Bulbs on a roll. Exploration of development options for sustainable flower bulb production.] Wageningen Agricultural University and AB-DLO, Science Office Report 103. In Dutch

Meijles JG and Marcelis RAL (1990) [Demonstration farms bulb production and environment, a preproposal.] CLM, Utrecht. In Dutch

Meynard JM and Rossing WAH (1997) Methodology for development of sustainable farming systems: prototyping and model-based explorations in an interactive research setting. Submitted

Rabbinge R (1993) The ecological background of food production. In: Crop protection and sustainable agriculture. Ciba Foundation Symposium 177, John Wiley and Sons, Chichester, pp 2–29

Rabbinge R and Van Latesteijn HC (1992) Long-term options for land use in the European community. Agricultural Systems 40: 195–210

Rappoldt C and Van Kraalingen DWG (1990) Reference manual to the Fortran utility library TTUTIL with applications. Simulation Reports CABO-TT nr. 20, CABO-DLO, Wageningen Agricultural University

Raven PWJ and Stokkers R (1992) Development of integrated flower bulb production. Netherlands Journal of Agricultural Science 40: 251–256

Röling N (1994) Platforms for decision-making about ecosystems. In: Fresco LO, Stroosnijder L, Bouma J and Van Keulen H (eds) The future of the land: mobilising and integrating knowledge for land use options (pp 385–393). Wiley

Schans J (1991) Optimal potato production systems with respect to economic and ecological goals. Agricultural Systems 37: 387–397

Schans J (1996) MGOPT_CROP, a multiple goal linear programming model for optimisation of crop rotations. AB-DLO and PE, Report 69

Schoonenboom IJ (1995) Overview and state of the art of scenario studies for the rural environment. In: Schoute JFT, Finke PA, Veeneklaas FR and Wolfert HP (eds), Scenario studies for the rural environment (pp 15–24). Kluwer Academic Publishers, Dordrecht

Schröder JJ, Van Asperen P, Van Dongen GJM and Wijnands FG (1993) [Nutrient recovery and nutrient loss in arable crops: a theoretical exploration.] AB-DLO report 186, Wageningen, 25 pp

Smit AL & Van de Werf A (1992) [Physiology of nitrogen uptake and utilization: crop and rooting characteristics.] In Van der Meer HG & Spiertz JHJ (eds) Stikstofstromen in Agro-ecosystemen. Agrobiologische Thema’s 6, CABO-DLO (pp 51–67). Wageningen. In Dutch

Stokkers R (1992) [Research plan integrated farming systems for flower bulbs, De Noord: 1991–1996.] Report 77, LBO, Lisse. In Dutch

Stokkers R and Van den Berg H (1993) [Research plan integrated farming systems for flower bulbs, De Zuid: 1992–1997.] Report 81, LBO, Lisse. In Dutch

Van de Ven GWJ (1994) A mathematical approach for comparison of environmental and economic goals in dairy farming at the regional scale. In: ‘t Mannetje L and Frame J (eds), Grassland and Society. Proceedings of the 15th General Meeting of the European Grassland Federation (EGF), Wageningen, 6–10 June 1994 (pp 453–457). Wageningen Press, Wageningen

Van de Ven GWJ (1996) A mathematical approach to comparing environmental and economic goals in dairy farming on sandy soils in the Netherlands. PhD Thesis, Wageningen Agricultural University, 239 pp

Van Ittersum MK & Rabbinge R (1996) Concepts in production ecology for the analysis and quantification of agricultural input-output combinations. Field Crops Research, in press

Van Rheenen T (1995) Farm household level optimal resource allocation. An explorative study in the limestone area of East Java. PhD Thesis, Wageningen Agricultural University

Veeneklaas FR (1990) Dovetailing technical and economic analysis. PhD Thesis, Wageningen Agricultural University

Vereijken P (1992) A methodic way to more sustainable farming systems. Netherlands Journal of Agricultural Science 40: 209–223

Vereijken P (1994) Designing prototypes. Progress report 1. Progress reports of research network on integrated and ecological arable farming systems for EU and associated countries. AB-DLO, Wageningen

Vereijken P (1995) Designing and testing prototypes. Progress report 2. Progress reports of research network on integrated and ecological arable farming systems for EU and associated countries. AB-DLO, Wageningen

Weel MPM, De Vries GJH and Pak GA (1995) [Environmental care in flower bulb cultivation.] Centre for Agriculture and Environment, Utrecht. In Dutch

WRR (1992) Ground for choices. Four perspectives for the rural areas in the European Community. Netherlands Scientific Council for Government Policy. Sdu uitgeverij, The Hague

WRR (1994) Sustained risks: a lasting phenomenon. Netherlands Scientific Council for Government Policy. Sdu uitgeverij, The Hague