Modelling Agricultural Production Systems using Mathematical Programming

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Abstract

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This thesis focuses on the economics of changing farm-level production practices. It is recognised that many decisions made in a firm or a market are interrelated. Economic analyses aiming at predicting behaviour or recommending on alternatives for action need to account for these relations, otherwise the results and prescriptions will be misleading. In each of the four articles a mathematical programming model of an agricultural production system is developed, and empirical analyses are performed using Swedish data. The first article analyses aggregate effects of on-farm potato processing, utilising a partial equilibrium framework. An analysis of the Swedish potato market shows that, in more densely populated regions, on-farm processing is a part of a socially optimal industry structure. Increased import competition results in a larger share of domestic potatoes being processed at the farm-level. In article II, alternative tillage systems for grain production are evaluated. A mathematical programming model with simultaneous selection of crop rotation, machinery investments and scheduling of tillage and drilling operations is developed, utilising discrete stochastic programming to model field time variability. The empirical results show that a tillage system characterised by lower machinery capital and labour requirements may be as profitable as a conventional system. The model from article II is further developed in article III and IV. Article III recognises that policy measures aiming at reducing nitrogen leaching from crop production often have indirect effects. As an example, the empirical results show that subsidies to catch crops and spring ploughing provide an incentive to increase the area of spring crops, such that these subsidies may increase rather than reduce nitrogen emissions. In article III it is also concluded that cost-effective nitrogen abatement requires a mix of various adjustments of production practices, rather than a focus on a few measures. Article IV analyses whether it is necessary to account for environmental and economic risk when analysing measures to reduce nitrogen leaching in crop production. Considering environmental risk increases abatement costs. However, it appears that the benefits from explicitly accounting for nitrogen leaching variability (environmental risk) in the model are rather small, since the majority of the environmental risk is non-diversifiable. The benefits from including economic risk associated with income variability seem to be limited.

Key words: agriculture, diversification, farm management, farm models, optimisation, nonpoint pollution, policy analysis, sector models, Sweden.

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Preface

Writing a thesis requires a stimulating working environment. I started to work with my thesis while I was employed at the Swedish Institute of Agricultural Engineering (JTI). During 1998 I studied at Department of Agricultural Economics, Purdue University. After that I have been in the Department of Economics at SLU (Swedish University of Agricultural Sciences) to finish my thesis.

Many people have helped me, inspired me and supported me during the work with this thesis. I would especially like to thank my supervisor Hans Andersson. Hans has contributed with his knowledge, has provided ideas and has taught me how to write good scientific articles. My fellow doctoral students, both at Purdue and SLU, have been an enormous support. Thanks to them all. Thanks also to all the staff at JTI, Department of Agricultural Economics (Purdue) and Department of Economics (SLU) for providing a good working environment and helping me with various practical matters. Data issues have been an important part of my work. I am grateful to all who have taken time to discuss data issues or have given me access to unpublished data, especially Helena Aronsson, Erik Ekre, Katinka Hessel, Markus Hoffmann, Holger Johnsson, Bengt Jonsson, Kjell Larsson, Daniel Lunneryd, Johan Orrenius, Tomas Rydberg, Maria Stenberg and Sune Sylegård. Besides Hans Andersson, I would like to thank Dennis Collentine, Katarina Elofsson, Rob Hart, Carl Johan Lagerkvist, Daniel Lunneryd, Gudbrand Lien, Christoph R. Weiss and a number of anonymous referees for helpful comments on earlier drafts. I am grateful to Rolf Olsson for procuring funding for the second article in this thesis.

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Finally, I am grateful to family and friends, whose support has been very important to me.

Sone Ekman
Uppsala, August 2002.

Articles appended to the thesis

The thesis is based on the following articles, which will be referred to by their Roman numerals:

I. Ekman, S. & Andersson, H. (1998). The economics of on-farm processing: model development and an empirical analysis. *Agricultural Economics* 18: 177-189.

II. Ekman, S. (2000). Tillage system selection: a mathematical programming model incorporating weather variability. *Journal of Agricultural Engineering Research* 77: 267-276.

III. Ekman, S. (2002). Cost-effective nitrogen leaching reduction as influenced by linkages between farm-level decisions. Submitted to Agricultural Economics.

IV. Ekman, S. (2002). Reduction of farm-level nitrogen leaching in the presence of environmental and economic risk. Submitted to European Review of Agricultural Economics.

Contents

Articles I-IV

Introduction

Individual farmers must make decisions about what to produce, by what methods, in which seasonal time period, and by what technology. In this thesis mathematical programming models are developed to analyse changes of such farm-level production practices (what products are produced and how they are produced). The objectives behind the various analyses made in the thesis are to predict changes of farmer behaviour, to assist policy makers when choosing alternatives for action, and to assist farmers when choosing production practices. Specifically, crop farming under Swedish conditions is studied.

The fundamental idea behind the thesis is that many decisions made in a firm or a market are interrelated. Economic analyses aiming at predicting behaviour or at recommending on alternatives for action need to account for these relations, otherwise the results and prescriptions will be misleading. First, it is vital to recognise that many management decisions within the agricultural firm are linked together. Due to the linkages it may be rational for farm managers to change several practices simultaneously, when adapting to changing economic or technological conditions. Farm profitability can be increased and limited farm resources can be used more efficiently if product mix, production method, and technology changes are considered simultaneously. This has implications for the potential costs and benefits of adopting new technologies, changing cultivation techniques, or changing the mix of products produced.

There may also be off-farm effects related to the choice of production practices, for example negative externalities influencing the natural environment. These externalities motivate policy interventions. Agricultural policy and environmental policy contain a wide range of regulations and economic incentives intended to influence the decisions made by individual farm-managers. The presence of linkages between various management decisions implies that indirect effects may arise when policy makers choose to intervene. An evaluation of alternative policy measures ignoring indirect effects, i.e. assuming that one variable in the production system can be changed without affecting other variables, will result in policy recommendations that are misleading and unnecessarily costly.

Changes of farm-level production practices can affect other actors in the food marketing chain. A widespread change of production practices at the farm-level can lead to a shift of aggregate supply of the products produced. This shift may then affect market prices of the products, providing an incentive for actors in latter stages to adjust their behaviour. Consequently, there are interactions between decisions made at the farm-level and decisions made by firms in latter stages of the food marketing chain and decisions made by consumers. These market level relations may impact the economic benefit of adopting a new production technology at the farm level, for example.

While the common theme of the four articles included in the thesis is analysis of economically optimal adjustments of farm-level production practices, perspectives and problems addressed vary between the articles. The first article investigates the economics of small-scale on-farm potato processing, considering aggregate and regional adjustments within the industry. In the second article, alternative tillage systems for grain production are evaluated, considering adjustments of various farm-level production practices given field time risk. Article III analyses cost-effective strategies to reduce nitrogen leaching from crop production, taking the linkages between various management decisions into account. Finally, article IV focuses on the consequences of considering economic and environmental risk when analysing measures to reduce nitrogen leaching from crop production. It can be noted that the approach chosen in article I is quite different from the approach in articles II to IV. Aggregate adjustments within the whole food marketing chain are accounted for in article I, while the remaining articles focus on the farm-level. The reason for this difference is that the changes of production practices considered in article I are expected to affect product prices, while no impact on product prices is expected in articles II to IV.

Mathematical programming models

Mathematical programming is the main method used throughout the thesis. It is basically a method for solving a problem where one function or objective is maximised or minimised while other functions or constraints are satisfied. As an example, mathematical programming can be used to maximise profit given constraints on available capital and labour. Mathematical programming models developed by agricultural economists can be divided into two main categories: farm models and sector models (Hazell & Norton, 1986). Since the 1960s mathematical programming techniques have been widely used to model farm-level management decisions (see for example Glen, 1987) and to model agricultural sectors (see for example Norton & Schiefer, 1980).

Farm models focus on the optimal organisation of farm production, given limited resources such as land and labour. They generally include a range of production activities representing production of various crops and livestock products, and the models often account for various ways of producing the products. The objective function in the model is intended to reflect the objective of the decision-maker (usually the farmer).

Agricultural sector models are used to analyse producers' reactions to external changes, at the aggregate level. Supply functions or production activities represent production in the sector model, and demand functions represent consumer demand of the various products. Both prices and quantities of the products considered are endogenous. The purpose of the objective function is to make the maximisation model simulate the market outcome.

The mathematical programming model developed in article I is a sector model, while the models developed in the remaining three articles are farm models. Table 1 provides an overview of the models. Even though different problems are analysed in each article, the models have many features in common. What all four models have in common is optimisation of product mix and scheduling of operations. In article I, product mix refers to types of consumer products being produced, while product mix refers to crops being produced in the other articles. Scheduling of operations refers to processing and transportation activities in article I, while field operations are scheduled in article II to IV. Another common base for the models in article II to IV is optimisation of land use. Both of the first two articles consider choice of production technology. The models in the last two articles include environmental effects (nitrogen leaching) related to the choice of production practices. Machinery investment decisions are endogenous variables in the models developed in article II and III. Sequential decision problems under uncertainty are modelled in the last three articles. (By 'optimisation' I mean that the model is used to select the economically optimal levels of the decision variables, the endogenous variables.)

Table 1. *Overview of the models developed*

Model characteristic	Article			
	I	II	III	IV
Farm level	x*	x	x	x
Sector level	x			
Endogenous product prices	x			
Environmental effects			x	x
Technology choice	x	x		
Product mix optimised	x	x	x	x
Land use optimised		x	x	x
Machinery investments optimised		x	x	
Fertiliser application optimised			x	
Scheduling of operations optimised	x	x	x	x
Processing activities optimised	x			
Transportation optimised	x			
Stochastic elements		x	x	x
Sequential decision process		x	x	x
Risk aversion				x
Environmental risk				x

* Aggregate farm production is modelled, not individual farms.

So why are the models different? Why not develop one single model that includes all the elements considered in the four models developed in the thesis? I argue that the benefits from combining all the model characteristics into one single model would be small compared with the costs of doing so. Particularly the excessive data and computer resource requirements prohibit development of one single, large model. Rather than considering as much as possible, model development is about identifying and focusing on relationships that are important for the particular problem under investigation. The model developed in each article is a representation of relationships I have identified as important for the problems analysed.

The contribution of the articles is to identify some important relationships in the production systems that have been overlooked in previous modelling approaches, and illustrate the relevance of considering these relationships. Article I analyses aggregate effects of on-farm processing. Article II considers simultaneous machinery and crop selection given field time risk. Article III recognises that measures to reduce nitrogen leaching from crop production are interrelated and may have indirect effects. Finally, article IV analyses whether it is necessary to account for environmental end economic risk when analysing measures to reduce nitrogen leaching.

Methodological issues

Why choose a mathematical programming approach? Does this choice affect which problems are studied in the thesis? Given the complexity of the systems analysed and the empirical nature of the problems, mathematical programming is certainly a suitable tool for analysis. However, the particular problems addressed in this thesis are partially a result of the choice of methodology; a certain method is best suited to answer certain questions. Other quantitative methods that could have been employed in the thesis include simulation models, econometric approaches, and theoretical analysis using mathematics. All of these methods require that the relevant economic relations be expressed in a theoretical mathematical model. Pure theoretical analysis, where the model is solved directly without inserting data into it, is a powerful tool to analyse optimisation problems including limited number of decision variables, with relatively simple relationships between the variables. With larger and more complex problems including a multitude of constraints it is often not realistic to derive a reduced form solution.

The large number of variables and the complexity of the problems in the four articles call for empirical analysis, such that numerical results can be obtained. Simulation models are generally easier to develop and understand than mathematical programming models or econometric models. With simulation models it is possible to handle complex problems. However, the number of decision variables (for which the economically optimal levels are sought) should be limited, unless relevant levels for the decision variables are known beforehand. The latter is seldom the case if the problem investigated is large and complex, wherefore simulation should be avoided if the focus is on economic optimality. Econometrics is a powerful tool for hypothesis testing. Econometric analysis provides information on how and to what extent the explanatory variables affect the outcome. The main disadvantage is the data requirements. It is not possible to for example take data regarding some variables from one period and location and other data from another period and location, which is possible if a mathematical programming or simulation approach is chosen. All variables that are to be considered need to be included in a single data set with a sufficiently large number of observations.

The mathematical programming models developed are based on a traditional activity analysis framework (see for example Hazell & Norton, 1986). The mathematical programming model is used to find the economically optimal levels of various activities, which are the decision variables in the model. A production activity refers to production of a certain product using a certain predetermined combination of inputs, where the term input is widely defined; it may include production technology and techniques as well as time and place of production. If a different input combination is to be considered, another production activity must be defined in the model. This is the disadvantage; the model will contain a large number of activities if the possibility to adjust the levels of several inputs is to be taken into account. The alternative way to model production is to use production functions, where quantity produced is a continuous (usually non-linear) function of input levels. While the production function approach is extensively used in theoretical analysis, it is not so common in applied mathematical programming studies. The reason is that it is difficult to specify multiple-input (and multiple-output) production functions and particularly to get data to estimate those functions. However, the production function approach is often used in studies where only the level of a single input, such as nitrogen fertiliser, is varied.

A major advantage of the activity analysis approach is that the production model becomes linear; the output of a certain product is a linear function of the level of the associated activity. The linear relationships facilitate incorporation of integer machinery investment variables (article II and III) and a non-linear objective function (article IV), making the models less computationally burdensome to solve. Computer resource requirements for solving the models are a factor that it has been necessary to take into account during the model development in article II, III and IV. The computational burden is mainly due to incorporation of sequential decision problems under risk, which increases the number of decision variables in the models substantially. Curse of dimensionality is a general problem of the discrete stochastic programming (DSP) (Cocks, 1968; Rae, 1971) technique used to model sequential risk in article II, III and IV. The dimensionality problem occurs since DSP models have a tendency to explode into a large number of outcomes in the last decision stage. The latter problem is discussed by for example Hardaker et al. (1997).

DSP is a general technique to model sequential risk in a multi-stage decision process. This technique is sometimes referred to as stochastic programming with recourse (SPR) or discrete stochastic sequential programming (DSSP). DSP allows parameters in the constraint set and the objective function to be random. Articles II to IV consider random parameters in the constraint set (article IV also considers random parameters in the objective function); it is recognised that field time (time available for performing field operations) varies from one year to another due to weather variability. This variability implies that drilling will be delayed in years with poor weather conditions, which affects crop yields negatively. In the models it is assumed that the farm-manager only has probabilistic knowledge of available field time the following season, and that field time (weather) outcome is independent of field time outcome in the preceding season. This assumption seems realistic given current meteorological knowledge. The decision problem becomes sequential (dynamic) because machinery investments and/or crop mix selection are decisions made prior to the decision-maker observes field time outcome, while tillage and drilling operations must be adjusted to available field time (actual weather conditions). Tillage and drilling decisions are second stage, and in article II also third stage, decisions. In article IV additional stochastic parameters are accounted for - stochastic nitrogen leaching levels, stochastic crop yields, and stochastic output prices are modelled. The uncertainty regarding these parameters is resolved after all decisions by the farm-manager have been made.

Dynamic programming (DP) is another common technique to model dynamic stochastic problems. DSP and DP are not directly interchangeable with each other. DSP can handle large and complex decision problems at each decision stage, but the number of stages must be limited due to dimensionality considerations. DP can handle an infinite number of stages. However, DP is not suitable to model field time variability in articles II to IV due to the large number of continuous variables and inequality constraints. A third alternative to account for field time variability in articles II to IV would be to use chance constrained programming (CCP) to approximate the true stochastic scheduling problem. This approach allows the problem to be solved using deterministic techniques. The resulting model is basically a deterministic model where field time availability is inflated in order to account for the impact of variability. The CCP approach results in a compact model with few variables, but the technique has some major drawbacks when it comes to modelling of field time constraints. First, the major problem is how to select the reliability levels for the chance constraints; a DSP model is required to get the correct values. Second, the appropriate reliability levels may change if there are major changes of production practices. Problems related to the modelling of field time constraints are discussed by Eytang et al. (1998).

It can be noted that no dynamic adjustments from one year to another are taken into account in this thesis. This implies that the models do not account for successive adjustments of production practices. Rather than analysing the adjustment process itself, the focus is on economic optimality after an adjustment process has taken place.

Throughout the thesis pure competition is assumed. This is a rather unproblematic assumption when it comes to the last three articles, where production of cereal grains, oilseed and sugarbeet is analysed at the farm-level. A change in crop mix on farms in a part of Sweden is unlikely to affect the price of these commodities to the extent that it affects the results of the analyses. When it comes to article I it is not so evident that pure competition can be assumed. First, the product (potatoes) is not necessarily homogenous; consumers may be able to distinguish between a product produced by a local farm and an imported product. The results in article I are conditional on the assumption that consumers regard the product as homogenous. Second, the may be a problem with a limited number of buyers of the product, at least at the retail level, considering that transportation costs for potatoes are relatively high in comparison with the product price. Article IV presumes that none of the actors in the food marketing chain are able to exercise market power.

The producer's objective is assumed to be maximisation of expected net revenue subject to some constraints imposed by the availability of resources. This is a common approach in microeconomic analysis. In article IV I also consider expected utility maximisation (utility of income), in order to examine the importance of accounting for risk aversion. Maximisation of expected utility of income is identical to maximisation of expected net revenue if the utility function is linear in income, i.e. the individual is risk neutral.

In article III and IV, a negative externality (nitrogen leaching) is incorporated in the analysis using a cost-effectiveness approach. The alternative to the cost-effectiveness approach would be a welfare analysis where an economic value is assigned to the environmental damage caused by the externality, such that the results provide information about socially optimal production practices. The cost-effectiveness approach is, however, the appropriate choice for article III and IV, since it is difficult to link nitrogen emissions to biological impacts measured in monetary terms (e.g. Gren et al., 1997). Cost-efficiency analysis involves minimising the costs to attain a specified goal; in this case the goal is a maximal annual nitrogen emission from an individual farm and the cost is foregone profit. The goal is given externally, implying that satisfying the target improves welfare.

The models developed in the thesis are solved using the software GAMS (Brooke et al., 1998). GAMS provides a high-level language for compact representation of large and complex models, as well as a set of solvers including different algorithmic methods.

Results and findings

Article I: The economics of on-farm processing: model development and an empirical analysis

The first article extends the literature on the use of sector programming models as well as the literature on the economics of on-farm processing. The novelty is to include small-scale on-farm processing in a partial equilibrium framework, allowing for analysis of aggregate and regional adjustments within the industry. Samuelson (1947) is cited as the first to recognise that the collective behaviour of groups of producers and consumers making up markets could be expressed as a constrained maximisation problem. Given the supply behaviour of producers and the demand behaviour of consumers of a commodity, market equilibrium may be derived by maximising consumer surplus plus producer surplus, subject to a market clearing constraint. This idea was first applied in the spatial equilibrium work of Takayama & Judge (1964). Article I extends the basic modelling framework introducing on-farm processing, accounting for farmers' choice between selling the primary product to large scale processors or processing the primary product on the farm and selling consumer products directly to retailers. The model developed includes all stages of the food marketing chain from primary producers to consumers.

Processing in the context of article I refer to grading, packaging and distribution of fresh potatoes. For the case of the Swedish potato industry it is demonstrated that on-farm processing is part of a socially optimal industry structure, and that increased import competition results in a larger share of domestic potatoes being processed at the farm-level. On-farm processing can serve as an effective diversification scheme for farmers, at least in more densely populated regions.

Article II: Tillage system selection: a mathematical programming model incorporating weather variability

The methodological contribution of article II is to model simultaneous selection of crop rotation and integer machinery investments, using discrete stochastic programming to model field time variability. The mixed integer and linear programming model developed is used to analyse the economics of three alternative tillage systems for grain production on clay soils in Sweden. The results illustrate the importance of considering choice of crops and machinery simultaneously. It is demonstrated that tillage systems characterised by lower capital and labour requirements may be as profitable as a conventional system. Adjusting crop mix and reducing tractor size can compensate for the lower crop yields with reduced tillage. It is also recognised that a deterministic model, which does not account for field time variability, may underestimate optimal machinery capacity.

Among previous studies analysing different tillage systems, no study has used a model with endogenous variables for both machinery and crops. However, Audsley (1981) presents a conceptual linear programming model for simultaneous selection of crops and machinery, where the link between these decision variables consists of the scheduling of field operations. Scheduling of field operations is important since there is a balance between reducing machinery costs by reducing machinery capacity and increasing gross revenue by reducing yield losses due to non-optimal timing of operations. The Audsley model is the foundation for the model developed in article II, in the sense that it appears to be the first mathematical programming model capable of choosing crops and machinery simultaneously. In article II, the Audsley model is extended to incorporate field time variability, a sequential decision process, different tillage systems, and integer (rather than continuous) machinery investment variables.

Article III: Cost-effective nitrogen leaching reduction as influenced by linkages between farm-level decisions

Article III points out that linkages between various farm-level decisions should be accounted for when measures to reduce nitrogen leaching from crop production are analysed and designed. Policy measures often have indirect effects since it is profitable for farm managers to adjustment more production practices than the practice a certain policy measure is focusing on. As an example, the empirical analysis shows that subsidies to catch crops and spring ploughing provide an incentive to increase the area of spring crops, such that these subsidies may lead to increased nitrogen emissions rather than reduced emissions. Regarding cost-effective measures to reduce nitrogen leaching from grain production, it can be concluded that a mix of various adjustments of production practices should be used. It is costly to focus on one or a few measures. EU direct income payments appear to have a large impact on nitrogen leaching and abatement costs. The empirical results refer to cereal grain and oilseed production on sandy soils in South Sweden.

Previous studies focus on farm-level management decisions that affect nitrogen leaching directly, such as choice of land use and fertiliser application rates. The novelty of the approach in article II is to also account for timeliness effects (yield losses) associated with delayed drilling, and the possibility to adjust machinery capacity. By incorporating timeliness effects it is possible to consider that crop yields are affected when changes in the crop rotation or tillage practices influence the scheduling of field operations. The scheduling of field operations is linked to the choice of machinery capacity. The model extends on the modelling framework developed in article II, by adding nitrogen leaching as well as additional management decisions (use of a catch crop, delayed tillage and choice of nitrogen application rates).

Article IV: Reduction of farm-level nitrogen leaching in the presence of environmental and economic risk

Article IV contributes to the literature on cost-effective nitrogen leaching reduction under uncertainty by analysing whether it is necessary to account for environmental and economic risk when analysing measures to reduce nitrogen leaching. Previous studies (as well as article IV) conclude that increasing the probability by which a certain abatement target is satisfied increases abatement costs drastically. However, I find that the benefits from explicitly accounting for nitrogen leaching variability in the model are small, since the majority of the environmental risk is non-diversifiable. It seems sufficient to choose production practices based on their impact on average nitrogen load, like in article III, and account for variability when the abatement target is determined. A farmer's level of risk aversion has some impact on economically optimal land use, but other elements of the production system are more important in determining optimal land use. Empirical data from South Sweden are used in the study.

A farm-level mathematical programming model incorporating environmental risk (nitrogen leaching variability), yield risk, output price risk and field time risk is developed. In comparison with previous mathematical programming models incorporating stochastic leaching constrains, article IV accounts for a larger number of farm-level management decisions and more sources of risk. The modelling framework from article III is further developed. Environmental risk is modelled by imposing a probabilistic constraint on farm-level nitrogen emissions, using the multiple realisation chance constrained programming (MRCCP) technique (Morgan et al., 1993; Wagner & Gorelick, 1989). An advantage of the MRCCP technique is that observed or simulated data can be inserted directly into the model without making any assumptions about the joint probability distribution. Economic, objective function risk is modelled utilising the direct expected utility maximising (DEMP) framework (Lambert & McCarl, 1985), which is theoretically appealing without becoming too complex to use in an applied mathematical programming study.

Directions and opportunities for further research

The modelling framework for analysing the economics of on-farm processing developed in article I can be extended and improved in a number of ways. First, on-farm processors' option to differentiate their product from products produced by large-scale processors could be accounted for in the analysis. Incorporation of such product differentiation requires additional information on consumer demand for local produce. Second, as mentioned above, there may be a problem with buyers exercising market power. The impact of various market structures on the opportunities for small-scale on-farm processing could be analysed using well-known oligopoly models. My third suggestion is a potential improvement of the sector modelling approach originally set out by Jonasson (1996); the model could be developed to allow for dynamic adjustments of farm structure and resource endowments. The impact of import competition on domestic production is likely to be overestimated in article I, since the model assumes a given (historical) farm structure and given resource endowments.

The results in articles II to IV point out the importance of considering crop selection, machinery selection and scheduling of field operations simultaneously. I suggest that also future research analysing changed production practices on crop farms consider the interactions among these decisions, in order to correctly reflect farmers' adjustment possibilities seen over a few years. Machinery selection may be exogenous to the model, as in article IV, if computer resources are a limiting factor and the number of potential machinery combinations is small enough to allow for simulations with all combinations. I also suggest that field time variability should be accounted for when modelling crop mix and machinery selection. Otherwise the solution of the mathematical programming model will overstate profits and suggest a crop rotation and/or a set of machinery that is inappropriate in poor weather years. CCP could eventually be used to approximate the stochastic scheduling problem that arises when field time variability is accounted for, if simplicity and few variables are highly desirable properties of the model.

In article IV I find that the impact of risk aversion on modelling results is relatively small; risk aversion needs to be very high for objective function risk to matter at all. The reason is that production plans to maximise expected net revenue are reasonably diversified before risk aversion is considered (diversification contributes to lower machinery costs and higher crop yields). My results support findings in other studies. For example, Pannell et al. (2000) states that "for the types of the decision problems most commonly modelled by agricultural economists, the extra value of representing risk aversion is commonly very little". I conclude that it is often sufficient to assume that the objective of farm-managers is to maximise expected net revenue (rather than expected utility of wealth or income). The decision-maker needs to be very risk averse, or the differences in risk levels between the alternatives considered need to be large, for risk aversion to influence the production plan.

The models in article II and III can be further developed to analyse different production systems. There appear to be a need for economic analyses of production practices in organic production, using more rigorous models of the production system. In organic production it may be even more important to account for the linkages between crop selection, machinery selection and scheduling of field operations. I think so because the crop rotation is used as a means for supplying the crops with nitrogen and for controlling weeds and diseases. In addition, organic farming relies heavily on tillage for controlling weeds. A desirable future development of the model in article III is to analyse cost-effective nitrogen leaching reduction on farms with both livestock and crop production. Several such studies exist, but the representation of crop production is generally much simpler in these studies than in the model developed in article III.

Regarding article IV there appear to be less need for future developments. The empirical results suggest that the problem, at least approximately, can be solved without explicitly accounting for environmental (nitrogen leaching) risk or economic (objective function) risk. Instead, the framework developed in article III can be used to analyse cost-effective nitrogen leaching reduction in crop production, but the desired abatement target should be adjusted to account for leaching variability (a tighter target should be chosen). However, I think than one or two additional studies should be done on other farm types in other regions to verify that a cost-effective reduction of leaching variability can be obtained by choosing abatement measures based on their impact on average nitrogen load.

An interesting challenge would be to apply the model of farm-level production and nitrogen leaching developed in article III at the watershed level. Existing watershed models are generally quite as simple in their representation of the production system at the farm-level, wherefore there is a risk that the results from these models are misleading. Some simplifications of the model in article III are however required to reduce computer resource requirements of an aggregate model. Additional production systems, such as farms with livestock, need to be included in the aggregate model. The resulting watershed model would contain a number of representative type farms at different locations in the watershed.

Finally, I want to highlight the problem of agricultural and environmental policies being designed without accounting for the linkages between the two. For example, my analysis of cost-effective nitrogen leaching reduction reveals that agricultural policy has a large impact on nitrogen leaching and therefore a large impact on the natural environment. At the same time, I show that the effectiveness of a certain environmental policy measure depends on the prevailing agricultural policy. I can also conclude that one environmental policy measure may affect the performance of another environmental policy measure. My point is that reforms of environmental and agricultural policies should be analysed simultaneously in order to avoid undesired effects of the policies.

References

Audsley, E. 1981. An arable farm model to evaluate the commercial viability of new machines and techniques. *Journal of Agricultural Engineering Research 26*, 135-149.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R. & Rosenthal, R.E. 1998. *GAMS a user's guide*. GAMS Development Corporation. Washington, DC.

Cocks, K.D. 1968. Discrete stochastic programming. *Management Science 15*, 72-79.

Eytang, M.N., Preckel, P.V., Binkley, J.K. & Doster, D.H. 1998. Field time constraints for farm planning models. *Agricultural Systems 58*, 25-37.

Glen, J.G. 1987. Mathematical models in farm planning: a survey. *Operations Research 35*, 641-666.

Gren, I.-M., Söderqvist, T. & Wulff, F. 1997. Nutrient reductions to the Baltic Sea: Economics and ecology. *Journal of Environmental Management 51*, 123-143.

Hardaker, J.B., Huirne, R.B.M. & Anderson, J.R. 1997. *Coping with risk in agriculture.* CAB International. Wallingford, UK.

Hazell, P.B.R. & Norton, R.D. 1986. *Mathematical programming for economic analysis in agriculture*. Macmillan Publishing Company. New York, NY.

Jonasson, L. 1996. Mathematical programming for sector analysis – some applications, evaluations and methodological proposals. *Swedish University of Agricultural Sciences, Department of Economics, Dissertations 18*. ISSN 0284-4842.

Lambert, D.K., & McCarl, B.A. 1985. Risk modeling using direct solution of nonlinear approximations of the utility function. *American Journal of Agricultural Economics 67*, 846-852.

Morgan, D.R., Eheart, J.W. and Valocchi, A.J. 1993. Aquifer remediation design under uncertainty using a new chance constrained programming technique. *Water Resources Research 29*, 551-561.

Norton, R.D. & Schiefer, G.W. 1980. Agricultural sector programming models: a review. *European Review of Agricultural Economics 7*, 229-264.

Pannell, D.J., Malcolm, B. & Kingwell, R.S. 2000. Are we risking too much? Perspectives on risk in farm modelling. *Agricultural Economics 23*, 69-78.

Rae, A. 1971. Stochastic programming, utility, and sequential decision problems in farm management. *American Journal of Agricultural Economics 53*, 448-460.

Samuelson, P.A. 1947. *Foundations of economic analysis.* Harvard University Press. Cambridge, MA.

Takayama, T. & Judge, G.G. 1964. Spatial equilibrium and quadratic programming. *Journal of Farm Economics 46*, 67-93.

Wagner, B.J. & Gorelick, S.M. 1989. Reliable aquifer remediation in the presence of spatially variable hydraulic conductivity: from data to design. *Water Resources Research 25*, 2211-2225.

Sammanfattning

Avhandlingen omfattar fyra artiklar där förändringar av produktionsteknologi, produktionsmetoder och produktmix inom lantbruket studeras. Matematiska modeller (mathematical programming) utvecklas för att finna samhälls- eller företagsekonomiskt optimala produktionssystem. Ett grundläggande problem som beaktas i avhandlingen är att många beslut inom ett företag eller på en marknad är sammanlänkade så att olika beslut påverkar varandra. En analys som syftar till att förutsäga effekten av en viss institutionell förändring (t.ex. ändrad miljö- eller jordbrukspolitik) kommer att ge missvisande resultat om viktiga anpassningsmöjligheter på företagsnivå förbises. Likaledes kommer en analys avsedd som beslutsunderlag till enskilda företagare att över- eller underskatta den ekonomiska potentialen hos en alternativ teknologi eller produktionsmetod om inte möjligheten att samtidigt förändra andra beslutsvariabler i produktionssystemet beaktas.

I den första artikeln utvecklas en sektorsmodell av den svenska matpotatismarknaden för att analysera potentialen för småskalig förädling på gårdsnivå, där odlaren själv sköter sortering, paketering och distribution. De småskaliga förädlarna förutsätts leverera direkt till butik eller storhushåll. Analyserna gjordes i anslutning till Sveriges inträde i EU. Gårdsförädlad potatis visar sig i södra Sverige kunna kan ta en betydande marknadsandel, medan storskaliga anläggningars marknadsandel minskar. Detta gäller under förutsättning att senare led i livsmedelskedjan inte begränsar konkurrensen (vilket är möjligt om det endast finns ett fåtal uppköpare). Ökad importkonkurrens kommer visserligen att leda till minskad potatisodling i Sverige, men en större andel av den inhemska produktionen kan förväntas förädlas på gårdsnivå vid ökad importkonkurrens. Småskalig förädling visar sig både kunna öka lantbrukarnas inkomster och förbättra deras konkurrenskraft gentemot utländska odlare.

Artikel II till IV fokuserar på de beslut som fattas av enskilda lantbrukare på gårdsnivå, till skillnad från artikel I där alla led från primärproducent till konsument beaktas. I artikel II studeras lönsamheten i tre olika system för jordbearbetning och sådd, i spannmåls- och oljeväxtodling på styvare lerjordar i Sverige. Resultaten visar att direktsådd utan någon föregående jordbearbetning kan vara väl så lönsamt som ett konventionellt system med mer intensiv jordbearbetning. Skördarna sjunker visserligen med starkt reducerad jordbearbetning, men företagsekonomiskt optimal insats av maskinkapital, arbete och bränsle sjunker dessutom så att kostnaderna kan minskas. Med starkt reducerad jordbearbetning kan en given areal skötas med färre maskiner på kortare tid. Resultaten pekar också på vikten av att beakta möjligheten att ändra växtföljd vid förändringar i maskinsystemet, samt att vädervariation ökar ekonomiskt optimal maskinkapacitet.

I artikel III och IV vidareutvecklas modellen från artikel II för att analysera kostnadseffektiva åtgärder mot kväveutlakning från vegetabilieproduktionen. Artikel III pekar på vikten av att ta hänsyn till sambanden mellan olika beslut på gårdsnivå. Sambanden medför att indirekta effekter kan uppkomma när en viss reglering eller ett ekonomiskt styrmedel införs i syfte att minska lantbrukets miljöbelastning. Exempelvis kan de stöd till fånggrödor och vårplöjning som införts i Sverige leda till ökad kväveutlakning, tvärt emot syftet. Anledningen är att dessa stöd utgör ett incitament att öka andelen vårsådda grödor och minska andelen mark i permanent träda. Vidare visar resultaten att kostnadseffektiv utlakningsreduktion kräver en mix av förändringar i hela produktionssystemet, snarare än att man koncentrerar sig på någon enstaka åtgärd. Det billigaste sättet att minska kväveutlakningen på gårdsnivå är att kombinera odling av fånggröda, minskad kvävegödsling, mer vårplöjning, mindre areal höstgrödor, och mark som läggs i permanent träda. Analyserna avser en lätt jord i södra Sverige, där läckaget är som störst.

Artikel IV utvärderar i vilken mån ekonomisk risk (lantbrukarens inkomst varierar från ett år till ett annat) och miljörisk (kväveutlakningen varierar) bör beaktas när man studerar åtgärder för att minska kväveförlusterna. På grund av att utlakningen varierar mycket kraftigt mellan olika år är det kostsamt att öka sannolikheten för att ett givet reduktionsmål nås ett enskilt år. Nyttan av att inkludera utlakningsvariation i analysmodellen är dock mycket begränsad, eftersom huvuddelen av miljörisken är icke-diversifierbar. Variationsmönstret är ungefär detsamma oavsett gröda och jordbearbetningsmetod, även om medelutlakningen skiljer sig åt. Det förefaller tillräckligt att basera valet av åtgärder på deras effekt på medelutlakningen, och i stället ta hänsyn till utlakningsvariation när målet för utlakningsminskning fastställs. Nyttan av att beakta ekonomisk risk i modellen är begränsad, eftersom modellresultaten blir relativt lika oavsett den enskilda lantbrukarens riskaversionsnivå. I de flesta fall torde det vara tillräckligt att i analysen anta att lantbrukaren maximerar vinsten.