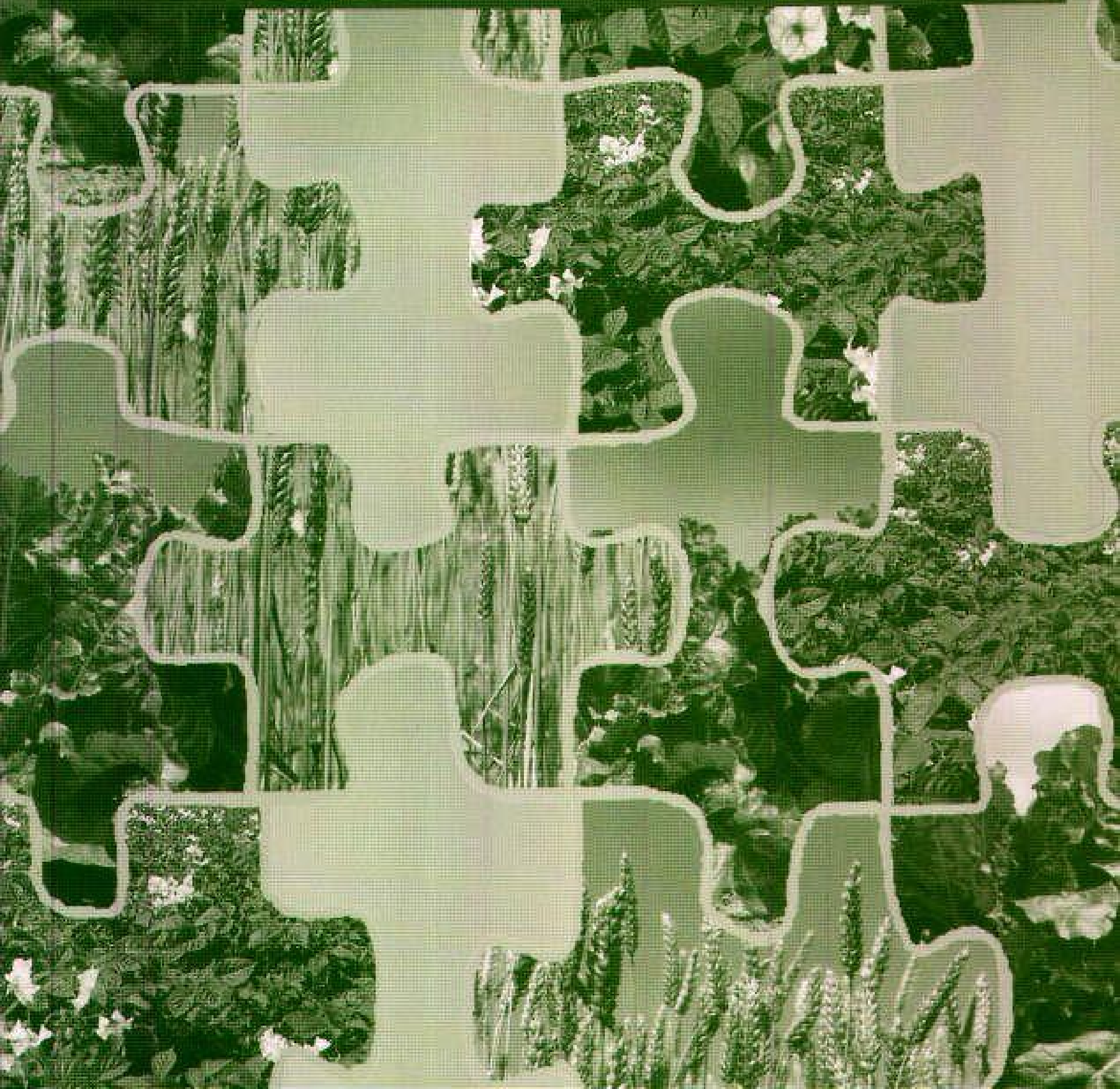
The role of production risks in the conversion to more sustainable arable farming

Abco de Buck



Stellingen

1. Een normatieve bepaling van het risico van een beslissing heeft slechts een beperkte voorspellende waarde voor het gedrag van een beslisser. (dit proefschrift)
2. Het is uit oogpunt van nutsmaximalisatie voor een individueel bedrijf niet rationeel om collectieve goederen (zoals een schoon milieu) te produceren zonder dat daar een beloning tegenover staat. (dit proefschrift)
3. Vanwege het duidelijke concept en de goede marktcondities is het aantrekkelijker om te schakelen naar biologische landbouw dan naar geïntegreerde landbouw. (dit proefschrift)
4. Biologische landbouw is geen blauwdruk voor duurzame landbouw.
5. De angelsaksische benaming ‘Farm Management’ dekt het onderzoeksterrein van de Vakgroep ‘Agrarische Bedrijfseconomie’ beter dan de Nederlandse benaming.
6. Introductie van GMOs (Genetically Modified Organisms) is onverantwoord zonder een uitvoerige risicoanalyse. Thans zijn meestal onvoldoende data voorhanden om dergelijke analyses uit te voeren.
7. De uitvoering van het voor veel problemen in de hedendaagse landbouw gewenste multi-disciplinair onderzoek wordt belemmerd door de voortschrijdende vercommercialisering van de partners binnen Wageningen UR.
8. De hoge frequentie van ‘toevallige’ ontmoetingen in den vreemde is een aanwijzing dat de nulhypothese van onafhankelijke kansen hier verwerpelijk is.
9. De functie ‘dubbelzijdig kopiëren’ van de huidige kopieerapparaten is nog onvoldoende bedrijfszeker en gebruikersvriendelijk om een werkelijke papierbesparing mogelijk te maken.
10. De naam ‘computer’ voor een apparaat wat zelden als rekentuig gebruikt wordt is misleidend.

Stellingen behorende bij het proefschrift
'The role of production risks in the conversion to more sustainable arable farming'.
Abco J. de Buck, Wageningen, 10 januari 2001.

Abco de Buck

The role of production risks in the conversion to more sustainable arable farming

Proefschrift ter verkrijging van de graad van doctor op
gezag van de rector magnificus van Wageningen
Universiteit,
dr. ir. L. Speelman,
in het openbaar te verdedigen
op woensdag 10 januari 2001 des namiddags te vier uur
in de Aula.

Omslag: Piet Kostense en Marjolijn de Vette

Druk: Grafisch Bedrijf Ponsen en Looijen B.V., Wageningen

ISBN 90-5808-351-9

The research described in this dissertation was funded by the Dutch Ministry of Agriculture, Nature Management and Fisheries.

The role of production risks in the conversion to more sustainable arable farming

De rol van productierisico's in de omschakeling naar een meer duurzame akkerbouw

Abco de Buck

Promotoren: dr. ir. J.A. Renkema
Emeritus Hoogleraar in de Agrarische Bedrijfseconomie

dr. ir. N.G. Röling
Hoogleraar in de Landbouwkennissystemen in Ontwikkelingslanden

Co-promotor: dr. ir. G.A.A. Wossink
Associate Professor of Agricultural and Resource Economics, NC State University, USA
en tevens Universitair Hoofddocent aan de leerstoelgroep Agrarische Bedrijfseconomie

Abstract

The role of production risks in the conversion to more sustainable arable farming

De rol van productierisico's in de omschakeling naar een meer duurzame akkerbouw

A.J. de Buck, 2001

The objective of the research described in this thesis was to determine the role of production risks in the conversion to more sustainable production systems of arable farming in The Netherlands. More specifically, the research goals were: (1) to specify the typical production risks that prevent farmers from changing to more sustainable farming, (2) to develop a method to quantify the size of these production risks, (3) to apply that method in order to quantify the risks involved in sustainable arable farming practices as compared to those involved in conventional practices, and (4) to assess farmers' behaviour when choosing from a set of sustainable and conventional farming practices. To achieve these objectives, descriptive research was done on the properties of the *innovator* (objective (1)) and normative research was done on the properties of the *innovation* (objectives (2) and (3)). Furthermore, an experimental analysis of adoption behaviour in a simulated, uncertain agro-ecological environment was conducted to integrate *innovator*-specific and *innovation*-specific properties (objective 4).

Ph.D.-Dissertation Department of Social Sciences, Farm Management Group,
Wageningen University, Hollandseweg 1, 6707 KN Wageningen, The Netherlands

Voorwoord

In het Voorwoord van dit proefschrift wil ik teruggaan naar de zomer van 1993. Ik kon me op dat moment en op die locatie (Spanje) niet voorstellen dat een jaren durend onderzoek naar één onderwerp me zou kunnen boeien. Dit veranderde toen het initiatief mij ter ore kwam voor het opzetten van een promotie-onderzoek naar de risico's van milieuvriendelijke teeltmethoden in de akkerbouw. De opzet van dit onderzoek met een team, waarin meerdere disciplines zijn vertegenwoordigd had meteen mijn interesse.

Met veel voldoening en plezier kijk ik terug op de periode van februari 1994 tot heden, waarin deze klus is geklaard. Hierbij ben ik ondersteund, begeleid en geholpen en heb ik samengewerkt met tal van personen uit diverse organisaties en groeperingen. Iedereen met wie ik op een constructieve wijze contact heb gehad tijdens mijn promotie-onderzoek (en dat betrof verreweg de meeste contacten), hierbij heel hartelijk dank.

In de eerste plaats een bijzonder woord van dank aan mijn promotoren, professor Niels Röling en professor Jan Renkema en aan mijn co-promotor en begeleidster Ada Wossink. Niels, jouw enthousiasme werkt zo aanstekelijk dat ik er altijd weer even tegenaan kon na een gesprek met jou. Renkema, uw kritisch constructieve houding heeft mij erg geholpen bij het nadenken over mijn onderzoek en bij het goed opschrijven daarvan in mijn en onze artikelen. Ada, zonder jouw inspanning was dit project nooit van de grond gekomen. Ik waardeer de ruimte die ik heb gekregen bij de invulling ervan; een manier van begeleiden die denk ik past bij een AIO project. Ik kon altijd een beroep op je doen, of het nu ging om overleg of om het leveren van commentaar. Een accurate afhandeling van e-mails waarborgde deze begeleiding ook na je vertrek naar de Verenigde Staten.

Ik wil de leden van de stuurgroep en begeleidingscommissie van dit project bedanken voor het op de rails zetten en het in de rails houden van dit onderzoek. De volgende personen hebben hierin zitting gehad: prof.dr.ir. N.G. Röling, prof.dr.ir. J.A. Renkema, prof.dr.ir. R.B.M. Huirne, dr.ir. J.H. v Niejenhuis, dr.ir. G.A.A. Wossink, dr.ir. C. van der Meer (LNV), H.E. Wielenga (LNV), drs. B.J.M. Meijer (PAV), ir P.J. Mur (toenmalig IKC-agv) en Dhr. Van Egteren (toenmalig Landbouwschap), ir. D.W. de Hoop (LEI), dr.ir. W.H.G.J. Hennen (LEI) en dr.ir. J.A.A.M. Verstegen (LEI).

Het platform voor overleg op het niveau van de werkvloer was de kernwerkgroep. In dit groepje is in een bijzonder collegiale en teamgerichte sfeer menige harde noot gekraakt, waarna het onderzoek weer verder kon. Bedankt, dr.ir. Ada Wossink, ir. Herman Schoorlemmer, ir. Arend Krikke, ing. Bas Janssens, ing. Jan Groenwold, drs. Ilonka van Rijn en ir. Rose-Marie Lambregts.

Ik had tijdens mijn AIO-schap het genoegen van twee werkkringen; de één was de leerstoelgroep ABE op de Leeuwenborch en de ander was de toenmalige afdeling Bedrijfssynthese van het PAV te Lelystad. Ik heb altijd veel plezier beleefd aan onze rondjes hardlopen of wandelen (het gaat niet altíjd om de prestatie), kroegbezoek en niet te vergeten de roddel bij de koffie. Alle collega's en in het bijzonder alle kamergenoten die ik heb 'versleten': bedankt!

Ik wil dr.ir. Eligius Hendrix hartelijk bedanken voor het meedenken en het plaatsen in wiskundige kaders van mijn onderzoek, wat menige grote mok koffie heeft gekost. Ik veel dank verschuldigd aan ing. Jouke Oenema voor zijn hulp bij het doorgronden en het nauwgezet parameteriseren van het computermodel WAVE en voor het uitvoeren van grote reeksen simulaties.

Ook in de persoonlijke sfeer ben ik veel mensen dank verschuldigd. Aan mijn ouders, Jo en Corry, heb ik meer te danken dan hier op te noemen is. Ik wil hier mijn grote waardering uitspreken voor de vrijheid die ik heb genoten om mijn eigen keuzes te maken. Jullie hebben mij hier altijd in gestimuleerd. Moeder Corry was nog betrokken bij de keuze om AIO te worden, maar mag het eindresultaat hiervan helaas niet meer meemaken.

De status van veel proefschriften is in de ogen van de schrijvers gedurende lange tijd 'bijna klaar'. Mijn geval was daar geen uitzondering op. Daarvoor zijn veel redenen aan te dragen, die meer of minder houtsnijdend zijn. Redenen die geen hout snijden wil ik de lezer besparen. Wel wil ik in dit kader mijn twee banen noemen, die ik vanaf de zomer 1999 tot heden vervuld heb. Ik wil mijn (ex-)collega's bij de bussiness unit Agro Systeemkunde van Plant Research International en bij de afdeling onderzoek van het Fruitteelt Praktijk Onderzoek bedanken voor hun inschikkelijkheid bij de afronding van dit proefschrift. Ook kan als houtsnijdende reden niet onvermeld blijven dat ik naast het scheppen van dit geesteskind tevens bezigheden kreeg met het grootbrengen van een kind van vlees en bloed.

Lieve Karin, dit brengt me tot het uitspreken van mijn grote dank en waardering voor jouw steun die ik heb mogen ontvangen voor het voltooien van dit werk. Door de laatste loodjes van dit proefschrift zijn er een aantal zaken bij ingeschoten, die jij altijd wist op te lossen. Jouw vraag 'wanneer ben je klaar met je proefschrift?' kan ik nu voor het eerst éénduidig beantwoorden met: 'vandaag'.

Abco de Buck,

's-Gravenzande, november 2000

Contents

1 General introduction

1.1 Background

Facilitated and stimulated by agricultural policy, extension and research, the agricultural production process in the twentieth century underwent a tremendous intensification all over the world. This intensification was also made possible by the introduction of an increasing range of relatively cheap agrochemicals (synthetic nutrients and pesticides). Farming systems based on high-yielding cultivars and a high level of inputs were widely adopted as the standard for modern arable farming.

The well-known fate of DDT illustrates an early awareness of the negative side-effects of pesticide use as manifested by health problems of farm workers and the emergence of resistant pest organisms. The negative effects of excessive pesticide use became increasingly apparent, which inspired the introduction of legislation listing all permitted pesticide applications on crops and objects.

Nonetheless, in the seventies and eighties arable farming was still characterised by rising productivity and increasing agrochemical use. Inevitably, the negative effects of this farming system on environmental quality and on the stability of agro-ecosystems became obvious, leading to particular concern in densely populated areas (like the Netherlands), where intensive human economic activity jeopardises environmental quality. Given the current trends in society, it seems likely that the consumers' wish for safe food and a clean environment will increasingly determine the context of arable production. New market conditions and policy instruments will require the use of synthetic inputs in agricultural production to be drastically reduced.

Since 1979 more environmentally sustainable production systems have been developed for the Dutch arable farming sector (Wijnands and Vereijken, 1992) in response to the national and EU environmental regulations on pesticide[1] and fertiliser[2] use. These farming systems, that

---

[1] Reduction of pesticide use in the EU has been institutionalised under the EU's Fifth Environmental Action Plan (CEC, 1993). The FEAPs targets include significantly reducing pesticide use per unit of land in production, and the adoption of integrated pest control, at least in all areas of importance for nature conservation. National governments are free to adopt stricter policies than those imposed by the EU. The reduction of pesticide use and emissions has been part of the national Dutch agri-environmental policy since the early 1990s (Multi-Year Crop Protection Plan; LNV, 1991).

[2] The EU Nitrate Directive sets a standard or maximum permitted concentration for nitrate (NO_3^-) of 50 mg l^{-1} in groundwater from agricultural sources (CEC, 1991). Member states are obliged to implement regulations to achieve this objective by 2003. By 2001, the Dutch government will have introduced a levy for arable farms that is based on the surplus of nitrogen (N) and phosphate (P) per ha, which will be assessed by nutrient 'bookkeeping' on the farm. Since 1998, Dutch national policy has set standards for manure handling, storage and application on arable farms to reduce ammonia (NH_3) emissions (LNV, 1998).

integrate economical and ecological goals, are termed as Integrated Arable Farming Systems (IAFS; Vereijken, 1992). IAFS comprise a multi-functional crop rotation that supports crop protection and nutrient management strategies. Crop protection is characterised by maximum prevention of weeds, pests and diseases (achieved by farm hygiene and resistant cultivars, supported by seed treatments), use of monitoring and guidance systems, the substitution full-field chemical control by mechanical methods and band spraying and the banning of persistent and mobile pesticides. Nutrient management aims at a balance between inputs and outputs on the farm to prevent losses of nutrients to the environment. Manure is attributed a major role in the maintenance of soil fertility, but nitrogen losses from manure[3] are of particular concern. In IAFS all these aspects of crop rotation, crop protection and nutrient management are deployed to integrate economical and ecological goals in farm management (Wijnands, 1992).

Piloting IAFS on experimental farms resulted in promising ready-to-use production systems, as savings on input use were considerable, yields were acceptable and the financial results were comparable to conventional farming (Wijnands, 1992; Wijnands en Vereijken, 1992). In 1990, a first, intensively supervised introduction project started to implement IAFS on commercial farms and to support its dissemination (Proost and Röling, in press). The first evaluation of this project confirmed the economic viability of IAFS (Janssens *et al.*, 1994). Adoption of IAFS increased gross margin per hectare by NLG 60-430 in 1990 and by NLG 185-360 in 1991. Compared to a group of non-adopters, the adopters saved on fertiliser and pesticide expenditure in both 1990 and 1991 (1990: NLG 110 and NLG 175 per hectare respectively). These savings compensated for increased labour costs, additional investments in machinery and in some cases for lower crop yields. Despite the promising technical and economic results of IAFS in practice and the popularity of a second, larger-scale, but less supervised introduction project, Dutch farmers have been reluctant to adopt these more sustainable farming systems.

Recent studies (see the interim evaluation in Proost *et al.*, 1995 and Van Weperen *et al.*, 1998) show that the arable sector may achieve the overall pesticide reduction targets in kg active ingredient set by the Dutch government for 2000 (LNV, 1991). This reduction has been mainly achieved by prohibiting specific pesticides (particularly soil disinfectants) and introducing more effective (less active ingredient per application, having the same lethal effect) but not necessarily less toxic pesticides. The rate of use remains, however, higher than in most European countries and the use of fungicides has increased (Woittiez *et al.*, 1996). Furthermore, though the targets for pesticide *volume* set for 2000 are likely to be achieved, those for *emissions* to surface water and the atmosphere will probably not (RIVM, 1998; Van Liere *et al.*, 1997).

Total N and P emissions to surface water hardly declined over 1995-97 in the Netherlands and in the same period, the quantity of N and P emissions from the agricultural sector even increased (RIVM/CBS, 1999a; RIVM/CBS, 1999b). By 2001, regulations limiting N and P

---

[3] Nitrogen losses due to the use of manure as a fertiliser include NH_3 volatilisation and NO_3^- leaching to groundwater.

surpluses on arable farms will have had the effect of generally decreasing nutrient losses to the environment. However, there is no scientific evidence that these regulations on nutrient management are sufficient or even effective to guarantee the attainment of the targeted environmental standards.

Given its moderate environmental performance, the Dutch arable farming sector will have to make a great effort to keep pace with the demands from society in the near future. Crucial to this is a farmers' large-scale adoption of more sustainable ways of farming: IAFS or even organic farming. To improve the poor current take-up of such farming systems, more needs to be known about the constraints to their adoption. With this in view, the research described in this dissertation set out specifically to investigate the role of production risk in the transition to more sustainable production systems in arable farming.

1.2 Risks of sustainable arable farming

In this study, risk is defined as the consequences of the exposure to uncertain conditions, particularly those consequences that are unfavourable to the decision maker, in this case the farmer (Hardaker *et al.*, 1997, Vlek and Stallen, 1979). The literature identifies three main sources of risk for agriculture (Sonka and Patrick, 1984; Hardaker *et al.*, 1997): (1) personal conditions, (2) external socio-economic conditions, and (3) the physical production environment. Risks and uncertainties associated with personal conditions include one's financial position, knowledge, capacities and ability to learn, entrepreneurial spirit, domestic situation and desire to farm. External socio-economic conditions refer to market characteristics, the agricultural industry and agribusiness, governmental policies and social factors. These risks and uncertainties include consumer behaviour (for instance, the acceptance of different cultivars used in sustainable farming), price trends for conventional versus 'green'-labelled produce, changes in policy objectives (such as regulatory measures and agricultural subsidies), relations within and between farming and non-farming communities, and the availability of inputs (such as labour).

Variable physical conditions (such as the weather) greatly determine the agro-ecological production environment of arable farming and lead to production risk. Agro-ecological factors include crop characteristics, soil parameters and the incidence of pests, diseases and weeds. These factors affect the ultimate quantity and quality of yields as well as the kind and timing of crop husbandry measures that impose production risks on the farmer. In this dissertation, production risks were specified as financial risks, yield risks, organisational risks (induced by peaks in labour demand), epidemiological risks and environmental risks. The use of polluting inputs such as pesticides and fertilisers causes environmental risks. A different farming system –that is a different set of husbandry measures available to the farmer– implies different production risks in terms of their nature and magnitude.

In moderate climates, a risk-averse farmer tends to over-supply agrochemical inputs in order to eliminate the possibly yield-depressing effects of variable natural conditions[4] (Babcock, 1992). This 'insurance premium' guarantees high production, because under a broad range of circumstances, the environment is kept free from weeds-, pests- and diseases and has sufficient nutrients; this is achieved at the cost of large risks of environmental pollution, however. Farmers may perceive production risks with respect to reducing agrochemical input use and introducing alternative (for instance mechanical) methods. The farmer's personal characteristics may play a role in the perception of production risks involved in switching to IAFS, for example because he feels uncertain about his ability to acquire new knowledge and skills. It therefore can be expected that personal characteristics are important in adopting sustainable farming.

The risk factors involved in sustainable arable farming and production risks in particular have been debated since the start of IAFS introduction projects (Wijnands and Vereijken, 1992). The developers and advocates of IAFS consider farmers' perception of larger production risks to be misjudged. However, when converting to a sustainable farming system, it is the farmer's *subjective* judgement that applies, rather than the *objective* judgement of experts. Where most arable farmers percieve the risks of sustainable arable farming to be greater than conventional farming, they have been, and will be unwilling to take up sustainable arable farming systems (Schoorlemmer *et al.*, 1994, Wossink *et al.*, 1997). For this reason, it seemed worthwhile to study more systematically the nature and the size of production risks involved in changing to sustainable arable farming systems. Such research is the more relevant because it can be expected that, in the near future, crop production will have to fundamentally change in response to environmental demands.

1.3 Objectives and scope

The overall goal of this study was to determine the role of production risks in the conversion to more sustainable production systems in arable farming. More specifically, the objectives were:

1. to specify the typical production risks that prevent farmers from changing to more sustainable farming,
2. to develop a method to quantify the size of these production risks,
3. to apply that method in order to quantify the risks involved in sustainable arable farming practices as compared to those involved in conventional practices, and

---

[4] Pesticide use resulting in less or more income variability depends on the balance of forces of positive and negative effects on risk. Pannell *et al.* (1991) argue that risk does not necessarily increase pesticide use by an individual farmer. Given a risk-averse decision-maker and a certain pest-free yield and output price, uncertainty about pest mortality or density (these are risks related to the production process itself) may increase pesticide use. Uncertainty about yield and output price (these are risks related to the output of the production process) may *de*crease pesticide use.

4. to assess farmers' behaviour when choosing among sustainable and conventional farming practices.

To achieve these objectives, both descriptive research on the properties of the *innovator* (objective (1)) and normative research on the properties of the *innovation* (objectives (2) and (3)) was conducted. Furthermore, an experimental analysis of adoption behaviour in a simulated, uncertain agro-ecological environment was conducted to integrate *innovator*-specific and *innovation*-specific properties (objective 4).

The descriptive part of the research investigated the risks and risk attributes of sustainable farming, as perceived by farmers. Production risks were placed in the context of other risk attributes that play a role in the conversion to sustainable farming. Supposed differences in motivations and the perception of attributes between farmers in a different stage of adoption received attention.

In the normative approach, production risks were assessed by the jointly calculated statistical value distributions of parameters, such as pesticide use, labour input, direct costs and nitrogen leaching. These quantified production risks involved in sustainable farming practices were compared to those involved in conventional practices.

The various crops grown on the arable farm (sugar beet, potato, wheat, etc.) were considered in isolation, each comprising specific elements of crop husbandry such as sowing, fertilising, weed control and protection against diseases and pests. Production risks were calculated for selected elements of crop husbandry (or cases) that are the main bottlenecks in the conversion to more sustainable production strategies. Criteria for the selection of cases were:

- most of the farms derived a large part of farm income from the investigated crop,
- the strategies currently practised for these elements of crop husbandry cause considerable environmental pollution,
- alternative, more environmentally sound strategies are available,
- these alternatives have not been adopted by most Dutch arable farmers.

A preliminary enquiry amongst researchers and extension officers, coupled with the criteria above, resulted in the decision to investigate the cases of weed control in sugar beet, Late Blight control in ware potatoes and nutrient management in ware potatoes.

Data on relatively new production systems that could be used to determine production risks was frequently incomplete or absent, so, in this study, data sets with a limited time scope or insufficient detail were completed with data generated by *bio-economic models*. This approach incorporated knowledge from agronomy, farm management, soil science, crop protection and other disciplines.

The feasibility of using methods from experimental economics to integrate insights from the descriptive and the normative part of this study, was explored. Farmers' strategic choices between 'conventional' and 'sustainable' production strategies and operational decisions were analysed.

1.4 Outline of this dissertation

Chapter 2 presents an exploratory study, based on in-depth interviews with representatives from different arable farmer categories, of farmers' perceptions (including risk perceptions) involved in decision making with respect to changing over to more sustainable practices. Chapter 3 presents the concept of a *bio-economic model*, used to elaborate three cases in the three chapters that follow. Chapter 4 calculates the risks regarding costs, pesticide and labour requirements of eight strategies for weed control in sugar beet differing in their environmental soundness. Chapter 5 is dedicated to the financial, environmental and epidemiological risks of six strategies for Late Blight control in potatoes. Chapter 6 elaborates the risks of nitrate leaching, potato yield and fertiliser costs for six strategies of manure application. This Chapter also includes a panel data analysis to estimate the remaining innovation capacity towards less polluting nitrogen management of the arable sector in the Netherlands. Chapter 7 describes a laboratory experiment in which farmers' behaviour in the choice for new techniques was analysed in a computer-modelled environment. Finally, Chapter 8 gives a general discussion and draws the major overall conclusions of this research.

References

Babcock, B.A. (1992) The effects of uncertainty on optimal nitrogen applications, *Review of Agricultural Economics* 14(2): 271-280.

CEC (Commission of the European Communities), 1991. Council Directive 91/676, Brussels, Belgium.

CEC (Commission of the European Communities), 1993. Towards sustainability: a European Union Community Program of policy and action in relation to the environment and sustainable development. Brussels, Belgium.

Hardaker, J.B., Huirne, R.B.M. and Anderson, J.R., 1997. Coping with Risk in Agriculture, Cab International, Oxford and New York.

Janssens, S.R.M., F.G. Wijnands and P. van Asperen, 1994. Experimental introduction of integrated arable farming in practice. In: P.C. Struik, W.J. Vredenberg, J.A. Renkema and J.E. Parlevliet (eds.) Plant production on the threshold of a new century. Kluwer Academic Publishers, Dordrecht, pp. 365-368.

LNV (Dutch Ministry of Agriculture Nature Management and Fisheries), 1991. Multi-Year Crop Protection Plan. *Meerjarenplan Gewasbescherming; Regeringsbeslissing.* Ministry of Agriculture, Nature Management and Fisheries, Tweede Kamer, vergaderjaar 1990-1991, 21667, nr.3-4. Staatsuitgeverij, The Hague, The Netherlands.

LNV (Dutch Ministry of Agriculture Nature Management and Fisheries), 1998. Besluit van 1 december 1997, houdende regels betreffende het op of in de bodem brengen van dierlijke meststoffen. Staatsblad 1997 nr. 601, The Hague, The Netherlands.

Pannell, D.J.,1991. Pests and pesticides, risk and risk aversion. *Agricultural Economics* 5: 361-383.

Proost, J. and N.G. Röling, in press. Desperate to get off the treadmill; Renegotiating arable farming in a densely populated industrialised country. In: B. Hubert, R. Ison, etc. (Eds.) Learning and knowing processes for change in agriculture in industrialised countries. INRA and Springer Verlag, Paris.

Proost, M.D.C., H. van Keulen and I. Schönherr, 1995. Gewasbescherming met een toekomst: de visie van agrarische ondernemers. Een doelbereikingsmeting ten behoeve van voorlichting. Report to the Ministry of Agriculture, Nature Management and Fisheries (LNV). Wageningen Agricultural University, Group Communication and Innovation Studies.

RIVM, 1998. Milieubalans 1998. Rijksinstituut voor Volksgezondheid en Milieuhygiëne, Bilthoven, The Netherlands.

RIVM/CBS, 1999a. Emissies en afval in Nederland. Jaarrapport 1996 en ramingen 1997. Rijksinstituut voor Volksgezondheid en Milieuhygiëne Rapport en Centraal Bureau voor de Statistiek, RIVM report nr. 47, Bilthoven, The Netherlands, 144pp.

RIVM/CBS, 1999b. Emissies in Nederland per regio. Jaarrapport 1996 en ramingen 1997. Rijksinstituut voor Volksgezondheid en Milieuhygiëne en Centraal Bureau voor de Statistiek, RIVM report nr. 48, Bilthoven, The Netherlands, 54pp.

Schoorlemmer H.B, A.J. de Buck and G.A.A. Wossink, 1994. Risks and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.E. Pedersen, J. Christensen and S. Rasmussen (Eds.) Farmers' decision making, a descriptive approach, Proceedings of the 38th EAAE Seminar, Institute of Agricultural Economics, Copenhagen, Denmark, pp. 191-202.

Sonka, S.T. and G.F. Patrick, 1984. Risk management and decision making in agricultural firms, In: Barry, P.J. (ed.) Risk Management in Agriculture, Iowa State University Press, Ames.

Van Liere L., H.J. van Jaarsveld, J.P.M. Ros, E.M. Paardekooper, H.E. Elzenga, J.E.M. Beurskens, A. Bleeker, H. Booij, J.W. Erisman, N.J.P. Hoogervorst, W.L.M. Smeets, J. Slootweg, J. van de Roovaart and G. Verstappen, 1997. Water Outlook 1996; emmissions to air and atmospheric deposition on the Netherlands and the North Sea (in Dutch). Rijksinstituut voor Volksgezondheid en Milieuhygiëne (RIVM) report 732404008, Bilthoven, The Netherlands, 26 pp.

Van Weperen, W., M.C.D. Proost and N. Röling, 1998. Integrated arable farming in the Netherlands. In:N. Röling and A. Wagemakers (Eds.) Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Vereijken, P., 1992. A methodic way to more sustainable farming systems. *Netherlands Journal of Agricultural Science* 40: 209-223.

Vlek, C.A.J. and P.J.M. Stallen, 1979. Persoonlijke beoordeling van risico's: over risico's, voordeligheid en aanvaardbaarheid van individuele maatschappelijke en industriële activiteiten. Rijksuniversiteit Groningen, Groningen, The Netherlands.

Wijnands F.G. and P. Vereijken, 1992. Region-wise development of prototypes of integrated arable farming and outdoor horticulture. *Netherlands Journal of Agricultural Science* 40: 225-238.

Wijnands, F.G., 1992. Evaluation and introduction of integrated farming in practice. *Netherlands Journal of Agricultural Science* 40: 239-249.

Woittiez, R.D., G.H. Horeman and J. Baas, 1996. MJP-G emissie-evaluatie 1995: achtergronddocument. Commissie van Deskundigen Emissie-evaluatie MJP-G, Ede, The Netherlands, 127 pp.

Wossink, G.A.A., A.J. de Buck, J.H. van Niejenhuis and H.C.M. Haverkamp, 1997. Farmer Perceptions of Weed Control Techniques in Sugarbeet. *Agricultural Systems* 55: 409-423.

2 Farmers' reasons for changing or not changing to more sustainable practices: an exploratory study of arable farming in the Netherlands

A.J. de Buck, I. van Rijn[a], N.G. Röling[a], and G.A.A. Wossink[b]

Submitted to *The Journal of Agricultural Education and Extension*

Abstract

The paper describes the results of an exploratory study of farmers' reasons for changing or not changing to more sustainable production methods in arable farming in The Netherlands. The background of the research is the disappointing adoption of Integrated Arable Farming Systems (IAFS). Perceived production risk was expected to be an important factor constraining adoption. This study suggests, however, that perceived risk is not a satisfactory explanation. One reason is that IAFS cannot be easily distinguished from conventional arable farming systems. A continuum of gradual adoption of IAFS methods, mainly for economic reasons, was observed within three groups of interviewed farmers. A real watershed difference was observed between these three groups of partial adopters and a fourth group of biological farmers who used no chemicals at all. Secondly, dealing with production risks, such as weather-dependent problems with weeds, pests and diseases, is considered part of professionalism of both conventional and IAFS farmers and hence not a reason for avoiding a specific crop husbandry technique. However, uncertainties emanating from market conditions and environmental policy were found to be important considerations.

Keywords: *Transformation of agriculture, Integrated Arable Farming Systems (IAFS), pesticide use, perceived risks, learning process, the Netherlands*

---

[a] *Communication and Innovation Studies Group, Wageningen University*

[b] *NC State University, Department of Agricultural and Resource Economics, Raleigh, NC, USA and Farm Management Group, Wageningen University*

2.1 Introduction

Growing resistance against the environmental consequences of input-intensive arable farming has led the Dutch government to develop policies to limit the use of agro-chemicals, reduce the emission of nutrients and limit the impact on landscape, bio-diversity, and water quality. Various experiments, regulatory frameworks, and gentlemen's agreements with farmer organisations have been promulgated, often against the wishes of farmers who see them as increasing their costs while doing nothing about the price squeeze in the relentless global 'treadmill' (Cochrane, 1958; Proost and Röling, in press).

As part of the process of transforming Dutch arable farming, experiments have been comparing the following farming systems since 1979 (Wijnands, 1992; van Weperen *et al.*, 1998): (a) *conventional arable farming,* the (very) high external input system that has been practised in the Netherlands since the sixties; (b) *biological (organic) arable farming*, using no chemical pesticides and fertilisers at all; and (c) *integrated arable farming systems* (IAFS) that replace inputs of chemical pesticides and fertilisers as much as possible with mechanical and biological products and processes, but do not ban them completely.

By 1990, the results of the IAFS experiments had shown that it was possible to reduce the use of herbicides, fungicides and insecticides by 50 – 60%, while nemacitides were no longer necessary at all. In addition, a reduction had been achieved on the use of fertilisers. IAFS were shown to be technically feasible on commercial farms and to have moderately better financial results than conventional farming (Janssens and Wijnands, 1994; van Weperen *et al.*, 1998).

In 1990, the Dutch government launched a Multi-Year Crop Protection Plan (MYCPP, 1991) in order to halve the use of pesticides by the year 2000[5], curtail pesticide emission to the environment, reduce pesticide dependency and implement stricter requirements for pesticide registrations (Oskam *et al.*, 1992; Jansma *et al.*, 1993). In a covenant signed in 1993, the arable farming sector agreed to commit itself to achieve the MYCPP goals if the government would drop plans to tax pesticides and until 2000 postpone the ban of a number of particularly hazardous pesticides (Proost and Matteson, 1997). The implementation of the MYCPP for the arable farming sector is based on consultation and negotiation with all parties involved (van Weperen *et al.*, 1998).

The MYCPP did not specify how farmers were to achieve the targets. No special subsidies, market conditions or other permanent assistance were provided, except through experimental research and special innovation and extension projects. Thus education and training were seen as key policy instruments in promoting the adoption of sustainable crop farming practices in the Netherlands (Jeger, 1997). Given these points of departure, it is small wonder that the

---

[5] Each sector of agricultural production has been given its detailed goals for the reduction in the use of active ingredient by the year 2000 compared with the average use of 1984-88. Those reduction goals for arable farming are: nematicides 70%, herbicides 45 %, insecticides 25 %, fungicides 25 %, others 69 % and total use of pesticides 60 %.

farming practices developed in the IAFS experiments described above were considered as the technology package for implementing MYCPP.

An IAFS 'Innovation Project' was initiated by the Ministry of Agriculture, Nature and Fisheries in 1990. It provided finance to the agricultural extension company (DLV; the recently privatised public extension service) to advise the participating farmers. An open call for participation in the Dutch farming media enticed 38 volunteers (of the roughly 14.000 eligible arable farmers in the Netherlands!) to register. All 38 were screened for motivation and eventually participated. Hence, these 'Innovation Farmers' represent a very selective group of arable farmers in terms of motivation, interest and knowledge, whose change to more sustainable practices was intensively guided by professional and highly motivated facilitators. Even now that the Innovation Project has long been terminated, the 38 Innovation Farmers continue to take up a very special place within the arable sector.

In an attempt to promote diffusion of IAFS among Dutch arable farmers, a follow-up project, Arable Farming 2000 (AF 2000), has been implemented with less investment in professional guidance. A group of five hundred farmers, with a large diversity in motivation, interest and knowledge, participated in this project from 1993 through 1996. This group is referred to as the AF 2000 Farmers in this article.

In a first, preliminary evaluation, Somers and Röling (1993) found that Innovation Farmers considered IAFS profitable when it comes to the reduction of the costs of chemical inputs. This *relative advantage* (Rogers, 1995) of IAFS was, however, constrained by the opinion that, compared to conventional farming, IAFS are more risky and labour intensive, without this being compensated by better prices. Such an association of IAFS with increased production risk has, however, been disputed from the start (Wijnands and Vereijken,1992). Its developers and advocates consider it a misjudgement: not IAFS as an innovation but the knowledge and experience of the farmers as the innovators should be considered the source of risk. Learning about IAFS can therefore sustain its adoption (Schoorlemmer *et al.*, 1994).

A similar observation is made by Van Weperen *et al.*(1998) and by Röling and Jiggins (1998). They claim, on the basis of their studies of the Innovation Project, integrated pest management (IPM) in Indonesia and Landcare in Australia, that the transformation of conventional farming to more sustainable forms of agriculture requires a transformation of farmers through an intensive learning process. Such a paradigm change is very different from the adoption of an innovation within the same paradigm.

This article presents an exploratory, descriptive study of farmers' perceptions involved in changing to more sustainable farming systems. It was part of a larger project which allowed for an approach of production risk from different angles:

- the assessment of actual production risks of 'conventional' and IAFS practices (such as innovative chemical and mechanical weed control strategies in sugar beet; De Buck *et al.*, 1999) with normative farm management models based on agronomic research, which can be used in the farmers' choice to change;

- farmers' subjective perception of risks reported in the current study and
- farmers' actual decision making when confronted with a simulated computer-based decision environment.

The original objective of the current study was to establish the extent to which perceived production risks of IAFS prevented their large scale adoption. However, during the study, the implicit hypothesis, *that* perceived risks played an important role, soon needed to be amended. The study then moved from hypothesis testing to a truly exploratory approach which allowed for considerable adjustment of the earlier perspectives which guided the research. This adjustment affected the assumed classification of farmers, their reasons for whether or not adopting more sustainable practices, and so on. Although the present study is based on a small data set, we believe it is worth publishing separately because it pictures farmers' attitudes that appear in the arable sector regarding less polluting production systems, which led to some surprises.

2.2 Conceptual framework

The conventional perspective with which innovation is studied is often unwittingly influenced by pro-innovation bias, the assumption that innovation is good. This perspective is understandable from the positivist stance most agricultural researchers subscribe to: fundamental research reveals the secrets of nature, and applied and adaptive research then develop the 'best technical means' to control it. Once one has developed the best technical means, it is small wonder that one considers their adoption unquestionably desirable. But farmers tend to be a bit recalcitrant. Hence there tends to be a 'time lag' between the moment at which a farmer learns about an innovation and the time when he or she adopts it, called Innovation Adoption Lag (IAL) by economists. Sometimes the IAL lasts forever. Given the perceived desirability of adoption, researchers have spent a lot of time studying factors that can explain this IAL. At one time, this type of research, with some 3000 empirical studies, masterfully synthesised by Rogers (1995), was the most popular type of empirical social science research around. Diffusion of innovations research has lost some of its influence in the early eighties because the large number of empirical studies looking at diffusion processes from an *ex post* perspective has failed to deliver in terms of effective *ex ante* policies and intervention strategies. In fact, the transfer of technology model that was largely informed by diffusion of innovation research, and that inspired such major policy efforts as the World Bank-supported Training and Visit System, has lost much of its lustre. This does not mean that diffusion of innovations does not 'work', but it does mean that it remains very difficult, in practice, to *design* strategies that lead to the autonomous diffusion of innovations in human populations. At present, hope is focussed more on participatory approaches, as operationalised, for example in the IPM farmer field school (Röling and Van de Fliert, 1998). Interestingly, economists have recently taken a new interest in the diffusion of innovations and the IAL (as in Feder and Umali, 1993).

And it must be said, it is of interest to consider sustainable farming systems, such as IAFS and IPM , from the point of view of diffusion, especially given the fact that one can expect the adoption of sustainable farming systems to require a paradigm change, rather than to represent an adoption of an innovation within the same paradigm, as we observed above. Somers (1993), D'Souza *et al.* (1993), Wossink *et al.* (1997), and others have looked at the diffusion of sustainable farming systems. Since direct financial benefits (relative advantages *vis-a-vis* other technologies) are small, and complexity is high, a host of other factors can be expected to be decisive in their adoption.

Economists usually attribute the IAL of sustainable practices to risk aversion, errors in farmers' estimates of the returns to new practices or to adjustment costs. Note that the nature of the innovation itself is not in question as can be expected with a pro-innovation bias. The *prescriptive* or *normative* economic approach, based on the (Subjective) Expected Utility Model tries to show how farmers, given an uncertain environment and a certain risk aversion, *should* make a rational choice (Anderson *et al.*, 1977; Moffitt, 1986; Pannell, 1991; Babcock, 1992; Deen *et al.*, 1993). The more recent applications of the prescriptive approach account for the IAL by incorporating the dynamics of the adoption process. For example, in the Bayesan learning model it is expected that, as farmers' stock of information improves through experience and learning, the divergence of objectively determined and perceived returns will decline (Tsur *et al.*, 1990; Fischer *et al.*,1997).

Descriptive research explains *how* decisions actually are made, not how decisions *should* be made. De Ortiz (1980) and Gladwin (1980) are examples of studies of how farmers actually perceive uncertainties and conceptualise their decision problems (Huijsman, 1986). The way farmers, as potential adopters, perceive innovations has received attention in Adesina and Zinnah (1993), Wossink *et al.* (1997) and Baidu-Forson *et al.* (1997). Wossink *et al.* (1997) show that farmers' perception of risk of direct and indirect yield losses, and not information deficiency, is a significant factor with respect to the IAL for new weed control technologies in sugar beet production. Very large differences in pesticide use were reported that could not only be explained by the actual level of attack (Penrose *et al.*, 1996; Janssen, 1996) but also by farmers' differential perception of pest development.

In other words, economic research suggests that perceived risk does play an important role in the adoption of IAFS technologies. The present study set out to explore farmers' perceptions with respect to production risks. *Risk* can be defined as the expected frequency of occurrence of an undesirable outcome. Farmers can differ with respect to: (a) what is considered an undesirable outcome, (b) the frequency with which they expect the undesirable outcome to occur; and (c) the degree to which they want to avoid the undesirable outcome (risk attitude). A recent study in the Netherlands (Leferink and Adriaanse, 1998) showed that conventional arable farmers and biological farmers both identified the same undesirable factors associated with biological farming practices, such as reliance on manual labour; difficulties of finding sufficient workers in peak times, variability of yields depending on the nature of the season and problems of marketing the produce. Thus they agreed on (a). As thoroughly experienced professionals, they seemed to have fairly similar ideas about the expected frequency of occurrence of the undesirable outcome (b). The big difference between the two groups which the study observed was in (c): the degree of acceptance of the undesirable outcomes. Thus the biological farmers considered them an acceptable part of their farming practice, while conventional farmers wanted to avoid them at all cost. This difference seemed instigated by other factors than the expected size of the risks. Such other factors can be expected to include the following:

- The outcomes of biological farming, and to a lesser extent IAFS, depend on the skills of the farmer to anticipate biological processes based on observation and ability to infer from what has been observed (Röling and Jiggins, 1998). Farmers might feel uncertain about their ability to develop such skills and prefer instead to continue to rely on practices that depend on chemicals to prevent and cure unwanted biological processes.
- In biological farming, yields are lower and costs are higher, both at a high variability. Higher prices of biological products make these negative outcomes acceptable to biological farmers. These outcomes are not acceptable to IAFS farmers, as, at the time this study was done, IAFS products did not bring higher prices.

These factors do not deal with risk as much as with *uncertainty*, as there is no expected frequency of occurrence. Uncertainty about one's own ability and uncertainty about market developments in a highly volatile agricultural policy framework are much harder to deal with professionally. The present study aims to provide insight into the relative role of risk and uncertainty that could explain the (non-)adoption of IAFS.

The conditions that affect decisions to adopt IAFS techniques were categorised as: *natural, external socio-economic* and *personal*. As sources of risk and uncertainty, these three categories of conditions receive specific attention in this paper (Hardaker *et al.*, 1997; Sonka and Patrick, 1984).

The *natural conditions* of an arable agro-ecosystem are determined by biological crop characteristics and the biotic and abiotic environment. These elements create a decision environment with complex temporal variations within and between seasons and complex spatial variations within and between fields (Almekinders *et al.*, 1995).

Weather is a main source of production risk, the effects of which can be different for different farming systems. For example, humid conditions are important for an effective chemical weed control that is primarily used in conventional farming. IAFS and biological farming use mechanical weed control, the effectiveness of which is highest under dry field conditions, while applying mechanical measures under humid conditions might damage soil structure.

A difference in the way of dealing with weeds, pests, diseases and nutrients between biological, IAFS and conventional farmers is that IAFS and biological farming focus on prevention by using varieties with a high tolerance and/or resistance, by utilising the fertility of the soil and by stimulating natural enemies. IAFS and biological farming require more observation, anticipation and knowledge about agro-ecosystems. Neglecting these, as a relative novice at IAFS methods might do, increases the risk on pests and diseases. The influence on yields and financial results can be considerable. Managing pests and diseases – especially according to IAFS– is complex, which brings about uncertainty; even for experienced IAFS practitioners. On the other hand, conventional farming can experience damaged crops due to an insufficiently selective effect of herbicides while insecticides can have adverse effects on beneficial natural predators (Pimentel *et al.*, 1993).

External socio-economic conditions refer to market characteristics and the power of agricultural industry and agri-business; governmental policies and social factors. In future, a quality label for IAFS products could enable a better market position and a reward for environmental care (Matteson *et al.*, 1996; Van Ravenswaaij and Blend, 1997). In another scenario, the market will dictate quality standards for arable products which can be achieved only by employing IAFS. The market situation or policy objectives are a reflection of changes in society. Changes in society also affect relations within and between farming and non-farming communities. The change-over to IAFS might lead to social isolation from the farmers' direct colleagues, while persisting in conventional production methods might lead to isolation from consumers. The possibilities and the willingness to hire extra labour in peak periods are major factors in biological farming, and to a lesser extent, in IAFS. Reviewing the literature on agricultural innovations, Feder *et al.* (1985) found that it is difficult theoretically to argue that labour constraints restrict adoption per se; though results from empirical analyses are less clear. All these socio-economic dynamic externalities are hard to judge by an individual farmer. Uncertainty in this respect makes one farmer to decide to 'wait and see' and another to change over to IAFS.

Finally, *personal characteristics* are the farmer's possibilities, inclinations and perceived attributes that affect the decision to adopt IAFS. Examples are one's financial position, knowledge, capacity and ability to learn, entrepreneurial spirit, domestic situation, age and desire to farm. The financial situation of the enterprise can be significant in relation to the ability to bear financial risks of changing or not changing to sustainable agricultural practices (D'Souza *et al.*, 1993). Entrepreneurial spirit is a broad concept that includes attribution of success and failure, achievement motivation, perception and judgement of risks (Wärneryd, 1988). As we saw above, studies of Dutch farmers have shown that fear of not being able to learn a totally new way of farming has been explicitly named as a reason for not switching to IAFS and especially to biological farming. Finally, one's ability to change depends on the domestic situation and family relations, *e.g.*, the availability of extra labour, time for study and a successor.

2.3 Methodology

The study focused on farmers in the Province of Flevoland which has efficient parcel lay-outs, fertile soils, a more than average farm size and a probably more than average level of professionalism among the farmers. The main reason to choose Flevoland was as much as possible to avoid distortions because of differences in these farm characteristics, which are considered to be fairly homogeneous in the region.

The data were collected in two phases during spring/summer 1995. In the first, preliminary phase, a list of topics was tested in interviews of approximately twenty minutes with ten farmers. The interviews were held simultaneously during one evening on an experimental research station (PAV, Lelystad) near the farmers' residences. The interviews were held in groups of three to four farmers by the first and second author and one farm management researcher. The answers were recorded in writing. To be able to look at the range of perceptions and knowledge about and experience with IAFS, three categories of farmers were interviewed: Innovation Farmers, AF 2000 Farmers and Conventional Farmers. To increase the contrasts further, Biological Farmers –who use no chemical inputs at all– were included as a fourth group.

This method, called theoretical sampling as opposed to statistical sampling, was used to select respondents who could be expected to represent extreme situations or polar types in which the processes of interest are transparently observable (Eisenhardt, 1989). The names of the respondents were obtained from the extension company DLV which has been contracted by the government to assist in the IAFS projects.

One striking result of this first exploration was that the differences between conventional farmers and farmers practising IAFS turned out to be quite blurred. As one farmer put it: "Also the so-called conventional farmers work integrated nowadays". This result is consistent with the finding by Proost *et al.* (1995) and by van Weperen *et al.* (1998) that implementation of the MYCPP and introduction of IAFS in the Netherlands has resulted in a continuum of adoption of a whole range of new technologies. IAFS is not adopted as a package, it is separated into technologies, each of which a farmer might or might not adopt. This implies that the intended coherence of IAFS is lost.

Initially we anticipated a clear distinction between conventional and integrated arable farming, and hence a marked threshold in moving from the one to the other. However, this was not the case. Instead, the distinction between the three categories was difficult to make. Because of this observed fluidity between categories, we made an inventory of the risks related to the different farming methods in potatoes, sugar beet and winter wheat (the three most important crops) and added more detailed questions about the methods the farmer actually used. Since the preliminary round had suggested that a limitation to the risks of transformation to IAFS would be inappropriate for understanding the hesitant conversion to IAFS, we expanded the interview topics to include all possible motives that could hamper further adoption if IAFS. The refined interview schedules were pre-tested in a 'study club' of nine AF 2000 Farmers.

Twenty-six farmers were interviewed in a qualitative, semi-structured way, using the expanded topic list. Since conventional and IAFS farmers could not be clearly distinguished empirically, the range of differences between farmers' practices was probably maximised by drawing the respondents from the following categories, thus again using theoretical sampling:

- Innovation Farmers (5);
- AF 2000 Farmers (5);
- Conventional Farmers(10); *i.e.* farmers who did not participate in one of these projects; and

- Biological Farmers (6); *i.e.* farmers who do not use chemical inputs whatsoever. One of the biological farmers had been a participant in the Innovation Project.

The names of biological farmers and project participants were obtained as selected samples from the extension company DLV. The ten non-participants were found by randomly taking their names from regional maps. Only one farmer did not want to co-operate because he was "fed up" with research. Some other respondents mentioned that the kind of research method used –qualitative interviews with open questions– made them willing to co-operate. The interviews were carried out by the second author at the respondents' farms and required one to one and half hours. A small tape recorder was used to record the interviews.

2.4 Results

2.4.1 Natural conditions

The observation that the differences between IAFS and conventional arable farming are not clear-cut was supported by the results of the interviews. The distinctions have been blurred due to the cultivation of more resistant and tolerant varieties that became available, the use of new, specific (as against broad spectrum) pesticides with a lower active ingredient content, and the adoption of those IAFS techniques that allow a considerable cost reduction by reducing the use of chemicals. Other IAFS practices that are widely adopted are commercial soil testing for nematodes and increased monitoring (of Late Blight (*Phytophthora infestans*) conditions in potato for instance).

Farmers also converged on a homogenous technology package because the Innovation Farmers to some extent were falling back on more conventional practices. An example is multi-functional crop rotation, which in IAFS is considered as important for conserving soil health. A good soil health sustains quality production with minimal external inputs. A rotation in which potatoes are grown with a frequency of 1:4 is considered an acceptable compromise between a sound frequency (1:5 or 1:6) and a more profitable higher frequency with more biotic stress, which therefore requires more pesticide input (Wijnands, 1992). However, the observed distinctions among the three categories of farmers are not as clear as one would expect: 50% of the Conventional Farmers, 20% of the AF 2000 Farmers and 40% of the Innovation Farmers used a 1:3 rotation. Farmers practising 1:3 mentioned the profitability of this rotation and believed that it could be sound as long as soil tests did not show harmful levels of soil-borne pathogens. The Innovation Farmers who use a 1:3 rotation gave their personal financial situation as the reason for using it, but indicated that they consider 1:3 not to be the ideal. In this awareness, they clearly distinguished themselves from the other interviewees. Conventional Farmers used a 1:6 rotation when they had opportunities to exchange land with livestock farmers, or when they cultivated tulips or grass seed as additional crops in the rotation.

The more crop-specific questioning decided upon after the preliminary phase allows us to describe the specific considerations of the interviewed farmers with respect to perceived risks of potato, sugar beet and winter wheat production, respectively.

Potato

The choice of a new resistant or tolerant potato cultivar is considered to be the basis for potato production according to IAFS. Bintje, which is a very susceptible cultivar to both Late Blight and potato cyst nematodes was still the only cultivar grown by one quarter of the respondents. Others produce Bintje in addition to resistant and tolerant cultivars as "a choice for certainty: the market is very good and farmers experience fewer cultivation problems with Bintje". Choosing for Bintje, however, implies choosing for chemical Late Blight protection with almost fixed time intervals and high dosages. Contract spraying by aeroplane suits this spraying regime and was carried out by one fifth of the respondents. They suggested that the soil and the crop would be damaged too much by other methods. Others overcame this problem by using special equipment to reduce soil damage. They argue that tractor spraying is more secure and controllable. However, adoption of some IAFS techniques for Late Blight protection had become more common as farmers became more aware that dosages and frequencies, that are suggested by manufacturers, have considerable safety margins which take the worst possible conditions into account. Some farmers pointed out that "too much insurance premium has been paid in the past". The indicated doses and spraying intervals did not vary much amongst farmers, but total yearly fungicide use varied a great deal as dosage and/or intervals were adapted to conditions and forecasts of weather and monitoring of Late Blight stress. This adaptive behaviour suggests a widespread partial adoption of IAFS techniques in Late Blight control by Dutch arable farmers. Still, fungicide use in arable farming probably will not meet the MYCPP targets (Proost and Matteson, 1997) and a large variance in fungicide use between years as well as between farmers is found (Janssen, 1996).

Some farmers claimed to have had bad experiences with Late Blight tolerant cultivar Agria because they said it to be vulnerable for decay in storage (*Erwinia ssp.*) and switched back to Bintje. Most farmers consider low dose chemical weed control in potatoes a better alternative than mechanical weed control because in the latter case, "some chemicals are needed anyway and potatoes might get damaged". The IAFS method of nitrogen management on the basis of petiole analysis is hardly practised. The farmers argue that the results of this method are too inconsistent and not suitable for the soil type on their farms. Finally, spraying against aphids by using damage thresholds is not commonly practised. Most farmers argue that they have to spray anyway to avoid excessive damage.

Sugar beet

Low dosage herbicide application methods are widely used, but most often in full field spraying, combined with some mechanical harrowing later in the season. This is said to be more efficient than row spraying and, because of the low dose, not to be very environmentally harmful.

Winter wheat

Mechanical weed control is said to be insufficient for some kind of weeds. Because costs savings are said to be marginal, prophylactic spraying is still used against aphids, diseases and to avoid lodging.

Practices which represent a fall-back

Some Innovation Farmers turned back to chemical weed control in winter wheat because they found it difficult to avoid using chemicals against certain kinds of herbs. For weed control in sugar beet, Innovation Farmers argue that the disadvantage of spraying 'full-field' is decreased with the use of the low dose system. Row spraying is considered to be more labour intensive and more damaging for the structure of the soil. Finally, some Innovation Farmers switched back to the use of chemical fertilisers instead of manure. They argue that with chemical fertilisers, the management of nutrients is more controllable and more efficient.

Overall, the Innovation, AF 2000 and Conventional Farmers tend to converge on a similar mix of practices, given the prevailing farm sizes, soil types and market conditions in the area of study. At the time of study, all these farmers received the same price for their products (controlled labels for IAFS products had not been introduced), and hence were faced with the same imperative to watch their cost price.

2.4.2 External socio-economic conditions

The market situation

Most respondents were sceptical about consumers' willingness to pay a higher price for ecological products. As one of them put it: "as long as people take their food with them on their holiday to France, I don't see them pay more." Especially AF 2000 and Conventional Farmers seemed to have a defensive attitude. Now that they had considerably cleaned up their act by partially adopting IAFS, they felt unfairly criticised by public opinion. They blamed agricultural trade-organisations, co-operatives and supermarkets for the prevailing marketing strategy of 'green' products (most of them were familiar with 'green labels' through their trade organisation or co-operative). They felt that the demands were easy to fulfil ("it is the 'paperwork' that takes the effort") but that, in the end, farmers would not profit from the extra effort. Hence, they rejected 'green' labels. They pointed to a large supermarket chain in The Netherlands which started its own 'green' label and subsequently lowered the prices for labelled products. Most Conventional and AF 2000 Farmers considered the requirements for a specific controlled label, Agro Milieu Keur (see Matteson *et al.*, 1996), introduced in a limited fashion at the time of this study, as too strict.

Innovation Farmers differed from AF 2000 and Conventional Farmers. Several Innovation Farmers preferred a distinct market that paid a better price for their quality products. In addition, they suggested specific promotion activities such as open days for the public and a participatory winter wheat project. They were willing to produce crops for the demanding AMK label. However, they remained uncertain whether there would be a market for AMK products. They believed they would be able to meet the standards of AMK, although they anticipated some difficulties, especially in situations were curative fungicide sprayings with high doses (against Late Blight for instance) would be required. This is an interesting example of a situation where a known production risk made respondents hesitant to adopt a 'green' label. It is worth mentioning in this connection that, in the very wet year 1998, *biological* farmers were allowed to spray a copper-based fungicide against Phytophthora infestans.

In all, consumer behaviour and market developments, sometimes in combination with production risks, were a source of uncertainty if not anxiety. At the time of writing (late 1999), the export market for products with a biological label has expanded very rapidly but Dutch producers are still very slow in changing over to Biological Farming.

The political situation

With respect to policy, some Conventional and AF2000 Farmers recognised the necessity of some regulation. But most did not understand why The Netherlands should play what they considered a leading role. They perceived Dutch policies to be more demanding than those in neighbouring countries and asked for European regulation, pointing out that farmers in other European countries can use chemicals which are forbidden in the Netherlands and hence have lower costs of production. As they also pointed out, their prohibition in The Netherlands "does not necessarily mean that those chemicals are not used here". Thus, as was the case with the market situation, some AF2000 and Conventional Farmers reacted defensively with respect to policy issues concerning IAFS.

Others perceived environmental policies as more or less inevitable and asked for realistic policies and financial compensation. They pointed out that "it is no use fighting against it. Farmers and farmers' organisations should talk and negotiate". Most of the farmers were familiar with the MYCPP and believed that the targets set by this plan were not too difficult to reach or were already met by themselves. This corresponds with the findings of an evaluation of the MYCPP by Proost *et al.* (1995) which established that the adoption of various innovations had resulted in a realisation of the MYCPP targets by many farmers. But this was the result of innovation within the same paradigm, there was no question of transformation of the farming system. Pilot farmers showed that a change of the farming system enabled a reduction of the level of chemical inputs to much below the norms set by MYCPP. Such an innovation would indeed prepare arable farmers for a future with increasing regulations that limit pollution from crop production.

In line with this, the interviewed AF 2000 and Conventional Farmers pointed out that, although some of their new practices were indeed less damaging for the environment, environmental considerations had not been their foremost objective but came as part of the package. As one of them said: "I don't want to pretend I am more catholic than the Pope". This is in line with the observation that most recent farm transformations to biological production were instigated by economic motives.

Again, Innovation Farmers differ from the other respondents: they have a stronger motivation to work in a more sustainable manner and call for policies that support more sustainable farming. The frustration that "we try to work as ecologically as possible, while our neighbours carry on as usual" is expressed by some Innovation Farmers. What all farmers do stress is that, in the end, a *sustainable income* is of greatest importance: "ecologically and economically sound farming should go hand in hand". There is no doubt that the increasingly free market-oriented policies continue to squeeze farm prices and force farmers to cut costs, while environmental regulation generally increases costs. The uncertainty with respect to farm continuity that results from this situation speaks loudly from the interviews (which were held in one of the most favourable arable farming areas in the Netherlands, if not in Europe). Arable farmers have been placed in a very difficult position.

2.4.3 Personal conditions

Participation in an IAFS project

Innovation Farmers as a group were critical of conventional farming practices that had led to over-production, stress on the biological system, environmental problems, and not enough control of chemical inputs. They had experienced the Innovation Project as an attractive opportunity to change their practices in a controlled manner and under guidance. Whereas some Innovation Farmers had experienced disapproval of their colleagues when they started the project (they were perceived as having changed to the enemy camp by helping to demonstrate that 'cost-increasing' IAFS methods were feasible), this disapproval had vanished over the years: "Nowadays it is stupid not to use the advantages of IAFS", as one Conventional Farmer put it. Farmers indicated that agricultural business and industry had adjusted in the same way.

Farmers participating in AF 2000 had heard about the results of the Innovation Project and had become interested because of its cost reduction effect. In addition, they thought the practices of IAFS were symptomatic of developments to come with regard to demands concerning the environment. For most of them, the opportunity to become more familiar with the new practices and the opportunity to get some guidance and advice from extension officers were an important factor in their decision to participate, especially since the costs of (privatised) extension were going up.

Conventional Farmers who did not participate in a project said they had not heard much about it when it started, or were not personally asked to participate. Others did not want to participate because of the commitment required and because of their rejection of criteria coming from 'the top' and their dislike of getting advice in order to fulfil standards. Some conventional farmers indicated that they preferred to wait what others experienced and to adopt the successful innovations later.

In their study of the Innovation Project, Van Weperen *et al.* (1998) describe how the participants experienced a learning process which affected their attitudes towards farming and introduced new knowledge and skills, especially with regard to monitoring and anticipation.

The intensive guidance by specialists had made them feel able to experiment. Moreover, the discussions, farm visits and the sharing of information within study groups had made a major contribution toward their learning process. The AF 2000 project had also organised participants in study groups, but their interaction was less frequent and intensive, as was the guidance by DLV advisors. The AF 2000 respondents in our study had a less strong sense of having experienced a learning process. Some of them said to have become more aware of their farming practices, more critical about the use of chemical inputs and more knowledgeable about low dose systems.

In general, the varied comments on their experiences and the mixed motivation for changing their practices reflect the fact that AF 2000 participants are less homogeneous and determined than the Innovation Farmers and more comparable to Conventional Farmers. It is not possible to sort them into sub-categories, or even to classify them according to some gradient from conventional to integrated farming. As a result, it is difficult to identify the effects of acquiring knowledge and experience by AF 2000 farmers, while the Innovation Farmers had experienced this effect very clearly. Meanwhile, we point out that our study suggests that even with their enhanced learning, the Innovation Farmers do not differ that much from AF 2000 and Conventional Farmers when it comes to their actual practices. Given the professionalism of farmers and the market and policy conditions they face, they converge on a similar set of practices.

Transformation to biological farming

In general, Biological Farmers combine their aversion of conventional farming with a strong belief in the future of biological farming. The opportunity to use chemical inputs in IAFS is "just not good enough, because it can be done without as well". Such strong beliefs are apparently a necessary condition for changing to biological farming. These views are related to the belief that the market for conventional products will collapse as a result of over-production and growing awareness of consumers. As Biological Farmers have a distinct market with its own -higher- prices, they feel they have a better market position, the more since they grow a greater diversity of crops. On the other hand, novice Biological Farmers confess that it requires much effort to organise the market, which is an unfamiliar task to them. Some farmers say they like this aspect of biological farming, which implies that this is not always problematic.

The higher prices for biological products are to compensate the lower yields and the higher production costs, mainly due to a high labour requirement. Biological Farmers feel that a higher level of skill is required for their type of farming. Risks were considered to be more diverse, such as those associated with the availability of labour for, and the success of manual weed control. Some Biological Farmers find that the amount of manual labour required, the knowledge intensity of their production and the need to work with hired labour constrain the conversion to biological farming. When asked for specific risks, the biological Farmers reported weed problems, soil fertility and yield variability. On this point, the Biological

Farmers responded differently from farmers in the other categories, who have the option of falling back on chemical inputs.

In addition to the need to work with a crew of hired labour, stepping out of mainstream farming has a social aspect: one loses the network of colleagues, informants, services and providers and has to establish a new one. The social consequences of this loss can be considerable: in some cases in Flevoland, Biological Farmers were ostracised by neighbours and colleagues. We feel this network change is a major and neglected factor that impedes the transformation to biological farming. The same effect for the Innovation Farmers at the start of the project has gradually been replaced with acceptance, as the whole sector –including the network of providers– changed in the direction of economically attractive IAFS practices. However, farmers who change to biological farming still have to become part of a totally new network.

Most Biological Farmers reported that the first years of conversion are complicated and de-motivating because of the regulations to produce for a biological (or: organic) label: nowadays it takes two years before one can produce for the biological market. Subsidies are available to bridge these years, but have to be paid back if one does not continue with biological farming. Most Biological Farmers also indicated that they had gone through a conversion process over many years, which started with long periods of thinking about it and doing courses on biological farming. Excursions to biological farms and the influence of colleagues; more financial stability, and the expectation of changing regulatory frameworks had been final triggers for change.

2.5 Discussion

The expectation that farmers' perception of production risks was a major barrier to adopting IAFS practices was not borne out by our exploratory study. There was no clear demarcation between conventional farming and IAFS but a rather fluid transition. Thus our study leads to the hypothesis that policy initiatives like the MYCPP, and the development and promotion of IAFS technologies in connection with it, have created a new partial IAFS farming system on which most arable farmers seem to converge under pressure of the market (with low product prices and demanding customers) and governmental regulations. This partial IAFS farming system has become the practice norm, even if farmers have different ideologies with respect to sustainable farming (especially the Innovation Farmers). Also 'the network' of co-operatives, pesticide providers, trade houses, extension services and so on has adjusted to the new package of technologies. In fact, it is largely due to the rapid grasping of the opportunities created by MYCPP by pesticide firms, commercial plant breeders, farm engineering companies and so on, that technologies came on the market which allowed arable farmers to adopt a partial IAFS without having to change their paradigm of farming. If this hypothesis were borne out by larger quantitative studies, this convergence on a partial IAFS can be considered a considerable policy success and some vindication for P. Vereijken, F.G. Wijnands, *c.s.* who started IAFS research in the seventies(Wijnands and Vereijken, 1992; Wijnands, 1992).

But the transformation is incomplete and innovation has taken place within the existing conventional paradigm. Farmers have realised the environmental gains that could be made within the existing system. Most farmers continue to depend on pesticides and chemical fertilisers. An example of the still strong dependency on pesticides, at the time of writing, are the defensive reactions of arable farmers to the ban of herbicides for weed management in onions. Despite the announcement of this ban years ago, there has been no initiative to change over to techniques that require fewer herbicides. Even if the MYCPP norms for arable farming might be attained in 2000, a movement in the direction of more sustainable arable farming is not to be expected in the coming years.

Our observations on the adoption of IAFS are similar to those made with respect to IPM adoption, which also consists of a package of various practices which are supposed to add up to a sustainable system. For many years, adoption of IPM has been viewed as a dichotomous choice: if farmers indicated use of one of the practices they were seen as having entered a learning process and expected to adopt all other practices in the package in due course. This view proved untenable. Analysts now recognise that IPM has to be viewed as a collection of individual practices that allow (very) partial adoption with the loss of the *systemic* change envisioned by the designers of the technology (Dorfman,1996).

Our study suggests that adoption of IAFS should be seen as a series of adoptions of separate methods. Even the Innovation Farmers rejected the initial ‘total package’ approach when IAFS was first introduced to them, and insisted on partial and selective adoption and sequencing of adoption over time (Van Weperen *et al.*, 1998). The IAFS as a *system* can therefore be considered as a construction by researchers.

This raises interesting issues with respect to the autonomous diffusion of more sustainable farming practices. The IAL of IAFS cannot be explained by looking at IAFS as a package. If one is serious about transforming the farming *system*, one has to consider the combinations of IAFS practices that farmers adopt and to assess the extent to which these combinations impact on environmental and ecological criteria. Further empirical research is needed to assess what combinations of IAFS technologies are adopted by which farmers.

A real paradigm change in Dutch arable farming is the transformation to biological farming. It would be of interest to look more specifically at the factors that determine whether a farmer makes up his/her mind to make this transition. So far, only a few percent of Dutch arable farmers have made it, notwithstanding very attractive export opportunities. Röling and Jiggins (1998) had hypothesised that intensive guidance, as provided in the Innovation Project, would be necessary to elicit the kind of paradigm change that Innovation Farmers report and that the transition to biological farming requires. However, our study suggests that, notwithstanding their expensive training and guidance, also the Innovation Farmers converge on what can be called a new conventional farming system. Although, a number of them saw their experience with IAFS as a step towards conversion; a few of them have indeed already converted to biological farming.

For the non-biological farmers we interviewed, changing over to biological farming is unacceptable because of the perceived risk that, in certain years, it will not be possible to farm without being able to fall back on chemical pesticides, especially fungicides for controlling Late Blight in the economic mainstay of the arable farm, the potato. But in addition to this perceived production risk, other kinds of uncertainties seemed to play a major role. The development of prices, European policies, the behaviour of consumers, the farmers' own ability to learn a totally new way of farming and undergo a paradigm shift, as well as the need to change networks are sources of uncertainty which our farmers explicitly mention as reasons for not transforming their farms.

If one uses a simple model of the cognitive system with (a) perception, (b) intentionality, and (c) action as main ingredients (Matarana and Varela, 1987; Capra, 1996), one can say that most Dutch arable farmers seem to have very similar professional *perceptions* with respect to the production risks and the economic and policy conditions. Non-biological farmers have a rather unchanging *intentionality*: to be an independent entrepreneur who has to 'make it' in a free global market with merciless competition. Hence cost of production remains the most important criterion for assessing whether to adopt an innovation. This observation is no different from the one made by Constandse (1964) for farmers in the IJssel Lake polders: their proverbial innovativeness served mainly to maintain their unchanging 'Leitbild' of being an independent entrepreneur. Given their similar perceptions and intentionality, it is little wonder that farmers do not differ much in *action*, *i.e.*, that they converge on a similar set of technological practices. Given their perceptions and intentionality, most farmers find that many IAFS technologies, let alone biological farming practices, do not have a relative advantage compared to the conventional system (Abler and Shortle, 1995). It is only when perception and intentionality change, as seems to be the case with biological farmers, that room is created for different practices.

Acknowledgements

Thanks are expressed to the extension company DLV for providing the sample, to Ir. H.B. Schoorlemmer (PAV Lelystad) for support in organising the interviews and to the farmers for their co-operation. Roswitha van Zon provided literature search assistance which is gratefully acknowledged.

References

Abler, D.G. and J.S. Shortle, 1995. Technology as an Agricultural Pollution Control Policy, American Journal of Agricultural Economics 77: 20-32.

Adesina, A.A., and M.M. Zinnah, 1993. Technology characteristics, farmers' perceptions and adoptions decisions: a tobit model application in Sierra Leone, Agricultural Economics 9, 297-311.

Almekinders, C.J.M., L.O. Fresco and P.C. Struik, 1995. The need to study and manage variation in agro-ecosystems. Netherlands Journal of Agricultural Science 43: 127-142.

Anderson, J.R., J.L. Dillon and J.B. Hardaker, 1977. Agricultural decision analysis, Iowa State University Press, Ames.

Baidu-Forson, J., B.N. Ntare and F. Waliyar, 1997. Utilizing conjoint analysis to design modern crop varieties: empirical example for groundnut in Niger, Agricultural Economics 16: 219-226.

Babcock, B.A., 1992. The effects of uncertainty on optimal nitrogen applications. Review of Agricultural Economics 14(2): 271-280.

Capra, F., 1996. The web of life. London, Harper Collins (Flamingo).

Cochrane, W.W. 1958. Farm prices : myth and reality. Minneapolis [s.n.], 189 p.

Constandse, A.K. 1964. Boer en toekomstbeeld: enkele beschouwingen naar aanleiding van een terreinverkenning in de Noordoostpolder. Bulletin afdeling Sociologie en Sociografie van de Landbouwhogeschool Wageningen. no. 24.

De Buck, A.J., H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens, 1999. Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model.*Agricultural Systems* 59: 283-299.

Deen, W., A. Weersink, C.G. Turvey and S. Weaver, 1993. Weed control decsion rules under uncertainty. Review of Agricultural Economics 15(1): 39-50.

De Ortiz, S., 1980. Forecasts, decisions and the farmers' response to uncertain environments. In: Barlett, P.F. (Eds.) Agricultural decision making: anthropological contributions to rural development. Academic Press, New York.

Dorfman, J.H., 1996. Modeling Multiple Adoption Decisions in a Joint Framework. American Journal of Agricultural Economics 78: 547-557.

D'Souza, G., D. Cyphers and T. Phipps, 1993. Factors Affecting the Adoption of Sustainable Agricultural Practices, Agricultural and Resource Economics Review 22(2): 159-105.

Eisenhardt, K.M., 1989. Building theories from case study research, Academy of Management Review 14: 532-550.

Feder, G.R., E. Just and D. Zilberman, 1985. Adoption of Agricultural Innovations in Developing Countries: A Survey. Economic Development and Cultural Change 34: 255-296.

Feder, G. and D.L. Umali, 1993. The Adoption of Agricultural Innovations: A Review. Technological Forecasting and Social Change 43: 215-239.

Fisher, A.J., A.J. Arnold and M. Gibbs, 1997. Information and the Speed of Innovation Adoption, American Journal of Agricultural Economics 78: 1073-1081.

Gladwin, C.H., 1980. A Theory of Real-Life Choice. Applications to Agricultural Decisions. In: P.F. Barlett (Eds.) Agricultural decision making: anthropological contributions to rural development. Academic Press, New York

Hardaker, J.B., R.B.M. Huirne and J.R. Anderson, 1997. Coping with Risk in Agriculture. CAB International, Oxford and New York.

Huijsman, A., 1986. Choice and uncertainty in a semi-subsistence economy: a study of decision making in a Philippine village. Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

Janssens, S.R.M. and F.G. Wijnands, 1994. Experimental introduction of integrated arable farming in practice. In: Plant production on the threshold of a new century. Kluwer Academic Publishers, Dordrecht.

Janssen, H., 1996. Oorzaken van verschillen in middelenverbruik tussen bedrijven. P. infestans in aardappelen. *LEI-DLO Publication 3.162*, The Hague, The Netherlands.

Jansma, J.E., H. van Keulen and J.C. Zadoks, 1993. Crop protection in the year 2000: a comparison of current-policies towards agrochemical useage in four western European countries, Crop Protection 12: 483-489.

Jeger, M.J., 1997. Approaches to integrated crop protection in university education and training, Agriculture, Ecosystems and Environment 64: 173-179.

Marris, C. and I. Langford, 1996. No cause for alarm. New Scientist, 26/9/1996.

Maturana H. and F. Valera ,1987. The tree of knowledge. New York, Shimbala.

Matteson, P., L. den Boer and J. Proost, 1996. Green labels in the Netherlands: Careful Negotiations and Clearer Choices, Global Pesticide Campaigner 6(4): 3-5,16

Leferink, J. and M. Adriaanse, 1998. Omschakelen: beren en bergen (onderzoek naar de redenen van akkerbouwers en vollegrondsgroententelers om niet om te schakelen naar biologische landbouw). IKC Landbouw, Ede, The Netherlands.

Moffitt, L.J., 1986. Risk-efficient thresholds for pest control decisions. Journal of Agricultural Economics 37: 69-75.

MYCPP, 1991. Multi-Year Crop Protection Plan. *Meerjarenplan Gewasbescherming; Regeringsbeslissing.* Ministry of Agriculture, Nature Management and Fisheries, Tweede Kamer, vergaderjaar 1990-1991, 21667, nr.3-4. Staatsuitgeverij, The Hague, The Netherlands.

Oskam, A.J., H. van Zeijts, G.J. Thijssen, G.A.A. Wossink and R. Vijftigschild, 1992. Pesticide use and pesticide policy in the Netherlands: an economic analysis of regulatory levies in agriculture. Wageningen Economic studies 26. PUDOC, Wageningen.

Pannell, D.J., 1991. Pests and Pesticides, Risk and Risk Aversion. Agricultural Economics 5: 361-383.

Penrose, L.J., C.C. Bower and H.I. Nicol, 1996. Variability in pesticide use as a factor in measuring and bringing about reduction in pesticide usage in apple orchards. Agriculture, Ecosystems and Environment 59: 97-105.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz and M. D'Amore, 1993. Assessmenst of Environmental and Economic Impacts of pesticide Use. In: D. Pimentel and H. Lehman (Eds.) The Pesticide Question. environmental, economics and ethics. Chapman & Hall, New York, *etc.*

Proost, M.D.C., H. van Keulen and I. Schönherr, 1995. Gewasbescherming met een toekomst: de visie van agrarische ondernemers. Een doelbereikingsmeting ten behoeve van voorlichting. Report to the Ministry of Agriculture, Nature Management and Fisheries (LNV). Wageningen Agricultural University, Group Communication and Innovation Studies.

Proost, J. and P.Matteson, 1997. Reducing Pesticide Use in the Netherlands. Journal of Pesticide Reform 17(3): 2-8.

Proost, J. and N.G. Röling, in press. Desperate to get off the treadmill. Renegotiating arable farming in a densely populated industrialised country. In: B. Hubert *et al.* (Eds.) Learning and knowing processes for change in agriculture in industrialised countries. INRA and Springer Verlag, Paris.

Rogers, E.M. (1995) Diffusion of Innovations. 4th ed. Free Press, New York.

Röling, N.G. and J. Jiggins, 1998. The ecological knowledge system. Chapter 16 in: Röling, N. and Wagemakers, A. (Eds.) Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Röling, N.G. and E. van de Fliert, 1998. Transforming Extension For Sustainable Agriculture: The Case of Integrated Pest Management in Rice in Indonesia. In: N. Röling and A. Wagemakers (Eds.) Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Schoorlemmer H.B, A.J. de Buck and G.A.A. Wossink, 1994. Risks and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.L. Pedersen (Eds.) Farmers' decision making, a descriptive approach, Proceedings of the 38th EAAE Seminar, Copenhagen, Institute of Agricultural Economics.

Somers B.M. and N. Röling, 1993. Kennisontwikkeling voor duurzame landbouw. NRLO rapport nr. 93/12. Nationale Raad voor het Landbouwkundig Onderzoek, Den Haag.

Sonka, S.T. and G.F. Patrick, 1984. Risk management and decision making in agricultural firms. In: P.J. Barry, (Ed.) Risk Management in Agriculture. Iowa State University Press, Ames.

Tsur, Y., M. Sternberg and E. Hochman, 1990. Dynamic Modelling of Innovation Adoption Process with Risk Aversion and Learning. Oxford Economic papers 42: 336-355.

Van Ravenswaaij, E.O. and J.R. Blend, 1997. Using Ecolabelling to Encourage Adoption of Innovative Environmental Technologies in Agriculture. Staff paper no. 97-19. Michigan State University, Dept. of Agricultural Economics.

Van Weperen, W., M.C.D. Proost, and N. Röling, 1998. Integrated arable farming in the Netherlands. Chapter 6 in N. Röling and A. Wagemakers (Eds.). Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Verschuren, P., N. Somers, and A. Daems, 1997. The need for qualitative methods in agricultural economics. Tijdschrift voor Sociaal-wetenschappelijk onderzoek van de Landbouw 12(4): 367-276.

Wärneryd, K.E., 1988. The psychology of innovative entrepreneurship. In: W.F. van Raaij, G.M. van Veldhoven and K.E. Wärneryd (Eds.) Handbook of economic psychology. Kluwer Academic Press, Dordrecht.

Wossink, G.A.A., de Buck, A.J., van Niejenhuis, J.H. and Haverkamp, H.C.M., 1997. Farmer Perceptions of Weed Control Techniques in Sugarbeet. Agricultural Systems 55(3): 409-423.

Wijnands, F.G., 1992. Evaluation and introduction of integrated farming in practice. Netherlands Journal of Agricultural Science 40: 239-249.

Wijnands, F.G. and Vereijken, P., 1992. Region-wise Development of Prototypes of Integrated Arable Farming and Outdoor Horticulture. Netherlands Journal of Agricultural Science 40(3): 225-238.

3 Analysing production and environmental risks in arable farming systems: a mathematical approach

A.J. de Buck, E.M.T. Hendrix[a] and H.B. Schoorlemmer[b]

Published in: *European Journal of Operational Research* 119 (1999): 416-426

Abstract

In response to a growing environmental concern in Dutch society, sustainable production systems in arable farming have been developed. Amongst other things, a reduction of the dependency on chemical inputs is attempted. This paper addresses the role of risk in the adoption by farmers of new systems by means of a model that determines differences in production risks between conventional and sustainable farming systems (CAFS and IAFS).

Timing of activities –setting out a management track– is particularly important in sustainable arable farming systems. Resource requirements of crop husbandry activities mainly depend on weather conditions. To assess risks caused by weather conditions, the major aspects of crop husbandry in various crops, have been modelled. Using tactics in crop husbandry (decision rules) and weather uncertainty as input, crop husbandry models (HMs) calculate management tracks that require resources. The value distributions of resource requirements of crop husbandry according to different farming systems are calculated in different HMs represented by stochastic dynamic directed networks. Hence, production risks of CAFS and IAFS can be compared.

On a farm, all the aspects of crop husbandry in the various crops are to be taken into account. Given the weather conditions, tactics for all the aspects are combined in an LP model of the whole farm where they compete for limited resources. In the LP model, tactics are re-assessed by means of the hms, using information of the LP solution. This iterative procedure enables production risks of CAFS and IAFS to be compared, considering fixed, allocable resources for the whole farm firm.

Keywords: *Agriculture, Decision making, Risk.*

---

[a] *Sub-department of Mathematics, Wageningen University*

[b] *Applied Research for Arable farming and Field production of Vegetables (PAV), Lelystad, The Netherlands*

3.1 Introduction

Operating a farm firm in the arable sector in the Netherlands stands for more than just looking after the various crops. In the range operational-tactical-strategic decisions, which is often used as a classification for levels of planning, a farmer has to cover the whole management field of production, marketing and finance (Boehlje and Eidman, 1984; Davis and Olson, 1984; Huirne, 1990). Considering the whole farm organisation, most decisions across levels of planning are inter-related.

Due to a growing concern for the environment in Dutch society during the last decade, farmers have to extend their management field with another task: environmental management. Researchers designed IAFS (Integrated Arable Farming Systems) in order to reduce the dependency on chemical crop protection and to reduce the emission of fertilisers to the environment (Vereijken *et al.*, 1994; Vereijken, 1992). IAFS research succeeded in integrating both economic and environmental goals. Practical research has proved IAFS to be implementable on farms, where production levels were according to the expectations (Wijnands, 1992; Janssens *et al.*, 1994; Wijnands and van Dongen, 1997).

The hypothesis, derived from Dutch farming practice, that production risks of integrated farming systems are higher than those of conventional systems, is the background of this paper. Risk is considered as one of the delaying factors in the dissemination of IAFS in practice. This paper describes a method to combine several crop problems into one whole-farm level, the purpose of which is to analyse production risks between farming systems. The conceptual framework is presented together with examples.

Risk can be distinguished in normatively computable risk and the perception of risk by individuals (Smidts, 1990). In a project financed by the Dutch Ministry of Agriculture, Fisheries and Nature, normative analysis of risk is combined with empirical analysis of behavioural aspects that play a role in the adoption of IAFS. The normative comparison of risks started with an analysis of ongoing applied research on farming systems. Based on the disciplines of Operations Research, Production Ecology and Farm Management, this paper describes a method for the normative calculation of production risks, induced by natural circumstances, of different farming systems. In terms of management fields, this paper covers production and environmental management.

The model presented in this paper can be used (1) to estimate risks of specific current or new farming systems, omitting innovations in the sector, using all possible natural conditions as model input, (2) to objectively compare farming systems under similar farm and management situations (risk included) and (3) to evaluate new techniques on their suitability for a farming system. Risk is portrayed by a value distribution of outcomes.

The outline of the paper is as follows. In section 2 we present the outline and theoretical background of the model. After a description of decision making and risk in crop husbandry a conceptual framework is presented. Sections 3 and 4 present the model in its' two main parts: (1) crop husbandry models for the several husbandry activities at the crop level, and (2) an LP model at the farm level. Special attention is given to the iterative procedure of adapting the decision at the crop level to the constraints imposed at the whole farm level. The model at farm level is also used to choose the management track for each aspect of crop husbandry, performing the best over all possible natural circumstances. Section 5 evaluates the total model approach and its potential applications and provides major conclusions and priorities in further research.

3.2 Outline and theoretical background

3.2.1 Decision making in crop husbandry

Implementing crop husbandry for a whole farm comprises many aspects. For each aspect of crop husbandry (*e.g.* weed control in sugar beet or late blight control in ware potatoes), a strategy has to be made up. We define a strategy as a design for several years with respect to the organisation of crop husbandry on the farm, *e.g.* determining the equipment needed on the farm and planning labour supply and demand. A division ranging from 'conventional' to 'integrated' and 'organic' strategies can be made, corresponding to the division in farming systems. Conventional, integrated and organic strategies can be distinguished for each aspect of crop husbandry.

Given a strategy, a tactic is to be made up: in which case to do what for a given aspect of crop husbandry and a given strategy. The objective of these decision rules is –corresponding with the farmers' objective– maximising a profit function, considering continuation of the agronomic production possibilities[6], which is in accordance with the so-called 'good agricultural practice'. We define operationalisation of a tactic for a specific season –being a part of the operational planning– as a management track. Operational planning concerns elaboration of strategic and tactical plans as well as control during implementation (Leutscher, 1995). Here, operational planning in one crop is integrated for the whole farm. The whole farm includes tactical and strategic planning in crop husbandry as well.

3.2.2 Risk in crop husbandry

Numerous papers on risk show that various disciplines use different definitions of risk. Even within the single discipline of *OR*, no generally accepted definition of risk exists (Hendrix, 1990). A definition of risk –useful within this multidisciplinary approach– compatible with the nature of risk in the problem under study, had to be adopted. Because prices for products from the various farming systems do not differ, risk caused by fluctuating prices, questioned in many economic studies (Smidts, 1990), is no topic here. The production processes in arable farming depend on various uncertain states of nature such as weather conditions (in this paper synonymous with natural conditions). Risk can be deduced from the value distribution of all outcomes under all possible conditions by assigning preferences to parts of the value

---

[6] Such profit functions consist of fixed input-output combinations, unlike the 'classical' production functions in macro economics, having a continuous course (Upton, 1976; Wossink and Rossing, 1998)

distribution (Hardaker *et al.*, 1997). Though using the term 'risk' in this paper, it is confined to the generation of value distributions, without adding preferences to them.

Depending on natural conditions, a farmer executes measures to obtain an aimed production level. Given an aimed production level, weather conditions result in a unique series of measures –a management track. Unfavourable natural conditions generally will result in a high level of required farm inputs. So, variation in natural conditions leads to variation in the measures executed in management tracks leading to variation in input requirements. Hence, variation in natural conditions as the source of risk is translated to variation in requirements (considered as risk in this paper). This idea is similar to the approach of a 'risk chain' of Vlek and Stallen (1979), where the outcomes of relevant processes (weed and crop growth for instance) –influenced by a source of risk (natural circumstances)– are evaluated for those concerned (in this case the farmer).

3.2.3 A system approach for crop husbandry

To quantify production risks in crop husbandry, explanatory crop growth and weed/disease/nutrient models that describe the crop-eco-system, are useful (Penning de Vries *et al.*, 1989). To create such an explanatory model, the plant-eco-system needs to be analysed and the effect of crop husbandry activities on the mechanisms and processes, describing the plant-eco-system, needs to be quantified. Here, each aspect of crop husbandry and the related plant-eco-system is seen as a separate sub-system (Figure 3.1). In each sub-system at crop level, one of the aspects of crop husbandry is analysed. For each aspect of crop husbandry, a number of strategies are distinguished; ranging from conventional to organic; only one strategy is chosen, combinations of strategies are not allowed. Risks of a strategy come together in a system of the whole farm. Implementation of Figure 3.1 in a model enables the normative quantification of risks and a comparison of risks between CAFS, IAFS and organic farming. In this way the hypothesis that more environmentally friendly farming systems are more risky, is judged.

3.3 Calculating risks at crop level

A model HM, describing a crop husbandry strategy, is based on a network that is directed by time stages. The network differs for each strategy. The path followed through the network (*i.e.* the management track) depends on weather conditions and on the tactic. In Figure 3.2, J stages during one season and a multidimensional state (representing the situation of the crop and the weed, disease or nutrient situation) are distinguished. State s at stage j is determined by decision x (if-then relations, according to a tactic). For reasons of simplification of Figure 3.2, the stochastic parameter ξ is not included in the illustration. Costs and requirements for resources (*e.g.* labour needed and chemicals) are attributes of each operational decision.

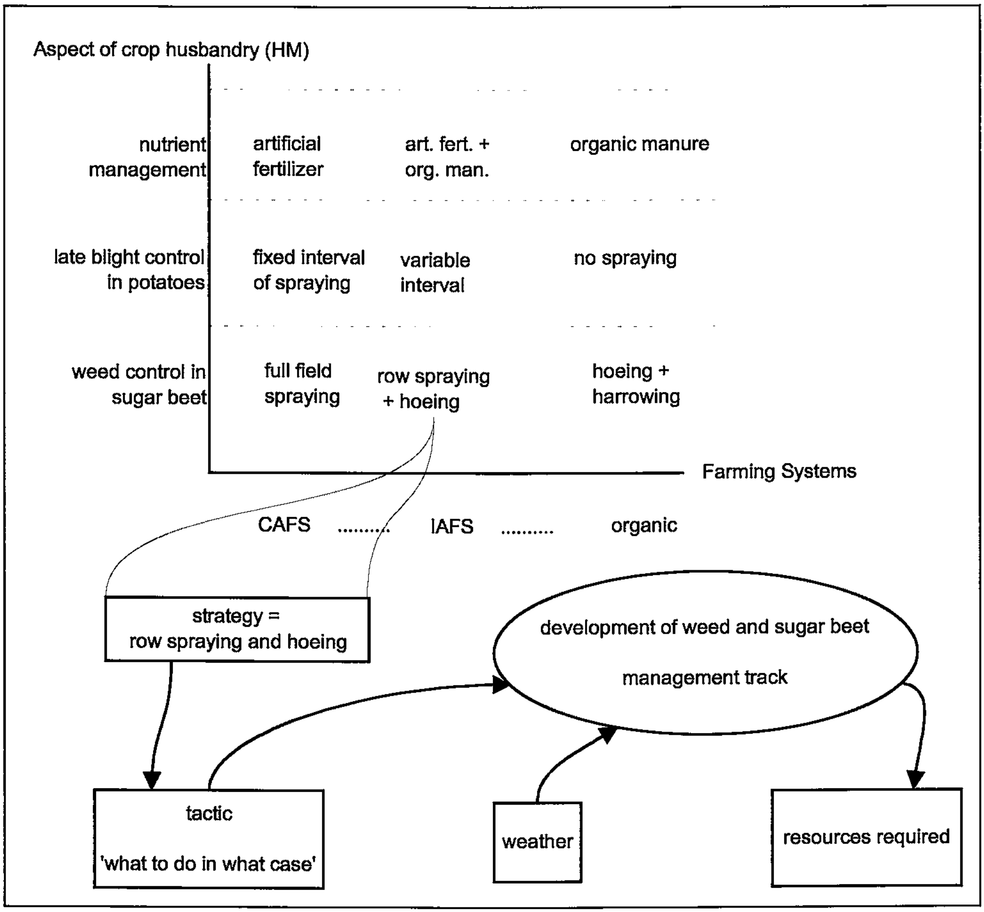


Figure 3.1 Conceptual framework for the analysis of production risks of different farming systems.

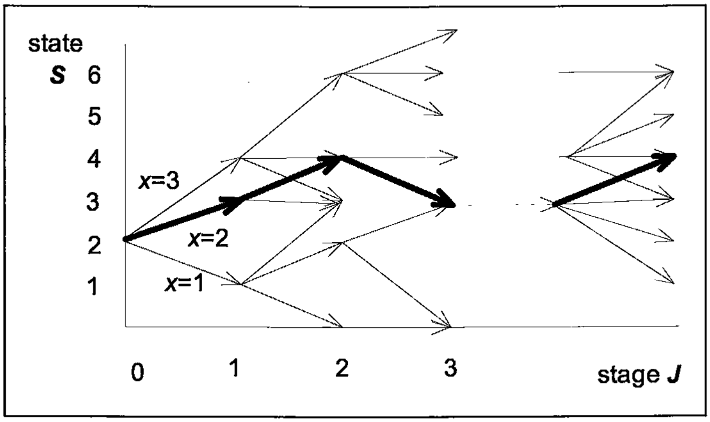


Figure 3.2 A Husbandry Model(HM) for a strategy with all possible decisions*x* in one growing season according to a tactic, represented as a deterministic directed dynamic network with *S* states and *J* stages.

At crop level, the optimal management track (represented by a continuing set of arrows in Figure 3.2) is the management track with minimal direct costs of execution c. At each stage j, the decision $x_{j,g}$ with the least cost c comes in the decision vector X (in this case a track). A decision $x_{j,g}$ requires $a_{i,j,g}$ units of resource i at stage j. The restriction describes that no damage is caused to the crop:

$$\min\left[\sum_{i=1}^{I}\sum_{j=1}^{J}\left(p_{i,j}\cdot a_{i,j,g}\right)\right] \tag{3.1}$$

$$\text{with} \qquad a_{i,j,g}=f(x_{j,g},S_{j,g})$$

$$\text{subject to} \qquad S_{j,g}\leq\delta_{j,g}\forall j$$

Transition function T describes the development of state, $S_{j+1,g}$ is a function of $S_{j,g}$, $x_{j,g}$ and a stochastic parameter ξ. So, costs c of required scarce resource a depend on weather conditions having a stochastic nature (Formula (3.2)) In Figure 3.3, Figure 3.1 and the two formulae are combined.

$$S_{j+1,g}=T_g\left(S_{j,g},x_{j,g},\xi\right) \tag{3.2}$$

A tactic results in a management track and a corresponding series of requirements (*e.g.* costs, labour, pesticides) for each season. The variation in outcomes of requirements when calculating all possible conditions of the random variate can be represented as value distributions. A measure of risk with respect to the implementation of a certain strategy in crop husbandry can be deduced from these distributions. Hence, risks of various **strategies** are calculated and compared.

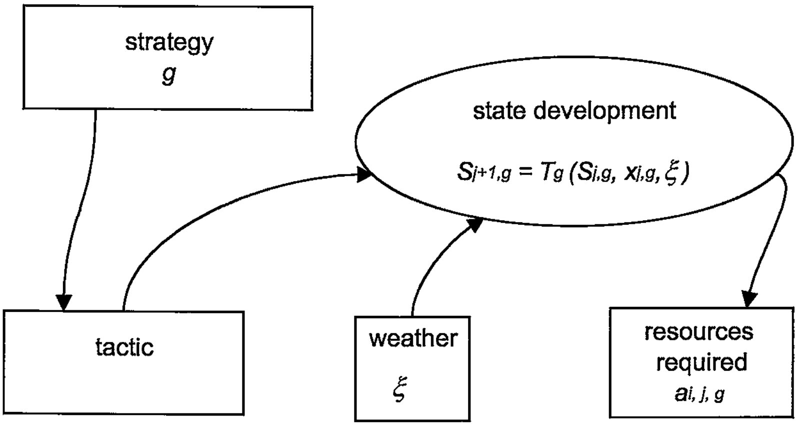


Figure 3.3 Conceptual framework for the calculation of production risks of one strategy

The three most important aspects of crop husbandry in the sense of risk were modelled (Figure 3.1, see Schoorlemmer *et al.*, 1994): nutrient management, late blight (*c.f.* a fungus disease) control in potatoes and weed control in sugar beet. Each aspect of crop husbandry is represented as a specific, mostly complex system of an agro-ecological and economic nature. Here, the crop husbandry problem of weed control in sugar beet is described in a global way[7]. The development of the sugar beet crop determines the begin and the end of the weed control season. To prevent yield reduction and the growth of a soil seed bank (which is considered as good agricultural practice in weed control), the weed population needs to be controlled from sowing date onwards. At full production capacity of the crop, the competitive power of the crop is such that weed control can be ceased. Weed control in sugar beet is a repetitive procedure, which has to be decided upon every half a week.

In De Buck *et al.* (1999), strategies in weed control range from strategy 1 (conventional), where only full field spraying is applied, to strategy 8 (organic) where only mechanical equipment is part of the inventory for weed control. The 'what to do in what case' decision rules, according to a tactic keeps the weed population within pre-defined boundaries to conduct good agricultural practice ($S_{j,g} \leq \delta_{j,g}$). Implementation of a tactic into a management track requires information on weed and on crop development as well as on weather and soil conditions. As a one dimensional example of state $S_{j,g}$, Figure 3.4 represents the simulated

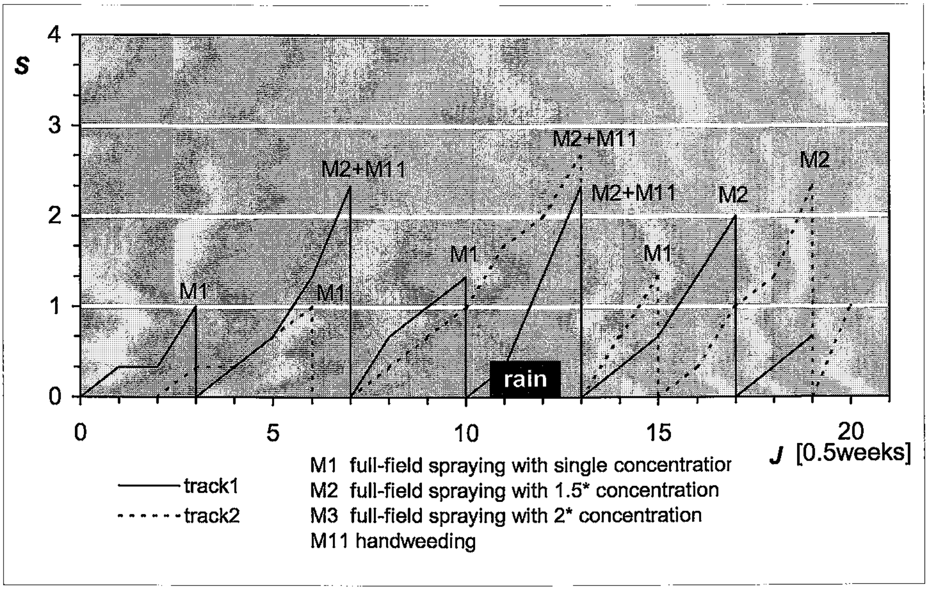


Figure 3.4 Weed development (S) as a result of two management tracks (two seasons) according to strategy 1 for weed control in sugar beet (illustrative example)

---

[7] For details: see the development and application of the bio-economic model 'Bio Economic model on STrategy

development of the weed population at application of 2 management tracks (2 seasons). Resource requirements are defined for each individual measure, and hence are known for each management track. As an example, Figure 3.5 represents the frequency distributions of the labour requirements for 2 strategies after calculation of 20 weather seasons.

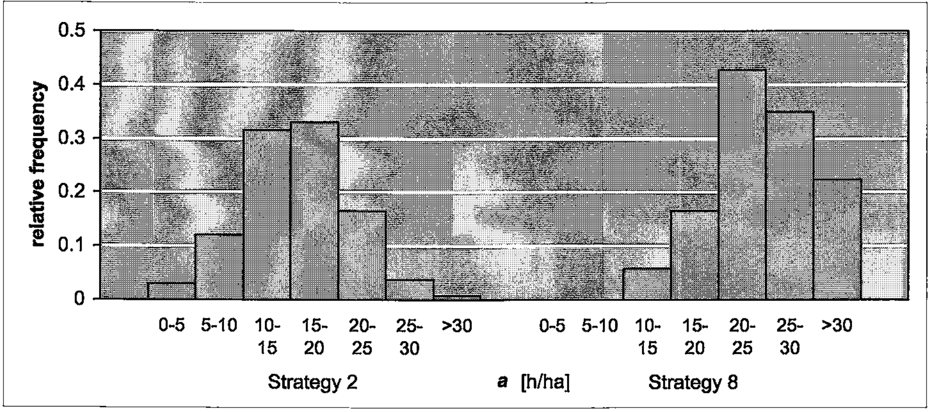


Figure 3.5 Frequency distribution for labour requirement(*a*) for strategy 1 and strategy 8 after simulation of 20 seasons (derived fromBESTWINS; De Buck et al., 1999).

3.4 Calculating risks at the whole farm level

In the model for calculating risks of different farming systems, the crop level and the level of the whole farm can be distinguished. Risk at crop level is calculated in the HMs. In this section, the integration of HMs into an LP model of the whole farm organisation (WF1) is described. The basic idea of WF1 is to select tactics so that the combination of all aspects of crop husbandry perform better on farm level. Each HM is one module in WF1. The required inputs, imposed by the execution of various aspects of crop husbandry according to management tracks, are the correcting element between the HM modules and WF1. The amount of required inputs $a_{i,j}$, summed for all G aspects of crop husbandry should not exceed the resources $b_{i,j}$ on the farm:

$$\sum_{g=1}^{G} a_{i,j,g} \leq b_{i,j} \forall i,j \qquad (3.3)$$

---

choice in Weed control IN Sugar beet (BESTWINS; De Buck *et al.*, 1999).

When running WF1 for one single growing season, the G HMs produce G management tracks, resulting in G requirement vectors $A_{g,r}$ (see Figure 3.6). The vectors $A_{g,r}$ become G activities in the LP model:

Model WF1:

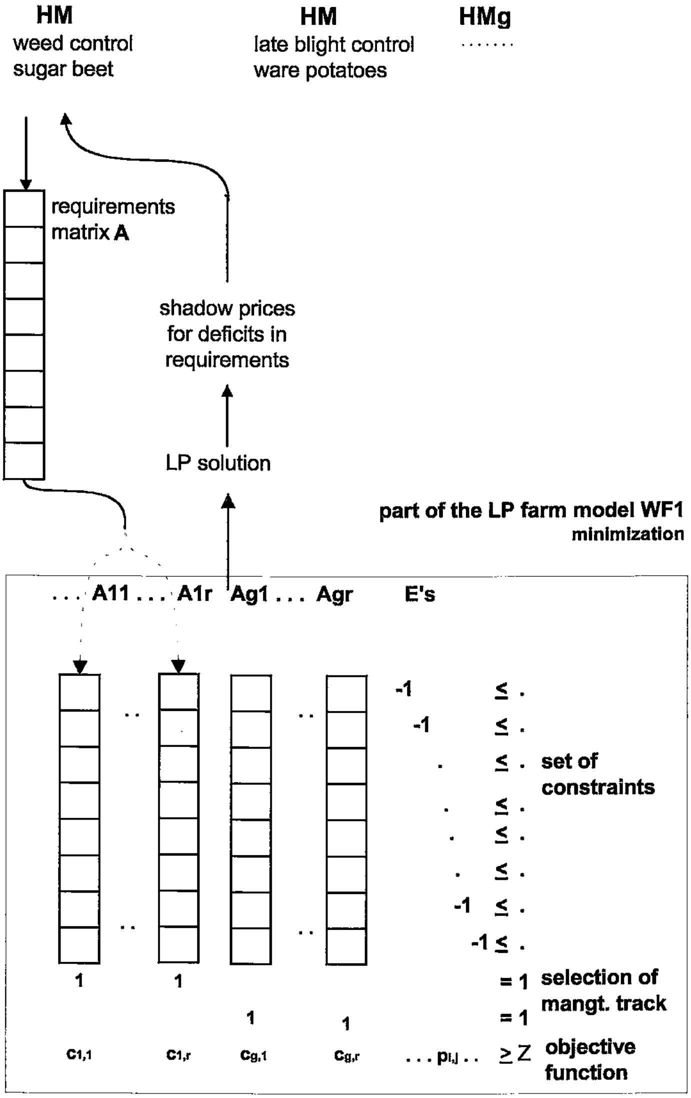


Figure 3.6 Management tracks, generated on HM level, entered as new activities in a LP model, representing the model of the whole farm (WF1). Improved management tracks are generated iteratively on HM level.

$$\min Z = \min \sum_{j=1}^{J} \sum_{i=1}^{I} \left(p_{i,j} \cdot e_{i,j} - c_{g,r} \cdot y_{g,r} \right) \tag{3.4}$$

$$\text{subject to:}$$

$$\sum_{r=1}^{R} \sum_{g=1}^{G} \left(a_{i,j,g,r} \cdot y_{g,r} \right) - e_{i,j} \leq b_{i,j} \forall i,j$$

$$\sum_{r=1}^{R} y_{g,r} = 1 \forall g$$

E is an added activity –with price *p*– that can be utilised to release the corresponding RHS constraint. *E* can be an artificial activity to ascertain a feasible solution or a real situation of *e.g.* hiring contract labour in a specific part of the season (in this case *p* equals the unit price for contract labour).

The release of constraints by generating new management tracks is illustrated by the simulation of weed control in sugar beet together with late blight control in potatoes in WF1. This example is elaborated for labour availability and requirement. In Figure 3.7 we see two bottlenecks in the availability of labour on the farm ($a_{i,j} > b_{i,j}$) at $j = 10$ and at $j = 13$. The shadow price for labour generates new management tracks for both husbandry problems. Due to rainfall, the periods 11 and 12 are not available. After the last iteration, a solution is found by delaying weed control (and implementing other measures later on) and by hiring contract labour at $j = 15$. Ultimately, the cheapest solution appears to be a new management track for weed control and no change in late blight control.

Calculating *T* seasons with WF1 results in *T* 'best' management tracks with their corresponding vectors of required resources $A_{g,r}$. Hence, value distributions of the requirements $a_{i,j}$ (risks in this case) for the management tracks of the various aspects of crop husbandry in the final solution, adapted for a specific farm situation can be calculated. Implementing the model for farms that are operated according to CAFS, IAFS and organic farming systems, allows comparison between farming systems at whole farm level with respect to production risks.

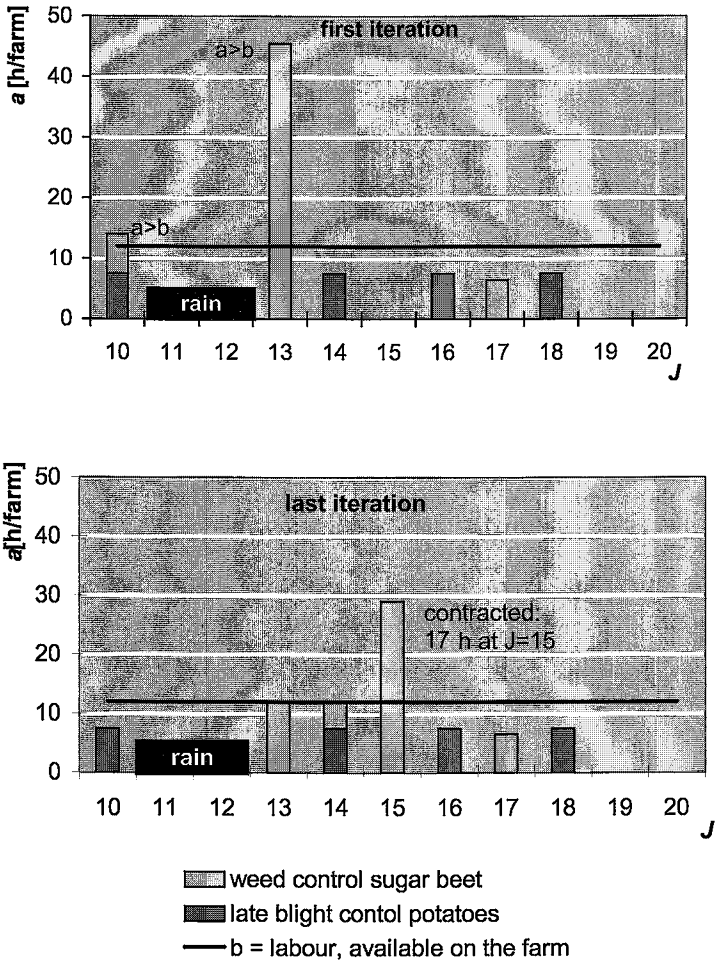


Figure 3.7 **Results of the first iteration with two labour bottlenecks and the final solution of WF1 for one season.**

The model for the whole farm level can also be applied to optimise the allocation of resources for a range of T seasons simultaneously (WFT, see Figure 3.8):

Model WF*T*:

$$\min \mathrm{Z} = \min \sum_{j=1}^{J}\sum_{i=1}^{I}\left(p_{i,j}\cdot\sum_{t=1}^{T} e_{i,j,t} - c_{g,r}\cdot y_{g,r}\right) \tag{3.5}$$

$$\text{subject to:}$$

$$\sum_{r=1}^{R}\sum_{g=1}^{G}\left(a_{i,j,g,r,t}\cdot y_{g,r}\right) - e_{i,j,t} \le b_{i,j} \forall i,j,t$$

$$\sum_{r=1}^{R} y_{g,r} = 1 \forall g$$

Conform the procedure in WF1, in WFT a new column is generated: management tracks are generated over T seasons to generate one LP activity. G tactics, performing best over T growing seasons appear in the final solution of WFT. Hence, risks of various farming systems, when applying a tactic that is optimal for a range of seasons can be calculated and compared. The most limiting resources are indicated by their shadow prices.

3.5 Final remarks, discussion and conclusions

With the individual HM modules, management tracks for a single aspect of husbandry can be determined, accounting for differences in weather situation. Considering the natural circumstances during a range of seasons enables assessment of risks –in this case value distributions of required resources– of alternative strategies for these individual husbandry problems; both in economic terms (costs, input requirements) as in environmental terms (emission of fertiliser and pesticides). The HMs generate management tracks by means of decision rules. From the perspective of the whole farm, the HMs as such cannot guarantee optimal selections to be made.

Combining outcomes of the HMs in an LP model at farm level takes account of three aspects: (1) limited availability of resources at the farm level; (2) competition between management tracks in the separate HMs for these limited resources and (3) assessment of these management tracks at the crop level that will give maximum profit at the farm level. The farm model selects optimal management tracks on an annual basis. Simulating with a representative set of seasons results in a frequency distribution of outcomes.

	$A_{1,1}$	$A_{1,r}$	$A_{2,1}$	$A_{g,r}$	$E_{i,1,1}$	..	$E_{i,j,t}$	RHS
season 1								
j=1	$a_{i,1,1,1,1}$	$a_{i,1,1,r,1}$	$a_{i,1,2,1,1}$	$a_{i,1,g,r,1}$	-1			≤ 10
j=2	$a_{i,2,1,1,1}$	$a_{i,2,1,r,1}$	$a_{i,2,2,1,1}$	$a_{i,2,g,r,1}$				≤ 7
..	.	.	.	.		.		.
..	.	.	.	.		.		.
..	.	.				.		.
j=J	$a_{i,j,1,1,t}$	$a_{i,j,1,r,1}$	$a_{i,j,2,1,1}$	$a_{i,j,g,r,1}$		.		≤ 13
season 2								
j=1	$a_{i,1,1,1,2}$	$a_{i,1,1,r,2}$	$a_{i,1,2,1,2}$	$a_{i,1,g,r,2}$		.		≤ 10
j=2	$a_{i,2,1,1,2}$	$a_{i,2,1,r,2}$	$a_{i,2,2,1,2}$	$a_{i,2,g,r,2}$		.		≤ 7
..	.	.	.	.		.		..
season t								
j=1	$a_{i,1,1,1,t}$	$a_{i,1,1,r,t}$	$a_{i,1,2,1,t}$	$a_{i,1,g,r,t}$		.		≤ 10
..	.	.	.	.		.		..
j=J	$a_{i,j,1,1,t}$	$a_{i,j,1,r,t}$	$a_{i,j,2,1,t}$	$a_{i,j,g,r,t}$			-1	≤ 13
	$y_{1,1}$	$y_{1,r}$						=1
			$y_{2,1}$	$y_{g,r}$				=1
Min Z	$c_{1,1}$	$c_{1,r}$	$c_{2,1}$	$c_{g,r}$	$p_{i,j}$	..	$p_{i,j}$	

Figure 3.8 Selection of tactics*r*, where activity *E* leads to a more cost-efficient allocation of scarce resources during a multitude of seasons.

The whole farm model can both generate tactics that are adapted to the farm organisation for single seasons (WF1) as well as tactics that perform the best over a set of seasons (WF*T*). Following WF*T*, the most limiting resources, distinguished by time in the season on a multi-season basis (RHS values) can be determined. This gives opportunities to point the bottlenecks regarding riskiness of the organisation of the farm.

As the field of our research is very broad and complex, the aim of this paper is to present a method together with illustrative, realistic examples. In forthcoming work, the method will be applied more extensively on different farm situations. For applications of the presented method, we see three options:

1. The model (the farm model as well as the individual HMs modules) is developed as a **research** tool to calculate differences in risks between more and less environmentally friendly strategies in the first place. Results of the module for weed control in sugar beet (BESTWINS) are available (De Buck *et al.*, 1999); results of other modules and the whole farm model are elaborated. The method can also be employed for new techniques that hardly have been used in practice yet. Besides, the method has been useful to organise the information needed for a comparison of the risks between different husbandry strategies and different farming systems.

2. The results of the model described in this paper can be used as a tool for **extension, education or decision support** to increase knowledge in decision making on (sustainable) farming systems. Information and knowledge on risks regarding operationalisation of farming systems has never been investigated for arable farming in the Netherlands. Information on risks is an attribute of strategies, which might hamper farmers' conversion to other farming systems. Hence, quantification of risks helps explaining this hampering conversion and can change farmers' perception of risk (Van Rijn *et al.*, submitted). The model BESTWINS (De Buck *et al.*, 1999) has been successfully used to determine the decision behaviour of individual farmers in a workshop. On the one hand, BESTWINS serves as a research tool here; on the other, farmers learn about the consequences of techniques that they might not apply on their own farm.

3. Considering the **methodology** employed in this paper, this paper shows that OR methods are very useful and flexible in linking agro-ecological knowledge with farm management models. Ideally, an optimising algorithm for the HM modules, consisting of dynamic networks, would be Dynamic Programming. Also, DP would facilitate a similar interaction between the HM modules and the LP problem as proposed. However, the problems described in this paper – even for a single HM- would require far too many states to be computable (the well-known curse of dimensionality; Winston, 1994).

References

Boehlje, M.D. and V.R. Eidman (1984). *Farm management*, New York, Wiley.

De Buck., A.J., H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens (1999). Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model. *Agricultural Systems* 59: 283-299.

De Buck, A.J., I. van Rijn, N.G. Röling, and G.A.A. Wossink. Farmers' reasons for changing or not changing to more sustainable practices: an exploratory study of arable farming in the Netherlands. (submitted).

Hendrix, E.M.T. (1990) *Risk and uncertainty in OR models which can be used in agriculture*. Wageningen Agricultural University, Department of Mathematics, Wageningen, The Netherlands.

Hardaker, J.B., R.B.M. Huirne and J.R. Anderson (1997). *Coping with risk in agriculture*. Wallingford: CAB International.

Huirne, R.B.M. (1990) Basic concepts of computerised support for farm management decisions.*European Review of Agricultural Economics* 17:69-84.

Janssens, S.R.M., F.G. Wijnands and P. van Asperen (1994). Experimental introduction of integrated arable farming in practice. In: "*Plant production on the threshold of a new century*" eds. P.C. Struik *et al.*, p365-368. Kluwer Academic Publishers, Dordrecht/Boston/London.

Leutscher, K.J. (1995). *Operational management in pot plant production.* Dissertation Wageningen Agricultural University, Wageningen, The Netherlands.

Penning de Vries, F.W.T., D.M. Jansen, F.M.H. ten Berge and A. Bakema (1989). *Simulation of ecophysical processes of growth in several annual crops.* PUDOC, Wageningen, The Netherlands.

Schoorlemmer H.B., A.J. de Buck, G.A.A Wossink (1994). Risks and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.L. Pedersen *et al.* (eds.), *Farmers decision making, a descriptive approach.* Proceedings of the 38th EAAE Seminar, November 1994, Institute of agricultural economics, Copenhagen

Smidts, A. (1990). *Decision making under risk.* Dissertation Wageningen Agricultural University, Wageningen, The Netherlands.

Upton, M. (1976). *Agricultural Production Economics and Resource Use.* London: Oxford University Press.

Vereijken, P., F. Wijnands, W. Stol and R. Visser (1994). 1. Designing prototypes. Progress reports of research network on integrated and ecological arable farming systems for EU and associated countries (*Concerted Action AIR 3 - CT920755*) AB-DLO, Wageningen, The Netherlands.

Vereijken, P. A. (1992). A methodic way to more sustainable farming systems. *Netherlands Journal of Agricultural Science* 40:225-238.

Wijnands, F.G. (1992). Evaluation and introduction of integrated arable farming in practice, *Netherlands Journal of Agricultural Science* 40:239-249.

Wijnands, F.G. and G.J.M. van Dongen (1997). Crop protection in Integrated Arable Farming Systems; environment exposure to pesticides. In: A.J. Oskam and R.A.N. Vijftigschild. "*Workshop on pesticides*", Wageningen, The Netherlands.

Winston, W.I., 1994. *Operations Research: applications and algorithms.* Belmont, Duxbury.

Wossink, G.A.A. and W.A.H. Rossing (1998). On increasing returns and discrete choice: integrating production ecological principles in economic analysis of crop management. *Journal of Environmental Management* 54(3):233-247.

4 Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model

A.J. de Buck, H.B. Schoorlemmer[a], G.A.A. Wossink[b] and S.R.M. Janssens[c]

Published in *Agricultural Systems* 59 (1999): 283-299

Abstract

In the Netherlands new farming systems have been developed that combine environmental sustainability with technical feasibility. Adoption of these new production strategies in practice seems to be hampered by their association with high levels of risks. In the case of weed control in sugar beet the risks of the new techniques concern manageability and probability of success in relation to meteorological aspects. The **Bio-Economic** *model on* **ST***rategy choice in* **W***eed control* **IN S***ugar beet (BESTWINS) allows an efficient and consistent comparison of strategies ranging from conventional to environmentally friendly with respect to risk. Risk is calculated by implementing the various strategies under a range of meteorologically determined conditions. Risk is measured by the statistical value distributions of characteristic parameters of the weed control strategies; e.g. cost and required labour and active chemical ingredient. Calculations show that more sustainable strategies do not necessarily imply an increase in risk. Labour requirements for manual weeding are generally higher for the biological strategy, but under exceptional conditions (95% point) other strategies show high requirements as well. Intensive tractor use increases labour requirements for strategies with row spraying combined with mechanical techniques.*

Keywords: Weed control, Sugar beet, Bio-economic model, Risk

---

[a] *Applied Research for Arable farming and Field production of Vegetables (PAV), Lelystad, The Netherlands*

[b] *NC State University, Department of Agricultural and Resource Economics, Raleigh, NC, USA and Farm Management Group, Wageningen University*

[c] *Agricultural Economics Research Institute (LEI), The Hague, The Netherlands*

4.1 Introduction

New crop production strategies, developed in response to growing concern about environmental pollution from agriculture, may neither be more profitable nor higher yielding than the conventional systems, but they often reduce emissions of plant nutrients and pesticides (Roberts and Swinton, 1996). The usual procedure for assessing these new strategies is by prototyping farming systems on an experimental station (Wijnands and Vereijken, 1992). Since 1979, experiments on Farming Systems Research have been carried out in the Netherlands comparing the integrated arable farming systems (IAFS) that replace chemical inputs as much as possible with mechanical and biological control and an organic farming system using no chemical inputs at all. Evaluation of the trade-offs between profitability and environmental impacts of the new farming systems is based on the limited time series of empirical data from these experiments. This may not reflect average values and certainly do not represent the full range of possible outcomes regarding profit and environmental impact. The systems are subject to prototyping and thus show a continuous development, making the relevant time series of data even more limited. Consequently, these evaluations do not fully cover the distributions of profitability, input use, and labour requirements that determine the financial and organisational stability of the new strategies that make up the new farming systems. The importance of risks partially explains why most of the farmers are reluctant to adopt the new strategies (Somers and Röling, 1993). Olson and Eidman (1992) confirm that risk is one of the aspects in the choice for weed control measures. Average outcomes of these new farming systems may be similar to those of conventional practices but this might hide significant higher variations in outcomes over a longer period or for other environmental components, such as soil types (Schoorlemmer *et al.*, 1994).

Quantitative information about these risks may provide a stimulus to an actual conversion to IAFS (Schoorlemmer *et al.*, 1994). Hence, it is necessary to generate additional data on the performance of the strategies used in IAFS and in organic farming systems. Within the existing research programme on IAFS the Netherlands, this could be achieved by long-term trials on experimental farms or on commercial farms. In the first place, this is a time and money consuming method. Furthermore, long term trials will hopefully lead to improvements to the strategies under research. In this case, the research method of executing long-term trials will not work, because the outcomes of the various years will not be fully comparable.

Conducting experiments by computer simulation can generate the data that are required to answer questions in the short term. Such a model should be based on knowledge of economic and physical interrelationships for which research on whole-farm level can be an important scource. Data generation is most likely to be achieved by integrating biophysical simulation models with economic optimisation methods (Antle and Capalbo, 1993). Doyle (1997) states that to fully understand crop development and the influence of control measures, mechanistic eco-physiological models are needed; see Kropff and Lotz (1992) for an example of weed-crop competion. Existing mechanistic models may not apply to many practical situations, whereas empirical models may be appropriate (see *e.g.* Kropff and van Laar (1993) for an overview of different kinds of crop-weed models).

Combining production ecological knowledge with economic principles of weed control into a bio-economic model can be employed to analyse the performance of alternative crop husbandry options under a range of conditions, such as variable weather and different farm sizes. Bio-economic models have been used for various applications such as modelling crop yield in response to input levels, control of wild oats in wheat (Sells, 1993 and 1995; Taylor and Burt, 1984), effluent control at farm level (Johnson *et al.*, 1991; Taylor *et al.*, 1992) and weed management in corn and soybeans (Lybecker *et al.*, 1991; Swinton and King, 1994b; Schweizer *et al.*, 1993)

A drawback of most existing bio-economic models is that they evaluate alternative pest management measures only on their financial performance which is insufficient when analysing systems designed with environmental objectives. Understanding benefits and risks involved for the farmer are equally important in the design of Integrated Crop Protection (Doyle, 1997). As pointed out by Roberts and Swinton (1996), their review of 58 studies comparing alternative crop production systems includes only one bio-economic model (Teague *et al.*, 1995) that incorporates both environmental and financial risks.

Existing models do not incorporate organisational risks. These risks are caused by the operational dynamics of crop husbandry activities (that is demands and timing of labour and machinery input). On Dutch arable farms with an intensive cropping pattern and the farmer as the only labourer, labour is a major constraining factor. Farmers particularly expect operational difficulties with labour organisation when changing-over to new strategies (Wossink *et al.*, 1997). With new, more environmentally friendly crop husbandry strategies, labour requirements are usually more substantial and timeliness is crucial (Swinton and King, 1994a; Westerdijk *et al.*, 1997). Timing and labour demands of different crop husbandry activities within the same crop, and in other crops on the same farm, make operational field level decisions interdependent. Applying more time consuming strategies into all crops grown on the farms could add up a much higher level of organisational risks than encountered with conventional practices.

Weed control is an important factor in arable farming particularly because of its organisational implications. Weed control decisions are made for the individual crops, but will affect weed control of the total rotation. In crops with a low plant density like sugar beet, weed control requires particular attention to avoid yield reduction and the formation of a considerable seed bank (Swinton and King, 1994b; Van der Weide, 1993). It is important to create an environment that allows the crop to interfere with weeds to the greatest possible extent (Doyle, 1997). Especially at the beginning of the season, a good timing of the right weed control measures is crucial (Westerdijk *et al.*, 1997). Van der Weide (1993) found a higher biomass and seed production of weeds in open crops like sugar beet as compared to other crops. Given the rotations common in specialised crop farming in the Netherlands, weed control in sugar beet is the critical factor and decisive for weed management in the other crops.

This paper presents BESTWINS, a stochastic, dynamic bio-economic model for weed control in sugar beet, that is based on empirical relations. The central polder area in the Netherlands with light marine clay soils has been chosen as the case study area, because of the relatively homogenous and rational farm structure. This paper aims to evaluate the effects of weed control strategies in sugar beet on risks (defined as calculated variation in outcomes). BESTWINS is a tool that enables the assessment of financial, environmental and organisational stability of various weed control strategies in sugar beet. The high stability of a strategy points to a low variation in outcomes. The stability of a strategy is an extra piece of information for farmers, extension economists or policy makers when considering the adoption process. To account for differences in farm situation (acreage and cropping pattern) the price of labour is variable. This makes it possible to interactively link BESTWINS to a whole farm model, of either a conventional, an IAFS, or an organic farming system (see De Buck *et al.*, 1998). BESTWINS was programmed in Borland Pascal 7.

After this brief review of relevant literature on weed science, the paper continues with the explanation of the theoretical model. Next, we consider the way in which the conceptual framework was implemented for sugar beet growing in the region of Oostelijk Flevoland in the Netherlands which was chosen as the case study region. Subsequently, the results of the model calculations are presented. Ultimately, a discussion on the method and on the results is presented and the main conclusions from this paper are given.

4.2 Methods

4.2.1 Conceptual model

Bio-economic decision models, developed to assist in making input recommendations begin with the standard optimisation framework based on marginal conditions. Choosing how to manage weeds in a crop, however, has features that make input demand and optimal control conditions different from marginal input use patterns (Carlson and Wetzstein, 1993; Deen *et al.*, 1993). Instead of marginal conditions, a breakeven criterion is common in recent bio-economic models of weed control. For the individual control measure, the breakeven criterion reduces the decision to a binary one, of either no treatment or treatment at a fixed dosage. When applied on a certain weed population it means treatment only if the weed reaches a threshold value in terms of plant density and development stage (Auld and Tisdell, 1987; Marra and Carlson, 1983; Headley, 1972). So, instead of a fixed schedule, timing and dosages are adapted to weed density (see also Shribbs *et al.*, 1990 and Wilkerson *et al.*, 1991) and the development stage of the weed population (Vereijken and Wijnands, 1990). If several control measures are available to control a certain weed population, the choice set will consist of discrete options, with fixed combinations of input (herbicides, labour, machine hours). Each set has a specific effect on the weed population. For weed control in sugar beet it is acceptable to assume that the optional measures have no harmful effects on root yield and recoverable sucrose (see *e.g.* Winter and Wiese, 1982; Shribbs *et al.*, 1990; Westerdijk *et al.*, 1997).

Figure 4.1 illustrates the concept of the multi-period weed control model BESTWINS. The general multi-period problem consists of multiple time periods, or stages j ($j = 1, .., J$). In one stage, one cycle is completed. For a given stage j, the state S_j of the system is described by a vector of state variables (representing the situation in the crop and weed size and composition). We define a strategy as a design for several years with respect to the organisation of crop husbandry on the farm, *e.g.* determining the equipment needed on the farm, planning labour supply and demand. A strategy for weed control is part of the strategy for the whole farm. In BESTWINS, a strategy is a coherent choice set of weed control measures and decision rules. Based on the situation of crop and weed S_j, at each stage a decision x is made within a strategy. Costs and requirements for inputs (herbicide use, for instance) are attributes of the control decision x. The optimal multi-period solution is the sequence of J decisions x ($x \in X$) with minimal costs of execution c (see De Buck *et al.*, 1999). This is

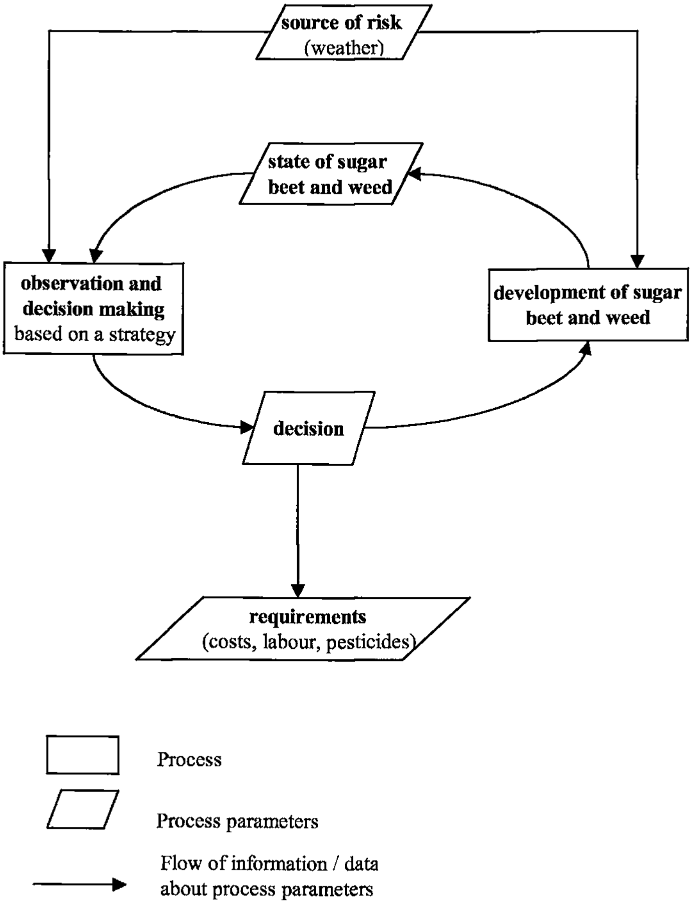


Figure 4.1 Conceptual model of weed control in sugar beet.

expressed in Equation 4.1[8]:

$$c = \min \sum_{i=1}^{I} \sum_{j=1}^{J} \left(p_{i,j} \cdot a_{i,j} \right) \tag{4.1}$$

$$\text{with} \quad a_{i,j}\left(x, S_j\right) \quad \text{and} \quad x \in X$$

where $p_{i,j} \cdot a_{i,j}$ denotes the price times the number of units needed of input i at stage j. Crop and herbicide prices are assumed to be constant. Equation 4.1 shows the economic objective function. Where environmental concern is the objective, Equation 4.1 has to be replaced by minimisation of the total use of herbicides (in kg active ingredient) over all stages j.

Many uncertainties arise in the decision problem in Equation 4.1. The focus is on weather as a main source of risk (Figure 4.1), contributing to an interperiod uncertainty in weed control and weed and crop development. Weather risk is assessed by a multi-period setting within one season, analysed for multiple seasons. Risk is introduced as stochastic weather conditions ξ_j in Equation 4.2. In Equation 4.2, the transition function T, or equation of motion, describes that current weed situation S_j and the weed control decision x affects the weed situation in the next period (S_{j+1}):

$$S_{j+1} = T\left(S_j, x, \xi\right) \tag{4.2}$$

The control efficacy (the effect of x on S) was assumed to be deterministic. The Equations 4.1 and 4.2 indicate that $a_{i,j}$ is dependent on the stochastic parameter ξ and the sequential decisions x. The Cumulative Distribution Function (CDF) is represented by:

$$\mathrm{F}(A_i) = \mathrm{P}(a_i \le A_i) \tag{4.3}$$

$$\text{with} \quad a_i = \sum_{j=1}^{J} a_{i,j}.$$

In fact, the probability density for ξ is estimated by a number of years T ($t = 1,...,T$) of weather data. Hence, the CDF can be written as:

$$\mathrm{F}(A_i) = \mathrm{freq}\left(\sum_{j=1}^{J} a_{i,j,t} \le A_i \right) \cdot T^{-1} \tag{4.4}$$

The approach above is to be applied separately to all weed control strategies investigated (ranging from conventional to organic). It enables these strategies to be compared and ranked on their A_i for various inputs i (in this case herbicide use in kg active ingredients per hectare, cost for herbicides per hectare and demand for labour per hectare).

---

[8] For reasons of uniformity in this book, the formulae in this Chapter differ slightly from those in the corresponding Journal article.

4.2.2 Construction of BESTWINS

Sugar beet development in BESTWINS

Weed control regarding annual dicotyledons in the Netherlands is based on maintaining or reducing the soil seed bank. Frequent operations prevent weed seed production and yield reduction due to competition between the weed population and the crop (Vereijken and Wijnands, 1990). For the absence of this weed-crop competition, crop simulation in BESTWINS omits crop yield and is confine to the development of canopy leaves. Crop development is simulated according to the temperature based approach of Smit and Struik (1995; after Goudriaan and Monteith, 1990)[9]. This is expressed in Equation 4.5:

$$Leafstage = (Cm\ /\ Rm\ ) * \ln(1 + \exp[Rm\ (tsum - tsum_b\ )]) \tag{4.5}$$

where:

$Leafstage$	average number of true leaves per plant
$Cm = 0.032$	maximum rate of crop development [leaf $\cdot$(°C$\cdot$d)$^{-1}$]
$Rm = 0.012$	maximum relative rate of crop development [(°C$\cdot$d)$^{-1}$]
$tsum$	sum of daily average temperatures (for basic temperature = 3.0 °C), calculated from crop emergence day onwards [°C$\cdot$d]
$tsum_b = 119$	temperature sum marking the turning point from exponential to linear growth phase [°C$\cdot$d]

In Equation 4.5, *tsum* is calculated from the day of emergence of the sugar beet crop (set at April 15). At full ground cover (from '*growth point date*' (GPD), or *leafstage* = 10 onward according to Smit and Struik, 1995), it is assumed that no new weed plants develop due to shading. The end of the weed control season is set at GPD + 1 week.

Weed development in BESTWINS

Simulation of weed emergence and subsequent development is required to provide information for weed control decisions. Weed control is based on the incidence of a representative set of annual weed species (see also Wiles *et al.*, 1996). A set of four weed species, was adopted as the weed population. A realistic situation in the Flevopolders area would include *Chenopodium album* L., *Galium aparine* L., *Solanum nigrum* L. and *Polygonum persicaria* L. An average seed emergence rate of 45 plants per m^2 per annum is assumed. This conforms to the expectation for an average field in the Flevopolders area (Van der Weide, pers. comm., 1994). The level of seed emergence and the seasonal periodicity

---

[9] Implicit in this approach is the assumption of optimal disease control and optimal water and nutrient conditions (which is plausible for the Flevoland area).

(Van den Brand, 1987) of the weed species were translated into a distribution of weed emergence for every half week period.

After emergence, four stages in the development of the weed vegetation are distinguished: *i*) the seedling stage, *ii*) 1-2 nodes with leaf pairs or whorls present, *iii*) 2-3 nodes present and *iv*) more than 3 nodes present. Weed development is modelled for two spatially separate areas: within and between crop rows. This enables the difference in spatial effect of some weed control techniques to be accounted for.

Development of *G. aparine* has been analysed by Van der Weide (1993) and appears to be mainly temperature related. In BESTWINS, the development of the complete weed population is related to the mean daily temperature (*Td*) dependent development of leaf whorls of *G. aparine*. To reduce computational effort, weed development is divided into 4 steps: a) no development (at $Td \leq 5.7$°C), b) 0.33 leafpairs 0.5 week^{-1} (at $5.7 < Td \leq 12.5$°C), c) 0.67 leafpairs 0.5 week^{-1} (at $12.5 < Td \leq 19.4$°C) and d) 1 leafpair 0.5 week^{-1} (at $Td > 19.4$°C).

Decisions in weed control

A weed control decision is taken in each period in BESTWINS. A weed control decision consists of waiting a period or executing a weed control measure. The available measures can be categorised into three *modes of action*: chemical, mechanical and manual. For the first group (measures 1-6 in Table 4.1) a herbicide cocktail[10] is applied. The so-called '*Low Dosage System*' (LDS) aims at weed seedlings (stage 1) with a low dosage; possibly to be increased for larger development stages in the weed population. The chemicals can either be applied full field (measures 1-3) or by means of band application approximately 15cm on either side of the crop rows (measures 4-6). Measures 4-6 require special row spraying equipment and are always combined with mechanical hoeing.

In the mechanical mode of action (measures 7-9), full field harrowing, hoeing and ridging are distinguished. Besides conventional hoeing –effective on the approximately 40cm wide strips between the crops– there is the more sophisticated technique of ridging, which has a killing effect within the rows as well. Manual weeding is effective for any large weed plants which may be present. Table 4.1 lists the effectiveness of weed control measures in BESTWINS in terms of the percentage of weed plants killed, assuming good weather and soil conditions. Effectiveness estimates were elicited from three experts on practical weed control and three experts on research in weed control. Each measure has a specific effectiveness on each weed stage within and between the rows[11].

---

[10] The cocktail contains the following *active ingredients* (in the standard *low dose* concentration at full field application): phenmedipham (0.08 kg *a.i.* ha^{-1}), metamitron (0.35 kg ha^{-1}) and ethofumesate (0.10 kg ha^{-1}). An additional 0.43 kg ha^{-1} mineral oil is not considered to be part of the active ingredient (Asselbergs *et al.*, 1996).

[11] Emergence and development of surviving weed plants is delayed after both chemical measures (indirect effect through soil) and mechanical measures (disturbance of the topsoil and physical damage to the weed plants). In BESTWINS, this side effect is accounted for by assuming no weed development and emergence in the first half week after treatment, except after harrowing. In the first half week after ridging, there is no weed emergence

Table 4.1 Effectiveness of weed control measures in reducing the number of weed plants under optimal conditions, specified for development stage of the weed plants and effects within ad between the crop rows.

	Development stage of weed							
	1		2		3		4	
Measure	Effect within %	Effect between %	Effect within %	Effect between %	Effect within %	Effect between %	Effect within %	Effect between %
1. full-field ld	98	98	70	70	30	30	0	0
2. full-field 1.5 · ld	98	98	85	85	50	50	0	0
3. full-field 2 · ld	98	98	98	98	70	70	30	30
4. row spray ld	98	0	70	0	30	0	0	0
5. row spray 1.5 · ld	98	0	85	0	50	0	0	0
6. row spray 2 · ld	98	0	98	0	70	0	30	0
7. hoeing	0	98	0	98	0	90	0	80
8. ridging	95	98	70	98	20	90	0	80
9. harrowing	90	90	60	60	20	20	0	0
10. manual weeding	0	0	0	0	80	80	98	98

ld, low dose. Source: expert elicitation (see text)

Weed control not only affects the development of the weed population, but can have a negative impact on crop growth as well (Westerdijk *et al.*, 1997). To prevent chemical or mechanical crop damage all measures are applied within a measure specific interval of development stages of the sugar beet crop (Table 4.2). Moreover, chemicals would not be able to reach the weed plants sufficiently after closing of the sugar beet canopy. Full suppression of small weeds by the crop is assumed from GPD onward.

In BESTWINS, a day without precipitation is required for any measure to be feasible. For good driving and cultivating conditions, the moisture retention (*pF*) of the upper 5 cm of the soil should not exceed 2.1 and 2.3 respectively. The *pF* values are calculated using the water movement module of the model for Water and Agrochemicals in the Soil, Crop and Vadose Environment (Vanclooster *et al.*, 1994)[12]. Furthermore, application of herbicides is only possible when there are three consecutive hours within a time step of half a week with average hourly windspeed less than 5 m s^{-1} (full field spraying) or 7 m s^{-1} (row spraying). Model

---

within the crop rows due to the shovelling effect towards the crop rows, while weed development continues (expert elicitation, see text).

[12] For these calculations, the physical parameters of the soil were taken from Groen (1997). The soil water levels throughout the season were averaged, using data of parcel S54 in the Flevopolder, measured by RIZA, Lelystad, The Netherlands in the years 1978-1986.

Table 4.2 Application window of weed control measures related to crop stage of sugar beet.

	Development stage of crop									
	sowing	pre-emergence	emergence	seedling	2-leaves	4-leaves	6-leaves	8-leaves	10-leaves (GPD)	GPD + 1 week
1. full-field ld	0	1	1	1	1	1	1	1	1	0
2. full-field 1.5 · ld	0	0	0	0	1	1	1	1	1	0
3. full-field 2 · ld	0	0	0	0	0	1	1	1	1	0
4. row spray ld	0	1	1	1	1	1	1	1	1	0
5. row spray 1.5 · ld	0	0	0	0	1	1	1	1	1	0
6. row spray 2 · ld	0	0	0	0	0	1	1	1	1	0
7. hoeing	0	0	0	1	1	1	1	1	1	1
8. ridging	0	0	0	0	0	0	0	1	1	1
9. harrowing	0	0	0	0	0	1	1	1	1	0
10. manual weeding	0	0	0	0	1	1	1	1	1	1

GPD, growth point date, which is reached at the 10-leaves stage (Smit and Struik, 1995); ld, low dose; 0, not applicable; 1, applicable. Source: expert elicitation (Wevers,Van der Weide, Westerdijk)

testings showed that wind speed is rarely a restraining factor for the execution of spraying[13] and hence it is omitted in the model.

Decision rule in BESTWINS

In BESTWINS, a strategy –an agronomically sound set of possible measures to execute– determines what decision is made, using fixed decision rules. Given the required availability of machines, a farmer will have specific measures at hand. This is reflected by the strategies in Table 4.3.

Table 4.3 shows the eight strategies that are compared using BESTWINS. Whereas the first strategy is a 'control', where all measures are allowed, the order of the strategies corresponds with a shift from dependency on chemical weed control via several combinations of mechanical and chemical control to dependency on mechanical control. The investment costs per strategy are the added costs per machine; calculated according to Table 4.4.

The decisions about weed control in a set of subsequent half week periods depend on the development stages of the weed population (Table 4.1) and the crop (Table 4.2) and on the weather and physical soil conditions. Each measure has a different effectiveness (Table 4.1), hence measures are not comparable exclusively on costs. Instead of equation 4.1, a *decision*

---

[13] For this test, hourly recorded windspeed data were used for the years 1993-1995. These data were derived from the meteorological station of PAV, Lelystad, The Netherlands.

Table 4.3 The modelled strategies in weed control in sugar beet.

	Strategy							
Measure	1	2	3	4	5	6	7	8
1. full-field ld	1	1	1	1	1	0	0	0
2. full-field 1.5 · ld	1	1	1	1	1	0	0	0
3. full-field 2 · ld	1	1	1	1	1	0	0	0
4. row spray ld	1	0	0	0	0	1	1	0
5. row spray 1.5 · ld	1	0	0	0	0	1	1	0
6. row spray 2 · ld	1	0	0	0	0	1	1	0
7. hoeing	1	0	1	0	0	1	1	1
8. ridging	1	0	0	1	1	1	1	1
9. harrowing	1	0	0	0	1	0	1	1
10. manual weeding	1	1	1	1	1	1	1	1
Machine investment costs (NLG)	-	98	198	215	261	252	298	163

ld, low dose; 1, inclued in the strategy; 0, no option in the strategy.

Table 4.4 Annual costs of investment, related to weed control strategies in sugar beet (Spigt and Janssens, 1997).

		Replacement value	Annual costs[a]		
			Total	Ascribed to sugar beet	
Device	Measure	NLG	%	%	NLG ha^{-1}
Full field sprayer (width=21m)	1..3	30000	13.1	25	98
Row sprayers (come with full field sprayer)	4..6	3700	13.3	75	37
Hoe (width=3m)	7	12000	11.1	75	100
Ridgers (w=3m; come with hoe)	8	1500	11.1	100	17
Harrow 6m	9	8300	11.1	50	46

[a] Assuming a farm size of 40 ha with 10 ha sugar beet, 10 ha ware potatoes, 10 ha winter wheat and 10 ha other crops, the total annual machine costs (depreciation, interest, maintenance and insurance) and the costs, ascribed to the sugar beet crop.

rule is used to select the best decision given the specific conditions. The discrete decision alternatives have a certain price and a certain killing effect on weeds. The optimization concept is operationalized as a minimization (summed over all *j*'s and over all *i*'s) of price *p* times effectiveness *e* (the killing effect of each measure).

The decision rule consists of a conjunctive part and a compensating part (Wierenga and Van Raay, 1987). In the conjunctive part, minimum criteria have to be achieved; in the compensating part, compensation between criteria is possible. The complete decision rule is defined as maximising:

$$e\_c\_ratio_x = \frac{\sum_{w=1}^{4} e_{x,w} \cdot \frac{S_w}{S_w^{thres}}}{c_x} \forall \left\{ \left(e_{x,w} > e_w^{thres} = 50 \right) \middle| \left(S_w > S_w^{thres} \right) \right\} \tag{4.6}$$

where:

$e\_c\_ratio_x$	effectiveness/cost ratio of measure (= decision) *x*
$e_{x,w}$	effectiveness of measure *x* on weed plants in development stage *w*
e^{thres}_w	threshold value for $e_{x,w}$ (independent of measure *x*)
S_w	state of the weed population (*viz.* number of weed plants) in development stage *w*
S^{thres}_w	threshold value for S_w
c_x	specific costs of measure *x*

The first, conjunctive, step involves comparing the weed population and the effectiveness of the measures with threshold values. To determine the necessity of weed control, the weed population is judged on the number of weed plants in each four stages of development within the crop rows and between the crop rows. Depending on the density and size of the weed population several control measures might be appropriate. This set of optional measures for the specific time step is assessed by the conjunctive rule in which the effectiveness of the control measures for each of the various weed stages S_w (Table 4.1) is compared with the threshold values S^{thres}_w and the required effectiveness (Table 4.5).

Table 4.5 Threshold values and required effectiveness.

	Threshold	
Weed stage w	Weed density S^{thres}_w plants m^{-2}	Required effectivity e^{thres}_w % plants killed
1	6	50
2	4	50
3	2	50
4	1	50

In the second -compensating- step of the decision rule, an effectiveness/cost ratio is calculated for each measure that passed the conjunctive step, with costs *c* including specific costs, with costs of active ingredient (*a.i.*) and labour costs[14]. Labour is sub-divided into unskilled labour for manual weeding and skilled labour for mechanical, tractor operated weed control

---

[14] It is assumed that the farmer carries out all measures himself at a calculated price of 38 NLG hour^{-1}. It is assumed that additional field inspection on the situation of weed and crop –that mainly consists of the inventory of small weed seedling plants– require the same length of time for all strategies. Therefore, labour for field inspection is not included in BESTWINS. For unskilled labour, employees can be hired for 20 NLG hour^{-1}.

measures (see Table 4.6). The amount of labour needed for manual weeding is dependent on the weed population, larger than development stage 2 (w≥2):

$$l_{unskilled} = 3 + \frac{\sum_{w=2}^{4}\left(S_{w,a=1}\right)}{3} \tag{4.7}$$

Assessing risks of a strategy

Weather variability is one source of stochasticity in weed control decisions in a sugar beet crop. For one season, this results in specific costs and in the requirement of *a.i.* and labour. In BESTWINS , risk of a strategy is assessed by the calculation of these results for the various strategies under all possible weather conditions, approximated by 30 years of weather data. In contrast to using weather as the source of variability in weed control, in BESTWINS the emergence of weed is simulated by an independent random process. Each year of weather data is repeated 10 times to account for random weed emergence.

Table 4.6 Specific costs and requirement of active ingredient and labour for the weed control measures.

	Active ingredient		Skilled labour
	Costs	Amount	
Measure	NLG ha^{-1}	kg ha^{-1}	h ha^{-1}
1. full-field ld	68.5	0.53	0.41
2. full-field 1.5 · ld	102.75	0.79	0.41
3. full-field 2 · ld	137	1.06	0.41
4. row spray ld	32.88	0.25	1.1
5. row spray 1.5 · ld	49.32	0.38	1.1
6. row spray 2 · ld	65.76	0.51	1.1
7. hoeing	0	0	1
8. ridging	0	0	1
9. harrowing	0	0	0.49
10. manual weeding	0	0	0

ld, low dose.

Hence, the bio-economic model BESTWINS assesses risks in terms of value distributions of costs, labour requirements and the required amount of *a.i.* for each strategy. Running BESTWINS 10 times with 30 years of weather data[15] for each strategy then provides value distributions regarding costs and requirements of labour and the amount of *a.i.* From these value distributions, averages and risk, represented by the 5% points (5% of worst outcomes), are determined.

---

[15] Weather data (maximum daily temperature and precipitaion) for the years 1966-1995 were obtained from the meteorological station 'Haarweg' of Wageningen Agricultural University.

Verification and validation

Firstly, the working of the computer programme for weed control in sugar beet was verified and corrected. In the last step of verification of BESTWINS, the group of experts that previously assisted in parameter estimation, were presented with the entire model. The adequately adapted model was ready for validation with two data sets: *i*) the results of an experiment (for which daily weather data of the location were available) aimed at replacing chemical herbicide treatments as much as possible by harrowing (growing seasons of 1993 and 1994; Westerdijk *et al.*, 1997), and *ii*) panel data of 9 farmers, applying IAFS in weed control in sugar beet (1992 and 1993). The data sets were independent and both concern situations in the Flevopolder, accompanied by local weather data.

The data set of the experiment provided observations (in this case application dates of weed control measures) to set some model parameters. In the experiment and at the panel farms, hoeing was implemented for weed-technical reasons as well as for its slight tillage effect. Hence, choosing a hoeing operation in practice does not comply with the decision rule in BESTWINS and the number of hoeing operations was omitted in the validation. In 1994, BESTWINS showed a similar result on the number of implemented measures (Table 4.7). In 1993, model results of strategies with harrowing showed a lower number of treatments than in the experiment.

Table 4.7 Number of weed control measures (without hoeing) as calculated with the Bio-Economic model on STrategy choice in Weed control IN Sugar beet (BESTWINS; in parentheses), versus executed measures by the panel (1992-93) and in the experiment (1993-94).

	Year and object			
	1992	1993	1993	1994
Strategy	Panel	Panel	Experiment	Experiment
1	6(4)	3..6(4)	-	-
5	-	-	-	5(5)
6	2(4)	4(4)	5(4)	4(4)
7	2..5(4)	4..6(4)	6(4)	5(5)
8	-	2(4)	7(4)	-

In the data set of the experiment, an annual weed emergence of 15 plants m^{-2} was observed (which is smaller than the assumed 45 emerging weed plants in BESTWINS; supposed to be representative for the research area). It is questionable whether the number of weed control measures is affected by an emergence of less than 45 plants m^{-2}. Comparing the number and the kind of measures there was no need to adapt figures for annual weed emergence and action thresholds.

In BESTWINS, the weed development stages 1, 2 and 3 correspond with single, 1.5 and double herbicide dosages in the LDS system. Larger plants in stage 4 cannot be killed effectively with the LDS system. A shortcoming appeared because the development stage of weed plants that are targeted by harrowing should actually be smaller than the smallest stage in BESTWINS.

Extending the model with an extra development stage would require additional research. This is beyond the scope of the current project. As a consequence, harrowing should possibly start one period (½ week) earlier than indicated in BESTWINS. This would lead to a model underestimation of the number of treatments in one season of 1 or 2.

BESTWINS was adapted so that the number of weed control measures corresponded with data from the experiment of Westerdijk *et al.* (1997). The adapted model was validated with the second, less detailed panel data set. Hence, the performance of BESTWINS was deduced from validation with the panel data set. Model results appeared to be largely within the interval of the panel (Table 4.7). The difference in the number of harrowing treatments between the panel farmer (2) and the experiment (7) is striking. In the experiment, harrowing was carried out as many times as possible (harrowing did not demand much labour and specific costs because of the sophisticated equipment with a high capacity).

4.3 Results

CDFs for the various strategies are derived to assess the outcomes of weed control strategies in sugar beet under uncertainty. From the CDFs mean, 95% point and stochastic dominance[16] are determined for specific costs, the required amount of *a.i.* and the requirements for skilled and unskilled labour per hectare.

Figure 4.2 shows the CDF for the use of *a.i* in kg ha^{-1}. Since the figures for *a.i.* and specific costs are fairly similar, only *a.i.* is presented. Based on First Degree Stochastic Dominance (FSD), the dominance between the two extremes is most obvious: strategy 8 –full based on mechanical measures with no use of *a.i.* at all– dominates all other strategies. The strategies 2 and 3 –mainly based on chemical treatment– are dominated by all others. Generally, a reduction in the use of *a.i.* and costs is reached when ridging (and hoeing) are introduced and when a full field chemical device is added through row spray equipment. The strategies comprising full field chemical spraying (strategies 1-5) tend to diverge from all other strategies under unfavourable situations (the right hand side of the curve). This indicates that, compared with strategies 6-8, the risk in absolute and relative sense for the use of high quantities of *a.i.* is higher for the strategies 1 to 5.

Figure 4.3 gives the CDF for skilled labour and unskilled labour. Strategies 2 and 3, based on full field chemical operations require little skilled labour (strategy 2 and 3 are dominant in the sense of FSD). Strategies based on row spraying (strategies 6 and 7) require more skilled labour. Strategies 6 and 7 combine a high level of skilled labour requirement with (compared to all other strategies) a risk of more than proportionally increasing requirements (the CDFs

---

[16] Stochastic dominance is a technique to rank-order decisions (Hardaker *et al.*, 1997), in this case strategies. Because of relatively little distinction in outcomes between strategies, this so-called dominance analysis is confined to First Degree Stochastic Dominance (fsd). Fsd only imposes the restriction that the decision maker prefers more utility over less utility. Hence, decision A dominates decision B (with cdfs of FA(x) and FB(x) respectively) in the first-degree sense if $FA(x) \geq FB(x)$ for all x.

diverge to the right part of the curve). The reduction in the requirement of skilled labour when introducing harrowing in strategy 6 (resulting in strategy 7) is notable. This labour reducing effect when harrowing is introduced in a strategy also appears slightly between strategies 4 and 5. Next in rank of dominance with respect to skilled labour are the group of strategies 4, 5 and 8. Within this group no dominance in the first-degree sense can be noticed.

Only strategy 8 is dominated with respect to the requirement for unskilled labour for hand weeding (Figure 4.4). The right tails (> 95% percentile) of the CDFs converge. Comparing strategy 8 with the other strategies, the requirement of unskilled labour requirement rises less than proportionally under unfavourable conditions. In other words: risk for high labour demands is not as high as one would expect on the basis of the other strategies.

In addition to graphic presentation (Figures 4.2-4.4), the rank numbers of the mean values, 95% points and FSD for the attributes *a.i.* and skilled and unskilled labour are presented in Table 4.8[17]. A low ranking, corresponding with a 'good' score for a strategy, implies dominance. Non-dominating strategies are ranked equally. Since the rankings of *a.i.* and specific costs are almost similar, only the ranking for *a.i.* is presented. A difference in ranking by FSD due to an exchange between skilled and unskilled labour (strategies 2 and 3 on the one hand and 6 and 7 on the other) is notable. Furthermore, strategy 8 shows a clear substitution of *a.i.* for unskilled labour. The mean values for the specific costs are presented as well. Specific costs comprise costs for *a.i.* and costs for tractor operation (fuel, lubricants and maintenance). Farmers consider labour input (manual work in particular) as important aspects of weed control. Therefore, labour hours were not valued by the costs per hour and were not included in the 'specific costs'.

Table 4.8 Absolute values and rankings of the outcomes of weed control strategies under uncertainty.

	Active ingredient (a.i.)				Mean specific costs	Labour requirement					
	Mean	Ranking				Ranking of skilled labour			Ranking of unskilled labour		
Strategy	kg ha^{-1}	Mean	FSD	95%	NLG ha^{-1}	Mean	FSD	95%	Mean	FSD	95%
2	1.30	6.5[a]	6.5[a]	6.5	173	1.5[a]	1.5[a]	1	3	4.5	4a
3	1.32	6.5[a]	6.5[a]	6.5	175	1.5[a]	1.5[a]	2	4	4.5	4a
4	1.00	5	5	5	136	5	4	5	2	4.5	1
5	0.75	4	4[b]	4	104	4	4	3.5[a]	5	4.5	4a
6	0.45	3	3[b]	3	78	7	7	7	1	4.5	4a
7	0.32	2	2	2	56	6	6	6	6	4.5	4a
8	0	1	1	1	6	3	4	3.5[a]	7	7	7

FSD, first degree stochastic dominance

[a] Objects are very close and therefore ranked equally

[b] FSD dominance is valid when situations with very low use of a.i. are omitted

---

[17] Strategy 1 is not included because it is not a realistic strategy.

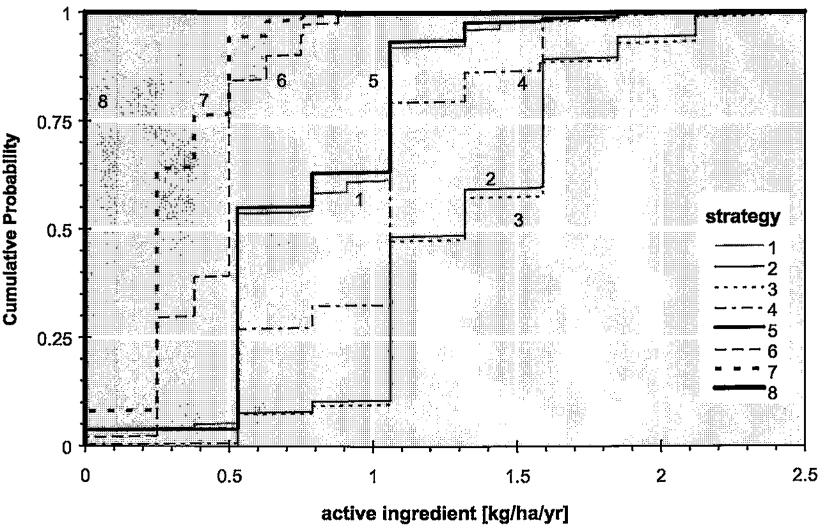


Figure 4.2 Cumulative frequency distribution function (CDF) for the use of active ingredient for eight weed control strategies.

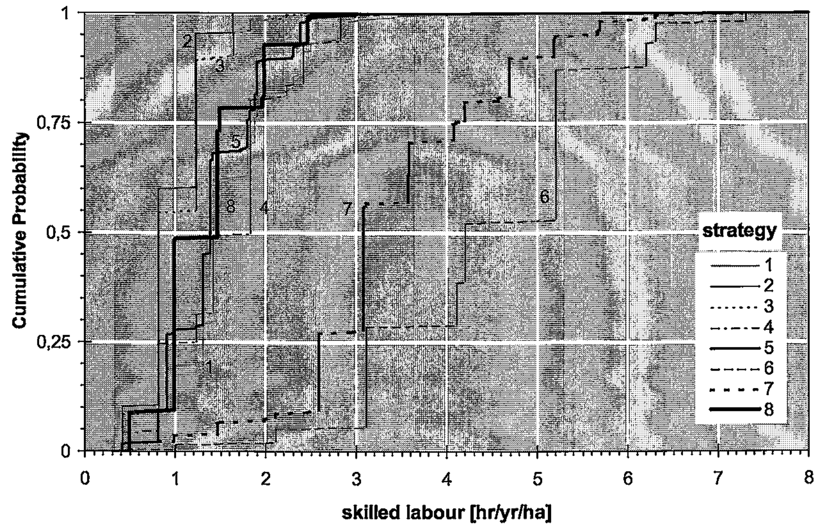
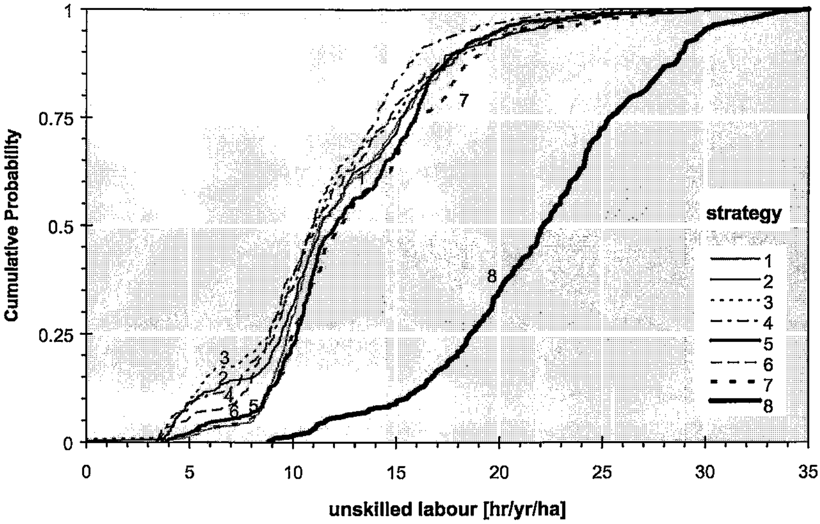


Figure 4.3 Cumulative frequency distribution function (CDF) for the requirement of skilled labour for eight wee control strategies.



Figuur 4.4 Cumulative frequency distribution function (CDF) for the requirement of unskilled labour for eight weed control strategies.

A sensitivity analysis was done for the price of pesticides (in NLG·ha^{-1}·kg *a.i.*) and the price of labour. The sensitivity analysis for pesticide price did not result in differences in the rankings as shown in Table 4.8. Doubling the price of *a.i.* had only a slight effect on the use of *a.i.* and consequently had an almost doubling effect on specific costs for the strategies 2-5. Specific costs of strategies 6 and 7 increase less because *a.i.* costs contribute relatively little in specific costs. Strategy 1 shows a considerable reduction (less than 50% however) because there is a maximum freedom of choice (especially a choice between chemical full field and row treatment), leading to a high sensitivity regarding the elements in the decision rule –the *e_c_ratio*. Strategies 2 and 4 show a small substitution of *a.i.* for unskilled labour only. Strategy 5 shows a lower value for the 95% point.

The rankings derived from the sensitivity analysis for the price of labour did not differ from the rankings in Table 4.8. Increasing the price for skilled labour from NLG 20 to NLG 38 per hour shows an increase in mean *a.i.* requirements (and hence specific costs) and especially in situations where the use of *a.i.* is already high (95% point). Together with a slight decrease in unskilled labour and an increase in skilled labour requirements, this indicates a switch to more herbicide treatments and less hand weeding. This substitution effect is most obvious (with respect to mean as well as the 95% point) for strategies 6 and 7, suggesting more possibilities for substituting handweeding in these strategies. Summarising, it would be possible to reduce handweeding by increasing the spraying frequency in all strategies (except strategy 8).

Investment costs (interest, depreciation, maintenance and insurance) for the various strategies are presented in Table 4.3. The lower specific costs of strategies 3 and 4 (compared to strategy

2) do not compensate for the extra investment costs of NLG 100 and NLG 117 respectively. Compared to strategy 1, where investment costs are very low, the extra fixed costs due to investments in row spray equipment eliminate the financial advantage of row spraying. However, when a hoe (with or without ridgers) is already present (strategy 3 or 4), the low specific costs after investment in a row sprayer (strategy 6) outweigh investment costs. Extra investment costs of a harrow are larger than the savings in specific costs. Strategy 6 is cost-extensive on specific costs as well as on investment costs.

4.4 Discussion and conclusions

The empirical bio-economic model BESTWINS determines financial, organisational and environmental stability of weed control in sugar beet. Combining agro-ecological and farm management knowledge into one model allows evaluation of the effects of weed control decisions on the weed-crop system and vice versa. Financial, organisational and environmental stability are calculated (costs, labour requirements and kg *a.i.* per ha. respectively) for different weed control strategies under all possible weather conditions. The primary goal of this study was to assess financial and organisational risk; cost effectiveness was maximised. Environmental sustainability was assessed by evaluating the herbicide requirements of cost efficient implementation of strategies differing in the possibilities of applying chemical and mechanic measures. This decision rule may be replaced with an *a.i.* minimising decision rule in order to assess minimisation of environmental impact. A similar approach can be used for other problems in IAFS, dealing with other crops and other types of husbandry activities. Husbandry problems with distinct strategies available are potential candidates for modelling. The distribution in labour requirements gives an indication of the organisational stability of a strategy. Organisational stability with respect to labour can only be fully assessed in a model of the whole farm organisation, where all crop husbandry problems and other farm-activities are integrated. This is the subject of current research.

The assumption of absence of competition during the weed control season suffices in the prevailing situation of intensive weed control. Therefore, weed-crop competition is not modelled in BESTWINS. As a consequence, the risk of running into intolerable weed populations –due to inadequate timing of applications for instance– cannot be assessed. Another property of BESTWINS is that the annual number of emerging weed plants appears to be a very sensitive parameter. Research on the relation between annual emergence and the action thresholds is necessary to make BESTWINS suitable for simulation with different seed bank sizes, resulting in different annual weed emergence.

Mechanical techniques applied in practice show that an excellent level of weed kill is possible. It is most important, however, to apply them at the right stage of weed development under good weather conditions. Unlike chemical measures, where the dose can be adapted to the size of the weed population, there are no good mechanical measures to ‘repair’ a failed mechanical weed control action within the crop rows which results in a lot of hand weeding. In a strategy based on row-spraying together with mechanical techniques, a harrowing operation that has failed can be repaired with a combination of hoeing and row-spraying with an adapted (higher) dosage.

One conclusion that can be drawn is that the lowest use of *a.i.* and the lowest specific costs are achieved by abandoning full field spraying. Just replacing a full field chemical device by row spray equipment reduces herbicide load and costs and lowers financial risk based on the 95% points of the statistical distribution (lower ranking of strategies 6 and 7 as compared to 2-5). Organisational risk (based on the 95% points for skilled labour), however, is higher.

A division between skilled and unskilled labour appeared to be useful, because strategies perform differently on both. Mechanical techniques that work full field are very attractive both because of cost reduction and reduction of skilled labour (one might save a field operation). Employing row spraying instead of full field spraying as well as introducing mechanical operations into a strategy increases the amount of skilled labour required and is also responsible for an increase in organisational risk (high rankings of the 95% points for skilled labour). Another obvious effect regarding labour is the high amount of unskilled labour for the organic strategy, but a relatively small risk for very high requirements.

As a signal to developers of new equipment, the bottleneck of the current full-field mechanical techniques relates to the weeks before the crop reaches its 4-leaf stage. During this most important period for weed control, none of the investigated techniques is available. A measure to overcome this problem is the use of a full-field chemical pre-emergence treatment, although this is obviously not an option on organic farms.

One can distinguish several potential policies to achieve a reduction in the use of pesticides: prohibition of the use of specific products, price-increasing measures (like a levy) and a maximum level of pesticide use, where necessary specified for the various components of the environment. Prohibition of herbicides will lead to a forced conversion to the 'organic' strategy. Model calculations show that especially the organisational stability (in this case a high labour demand in combination with high peaks) of 'organic' weed control is lower than in the other strategies.

BESTWINS mainly is developed as a research tool. It has the potential to support farmers and extention economists who consider a change in weed control strategy, by generating information on risks. For further use in our research project, BESTWINS has been made accesible with a user shell that presents outcomes in a way that appeals to farmers. Incorporation of other weed control strategies and techniques could be a way to enhance flexibility. Provided that effectiveness and conditions for application are known, BESTWINS provides opportunities to assess new techniques. The model could also be used as a source of information for policy makers on the relationships between weed control strategies, income effects and the potentials for reduction of pesticide use.

Acknowledgement

The model BESTWINS could not have been developed without the use of research results and practical experience. The authors are indebted to the following persons for the valuable judgements they made in the course of 1994 and 1995: C. Westerdijk, R.Y. Van der Weide, M.G. Verdonschot, J.R. Lubberink, and P. de Fouw (all working at PAV Lelystad) and J.D.A. Wevers (Sugar Beet Research Institute (IRS), Bergen op Zoom, The Netherlands). Further, the authors would like to acknowledge gratefully the constuctive comments of professor J.A. Renkema of the Department of Farm Management at the Wageningen Agricultural University as well as one anonymous reviewer.

References

Antle, J.M. and S.M. Capalbo (1993) Integrating economics and physical models for analyzing environmental effects of agricultural policy on nonpoint-source pollution. In: C.S. Russell and J.F. Shrogren (Eds.) *Theory, Modeling and Experience in the Management of Nonpoint-Source Pollution*, Boston MA: Kluwer, pp. 155-178.

Asselbergs,D.J.M., S. van Nierop, P.A. Oomen and P.F.J. Oostelbos, 1996. Gewasbeschermingsgids 1996. Plantenziektekundige Dienst, Wageningen, The Netherlands, 631 p.

Auld, B.A. and C.A.Tisdell (1987) Economic thresholds and response to uncertainty in weed control. *Agricultural Systems,* 25, 219-227.

Carlson, G.A and Wetzstein, M.E. (1993) Pesticides and Pest Management. In: (G.A. Carlson, D. Zilberman, and J.A. Miranowski, eds) *Agricultural and Environmental Resource Economics.* Oxford University Press, New York. pp. 221-267.

De Buck, A.J., E.M.T. Hendrix and H.B. Schoorlemmer (1999). Analysing production and environmental risks in arable farming systems: a mathematical approach. *European Journal of Operational Research* 119: 416-426.

Deen, W., A. Weersink, C.G. Tuvey and S. Weaver (1993) Weed control decision rules under uncertainty. *Review of Agricultural Economics,* 15, 41-50.

Doyle, C.J. (1997) A review of the use of models of weed control in Integrated Crop Protection. *Agriculture, Ecosystems and Environment,* 64, 165-172.

Goudriaan, J. and J.L. Monteith (1990) A mathematical function for crop growth based on light interception and leaf area expansion. *Annals of Botany,* 66, 695-701.

Groen, K.P. (1997) *Pesticide leaching in polders; field and model studies on cracked clays and loamy sand* PhD. dissertation, Wageningen Agricultural University, Wageningen, The Netherlands.

Hardaker, J.B., R.B.M. Huirne and J.R. Anderson (1997) Coping with risk in agriculture. *CAB International,* Oxon, New York, 274pp.

Headley, J.C. (1972) Defining an economic threshold. In: R.L. Metcalf (ed). Pest control strategies for the future. *National Academy of Science,* Washington D.C, pp. 100-108.

Johnson, S.L., R.M. Adams and G.M. Perry (1991) The on-farm cost of reducing groundwater pollution, *American Journal of Agricultural Economics,* 73, 1063-1073.

Kropff M.J. and L.A.P. Lotz (1992) System approaches to quantify crop-weed interactions and their application in weed management. *Agricultural Systems,* 40, 265-282.

Kropff M.J. and H.H. van Laar (1993) Modelling crop-weed interactions. *CAB International,* Oxon, 274pp.

Lybecker, D.W., E.E. Schweizer and R.P. King (1991) Weed management decisions in corn based bioeconomic modelling. *Weed Science,* 39, 124-129.

Marra, C.M. and G.A. Carlson (1983) An economic threshold model for weeds in soybeans (*Glycine max.*). *Weed Science,* 31, 604-609.

Olson, K.D. and V.R. Eidman (1992) A farmer's choice of weed control method and the impacts of policy and risk. *Review of Agricultural Economics,* 14, 125-137.

Roberts, W.S. and S.M. Swinton (1996) Economic methods for comparing alternative crop production systems: A review of the literature. *American Journal of Alternative Agriculture,* 11, 10-17.

Schoorlemmer, H.B., A.J. de Buck and G.A.A. Wossink (1994) Risk and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.E. Pedersen, J. Christensen and S. Rasmussen (Eds.) *Proceedings from the 38th EAAE Seminar "Farmers' decision making - a descriptive approach*", October 3-5 1994, Copenhagen, Denmark, pp.191-202.

Schweizer, E.E., D.W. Lybecker, L.J. Wiles and P. Westra (1993) Bio-economic weed management models in crop production. In: *International crop science 1. Crop Scientific Society of America*, Madison Wisc., D.R. Boxton, R. Schibes, R.A. Forsberg, B.L. Blad, K.H. Asay, G.M. Paulsen, R.F. Wilson, pp.103-107.

Sells, J.E. (1993) Calculating transition probabilities for modelling weed management options using stochastic dynamic programming. *Agricultural Systems,* 41, 41-52.

Sells, J.E. (1995) Optimizing weed management using stochastic dynamic programming to take account uncertain herbicide performance. *Agricultural Systems,* 48, 271-296.

Shribbs, J.M., E.E. Schweizer, L. Hergert and D.W. Lybecker (1990) Validation of four bio-economic weed management models for sugarbeet production. *Weed Science,* 38, 445-451.

Smit, A.B. and P.C. Struik (1995) PIEteR: a field-specific production model for sugar beet growing. *Journal of Agronomy and Crop Science,* 175: 335-348.

Somers B.M. and N. Röling (1993) *Kennisontwikkeling voor duurzame landbouw* (in Dutch). NRLO- rapport nr. 93/12. Nationale Raad voor het Landbouwkundig Onderzoek, Den Haag.

Spigt, R.M. and T.L.J. Janssen (1997) Kwantitatieve informatie akkerbouw en vollegrondsgroenteteelt. Publication nr.85, *Applied Research for Arable farming and Field production of Vegetables* (PAV), Lelystad.

Swinton, S.M and R.P. King (1994a) The value of pest information in a dynamic setting: the case of weed control. *American Journal of Agricultural Economics,* 76, 36-46.

Swinton, S.M. and R.P. King (1994b) A bio-economic model for weed management in corn and soybean. *Agricultural Systems,* 44, 313-335.

Taylor, C.R. and O.R. Burt (1984) Near-optimal management strategies for controlling wild oats in spring wheat. *American Journal of Agricultural Economics,* 66, 50-60.

Taylor, M.L., R.M. Adams and S.F. Miller (1992) Farm-level response to agricultural effluent control strategies: The case of the Willamette Valley. *Journal of Agricultural and Resource Economics,* 17, 173-185.

Teague, M.L., D.J. Bernardo and H.P. Mapp (1995) Farm-level economic analysis incorporating stochastic environmental risk assessment. *American Journal of Agricultural Economics,* 77, 8-19.

Vanclooster, M., P. Viaene, J. Diels and K. Christiaens (1994) WAVE: a mathematical model for simulating water and agrochemicals in the soil and vadose environment, reference and users manual (release 2.0). *Institute for land and water management*, Katholieke Universiteit Leuven, Leuven, Belgium.

Van den Brand, W.G.M. (1987) Opkomstperiodiciteit bij veertig eenjarige akkeronkruiden en enkele daarmee samenhangende onkruidbestrijdingsmaatregelen. *Gewasbescherming,* 18, 38-45.

Van der Weide, R.Y. (1993) Population dynamics and population control of *Gallium aparine* L. *PhD. dissertation, Wageningen Agricultural University*, Wageningen, The Netherlands.

Vereijken, P. and F.G. Wijnands (1990) Integrated agriculture into practice: strategy for farm and environment. (In Dutch) *Research Station for Arable Farming and Field Production of Vegetables*(PAGV) publication.50, Lelystad, The Netherlands, 85pp.

Westerdijk, C.E., R.Y. van der Weide and J.D.A. Wevers (1997) Integrated weed control (harrowing) in sugar beet. *Proceedings of the 60th IIRB congress*, july 1997, Cambridge, England.

Wierenga, B. and W.F. Van Raay (1987) Consumentengedrag: theorie, analyse en toepassingen. *H.E. Stenfert Kroese b.v.*, Leiden, Antwerpen, 291pp.

Wijnands F.G. and P. Vereijken (1992) Region-wise development of prototypes of integrated arable farming and outdoor horticulture. *Netherlands Journal of Agricultural Science*, 40, 225-238.

Wiles, L.J., R.P. King, E.E. Schweizer, D.W. Lybecker, S.M. Swinton (1996) General Weed Management Model. *Agricultural Systems*, 50, 355-376.

Wilkerson, G.G., S.A. Modena and H.D. Cable (1991) HERB: Decision model for postemergence weed control in soybean. *Agronomy Journal*, 83, 413-417.

Winter, S.R. and A.F. Wiese (1982) Economical control of weeds in sugarbeets (*Beta vulgaris*). *Weed Science*, 30, 620-623.

Wossink, G.A.A., A.J. de Buck, J.H. van Niejenhuis and H.C.M. Haverkamp (1997) Farmer perceptions of weed control techniques in sugarbeet. *Agricultural Systems*, 55, 409-423.

5 A bio-economic model for assessing the risks of Late Blight control strategies in ware potatoes

A.J. de Buck, H.B. Schoorlemmer[a] and G.A.A. Wossink[b]

Submitted to the *Journal of Agronomy and Crop Science*

Abstract

As Late Blight control in potatoes in The Netherlands is characterised by large amounts of fungicide, great variability between years and large risks, it hampers conversion to more sustainable arable farming. The Bio-Economic model of LAte Blight control Options and Risk (BELABOR) was developed and employed to investigate the risks in economic, environmental and epidemiological sense. Spraying with fungicides at fixed 7-day scheme versus spraying at variable intervals, that depend on whether conditions favour Late Blight, were compared for potato cultivars of different Late Blight resistance. The results showed that fungicide load was more dependent on weather conditions than on control strategy or cultivar. The most resistant cultivar investigated was found to offer the best possibilities to reduce fungicide costs, use of active ingredient and the frequency of both protective, curative and eradicant applications under the full range of conditions. With fixed intervals, a 'premium' was paid in the form of protective applications to preclude the risk on Late Blight infestation, which makes curative or eradicant applications necessary. By comparison, variable intervals combined far fewer protective low-dose applications with slightly more high-dose curatives; especially for a susceptible cultivar, a variable interval scheme showed a large probability of a large fungicide requirement, denoting a large environmental risk. Variable intervals showed a cost reduction, which was smallest with a susceptible cultivar.

Keywords: sustainable agriculture, risk management, Late Blight control, bio-economic model.

---

[a] *Applied Research for Arable farming and Field production of Vegetables (PAV), Lelystad, The Netherlands*

[b] *NC State University, Department of Agricultural and Resource Economics, Raleigh, NC, USA and Farm Management Group, Wageningen University*

5.1 Introduction

The arable farming sector accounts for about 70% of total pesticide use in Dutch agriculture (Oskam *et al.*, 1992). The Dutch government is committed to reducing pesticide use, and in its Multi Year Crop Protection Plan (MYCPP; see MJP-G, 1990) has set reduction targets for all categories of pesticide. In May 1993, representatives of the Dutch arable farming community signed an agreement that commits them to achieving these targets. The MYCPP target for fungicide use in 2000 in the agricultural sector is a 35% reduction in kg *a.i.*[18] (active ingredient). In ware potato growing, fungicide use must decrease from 13 to 8.5 kg *a.i.* ha^{-1}. Crucial for this commitment were the high expectations that Integrated Arable Farming Systems (IAFS), that are sustainable both environmentally and economically, would be developed and adopted by Dutch Farmers. Yet, though IAFS offer significant potential for reductions in pesticide use, the targeted reductions in fungicide use are proving difficult to accomplish: more than 5 years after the agreement, fungicide use had hardly changed (NEFYTO, 1994 and 1998).

The main cause for this high fungicide input in arable farming is to achieve Late Blight control in potatoes. This control is notable not only for the large volumes of fungicide used, but also for the large variation in fungicide use from one year to the next (Janssen, 1996); this variation reflects Late Blight's dependence on meteorological conditions. Most farmers know seriously that Late Blight can depress yield and quality (De Buck *et al.*, 2000b). These economic repercussions, coupled with the difficulty of predicting outbreaks of the disease, explain that farmers perceive that there is a high risk of Late Blight. Therefore, most farmers still apply fungicide intensive Late Blight control strategies. This makes Late Blight control a crucial factor in the conversion to more sustainable farming.

Integrated Arable Farming Systems (IAFS) and organic farming systems have been developed and compared in The Netherlands since 1979 (Wijnands and Vereijken, 1992). IAFS aim at environmental and agronomic sustainability by minimising the use of harmful inputs whereas organic systems use no synthetic chemical inputs at all. The latest IAFS strategies in Late Blight control use more sophisticated application criteria, lower dosages, and new, less polluting fungicides.

Farmers would more readily switch to IAFS if an objective comparison of the risks involved in different strategies for Late Blight control were available (Schoorlemmer *et al.*, 1994). This entails quantifying the risks envolved. The usual procedure for assessing new strategies in crop husbandry, including the evaluation of profitability, environmental impacts and stability, is by prototyping farming systems on an experimental station (Wijnands and Vereijken, 1992). But this is time consuming and costly because it implies long-term trials in which practices are

---

[18] The benchmark is pesticide use in The Netherlands from 1984 to 1988. The targets to be achieved in 2000 were expressed as a percentage of use in the reference period. The targeted reduction for fungicides for the entire agricultural sector was set at 35% (MJP-G, 1991).

continuously refined. Such trials are unlikely to provide sufficiently long time series of consistently executed strategies.

A cheaper and quicker alternative is to run simulations on a computer model that incorporates economic and physical interrelationships based on whole-farm research. Such a bio-economic model that integrates biophysical simulation with economic knowledge can be used to generate data (Antle and Capalbo, 1993), in our case to generate time series.

There are several Late Blight prediction models; see Duvauchelle (1993), Kluge and Gutsche (1990), Fry *et al.* (1983) and Schepers *et al.* (1995). These models are implemented as warning systems to help farmers tune the consecutive Late Blight sprayings on meteorological and epidemiological conditions. What we aimed to do was the comparison of the risks of different Late Blight control strategies. The variables within a strategy were the cultivated potato variety (*cv.*), a fixed versus a variable spraying interval scheme and the dosage of fungicides used. To account for all possible conditions that determine risks, the strategies were evaluated for a range of years. The strategies were compared on treatment costs, amount of fungicides used and the risk of a Late Blight infection. This paper describes how a model was developed, tested and used for the generation of time series on these parameters.

5.2 Materials and methods

This section presents the development of a Bio-Economic model of LAte Blight control Options and Risk (BELABOR); which was based on the Late Blight warning model of Fry *et al.* (1983). To understand BELABOR, this paper outlines the background to Late Blight control. Next, this section presents the theoretical concept, the implementation of this concept into BELABOR and the calibration and validation of BELABOR.

5.2.1 Background to Late Blight control

Late Blight development is characterised by complex interactions between stochastic weather conditions, the epidemiology of *Phytophthora infestans*, the efficacy of fungicide applications and cultivar resistance. Because the development and repercussions of the disease are imperfectly known, the recommended Late Blight control in The Netherlands includes a 'risk insurance' that tends to increase fungicide applications as a risk premium. A better understanding of how the disease develops would reduce the risk, and therefore the risk premium, which would reduce fungicide use (Schepers *et al.*, 1995).

The causal agent of Late Blight, *P. infestans*, overwinters mainly as mycelium inoculum in tubers or other parts of the potato plant. When circumstances become favourable, the mycelium grows and sporulation starts (Schepers *et al.*, 1995). The spores disperse readily through the air, spreading the infection. According to Fry *et al.* (1983), favourable conditions for infection are a long period (at least 6 hours) of wet canopy leaves and a moderate temperature (optimum between 12-23°C). The incubation period is four to five days (at temperatures between 15 and 20°C), after which Late Blight becomes visible as leaf lesions (Schepers *et al.*, 1995).

Good agricultural practice (*GAP*) in The Netherlands advocates Late Blight management starting with on-farm hygiene to prevent *P. infestans* inoculum surviving and multiplying and to preclude early infections. The recommended measures to minimise the incidence of Late Blight, particularly early in the season, are covering or destroying cull piles, destroying volunteer plants in other crops in the rotation, and planting certified seed.

The risks accompanying Late Blight control in The Netherlands depend on the epidemiological parameters that determine infection pressure and farmer's control activities. By applying hygienic measures as a part of GAP, an individual farmer can only partly reduce infection pressure. All the farmers in the neighbourhood have an equal influence on the infection pressure, given the high mobility of spores and the relatively small size of the Dutch farms (most Dutch arable farmers farm 30 to 50ha, of which almost 25% ware potatoes; LEI-DLO/CBS, 1998). The epidemiological conditions for the development of Late Blight depend largely on the weather and vary within and between growing seasons.

Despite farm hygiene, some potato plants may become infected and initiate a spread of *P. infestans* spores in the region ending the disease free period (Schepers *et al.*, 1995). From this moment on, a permanent infection pressure should be assumed for the rest of the season. There is no satisfactory way farms can measure the presence of spores. Therefore, they must protect the crop when circumstances favour the development of Late Blight. Protective fungicides block infection and sporulation by forming a layer on the leaves. The protection declines over time due to chemical degradation and wash-off by rainfall. So, repeated application of protective fungicides is necessary to maintain protection and avert infection. The rule of thumb is to apply the first treatment –which is protective– at closing of the crop canopy, because from then on the crop micro-climate will be increasingly moist (Schepers *et al.* 1995). A more accurate way to determine first application date is by gathering additional information on crop micro-climate and the incidence of Late Blight in the region. Delaying the first application helps to reduce total fungicide loads.

For optimal timing and dosage of Late Blight sprayings, a farmer can use specific weather data to estimate the severity of the conditions for Late Blight development and the remaining fungicide protection and he can observe the development of the crop canopy. Reducing the dosages to below the manufacturers' recommendations and spraying intervals of longer than the standard of one week will reduce total fungicide loads.

According to GAP, curative fungicides rather than protective fungicides should be sprayed if crop infection is suspected. Since this is still the incubation period, during which no symptoms are visible, the farmer relies on the rule of thumb of applying a curative fungicide within 48 hours after expiration of the protection provided by the last spray. If the delay exceeds 48 hours or when Late Blight is spotted in the field, an eradicant fungicide should be sprayed; its efficacy will depend on weather conditions and the degree of injury (Asselbergs, *et al.*, 1996). The disadvantage of curative and eradicant fungicides is that they contain large amounts of more harmful *a.i.* per application than protective fungicides (Asselbergs *et al.*, 1996). There is also a danger that frequent application of curatives and eradicants will cause to develop resistent pathotypes of *P. infestans* (Urech, 1994; Georgopoulos, 1994).

In The Netherlands the commercial, computerised OPTICROP and DACOM systems (Postma, 1995) can assist the farmer to gather relevant information on Late Blight development and can generate control advice. The advice comprises spraying date, fungicide dose and kind of fungicide to be applied. The costs of a local, field-based weather station and a management information software package were estimated at 1,000 NLG per year per farmer for purchase and maintenance, if the weather station is shared with other farmers. Assuming a potato area of 10 ha, this means 100 NLG ha^{-1} yearly costs.

A farmer can choose between several strategies to control Late Blight. A strategy can be seen as a set of decision rules for fungicide sprayings in the potato crop. An important determinant for a strategy is the accuracy of the estimation of the point of possible infection after the first application. A good accuracy, based on adequate information, allows a strategy with variable intervals or dosages instead of a fixed, calendar-based schedule with a fixed dosage.

Fungicide input on the individual farm can be reduced appreciably by choosing a more resistant potato cultivar, postponing the first treatment, and varying spraying intervals and dosages. Variable interval schemes have been investigated since the outset of IAFS research (Wijnands and Vereijken, 1992), yet few farmers actually apply them. Most farmers who save on fungicides, use variable dosages at fixed interval schemes (Janssen, 1996), probably because this requires less planning or because they percieve a lower risk of a Late Blight outbreak.

5.2.2 Conceptual model

Economic rationality in pest control recommendations starts with the standard economic optimisation framework based on marginal conditions. The biological interactions between disease, crop and control measure causes Late Blight control in a potato crop to have features that differ from marginal input use patterns. Instead, a breakeven criterion is used (Carlson and Wetzstein, 1993). A similar approach is used for weed management (De Buck *et al.*, 1999b; Deen *et al.*, 1993). For each control measure, the breakeven criterion reduces the decision to a binary one of either no treatment, or, if a certain threshold value is exceed, treatment at a fixed dosage (Headley, 1972; Wossink and Rossing, 1998). The threshold is called the Economic Injury Level (EIL). It represents the point prior to treatment at which yield damage caused by pest incidence equals the total costs of pest control. In our model, control measures were implemented at certain thresholds before the EIL is reached, to take account of time lags in farming practice (as described in Wossink and Rossing, 1998).

Figure 5.1 illustrates the multi-period concept of the model we used, with stages j ($j = 1, .., J$) and the relations between the processes and data requirements. In one stage, one cycle is completed. For a given stage j, the state S_j of the system can be represented as the result of four processes: (1) introduction of first infection; (2) weather-dependent diminishing of fungicidal protection against Late Blight; (3) weather-dependent development of Late Blight and (4) collection of information, followed by decision making according to a strategy. Let S_j be described by a vector of state variables; representing the disease free period, the severity of the conditions for Late Blight development (severity value), the remaining fungicidal protection (protection grade) and the delay (in number of days; is not included in Figure 5.1) since a protective fungicide should have been applied. In BELABOR, a threshold value for the moment of first infection determined the first spraying; thresholds for severity value and protection grade determined the timing of consecutive protective sprayings and the duration of the delay of a protective spraying determined the type of fungicide to spray.

BELABOR simulated the decision process separately for each strategy. Conceptually, a strategy is a multi-year design with respect to the organisation of crop husbandry on the farm according to decision rules, determining for instance the equipment needed on the farm and the planning of labour supply and demand (De Buck *et al.*, 1999a). A strategy for Late Blight control is a component of the whole farm strategy for crop husbandry. Examples of other components include weed control in sugar beet (De Buck *et al.*, 1999b) and nutrient management (De Buck *et al.*, 2000a).

Based on the state S_j, at each stage j a decision x is made: see box 4 in Figure 5.1. Costs p and requirements for inputs a (herbicide use, for instance) are attributes of the control decision x.

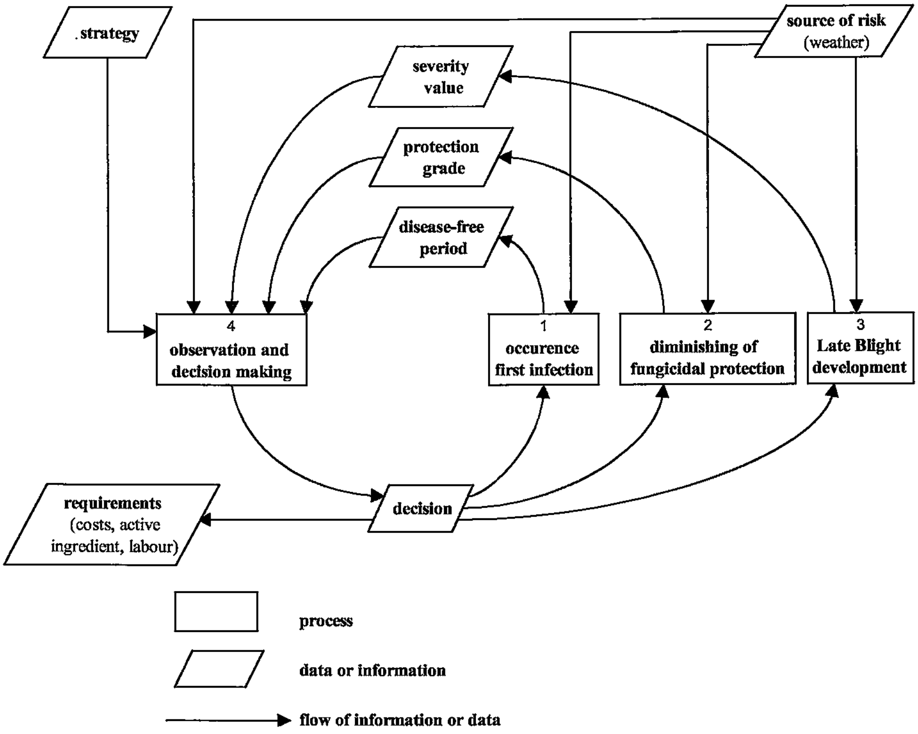


Figure 5.1 Conceptual model of Late Blight control in potatoes.

The optimal multi-period solution is the sequence of J decisions x with minimal costs c of execution (that is the economic objective function; see De Buck *et al.*, 1999a):

$$c = \min \sum_{i=1}^{I} \sum_{j=1}^{J} \left(p_{i,j} \cdot a_{i,j}\right) \qquad (5.1)$$
$$\text{with } a_{i,j}\left(x, S_j\right),$$

where $p_{i,j}$ denotes the price times the number of units $a_{i,j}$ needed of input i at stage j. Breakeven criteria determine the input of $a_{i,j}$ and, hence, minimal costs of execution. If environmental concern is the objective, Equation 5.1 must be replaced by minimisation of the total use of fungicides (in kg *a.i.*) over all stages j.

The state S_j is subject to uncertainty caused by stochastic weather conditions. Risk is introduced via stochastic weather conditions ξ (Equation 5.2). In Equation 5.2, the transition function τ –or equation of motion– updates situation S_j and the Late Blight control decision x to the next period (S_{j+1}):

$$S_{j+1} = \tau\left(S_j, x, \xi\right). \qquad (5.2)$$

Equation 5.2 describes the cumulating severity value and protection grade that are restored by a fungicide application. This control efficacy was assumed to be deterministic.

The Cumulative Distribution Function (CDF) is represented by:

$$\mathrm{F}(A_i) = \mathrm{P}(a_i \leq A_i)$$
$$\text{with } a_i = \sum_{j=1}^{J} a_{i,j}. \qquad (5.3)$$

From Equations 5.1 and 5.2 it follows that $a_{i,j}$ depends on the stochastic parameter ξ. Realisations ξ_t of parameter ξ, based on existing weather scenarios T $(t = 1,\ldots,T)$ can now be used to determine values of $\sum_{j=1}^{J} a_{i,j,t}$.

Hence, the CDF is approximated by:

$$\mathrm{F}(A_i) = \mathrm{freq}\left(\sum_{j=1}^{J} a_{i,j,t} \leq A_i\right) \cdot T^{-1} \qquad (5.4)$$

BELABOR was intended to enable comparison of the outcomes of the strategies under different weather scenarios. The outcomes of a strategy were the statistical value distributions of costs, use of *a.i.*, number of fungicide sprayings and labour required. The different kinds of outcomes were analysed without giving any subjective weight to these outcomes.

5.2.3 BELABOR: a bio-economic model for Late Blight control

How BELABOR calculates

BELABOR has been programmed in Borland Pascal 7.0 on a PC. The core of the model was the iterative feedback procedure (Figure 5.1) between decision-making (process 4) and the processes of 'first infection' (1), 'fungicidal protection' (2) and 'Late Blight development' (3) for cycles of one day. The processes 2 and 3 were modelled according to Fry *et al.* (1983). The first and the last cycle were determined by fixed planting and harvest dates. BELABOR was used to simulate the strategies one by one for 17 seasons[19] representing a range of conditions, which were assumed to represent all possible meteorological scenarios for the Flevopolder area of The Netherlands.

Simulation of first infection

The moment of first fungicide application, which coincides with the end of the disease-free period, was identified by the moment of canopy closing (Asselbergs *et al.*, 1996). BELABOR calculated canopy covering with the potato growth model developed by Spitters (1987), that is based on the T-sum.

Simulation of protection grade

BELABOR measured the decline in Late Blight protection (protection grade) since the most recent fungicide application in *fungicide units* (according to Fry *et al.* 1983). The protective value of a fungicide spraying decreases over time: every day the *fungicide units* increase with one unit. Note that a *large* amount of *fungicide units* means a *low* grade of protection. The protective value also decreases as a result of wash-off by rainfall; the decrease can result in as much as 7 units, over and above the fixed daily increase of 1 unit. The effect of rainfall on *fungicide units* decreases with increasing interval length. *Fungicide units* at stage j are updated to stage $j+1$, according to Equation 5.2 (in the case of *fungicide units*, ξ was represented by daily rainfall).

More *fungicide units* are allowed to accumulate if the potato cultivar has a higher resistance index. The cultivars considered in our research were Bintje (resistance index = 3 on a scale of 1-10 [Ebskamp and Bonthuis, 1997]), Agria (index = 5.5) and Texla (index = 8.5). The threshold levels of fungicide units for these three cultivars were initially taken from Fry *et al.* (1983) for susceptible, moderately susceptible and moderately resistant cultivars respectively and were modified during model calibration.

---

[19] The meteorological data used in this research was acquired from the Dutch Royal Meteorological Institute, De Bilt, The Netherlands; supplemented with data from the Department of Meteorology of WAU and from PAV, Lelystad, The Netherlands. The data consist of the parameters of minimum and maximum temperature and precipitation on a daily basis and temperature and relative humidity on an hourly basis; recorded at various locations in Flevopolder (The Netherlands) for the years 1981-1997.

Simulation of Late Blight development

Fry *et al.* (1983) introduce *blight units* as a measure of favourability of weather circumstances for the development of *P. infestans*. *Blight units* account for temperature (optimum is between 12°C and 23°C) and the duration of leaf wetness required for *P. infestans* to develop (the minimum is 6 hours). Following Fry *et al.* (1983), in BELABOR, leaf wetness was estimated as the number of hours with relative humidity ≥ 90% (measured at 1.5m height). The amount of *blight units* per day for a moderately resistant, a moderately susceptible and a susceptible cultivar, respectively ranged from zero to a maximum of 5, 6 and 7. As with *fungicide units, blight units* were updated according to Equation 5.2 (ξ was represented by temperature and number of hours with relative humidity ≥ 90%).

Hence, *blight units* and *fungicide units* both trigger fungicide application independently: with a variable interval scheme, a next protective fungicide is advised when a cultivar-specific threshold for *blight units* (*blimax*) **or** *fungicide units* (*funmax*) is reached. Late Blight resistance of a cultivar is accounted for by a slower daily accumulation of *blight units* and higher *blimax* and *funmax* levels than susceptible cultivars.

Observation and decision making

Six strategies for Late Blight control were possible in BELABOR: a fixed and a variable application interval scheme applied with 3 *cvs*. (Table 5.1).

Table 5.1 Modelled strategies in Late Blight control, distinguished by *cv.* and *spraying interval*.

Strategy	*Cultivar*	Late Blight resistance	*Spraying interval*	Fixed costs of investment NLG ha^{-1} $year^{-1}$
1	**Bintje**	susceptible	**fixed**	0
2	**Bintje**	„	**variable**	100
3	**Agria**	moderately susceptible	**fixed**	0
4	**Agria**	„	**variable**	100
5	**Texla**	moderately resistant	**fixed**	0
6	**Texla**	„	**variable**	100

Figure 5.2 explains the *black box* of "observation and decision making" in Figure 5.1 for a cycle of one day. The first step in the decision was to determine the number of days since the last application. A new application was only considered if that interval exceeded 5 days. EIL was reached when *blight units* equalled *blimax* **or** when *fungicide units* equalled *funmax*. In order to simulate the farmers' anticipation of unfavourable spraying conditions[20], the application of a protective fungicide was triggered at 0.8·EIL in strategies 2, 4, and 6; provided

---

[20] In BELABOR, pF values are used to determine the trafficability of the soil for tractor operations. Daily precipitation and soil physical parameters representative of the situation in the Dutch Flevopolders were used. pF values, are calculated with the water movement module of the model for Water and Agrochemicals in the soil, crop and Vadose Environment (Vanclooster, 1994). Spraying is considered to be impossible when $pF < 1.8$.

that conditions for application are good. In Fry *et al.* (1983) an application is triggered at 1·EIL, regardless of the conditions for spraying. For strategies 1, 3 and 5 with a fixed interval, an interval of 7 days long triggered necessity of an application (shaded part in Figure 5.2).

A delay of one or two days, due to bad weather conditions, leaded to the application of a curative fungicide. A maximum permitted delay of three days was assumed; followed by an eradicant application, regardless of the weather conditions assumed in BELABOR. Protective, curative and eradicant fungicides were assumed to have the same protective characteristics.

Calibration and validation

As the Late Blight warning model of Fry *et al.* (1983) was divised for the agronomic and meteorological conditions of the State of New York, USA, BELABOR had to be calibrated for the situation in The Netherlands. The model was calibrated on spraying dates by adjusting the thresholds for *blight units* and *fungicide units* and was then tested for each cultivar, using field-specific weather data[21].

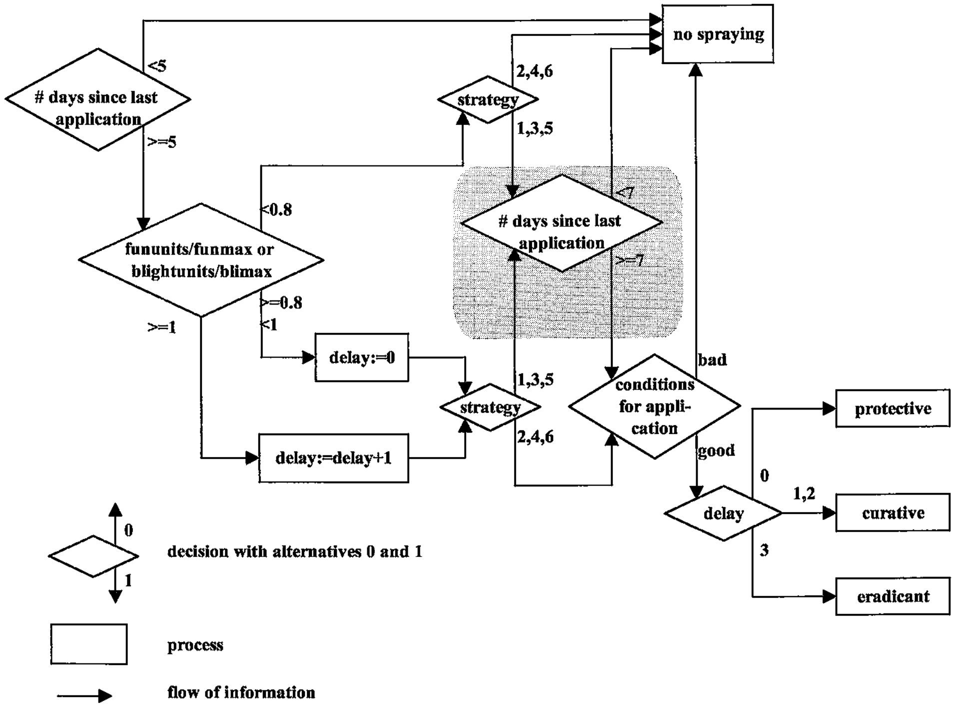


Figure 5.2 Decision process for six strategies of Late Blight control.

The data used for the calibration came from field trials on *cvs*. Bintje, Agria and Texla during 1993-1995 at two locations with variable spraying interval schemes (Ridder and Bus, 1994a, 1994b, 1995-1996a, 1995-1996b). A commercial, computerised warning model (by Opticrop) was employed to determine spraying dates in these trials. None of the trials became infected with *P. infestans* and only protective fungicides were applied. Our model was calibrated to show spraying intervals that are similar to those in the corresponding field trial. Hence, BELABOR was calibrated to obtain the same safety –no infection– as achieved in the experiment. As in the experiments, in BELABOR, the doses of protective fungicide were adjusted in accordance with the cultivar. Table 5.2 shows the attributes of the various decisions that were included in BELABOR. According to the findings of the calibration, a dose of 0.15 kg ha^{-1} of protective fungicide was applied to susceptible (in this case *cv.* Bintje) and moderately tolerant (*cv.* Agria) cultivars, while moderately resistant cultivars (*cv.* Texla) received 0.10 kg ha^{-1}. BELABOR could not be calibrated for the situation where curative and eradicant sprayings were necessary.

Table 5.2 Fungicide type, loads of active ingredient and fungicide costs of the various decisions in Late Blight control.

Decision	Requirements				
	Fungicide				Labour[c]
	Name	Type	Active ingredient[b] kg ha^{-1}	Costs[a] NLG ha^{-1}	h ha^{-1}
1	fluazinam	protective	0.15	34.5	0.40
2	fluazinam	protective	0.10	23.0	0.40
3	cymoxanil	curative	1.88	45.0	0.40
4	metalalyx	eradicant	0.99	60.0	0.40
5	no spraying	-	0.00	0.0	0.00

Janssen (1996), Asselbergs *et. al* (1996), Spigt and Jansen (1997)

During calibration, it was remarkable, that at the beginning of the control season, the simulated spraying frequency tended to be longer than in the experimental trials. Further, at the end of the control season, BELABOR simulated a few intervals of three days. This very high spraying was not found in the corresponding field trials. Hence, a minimum interval of 5 days was introduced in BELABOR, which coincided with the shortest intervals in the calibration material as well as with farming practice.

Data from four years of trials of Late Blight management (1991-1994) on whole-farm scale, carried out at PAV, Lelystad, The Netherlands, was used for validation. One strategy with *cv.* Agria and a variable spraying interval was available. As no field specific weather data had been recorded, we used data from nearby meteorological stations. A major outcome of the validation was that (as was the case with the calibration) the first intervals predicted by BELABOR tended to be longer, resulting in 1 or 2 predicted sprayings less than the 10-13

---

[21] The hourly registrations of temperature and relative humidity (both measured in the canopy of the various trials) and precipitation were kindly made available by Opticrop, Vijfhuizen, The Netherlands.

sprayings per season in the PAV trials[22]. Generally, the predicted number of curative and eradicant sprayings was higher than in the validation material.

From the calibration and validation, we concluded that BELABOR was suitable to describe a possible situation of Late Blight control in a potato field, representative of the Flevopolder area in The Netherlands. This was sufficient for our purpose. The fact that BELABOR's predictive value for a specific field is probably insufficient was not important for this particular study. Field specific recommendations would require a model that can handle actual field crop observations.

5.3 Results

Figure 5.3 shows the number of protective, curative and eradicant fungicide applications after simulation for 17 seasons (n = 17) as a group of histograms for each strategy. The probability distributions of total (summed for each season) fungicide costs and total requirements of *a.i.* are represented as CDFs. (Figure 5.4). In addition to graphic representation, Table 5.3 presents average frequencies of the number of applications of the various types of fungicides, as well as averages and rankings of FSD in terms of labour requirement and fungicide use (amount of *a.i.* and costs).

Table 5.3 Characteristics of the probability distributions of the simulated outcomes for six Late Blight strategies regarding labour requirement and parameters, linked with fungicide use.

Strategy	Labour requirement	Active ingredient use			
		Amount		Costs	
	average h ha^{-1}	average kg ha^{-1}	ranking[a] FSD	average NLG ha^{-1}	ranking[a] FSD
1	4.2	4.0	BC	393	D
2	3.5	4.4	C	337	C
3	4.5	3.8	B	417	E
4	3.2	3.8	B	307	B
5	4.5	2.3	A	288	B
6	2.7	2.7	A	203	A

An 'A' as ranking stands for the best score; an 'E' for the worst

---

[22] On the practical trial, two extreme short intervals of three days were applied. The fungicides used in these two applications (cymoxanil/mancozeb and maneb/fentin-acetate) were considered as one compound with a curative effect (Asselbergs *et al.*, 1996).

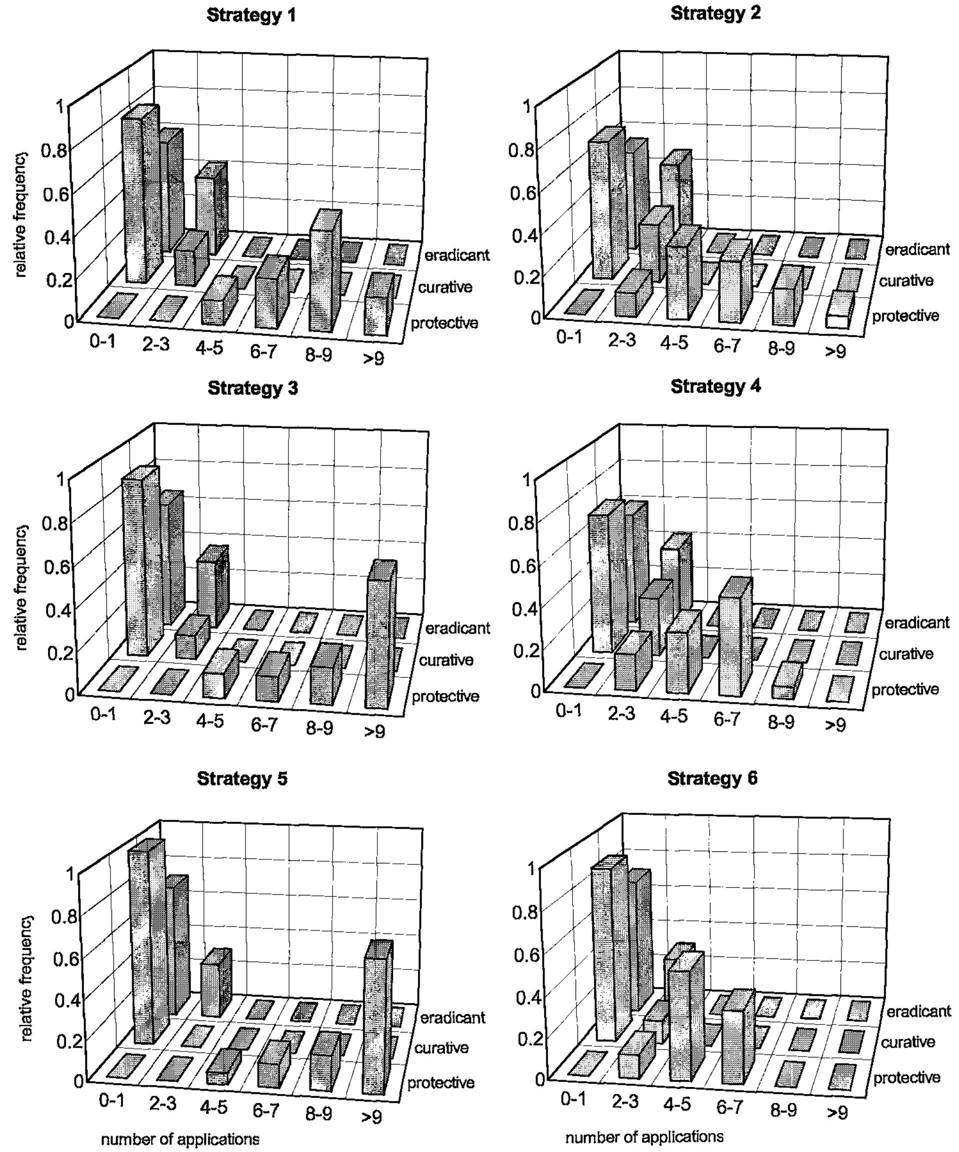


Figure 5.3 Relative frequency distributions (n = 17) of the number of protective, curative and eradicant fungicide applications for six Late Blight control strategies.

The use of *a.i.* ranged from approximately 1.5 kg ha^{-1} in a year with good contitions to 7 kg ha^{-1} in a year with unfavourable conditions (Figure 5.4). Hence, stochastic weather conditions strongly limited the controllability of fungicide load by strategy choice. Comparatively, costs show less yearly variation and large differences between strategies.

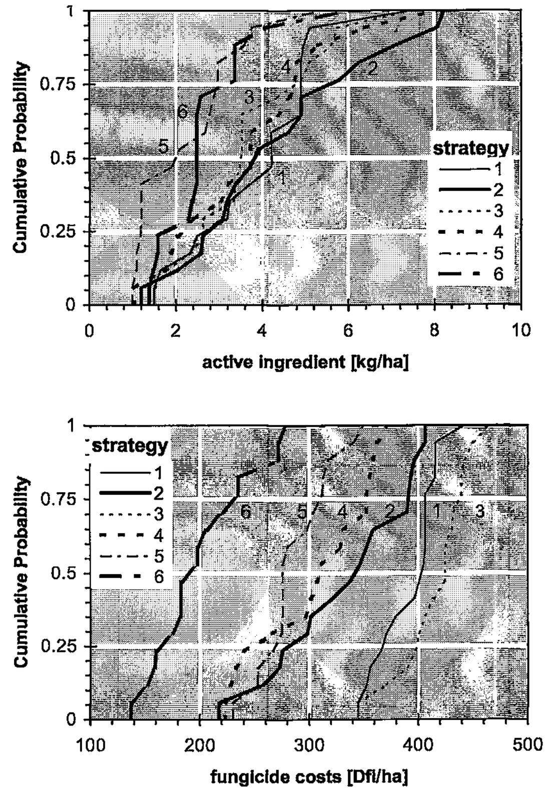


Figure 5.4 CDFs for the use of active ingredient and fungicide costs for six Late Blight control strategies.

The total number of sprayings decreased when a variable interval is used (Table 5.4). The growing season of *cvs.* Agria and Texla was 10 days longer than that of *cv.* Bintje, which is why these cultivars required more fungicide sprayings at fixed intervals compared with *cv.* Bintje. With variable interval lengths, moderately resistant *cv.* Texla showed a larger reduction in the number of applications than the other cultivars. These small numbers of simulated sprayings were due to the fewer protective applications, rather than curative and eradicant applications (see also Figure 5.3).

Table 5.4 Average number of simulated annual sprayings per type of fungicide for six Late Blight control strategies.

Strategy	Average number of sprayings (standard deviation)			
	Protective	Curative	Eradicant	Total
1	8.2	0.8	1.2	10.2 (0.8)
2	6.0	1.2	1.2	8.5 (1.5)
3	9.2	0.7	1.1	11.1 (1.0)
4	5.5	0.9	1.2	7.7 (1.3)
5	9.8	0.2	0.9	10.9 (1.2)
6	4.9	0.6	1.0	6.6 (0.9)

It was assumed that the required number of eradicant and –to a lesser extent– curative applications are positively correlated with the risk on a Late Blight infection (or: epidemiological risks). *Cv.* Texla, with fixed and variable intervals (strategies 5 and 6) required fewer eradicant and curative sprayings than *cv.* Bintje (this is less clear for *cv.* Agria). Hence, strategies based on more resistant cultivars were less risky. Compared with variable intervals, a fixed interval scheme showed risk reduction by a high number of protective sprayings. This can be seen as a 'risk premium'. The average 'risk premium' of 4.9 protective applications for *cv.* Texla, 3.7 for *cv.* Agria and 2.2 for *cv.* Bintje resulted in approximately 0.5 less curative and eradicant sprayings.

Amounts per application of eradicant and curative fungicides, especially the latter, were remarkably large (Table 5.2). Compared to a variable interval scheme, with fewer protective treatments and (slightly) more curative and eradicant applications, resulted in an increase in *a.i.* use (except for *cv.* Agria). For *cv.* Bintje, a variable interval scheme also showed a relatively (compared to a fixed interval) large probability of heavy *a.i.* input (Figure 5.4), denoting a large environmental risk.

Number of applications was proportional to labour requirement (Table 5.3 and 5.4), because the various fungicide applications have equal labour requirements (Table 5.2). As the CDFs for labour requirement can be deduced from Figure 5.3, they are not presented here.

The rankings of the CDF's on fungicide use (Figure 5.4) show that over the full range of conditions, there was an obvious reducing effect of Late Blight resistance on amount of fungicides used. Compared with *cv.* Agria, *cv.* Texla showed reductions of the average fungicide use for fixed and variable intervals respectively of 1.5 and 1.1 kg ha^{-1} $year^{-1}$. The low dose of protective fungicides for *cv.* Texla (0.10 kg ha^{-1} instead of 0.15 kg ha^{-1} for the other *cvs.*) contributed to this small fungicide input with respectively 0.5[23] and 0.2 kg ha^{-1} $year^{-1}$ for fixed and variable intervals. Fungicide costs were much lower for *cv.* Texla, compared to all other *cvs*. For all *cvs*, a variable interval scheme resulted in lower costs compared to fixed intervals.

---

[23] An average of 9.8 sprayings per year at (0.15 - 0.10 =) 0.05 kg ha^{-1} *a.i.* per application.

Fungicide costs for the fixed interval scheme with *cv.* Agria and *cv.* Bintje (strategies 1 and 3) were higher than for the other strategies. Figure 5.4 shows that this was most obvious under favourable conditions for Late Blight (the first quartile of the distribution, for instance). Moderately resistant *cv.* Texla offered the best opportunities for combining both low costs and small amounts of *a.i.* under the full range of conditions. Only with *cv.* Agria did the yearly reduction in pesticide costs of a strategy with a variable interval compensate for the 100 NLG of extra investment costs (Table 5.1).

5.4 Discussion

This paper describes the use of bio-economic modelling to generate a time series, that is representative of all possible weather conditions. The construction of a bio-economic model leans heavily on combining the results from field trials with expert knowledge. The availability of both meteorological and field-trial data of appropriate detail and for a certain time-span is essential in the building, calibration and validation phases of such a model and should be considered carefully in advance. Dutch farmers have switched to a system of fixed intervals in combination with variable dosages (Janssen, 1996). This could be a strategy in BELABOR as well, but no data were available for calibration.

The assumption that no yield loss would occur –as a part of GAP– excluded a large number of possible states in BELABOR. BELABOR did not go beyond a delay of application of more than 3 days, after which favourable conditions for Late Blight are more likely to lead to serious damage. Epidemiological risks were deduced from the frequency of curative and eradicant applications. Epidemiological risks would be assessed more adequately by incorporation of more knowledge on the epidemic of Late Blight, preferably in commercial crops. Environmental risks were assesed by considering peak loads in *a.i.*. Considering harmfulness of the fungicides used would provide more detail.

Validation with the available data showed that BELABOR was suitable for our purpose: it adequately predicted variation between years in the number of applications. The lack of sufficiently detailed material obstructed the validation of the distinction between the use of the different types of fungicides The number of curative and eradicant applications according to a generally applied rule of thumb seemed to be over-estimated (compared to the validation material)..

The Dutch government's long-term strategy for reducing pesticide use (MJP-G, 1991) aims to achieve a maximum average fungicide use of 8.5 kg ha^{-1} $year^{-1}$ in 2000. Our results indicate that fungicide use achieved by all strategies we considered will comply with this limit, even under unfavourable conditions. This small fungicide input is mainly achieved by using the protective fungicide 'fluazinam', which requires only very low doses compared to compounds containing 'maneb' (requiring 1.0 kg ha^{-1} *a.i.* per application; Asselbergs *et al.*, 1996). Hence, a shift in the arable sector from products containing 'maneb' to those containing 'fluazinam' would reduce average *a.i.* use in Late Blight control considerably (Janssen, 1996). Unlike in this research, in Janssen (1996), heavy fungicide loads could be due to non-optimal Late

Blight control (that is not according to GAP). A large variation in fungicide use over years (about 400%), however, was also found in this research. The main way to further reduce both average and peak levels of fungicide input, was to opt for more resistant cultivars, which also reduced epidemiological risks.

With fixed spraying intervals, a 'risk premium' in the form of protective sprayings was paid to reduce the number of curative and eradicant sprayings. Especially for the susceptible cultivar, the results did not show that a variable interval was a good option to reduce fungicide load. The main cause for this result was the larger average requirement for curative fungicides with a variable interval scheme; curatives are applied at an *a.i.* concentration which is more than ten times the concentration of a protective fungicide. The application of curatives and eradicants, according to rules of thumb from farming practice, was not validated in BELABOR. These simulated numbers were expected to be over-estimated, as in the model, the conditions for the development of Late Blight when the crop is unprotected were assumed to be favourable. This over-estimation weighs heaviest for strategies with variable intervals, as they required more curative sprayings than strategies with fixed intervals. Conclusively, next to the choice for a more resistant cultivar, a change from a fixed to a variable interval offered possibilities for reducing protective applications. Cautious observation of the conditions for Late Blight should prevent epidemiological risks and high costs and heavy fungicide loads of eradicant and curative applications.

In the validation material, the doses of fluazinam were lower than recommended by Asselbergs *et al.* (0.20 kg *a.i.* ha^{-1} $application^{-1}$) but were equally effective. In BELABOR, the doses of 0.15, 0.15 and 0.10 were adopted for *cv.* Bintje, *cv.* Agria and *cv.* Texla respectively. However, the years in which the validation experiments were carried out, showed little infection pressure for Late Blight. In years with a higher infection pressure, the reduced doses might not protect the crop sufficiently. During the last years, a more aggressive genotype of *P. infestans* has been emerged. Application in BELABOR of full doses, as recommended by Asselbergs *et al.* (1996), to reduce the epidemiological risks that might arise, would increase the average fungicide use for all strategies (to a level that still is below the MYCPP limit), without changing the various rankings in outcomes.

A major obstruction hampering the switch to alternative cultivars is the uncertainty of the agronomic and post-harvest properties and market uncertainties of these cultivars. Besides, cultivar choice is mainly determined by resistance to Potato Cyst Nematodes *(Globodera spp.)* and this does not always go together with Late Blight resistance. Variation in price and post-harvest properties make strategies with alternative cultivars more uncertain than strategies with conventional cultivars (Smidts, 1990). A relatively small price difference of 0.01 NLG kg^{-1} results in a yield difference[24] of 500 NLG ha^{-1}; which is much larger than the maximum reduction in costs between Late Blight control strategies. When alternative cultivars will be grown as an answer to rotational problems, the dependency of the potato marked on these

---

[24] A price of NLG 0.20 and a yield of 50,000 kg ha^{-1} are assumed (Spigt and Janssen, 1997).

cultivars is likely to increase. This will enhance a stable market and ditto prices. A large marked for alternative cultivars will increase experience and knowledge, which will take away some agronomic and post-harvest uncertainties.

To avoid the marketing risks, most farmers grow a conventional –susceptible– cultivar, possibly next to alternative –tolerant– cultivars. Working with different spraying frequencies for different cultivars on the farm is found too complicated. So, most farmers adjust their fungicide sprayings to the most susceptible cultivar on the farm; not using the potential of more resistant cultivars to reduce spraying frequency. Another complication brought about by a variable interval scheme is that some farmers do not work on Sundays for religious reasons. Such considerations might explain the broader dissemination of fixed interval schemes with adapted doses instead of variable intervals.

5.5 Conclusions

Growing a more resistant cultivar not only offered opportunities in cutting down average load of fungicide input for Late Blight control; also peak levels in fungicide input in unfavourable years (denoting a high environmental risk) were reduced. A more resistant cultivar was a safe option to reduce fungicide loads, as epidemiological risks were lower.

In a scheme with fixed spraying intervals, protective sprayings partly serve as a risk premium to avoid situations that require eradicant and curative sprayings. On average, with a variable scheme, 2.2 to 4.9 less protective sprayings resulted in 0.5 more eradicant and curative applications. In addition, a variable scheme requires cautious observation of the conditions for Late Blight to prevent heavy loads of eradicant and curative fungicides –pointing at high epidemiological and environmental risks– and high costs.

A variable spraying interval scheme, applied on the most resistant cultivar in the study (*cv.* Texla) showed lowest fungicide costs for Late Blight control. Under the full range of simulated conditions, these costs were approximately 210 NLG ha^{-1} lower than the most expensive strategy (*cv.* Agria with a fixed interval). A variable interval scheme was more profitable on more resistant cultivars. The savings on fungicide costs of a variable scheme did only occasionally compensate for the extra investment costs involved.

Acknowledgments

The authors are indebted to H.T.A.M. Schepers, C.D. van Loon, W.A. Dekkers and F.G. Wijnands of PAV (Applied Research for Arable Farming and Field Production of Vegetables) as well as D. Spijkerboer and H.J. Schouten of Plant Research International) for their contributions to the research and their comments on this paper.

References

Asselbergs, D.J.M., S. van Nierop, P.A. Oomen and P.F.J. Oostelbos, 1996. Gewasbeschermingsgids 1996. Plantenziektekundige Dienst, Wageningen, The Netherlands, 631 pp.

Antle, J. and S. Capalbo, 1993. Integrating economics and physical models for analyzing environmental effects of agricultural policy on nonpoint-source pollution. In: C.S. Russell and J.F. Shrogren (eds.) *Theory, Modeling and Experience in the Management of Nonpoint-Source Pollution* Boston MA: Kluwer, pp. 155-178.

De Buck, A.J., E.M.T. Hendrix and H.B. Schoorlemmer, 1999a. Analysing production and environmental risks in arable farming systems: a mathematical approach. *European Journal of Operational Research* 119: 416-426.

De Buck, A.J., H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens, 1999b. Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model. *Agricultural Systems* 59: 283-299.

De Buck, A.J., A.B. Smit, T.J. De Koeijer, O. Oenema and J. Oenema, 2000a. Risks and environmental sustainability of strategies in nitrogen management with or without manure in potato growing. (submitted).

De Buck A.J., I. van Rijn, N.G. Röling, and G.A.A. Wossink, 2000b. Farmers' reasons for changing or not changing to more sustainable practices: an exploratory study of arable farming in the Netherlands. (submitted).

Carlson, G.A and M.E. Wetzstein, 1993. Pesticides and Pest Management. In: G.A. Carlson, D. Zilberman, and J.A. Miranowski (eds.) *Agricultural and Environmental Resource Economics.* Oxford University Press, New York. pp. 221-267.

Deen, W., A. Weersink, C.G. Tuvey, S. Weaver, 1993. Weed control decision rules under uncertainty. *Review of Agricultural Economics* 15: 41-50.

Duvauchelle, S., 1993. Strategie de lutte contre le mildou de la pomme de terre en France. *Mededelingen Faculteit der Landbouwwetenschappen Gent* 58, Gent, Belgium. pp. 1441-1449.

Ebskamp, A.G.M. and H. Bonthuis, 1997. 73e Rassenlijst Landbouwgewassen 1998 (73rd List of Varieties of field crops 1998). Wageningen, CPRO-DLO, 305 pp.

Fry, W.E., A.E. Apple and J.A. Bruhn, 1983. Evaluation of Potato Late Blight forecasts modified to incorporate host resistance and fungicide weathering. *Phytopathology* 73: 1054-1059.

Georgopoulos, S.G., 1994. Early evaluation of fungicide resistance risk. In: S. Heaney, D. Slawson, D.W. Hollomon, M. Smith, P.E. Russell and D.W. Parry (eds.). *Fungicide Resistance.* Proceedings of a symposium held on 28-30 March at the University of Reading, U.K. pp. 389-396.

Headley, 1972. Defining an economic threshold. In: R.L. Metcalf (ed.). *Pest control strategies for the future.* National Academy of Science, Washington D.C, pp. 100-108.

Janssen, H., 1996. Oorzaken van verschillen in middelenverbruik tussen bedrijven. P. infestans in aardappelen. *LEI-DLO Publication 3.162,* The Hague, The Netherlands.

Kluge E. and V. Gutsche, 1990. Krautfäuleprognose mittels Simulationsmodell-ergebnisse der Anwendung 1982 bis 1988. *Archiv für Phytopathology und Pflanzenschutz DDR* 38: pp. 95-98.

LEI-DLO/CBS, 1998. Land- en Tuinbouwcijfers 1997. LEI-DLO/CBS, Den Haag, The Netherlands, computer diskette version.

MJP-G, 1991. *Meerjarenplan Gewasbescherming; Regeringsbeslissing.* Ministry of Agriculture, Nature Management and Fisheries, Tweede Kamer, vergaderjaar 1990-1991, 21667, nr.3-4. Staatsuitgeverij, The Hague, The Netherlands.

NEFYTO, 1994. Voortgangsrapportage Bestuursovereenkomst Uitvoering Meerjarenplan Gewasbescherming, NEFYTO (Dutch Foundation for Phytopharmacy), The Hague, The Netherlands.

NEFYTO, 1998. NEFYTO bulletin. NEFYTO (Dutch Foundation for Phytopharmacy), The Hague, The Netherlands.

Oskam, A.J., H. Van Zeijts, G.J. Thijssen, G.A.A. Wossink, and R. Vijftigschild, 1992. *Pesticide use and pesticide policy in The Netherlands: an economic analysis of regulatory levies in agriculture. Wageningen Economic Studies* 26. Pudoc, Wageningen, The Netherlands.

Postma, A, 1995. Geleide bestrijding van schimmelziekten in de praktijk. *Agro informaticareeks.* 9:127-136.

Ridder, J.K. and C.B. Bus, 1994a. Effect van lagere doseringen van middelen en grotere intervallen tussen bespuitingen op de aantasting van aardappelen door *Phytophthora infestans.* In: ROC Westmaas and Proefboerderij "Rusthoeve" *Resultaten van het landbouwkundig onderzoek in Zuidwest-Nederland over 1993.* Proefboerderij Zuid-Holland [etc.], Barendrecht [etc.], pp. 21-23.

Ridder, J.K. and C.B. Bus, 1994b. Effect van lagere doseringen van middelen en grotere intervallen tussen bespuitingen op de aantasting van aardappelen door *Phytophthora infestans.* In: Proefboerderij "Kollumerwaard" *Proefveldverslag Kollumerwaard 1993.*

Ridder, J.K. and C.B. Bus, 1995-1996a. Onderzoek naar Phytophthora bestrijding bij aardappelen met een verschillende mate van loofresistentie, met doseringen en tijdstippen van spuiten. In: ROC Westmaas and Proefboerderij "Rusthoeve" *Resultaten van het landbouwkundig onderzoek in Zuidwest-Nederland over 1994* and *over 1995.* Proefboerderij Zuid-Holland [etc.], Barendrecht [etc.], pp. 25-27.

Ridder, J.K. and C.B. Bus, 1995-1996b. Onderzoek naar Phytophthora bestrijding bij aardappelen met een verschillende mate van loofresistentie, met doseringen en tijdstippen van spuiten. In: ROC "Kollumerwaard" *Proefveldverslag Kollumerwaard 1994* and *1995,* pp. 80-82 and pp. 64-66.

Schepers, H.T.A.M., E. Bouma, C.B. Bus and W.A. Dekkers, 1995. Inventarisatie naar de mogelijkheden van een waarschuwingssysteem voor P. infestans in aardappelen. *PAGV report* 195, Lelystad, The Netherlands, 75pp.

Schoorlemmer, H.B., A.J. de Buck and G.A.A. Wossink, 1994. Risk and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.E. Pederson, J. Christensen, S. Rasmussen (Eds) *Proceedings from the 38th EAAE Seminar "Farmers' decision making – a descriptive approach"*, October 3-5 1994, Copenhagen, Denmark, pp.191-202.

Smidts, A., 1990. Decision making under risk: a study of models and measurement procedures with special reference to farmer's marketing behaviour. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 329pp.

Spigt, R.M. and T.L.J. Janssen, 1997. Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt 1997/1998. *PAV publication* 85, Lelystad, The Netherlands, 219pp.

Spitters, C.J.T., 1987. An analysis of variation in yield among potato cultivars in terms of light absorption, light utilization and dry matter partitioning. *Acta Horticulturae* 214: 71-84.

Urech, P.A., 1994. Fungicide resistance management: needs and success factors. In: S. Heaney, D. Slawson, D.W. Hollomon, M. Smith, P.E. Russell and D.W. Parry (eds.). *Fungicide Resistance.* Proceedings of a symposium held on 28-30 March at the University of Reading, U.K. pp. 349-356.

Vanclooster, M., P. Viaene, J. Diels and K. Christiaens, 1994. WAVE: a mathematical model for simulating water and agrochemicals in the soil and vadose environment, reference and users manual (release 2.0). Institute for land and water management, Katholieke Universiteit Leuven, Leuven, Belgium.

Wijnands F.G. and P. Vereijken, 1992. Region-wise development of prototypes of integrated arable farming and outdoor horticulture. *Netherlands Journal of Agricultural Science,* 40: 225-238.

Wossink, G.A.A. and W.A.H. Rossing, 1998. On increasing returns and discrete choice: integrating production ecological principles in economic analysis of crop management. *Journal of Environmental Management* 54(3):233-247.

6 Agronomic and environmental risks of nitrogen management with or without manure in potato cropping

A.J. de Buck, T.J. de Koeijer[a], A.B. Smit[a], S.R.M. Janssens[a] and J. Oenema[b]

Submitted to: *Agricultural Systems*

Abstract

Manure from livestock is important to maintaining soil fertility in crop production but carries the risk of nitrate contamination of the groundwater. This paper is about ware potatoes and presents a comparison of six N fertilisation strategies on the risks of yield reduction, nitrate leaching to groundwater, organisational compatibility, nitrogen release from manure and fertiliser costs. The six strategies covered conventional and less polluting practices and varied according to whether or not pig slurry applied, application date of the manure and additional amount of N fertiliser used. We determined the risk entities by model calculations using 43 years of weather data. The results showed that stochastic environmental conditions caused a wide distribution of leaching values with peaks of 200 kg N ha^{-1}*. When manure application was changed from autumn to spring the following year, leaching was reduced to levels that were comparable with only fertiliser use. Additional to the normative simulation, an empirical analysis was done of current N fertilisation practices, based on 136 farm-year records. The empirical analysis showed that current nitrogen management has the potential (rationalisation and a shift in application date) to improve the environmental performance of the application of organic manure.*

Key words: Nitrogen management, Risk, Nitrate leaching, Manure, Simulation, Panel analysis.

---

[a] *Agricultural Economics Research Institute (LEI), The Hague, The Netherlands*

[b] *Alterra, Wageningen, The Netherlands*

6.1 Introduction

Animal manure is a factor critical to maintaining the soil's organic matter content in arable rotations on soils with a low humus content, like the reclaimed clay soils in the Netherlands. An agronomic disadvantage of the use of manure is the erratic nature of mineralisation which causes fluctuations in nitrate concentration that might not correspond with actual crop demand. A temporal over supply of nitrate is likely to occur, which can lead to poor product quality, high pesticide use and yield losses. Leaching of the soil nitrate might also occur, contaminating subsoil and surface water. This is vital concern, given the EU Nitrate Directive that has set the standard for drinking water at 50 $mg \cdot l^{-1}$ nitrate (European Union, 1991), which is the accepted standard in the Netherlands for all subsoil water under arable land (Hellegers, 1996).

Nitrogen leaching is highest in the case of potatoes (which is an important crop in the Netherlands) because its root system is inefficient. On clay soils, animal manure is commonly applied in the autumn preceding the potato crop, so that only a small fraction of the total N supply with manure is available for crop growth by spring. An average nitrate concentration of 55 mg l^{-1} in the subsoil water under ware potato crops has been reported (De Koeijer and Wossink, 1990; Wossink, 1993). We anticipate peaks in temporal variation in both precipitation and in nitrate content of the soil that considerably exceed the EU standard for drinking water. The conflict of interests between the agronomic and environmental use of organic manure pinpoints its key role in environmentally sustainable nitrogen strategies. The nitrogen dose and the timing of application are critical to obtaining maximum nitrogen efficiency for the benefit of the crop with the least impact on water quality.

Development and testing of new farming prototypes have been ongoing in Farming Systems Research since 1979 (Wijnands and Vereijken, 1992). New nitrogen management strategies have been investigated that shift manure application from autumn to spring. Application of manure in spring can reduce nitrate leaching quite considerably. With regard to timeliness and the reduction of nutrient losses, manure can successfully be applied on lighter soils in spring. On heavier soils, however, wet soil conditions might hinder a timely application of manure in spring. Farmers believe that a shift in application from autumn to spring would put soil structure, planting date and hence crop yield at risk.

The problems discussed above led to the research aims of determining: (1) the compatibility of manure application in spring with soil conditions; (2) the risk of N leaching of nitrogen management strategies with or without manure; (3) the financial risk of the substitution of manure for fertiliser (savings on fertiliser and yield effects); and (4) the technical innovation capacity of the arable sector towards more environmentally sustainable nitrogen management strategies. We chose The Flevopolders as the research area, as this is a major arable production region in the Netherlands with rather homogenous, highly productive soils and a homogenous structure of the farm enterprises. Furthermore, all considerations as discussed above apply to the reclaimed clay soils in this region (low humus contents and mostly wet soil conditions in early spring).

To answer such questions, the usual procedure would be to develop, test and evaluate new strategies in nitrogen management (as in Farming Systems Research; Wijnands and Vereijken, 1992). Collecting data from experimental field trials was inappropriate for our purpose due to resource and time constraints, more so because the high dependency of the outcomes of strategies on weather conditions and hydraulic state of the soil would necessitate repetition over several years. As an alternative we chose to simulate the output characteristics of alternative N management strategies with a bio-economic model (Yiridoe *et al.*, 1997) using a representative set of data on weather and subsoil water levels for multiple years.

We used the model WAVE (Water and Agrochemicals in soil and Vadose Environment; Vanclooster *et al.*, 1996) to simulate six nitrogen management strategies for ware potatoes that covered a range from conventional to less polluting. The strategies varied according to whether or not pig slurry was applied, application date of the manure, and amount of N fertiliser used. Our calculations evaluated the agronomic and environmental risks and the average nitrate mass balances of the strategies covering a period of 43 years.

We selected a panel of arable farmers with a representative cropping pattern from the research area for our analysis of the practice of nitrogen management with and without manure. Their management was then compared with the simulated normative nitrogen strategies. This enabled us to estimate the effect of nitrogen management by farmers on nitrate leaching and to come up with possibilities to improve environmental and technical performance of the arable sector (*i.e.* innovation capacity).

This paper first elaborates on the method used, including the conceptual model, a description of the simulation model with its parameter settings and the panel analysis. Next, the results are presented of the simulations and the empirical analysis. The paper continues with a discussion on the methodology and the results, and finally, we present the main conclusions drawn.

6.2 Methods and material

6.2.1 Conceptual model

Nitrogen management was considered as a multi-period problem with J decision stages j $(j = 1, .., J)$ in the production process of one growing season. This was similar to other husbandry activities in arable farming (De Buck *et al.*, 1999a; De Buck *et al.*, 1999c). Let potato cultivation during the stages j be characterised by a stochastic production process:

$$q = \mathrm{f}(a_{i,j}, \xi), \qquad (6.1)$$

where q denotes the physical yield, $a_{i,j}$ is the use of input i at stage j and ξ represents a stochastic weather parameter. Precipitation, evapotranspiration, irradiation and temperature were elements of ξ, which directly affected crop production.

For a given stage j, the state S_j of the system was described by a vector of state variables (representing the nitrogen state of the soil). Based on S_j, at each stage j a decision x was made according to the decision rule of a strategy. The decision rule determines whether manure is applied, the moment of manure application and the nitrogen fertiliser application rate.

These decisions were made in three stages, prior to the potato crop. The optimal multi-period solution for one season was the sequence of J decisions x that maximised income π:

$$\pi = p_q \times q - \sum_{i=1}^{I}\sum_{j=1}^{J}(p_i \times a_{i,j}) \qquad (6.2)$$
$$\text{with } a_{i,j}(x, S_j).$$

where p_q and p_i are the –constant– prices for one unit of output q and input a_i respectively.

The transition function τ described the changing state of the system between the current period j and the next period $j+1$ due to decision x and uncertainty factor ξ:

$$S_{j+1} = \tau(S_j, x, \xi). \qquad (6.3)$$

So, besides its direct effect on q (Equation 6.1), ξ affected the transition of the system indirectly from stage j to stage $j+1$ via nitrogen management decisions x (Equation 6.3), that determined input use $a_{i,j}$ (Equation 6.2). The weather conditions influenced the nitrogen state of the soil (as a state variable of S_j) during the growing season serves as an example of this indirect effect. The amount of nitrogen in the soil determined the amount of nitrogen $a_{i,j}$ required at decision $x_{i,j}$.

The Cumulative Distribution Function (CDF) of input use, summed for $j = 1$ to $j = J$ was represented by F:

$$\mathrm{F}(A_i) = \mathrm{P}(a_i \le A_i) \qquad (6.4)$$
$$\text{with } a_i = \sum_{j=1}^{J} a_{i,j}.$$

From Equations 6.2 and 6.3 it follows that $a_{i,j}$ depends on the stochastic parameter ξ. Realisations ξ_t of parameter ξ based on weather outcomes T $(t = 1,\dots,T)$ were used to determine values of $\sum_{j=1}^{J} a_{i,j,t}$. Hence, the Cumulative Distribution Function (CDF) was approximated by F:

$$\mathrm{F}(A_i) = \mathrm{freq}\left(\sum_{j=1}^{J} a_{i,j,t} \le A_i\right) \cdot T^{-1} \qquad (6.5)$$

The framework outlined in Equation 6.1-6.5 was applied to all investigated nitrogen management strategies and enabled comparison and ranking of these strategies on their CDFs for various inputs (A_i) and yield (q). Stochastic dominance was employed to identify efficient management alternatives (Hardaker *et al.*, 1997; De Buck *et al.*, 1999a and c).

6.2.2 Simulation model

Main processes and parameter settings in WAVE

The process-based model WAVE (Vanclooster *et al.*, 1996) simulates vertical soil water transport, the fate of nitrogen and crop production. WAVE integrates four existing models: soil water flow based on SWATRER (Dierkx *et al.*, 1986); nitrogen cycling based on SOILN (Bergström *et al.*, 1991); heat and solute transport based on LEACHN (Hutson and Wagenet, 1992); and crop growth based on SUCROS (Spitters *et al.*, 1988). WAVE requires input data on crop, weather, soil type and nitrogen application. Its validity holds good for several years and locations (Verhagen and Bouma, 1997; Vanclooster, 1995). We used WAVE to generate crop production of a nitrogen management strategy according to Equations (6.1) and (6.2). We set parameters that were not particularly relevant for our purpose, to standard values as described in Vanclooster *et al.* (1996). A light marine clay soil rich in lime with a low humus content is common in Eastern Flevoland. The parameter values that apply to this soil are listed in the appendix together with those of relevance used in WAVE.

Water movement in WAVE is described using the Richards equation (Jury *et al.*, 1991) which is driven by models for: 1) the soil moisture retention property; and 2) the relation between hydraulic conductivity and soil water content, the parameters of which were estimated according to Stolte *et al.* (1996). Groundwater levels used were those from daily records on a representative field in the research area, averaged over the years 1979 to 1986 (made available by RIZA[25]). Water extraction by the crop was simulated by a water sink term (Vanclooster, 1995).

WAVE subdivides the soil organic matter into three pools: litter, manure and humus. A target C/N quotient of 10 drives mineralisation from the organic pools into mineral nitrogen and immobilisation from mineral nitrogen into organic matter. The transfers between the organic pools and the mineral nitrogen transformation processes of nitrification and denitrification are simulated by first order rate constants. These potential nitrogen transfer rates can be reduced by extreme moisture and temperature conditions; the rates vary with depth (Vanclooster *et al.*, 1996).

Crop growth was simulated using the universal crop growth model SUCROS, describing the dry matter accumulation in different plant parts as a function of the development stage, air temperature, irradiation and crop physiological parameters (Spitters *et al.*, 1988). This reduces the daily gross photosynthesis when water and/or nitrogen is limited in the root zone. Half of the growth of new roots was assumed to take place at a depth of 0 to 20 cm; 20% between depths of 20 and 30 cm and 30% between 30 and 60 cm .

The different stages of development of a potato crop are represented in WAVE by a certain temperature sum from day of emergence onward. Development stages were estimated using

---

[25] RIZA = Institute for Inland Water Management and Wastewater Treatment, Lelystad, The Netherlands.

average calendar-based development stages of a potato cultivar with an average maturity class (De Jong, 1985) and average daily temperatures for 1985-95 (PAGV, 1989). Planting and harvesting date were set at 7 April and 9 September respectively (De Jong, 1985).

The sink term that represents root water uptake came from SUCROS. The extraction rate determined potential uptake. The maximum extraction rate decreases from 0.02 at soil surface to 0.005 day^{-1} at 50 cm depth (Diels, 1994; Vanclooster *et al.*, 1996). Soil water tension (*pF*) can reduce this rate. Water uptake was assumed to occur at a *pF* between 4.2 (wilting point) and 1. Water tension is optimal for uptake at a *pF* between 2.8 (or 2.5 at a high evaporative demand) and 1.4 (Wesseling, 1991). When actual root water uptake is lower than the potential, water stress will reduce crop growth.

The potential nitrogen content in the crop organs determines target nitrogen demand of the crop in the root zone. The nitrogen weight of 5% of foliage dry matter at emergence and 4.7% at tuber initiation (Neeteson *et al.*, 1987) was extrapolated linearly to nitrogen fraction at harvest (~ 3%). Nitrogen content of the tubers was set at 1.8%. Nitrogen in the potato crop at harvest was allocated to the above ground fraction (30%), the living root fraction (10%) and the harvest fraction (60%)[26].

In the Netherlands, winter wheat usually precedes potatoes in a rotation on clay soils. In WAVE, winter wheat was assumed to leave a stock of 45 kg ha^{-1} of mineral nitrogen in the upper 60 cm of the profile. A yearly wet and dry nitrogen deposition of 42 kg ha^{-1} was assumed at a yearly rainfall of 750 mm (Meeuwissen, 1987). We assumed ploughing to a depth of 30 cm on 10 November. Nitrate leaching was defined as the solute flux at –60 cm, integrated from 17 September in year *n* to 16 September in year *n*+1.

Convective nitrogen uptake is proportional to actual root water uptake and nitrogen concentration in the solute. When convective uptake is smaller then potential uptake, there is also diffusive nitrogen uptake (Vanclooster *et al.*, 1996). For diffusive uptake, the average root radius to 0.224 mm (De Willigen, 1987). We set the average distance between soil solution and root surface –which is a measure of resistance in diffusive uptake– at $2 \cdot 10^{-4}$ mm (which was in between the values given by De Willigen, 1987 and Diels, 1994).

---

[26] Assuming a protein content of 2.1% (Burton, 1989) and an N/protein ratio of 1/6.25, the N content of the tubers equals 0.34%. With a yield of 50 10^3 kg ha^{-1} there was an uptake of 170 kg ha^{-1} by the tubers. Relating the amount of N that was destined for the tubers to the total crop uptake of 285 kg ha^{-1} (Smit and Van der Werf, 1992), this means a ratio of 60% for the N in the harvest fraction. The N that was allocated to the living roots was set at 10%. Hence, 30% of the total N uptake was allocated to the above ground fraction.

Calibration

A strategy consisting of the application of 27 10^3 kg ha^{-1} of pig slurry on 15 October was used to calibrate the parameters that determine water transport and the fate of nitrogen. First, we followed the various physical and chemical processes regarding nitrogen day by day. On a yearly basis, we calibrated WAVE on a weather data set from 1984-94. All nitrogen transfer rates and the average distance between soil solution and root surface as model input parameters appeared to have a substantial effect on the nitrogen balances. We took common transfer rates from literature and valued by expert elicitation (Oenema, pers. comm., 1998). Unlike the values of the parameters that described the transfer rates, the value of the average distance between soil solution and root surface was barely arguable. In the absence of empirical data on this parameter, we carried out a trial and error session to obtain a realistic pattern of nitrogen uptake and yield. The model output of the 10 years is presented as an average nitrogen balance (Table 6.1). In WAVE, the summed model errors are integrated into a balance error, which cannot be accounted for. The balance error in our calculations of about 10% is considered to be acceptable.

Table 6.1 Simulated nitrogen mass balance from September to September, averaged for 1984-94 for a potato crop with application of 27 10^3 kg ha^{-1} of pig slurry in mid-october.

Incoming mineral nitrogen [kg ha^{-1}]		Outgoing mineral nitrogen [kg ha^{-1}]	
Stock after preceding crop	45	Crop uptake	274
Fertiliser (*Na*)	150	Denitrification	49
Manure (mineral N fraction)	104	Volatilisation	13
Mineralisation (from soil and manure)	195	Leaching	89
Deposition (*Ndep*)	42	Stock after current crop	50
Total in	536	**Total out**	475
Not accounted for [kg ha^{-1}]	61		
Yield[10^3 kg d.m. ha^{-1}]	13.5		

Decisions and strategies on nitrogen application

Six strategies were designed and simulated using WAVE (Table 6.2). These strategies varied according to whether or not manure was applied, application date of manure and additional amount of N fertiliser used (2 levels). The pig slurry was assumed to contain 0.77% nitrogen (0.385% mineral N and 0.385% organic N) and 0.30% P_2O_5 (IKC-L, 1997). The application of 27 10^3 kg ha^{-1} of slurry was simulated using WAVE complying with the governmental phosphate supply regulation (a maximum of 85 kg P_2O_5 ha^{-1}; IKC-L, 1997). Two application dates for manure were investigated: a common application in the autumn on 15 October and an application in spring on 1 April.

Table 6.2 **The modelled strategies for organic manure (pig slurry) and fertiliser(N_f) application in ware potatoes.**

Strategy	Manure		N_f
	Amount 10^3 kg ha^{-1}	Application date	kg ha^{-1}
1	-	-	$285-1.1 \cdot N_{m,soil}-10$
2	-	-	$240-1.1 \cdot N_{m,soil}-10$
3	27	1 April	$285-1.1 \cdot N_{m,soil}-10-104-50$
4	27	1 April	$240-1.1 \cdot N_{m,soil}-10-104-50$
5	27	15 October	$285-1.1 \cdot N_{m,soil}-10$
6	27	15 October	$240-1.1 \cdot N_{m,soil}-10$

The amount of fertiliser applied in spring, just before crop planting was calculated as:

$$N_f = N_a - 1.1 \cdot N_{m,soil} - \overline{N_{dep}} - N_{m,mapr} - \overline{N_{min,mapr}}, \tag{6.6}$$

where N_a is the advised mineral nitrogen level; $N_{m,soil}$ the soil mineral nitrogen in stock (0-30 cm) at March 1 and $\overline{N_{dep}}$ the expected deposition of nitrogen during the growing season. Two nitrogen levels recommended to farmers (N_a) were investigated: a high level of 285 kg ha^{-1}, which is the standard recommendation to farmers (strategies 1, 3 and 5) and a lower level of 240 kg ha^{-1} (strategies 2, 4 and 6), denoted as the 'environmental' recommendation. The low nitrogen level aims both at a higher product quality and at lower N losses (Van Loon *et al.*, 1993). In Table 6.2, fertiliser application rate was calculated according to Equation 6.6. When manure was applied in spring, the nitrogen fraction ($N_{m,mapr}$, which is 50% of total nitrogen in manure) and the expected mineralisation during the growing season ($\overline{N_{min,mapr}}$) were subtracted. With application in the autumn, these terms were accounted for with $N_{m,soil}$.

Calculating risks of six nitrogen strategies

Simulation of all six strategies using wave for 43 years (1954-97) generated CDFs of the most important outcomes. The environmental risks were represented by a CDF for nitrogen leaching. The CDF for mineralisation illustrated the agronomic risk caused by uncertain nitrogen release of soil organic matter. The average nitrogen mass balances for each strategy summarised these nitrogen-related processes. We deduced financial risks from the CDFs for fertiliser costs and yield. Organisational risk of each strategy was calculated as the probability that the planned time schedule of planting was feasible, considering soil moisture conditions.

6.2.3 Analysis of panel data from the arable sector

We conducted a panel analysis with data from the Farm Accountancy Data Network (FADN) of LEI (Agricultural Economics Research Institute, The Netherlands). The survey of arable farms in the Flevopolder with ware potatoes in the years from 1992-96 resulted in 136 (farm-year) observations.

Table 6.3 Division into groups (or nitrogen management strategies) in the panel analysis, based on nitrate efficiency of manure and fertiliser rate (N_f).

Group	Nitrate efficiency %	N_f Lower limit level > ... kg ha^{-1}	 Upper limit level ≤ ... kg ha^{-1}
1	no manure	$265-1.1\cdot N_{m,soil}-10$	285
2	no manure	0	$265-1.1\cdot N_{m,soil}-10$
3	> 0.5	$265-1.1\cdot N_{m,soil}-164$	285
4	> 0.5	0	$265-1.1\cdot N_{m,soil}-164$
5	≤ 0.5	$265-1.1\cdot N_{m,soil}-10$	285
6	≤ 0.5	0	$265-1.1\cdot N_{m,soil}-10$
3a	> 0.5	285	-
5a	≤ 0.5	285	-

We divided the panel into three classes of manure application: no manure application and manure application with a high and a low level of nitrogen efficiency (Table 6.3). Data on nitrogen efficiency was used to determine time of application and was available in FADN[27]. A nitrogen efficiency > 0.5 was assumed to correspond with application in spring, ≤0.5 with an autumn application.

We subdivided each class of manure application into two nitrogen levels (as in Equation 6.6): the 'environmental' and the standard recommendation. Farmers that used less than 265 kg ha^{-1}, were assumed to follow the 'environmental' recommendation (strategy 2, 4 and 6). Farmers that applied more nitrogen than the environmental guideline but less than 285 kg ha^{-1}, were assumed to follow the standard recommendation (strategy 1, 3 and 5). Farmers that used more than 285 kg ha^{-1} of fertiliser, irrespective of any other nitrogen source (like animal manure), were classified into groups 3a and 5a, with the same nitrate efficiency as strategies 3 and 5 respectively. Hence, we distinguished eight groups in the panel analysis. Groups 1-6 corresponded with strategies 1-6 in the normative simulation analysis. Groups 3a and 5a showed levels of nitrogen fertilisation that exceeded the standard recommendations and was beyond the scope of WAVE.

Data for an average mineral nitrogen mass balance for each group were only partially available in FADN. We estimated stock and mineralisation of remnants after the preceding winter wheat crop and deposition with the simulations with WAVE for 1992-96. Fertiliser and manure application rates were recorded in FADN; mineralisation rate and initial mineral nitrogen content were derived from WAVE calculations. Uptake of the total crop was 0.4% (derived from WAVE) of fresh yield (recorded in FADN). The other outgoing posts were not recorded in FADN. For each group in the panel analysis leaching was determined by using the fractions of total nitrogen input that leached in the corresponding simulated strategies for

---

[27] Nitrogen efficiency of manure was defined as the fraction of the total nitrogen expected to be taken up by the crop. In FADN, nitrogen efficiency was determined normatively and depends on type of manure, soil type and time of application, assuming a direct tillage operation after manure application.

1992-96. We calculated denitrification, volatilisation and the stock of mineral nitrogen after the potato crop likewise.

We made comparisons between nitrogen balances of the simulated normative strategies and the eight groups from the panel analysis. It enabled us to estimate the effect of nitrogen management by farmers on nitrate leaching. The number of practitioners of each strategy was used to estimate the probabilities of improving environmental and technical performance of the arable sector (that is innovation capacity).

Some systematic differences were recognised between the model outcomes and data of realised production practices. Though the research area –which was fairly homogenous with respect to soil type and farm structure– was the same for both the model and the empirical analysis, the latter reflected the diversity that can be found on commercial farms. The simulated normative strategies did only cover a part of the variety in management practised.

6.3 Results

6.3.1 Model simulations

Table 6.4 presents the average nitrogen balances of the model calculations for 43 years. When manure was applied in the autumn, (strategies 5 and 6) leaching was considerably higher than after application in spring (strategies 3 and 4). After manure application in spring, about the same amount of nitrogen leached as when only fertiliser was applied (strategies 1 and 2). Compared to the 'environmental' nitrogen level (strategies 2, 4 and 6), the extra nitrogen input of the standard level (strategies 1, 3 and 5) led to a higher crop uptake and yield with no increase in leaching.

On average, 72 kg N ha^{-1} leached after the autumn application of manure and about 33 kg N ha^{-1} after application in spring (Table 6.4). The yearly variation in leaching was large for all strategies (Figure 6.1) and largest when manure was applied in the autumn. Occasionally, simulated values of more than 150 kg ha^{-1} (strategies 1-4) and 200 kg ha^{-1} were obtained with the autumn application (strategies 5 and 6). Towards probably dry conditions with little leaching (left part of the curve), the strategies with and without manure application in autumn converged with regard to leaching.

Fertiliser use was highest in strategies 1 and 2 without manure application. On average, an autumn application of 27 10^3 kg ha^{-1} of pig slurry (strategies 5 and 6) reduced the quantity of fertiliser (N_f) by about 55 kg ha^{-1}, which resulted in a substantial total mineral nitrogen input (Table 6.4). Less additional fertiliser was required after manure application in spring (strategies 3 and 4): for example, compared to strategy 1, the average quantity of fertiliser was reduced by 154 kg ha^{-1} in strategy 3.

Total mineralisation was least when no manure was applied (strategy 1 and 2) and ranged from approximately 115 to 145 kg N ha^{-1} (Figure 6.2). More mineralisation (from 15 September to 15 September) took place after application of manure in spring (strategies 3 and 4); ranging from approximately 142 to 201 kg N ha^{-1}. After manure application in autumn, the largest amount of mineralisation simulated ranged between 162 and 212 kg N ha^{-1} (strategies 5 and 6). Strategies using manure application showed a higher yearly variation in mineralisation than those using fertiliser alone. Large amounts of mineralisation in winter explained the considerable risk of nitrate leaching after manure application in the autumn, which was compensated by large amounts of fertiliser input.

Table 6.4 Average nitrogen balances (15 September – 15 September) and yields of the six nitrogen management strategies, simulated for 1954-97.

	Simulated strategies					
	1	2	3	4	5	6
Incoming mineral nitrogen [kg ha^{-1}]						
Stock after preceding crop	45	45	45	45	45	45
Fertiliser (N_f)	227	180	73	50	172	127
Manure	0	0	105	105	105	105
Mineralisation from:						
soil + crop remnants	129	129	129	129	129	129
manure	0	0	46	46	61	61
Deposition (N_{dep})	41	41	40	40	40	40
Total in	443	395	439	416	553	508
Outgoing mineral nitrogen [kg ha^{-1}]						
Crop uptake	265	234	262	240	290	249
Denitrification	27	11	23	23	42	40
Volatilisation	8	7	11	10	13	12
Leaching	49	50	49	49	91	91
Stock after current crop	45	46	51	52	54	55
Total out	394	348	397	373	490	447
Not accounted for [kg ha^{-1}]	49	47	43	43	64	61
Calculated	40	38	31	31	53	50
Rest	9	9	11	11	11	11
Yield[10^3 kg ha^{-1}]						
Dry matter (21%)	13.4	12.1	13.2	12.2	13.9	12.5
Fresh	63.6	57.4	63.1	58.1	66.0	59.7

Figure 6.3 shows the CDF for mineral fertiliser costs[28] assuming a fertiliser price of NLG 1.33 (= 0.60 €[29]) per kg. The strategies without manure application showed the highest fertiliser costs with a small risk of extremes. Strategies 3 and 4 with manure application in spring had low fertiliser costs with a small variation between years. Strategies with the autumn application (5 and 6) showed high fertiliser costs and a larger variation, caused by the

---

[28] The costs for manure (pig slurry in this case) were excluded here, as the price of manure is very low and uncertain due to large market surpluses.

[29] €, Euro, European currency.

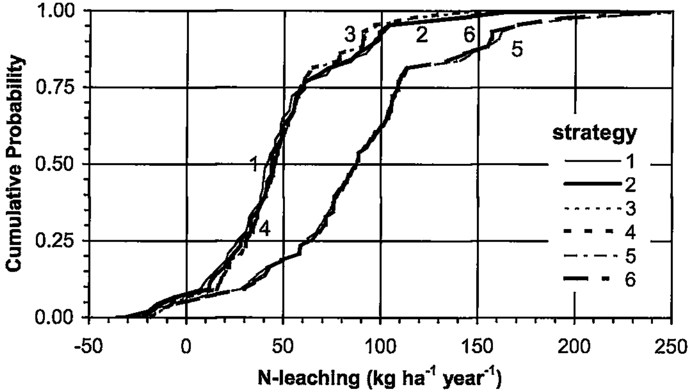


Figure 6.1 Cumulative distribution function of nitrate leaching (from september to september) for six nitrogen management strategies.

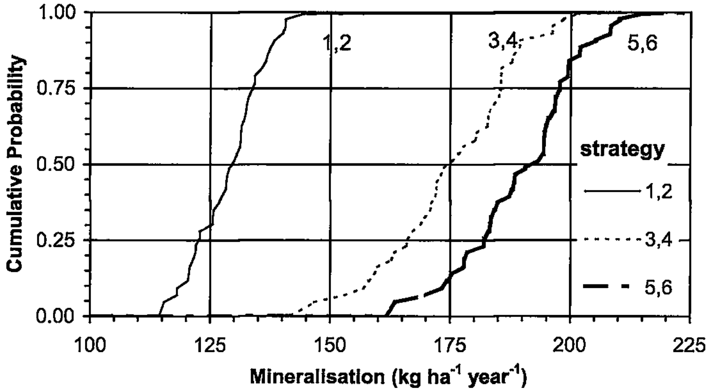


Figure 6.2 Cumulative distribution function of total mineralisation (from september to september) for six nitrogen management strategies.

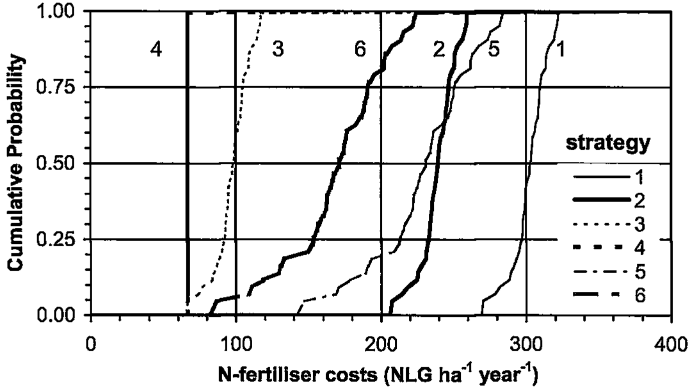


Figure 6.3 Cumulative distribution function of fertiliser costs for six nitrogen management strategies.

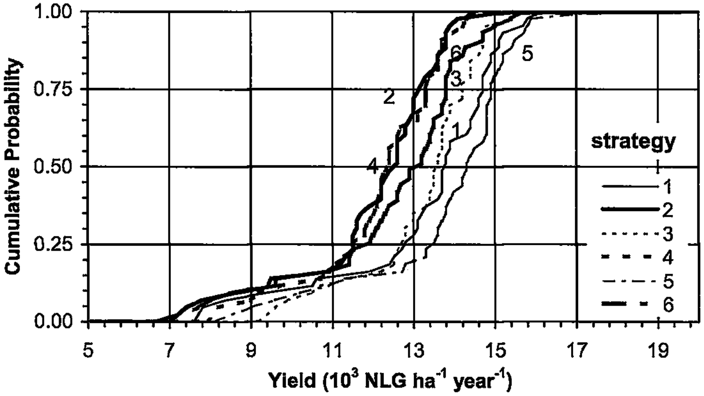


Figure 6.4 Cumulative distribution function of yield for six nitrogen management strategies.

whimsical behaviour (such as mineralisation and leaching) of nitrogen during winter. Conclusively, all strategies demonstrated that even after the autumn application of manure, the risk of high fertilisation costs was relatively small. In approximately 5 to 10% of the years the reduction in fertiliser costs was remarkable: approximately NLG 80 (36 €) per ha after manure application in autumn. This was probably due to dry conditions in winter.

The agronomic value of the nitrogen fraction in manure was determined using Figure 6.3. Highest savings in fertiliser costs were achieved when applying manure in spring at the high nitrogen level (strategy 3 compared with strategy 1): 27 10^3 kg of pig slurry per ha represented a value of about NLG 200 (€ 90). Hence, the maximum value of manure as a source of nitrogen (that is when manure is applied in spring at the high nitrogen level) was NLG 7.41 (€ 3.34) per 10^3 kg.

Considering savings on fertiliser and a higher potato yield, manure had the highest value in strategy 5. Compared to strategy 1, strategy 5 generated an increase in yield of 2.4 10^3 kg ha^{-1} equivalent to NLG 480 (€ 216) per ha. The application of 27 10^3 kg ha^{-1} of pig slurry enabled a savings on nitrogen fertiliser costs of NLG 80 (€ 36) per ha together with an extra yield of NLG 480 per ha. Hence, in strategy 5 manure represented a value of some 560/27 = NLG 21 (€ 9) per 10^3 kg.

The 'environmental' nitrogen level (strategies 2, 4 and 6) resulted in a mean yield reduction of 1 10^3 kg dry matter per ha compared to the conventional level. The high level of total N with the autumn manure application led to an increase in both N uptake and yield. Assuming a product price of NLG 0.20 (= € 0.09) per kg, the CDF for financial yield is drawn as shown in Figure 6.4. Nitrogen strategy influenced yield most obviously around the median of the CDF (conditions that are most likely to occur).

For all strategies, the distances between the highest simulated yields and the median were smaller than the distance between the lowest yields and the median, pointing at 'downside' yield risk (Hardaker *et al.*, 1997). Yields of the various strategies converged in 20% of the years with the most unfavourable growing conditions. The relatively large yield risks as a result of variation in natural conditions were hardly affected by the choice of strategy.

Analysis of simulated *pF* values before planting date showed that in 40% of the years, manure application in spring (strategies 3 and 4) just before the scheduled planting date was unfeasible. In these years, soil conditions were too wet for planting –that is $pF < 2$ in the upper 10 cm of the soil– on the scheduled planting date. Postponing the planting date until one or three weeks later allowed appropriate scheduling of manure application and planting with a probability of 71% or 88% respectively.

6.3.2 Panel analysis

A comparison was done of the outcomes of the panel analysis and the simulation study for the same interval of time. The simulated leaching, mineralisation, yield and fertiliser costs for the

Table 6.5 Average nitrogen balances and yields for the years 1992-96 of the simulated nitrogen management strategies and of the groups of the panel analysis.

	Strategy or group													
	1		2		3		4		5		6		3a	5a
	sim.	panel	sim.	panel	sim.	panel	sim.	panel	sim.	panel	sim.	panel	panel	panel
Number of observations (n = 136)	-	7	-	16	-	8	-	2	-	59	-	26	1	17
Incoming mineral nitrogen [kg ha^{-1}]														
Stock after preceding crop	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Fertiliser (N_f)	228	269	181	167	75	123	50	0	176	142	131	82	260	228
Manure	0	0	0	0	105	180	105	77	105	179	105	95	278	158
Mineralisation from:														
soil + crop remnants	128	130	128	127	128	124	128	122	128	131	128	128	115	127
manure	0	0	0	0	43	73	43	31	59	100	59	53	113	88
Deposition (N_{dep})	42	42	42	42	41	39	41	37	41	42	41	44	32	40
Total in [kg ha^{-1}]	443	486	396	381	436	584	411	312	554	639	508	446	842	686
Outgoing mineral nitrogen [kg ha^{-1}]														
Crop uptake	280	224	247	201	272	211	249	136	306	236	265	186	232	236
Denitrification	24	27	10	10	21	27	20	15	38	44	37	32	40	47
Volatilisation	8	9	7	7	11	14	10	8	13	15	12	11	20	16
Leaching	35	38	37	36	39	52	39	30	78	90	79	70	75	97
Stock after current crop	45	49	45	43	50	67	50	38	53	61	53	47	97	66
Total out [kg ha^{-1}]	387	347	342	297	389	372	364	227	482	447	440	345	465	462
Not accounted for [kg ha^{-1}]	56	139	53	84	47	211	47	85	71	193	68	101	378	223
Calculated	46	-	44	-	36	-	35	-	60	-	57	-	-	-
Rest	10	-	10	-	12	-	12	-	11	-	11	-	-	-
Yield[10^3 kg ha^{-1}]														
Dry matter (21%)	14.1	-	12.5	-	13.5	-	12.4	-	14.5	-	13.1	-	-	-
Fresh	67.3	56.0	59.3	50.3	64.4	52.8	58.9	34.1	68.9	59.0	62.5	46.5	58.1	59.1

six strategies for the interval 1992-96 lie evenly scattered over all the respective CDFs for the interval 1954-97 (Figures 6.1-6.4). These are representative results and therefore we consider representative circumstances for the interval 1992-96.

Table 6.5 presents average simulated outcomes for the years 1992-96 of the six simulated strategies, together with the results of eight groups of the panel analysis. Among them, only the average simulated crop uptake and leaching seemed not to be fully representative. In all of the strategies, the average simulated crop uptake was higher and leaching was lower during the short interval (1992-96) than in the interval 1954-97.

The total nitrogen input in the 'environmental' groups in the panel analysis was less than that in the simulated strategies (groups or strategies 2, 4 and 6). This is because farmers with a very low fertilisation level were classified in these groups (see the classification criteria in Table 6.3). The higher totals of incoming nitrogen in groups 1, 3 and 5 in the panel analysis when compared with the simulated totals for strategies 1, 3 and 5, was attributable to the classification criteria as well. For all strategies, simulated yields tended to be higher than the yields from the panel analysis.

The environmental fertiliser recommendation (groups 2, 4 and 6) was only popular when no manure was applied (12% of the farmers was classified under group 2). Forty-three percent of the farmers was classified under group 5, with a large (compared to strategy 5) manure input in the autumn and a large incoming balance total. In the determination of fertiliser rate, 13% of the farmers (group 5a) completely ignored the fertilising value of manure applied in the autumn. Group 3a had an exceptionally large incoming balance total. Group 4 used no fertiliser at all. In combination with a very low yield, this suggests that group 4 represented organic farmers. Because of the small number of observations, we omitted the exceptional results of groups 3a and 4 in the panel analysis.

Given the discrepancy between the incoming and outgoing totals in the panel analysis, the outgoing items were probably estimated too 'conservatively'. So, leaching in groups 3 and 5 was probably under-estimated, making the difference between the corresponding simulated strategies 3 and 5 larger.

6.4 Discussion and conclusions

6.4.1 Methodological issues

This research taught us a model originating from soil science is a useful tool in a bio-economic study, and in this case, to calculate agronomic and environmental risks of six nitrogen management options. WAVE was calibrated for situations (*e.g.* soil type) that were representative of the investigated area with a relatively homogenous farm structure and physical conditions. These normative calculations enabled a consistent analysis of the risks of the nitrogen management strategies, but were insufficient to describe the consequences of the large variety in nitrogen management strategies that farmers employ.

The strategies practised by potato growers were assessed by means of a panel analysis. In this empirical study, farmers were clustered into groups with a nitrogen management that was comparable with –but not completely identical to– the six simulated nitrogen management strategies. We combined the outcomes of this panel analysis with the more detailed outcomes of the simulated strategies in nitrogen management. This methodology allowed us to describe the environmental and agronomic performance of nitrogen management in potato cropping and the innovation capacity of the sector to improve this performance.

The combination of the simulation approach with a panel analysis in this paper did raise some methodological difficulties, because of the diversity in management in the clustered groups. We clustered the largest deviations from optimal nitrogen management into two separate groups. Due to the criteria for clustering, the level of incoming nitrogen of the groups differed from the corresponding simulated strategies. The section 'Results' of this paper argues the effects of these deviations on the outcomes.

No detailed information was available about the contents of the animal manure in the panel analysis, such as the proportion of mineral nitrogen to total nitrogen. The same proportion was assumed as in the model simulations, which biased the mineral nitrogen balances of the groups in the panel analysis.

A more refined classification into strategies actually employed by farmers would be feasible if additional technical data were collected as well as information on the farmers' goals of nitrogen management and manure application. Conducting interviews amongst farmers would be an appropriate method to collect these data.

6.4.2 Nitrogen input in practice

The abundance of nitrogen on farms in groups 3, 5 and 5a in particular leads us to suspect that the input levels were not agronomically rational: the fertilising value of manure was completely ignored in the determination of fertiliser application rate in group 5a. Given that the balances for the strategies 3, 5 and 5a represent 6%, 43% and 13% of the observations respectively, we expected the arable sector's use of more sustainable nitrogen management strategies to be potentially greater.

In the model simulations, we specified exact contents of manure. Instead of testing the nitrogen contents of manure, most farmers assume the average contents published for each type of manure. The farmers in the panel analysis might have employed large quantities of fertiliser to cope with the risk of a nitrogen shortage due to uncertainty of the manure contents. Besides, there were no stipulated limits of nitrogen inputs.

6.4.3 Environmental performance of nitrogen management

On average, nitrate leaching was highest after manure application in the autumn. About the same small amounts of nitrogen leached after manure application in spring and after application of fertiliser only. In all the strategies, the risk of nitrate leaching was high and highest when manure was applied in the autumn (peak values of more than 150 and 200 kg ha^{-1} respectively were calculated). In the research area, 91% of the farmers that applied manure, did so in the autumn, and only 9% in the spring , proving a considerable potential for the sector to reduce nitrate leaching.

The drinking water standard of 50 mg nitrate l^{-1} can be translated as 44 kg N ha^{-1} leaching (assuming an annual precipitation surplus of 390 mm). On average, only the fertiliser strategies and strategies where manure was applied in spring comply with the drinking water standard. However, all strategies –particularly with manure application in autumn– showed considerable risks of peak values in leaching, that most likely violated the drinking water standard.

Nitrogen surpluses in the groups 3, 5 and 5a in the panel analysis were considerably larger than in the corresponding simulated strategies 3 and 5. Given the large surpluses of these groups, leaching was probably under-estimated. Only the groups that did not apply manure – groups 1 and 2 which constituted only 17% of the farmers in the panel– are likely to meet the drinking water standard. However, the Nitrate Directive allows spatial and temporal averaging, which is a less strict interpretation of the drinking water standard as applied in this study.

6.4.4 Simulated crop yield

Instead of yield effects of nitrogen strategies, this research focused on the fate of nitrogen in the soil and nitrate leaching in particular. Some irregularities in the simulated crop yields are worth mentioning.

The 'environmental' nitrogen level (strategies 2, 4 and 6) resulted in a mean yield reduction of 5.8 10^3 kg ha^{-1} fresh product (1.2 10^3 kg ha^{-1} dry matter) compared to the conventional level (strategies 1, 3 and 5) in WAVE. Van Loon *et al.* (1993) report a much lower response of 1 10^3 kg ha^{-1} of fresh yield between similar nitrogen levels. Hence, the high yield response that was found in the simulations might not be representative of farming practice. We can still conclude that risks of yearly yield differences were of a much greater order than differences in yield between strategies. Plausibly, the average yields from the panel data corresponded with 25% of the lowest simulated yields, as simulated yields were water and nutrient limited and yields from the panel study were reduced by diseases and weeds as well.

There was no analytical or empirical evidence for the diffusive nitrogen uptake model in WAVE. We felt that these modelled interactions between soil solute and plant roots caused irregularities in crop yield. We recommend a better calibration or an alternative formulation of the uptake model.

6.4.5 Value of manure for the farmer

Manure surpluses on the market resulted in reports of very low prices. In this paper, we calculated the value of manure as a nitrogen fertiliser at NLG 7 (€ 3) per 10^3 kg. Taking the extra yield due to manure application in autumn into consideration we arrived at a value of NLG 20 (€ 9) per 10^3 kg, with a chance of about 5 to 10% of remarkably lower fertiliser costs

(NLG 80 or € 36 per ha). All the strategies had only a small risk of high fertiliser costs. When we considered transaction costs of manure application, such as transportation and application costs, there probably was only an economic stimulus to use it in the autumn. As discussed above, most farmers practised this, which imposed the risk of leaching on the environment.

Our finding that manure is widely used while the value as a nitrogen fertiliser is hardly exploited can be explained by other major advantages of manure use. Other agronomic values of manure are for instance the favourable effect of its organic matter on soil structure and its value as phosphate and potassium fertiliser.

We calculated the probability of insufficient soil conditions for manure application in spring at 40%. Practical difficulties can explain the few farmers that apply manure in spring. The probability of good soil conditions increased considerably when a farmer was willing to postpone planting date for two or three week. Possible negative effects of application of manure in spring on yield and/or soil structure outweigh the only stimulus that emerges from this paper: better exploitation of nitrogen from manure.

6.4.6 Outlook for the future

The benefit to the national mineral balance in the Netherlands is used as an argument to stimulate the use of organic manure in the arable sector. Besides the validity of this reasoning, manure is essential to enhance arable soils with an originally low humus content by way of its organic matter content. To achieve an environmentally sound use of manure, this paper shows that a major proportion of the potato growers in the research area needed to change their nitrogen management. Apparently, farmers paid little attention to the nitrogen efficiency of manure. Simply by shifting the application date of manure from autumn to spring improved environmental performance by a better exploitation of nitrogen from manure. Manure application in spring, however, had predominantly agronomic disadvantages. A strict interpretation of the Nitrate Directive –a parcel- or year-specific implementation or even a ban on any peak concentration beyond the drinking water standard– or other governmental regulations to prevent nitrate leaching would make manure application in spring a more attractive alternative for the farmer.

The key question to maximise nitrogen efficiency from manure is how to get the right amount of mineral nitrogen at the right time (*i.e.* synchronous to crop demand) in the right place (*i.e.* within reach of the plant roots). A more homogenous product and an analysis of the contents of manure are probably the easiest ways to improve the use of manure in arable farming. More demanding solutions are innovations in application techniques or in the processing of manure into a fertiliser with the properties of a mineral fertiliser.

Acknowledgements

We are indebted to O. Oenema (Alterra, Wageningen) for expertise in the calibration and validation of the model. We also wish to express our thanks and appreciation to G.A.A. Wossink (NC State University, Department of Agricultural and Resource Economics, Raleigh, NC, USA and Farm Management Group, Wageningen University) and J.A. Renkema (Farm Management Group, Wageningen University) for their constructive cooperation in the writing of this article.

References

Bergström, L., H. Jonhsson and G. Tortensson, 1991. Simulation of nitrogen dynamics using the SOILN model. Fertiliser Research 27: 181-188.

Boons-Prins, E.R., G.H.J. de Koning, C.A. van Diepen and F.T.W. Penning de Vries, 1993. Crop specific simulation parameters for yield forecasting across the European Community. Simulation report CABO-TT 32, CABO-DLO, SC-DLO, Wageningen, The Netherlands, 43 pp.

Burton, W.G., 1989. The potato. Third edition. Longman, London.

De Buck, A.J., H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens, 1999a. Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model. *Agricultural Systems* 59: 283-299.

De Buck, A.J., E.M.T. Hendrix and H.B. Schoorlemmer, 1999b. Analysing production and environmental risks in arable farming systems: a mathematical approach. *European Journal of Operational Research* 119: 416-426.

De Buck, A.J., H.B. Schoorlemmer and G.A.A. Wossink, 1999c. Risks of Late Blight control strategies in ware potatoes: development and application of a bio-economic model. Submitted.

De Jong, J.A., 1985. De teelt van aardappelen. First edition, Krips Repro, Meppel, The Netherlands, 320pp.

De Koeijer, T.J. and G.A.A. Wossink, 1990; Emissies van meststoffen en bestrijdingsmiddelen in de akkerbouw. Department of Farm Management, Wageningen Agricultural University, Wageningen, The Netherlands.

De Willigen P., 1987. Roots, plant production and nutrient use efficiency, Ph.D. thesis Wageningen Agricultural University, Wageningen, The Netherlands.

Diels, 1994. A validation procedure accounting for model input uncertainty: methodology and application to the Swartrer model. Ph.D. thesis 256, Faculty of Agricultural and Applied Biological Sciences, Catholic University Leuven, Leuven, Belgium.

Dierkx J., C. Belmans and P. Pauwels, 1986. SWATRER, a computer package for modelling the field water balance. Reference manual. Catholic University Leuven, Leuven, Belgium.

Eilander, D.A., W. Heijink, F.H. Jong, J. Koning, G.G.L. Steur, H. Bakker, O.H. Boersma and C. Hamming, 1990. Bodemkaart van Nederland 1:50000; toelichting bij de kaartbladen 20 west Lelystad (gedeeltelijk), 20 oost Lelystad en 21 west Zwolle. Staring Centrum, Wageningen, 165pp.

European Union, 1991. Nitrate Directive. Council Directive 91/676/EEC, Brussels.

Hardaker, J.B., R.B.M. Huirne and J.R. Anderson (1997) Coping with risk in agriculture. CAB International, Oxon, New York, 274pp.

Hellegers, P.J.G.J., 1996. The impact of environmental policy on nitrogen balances at farm level in the European Union. Research report 153, LEI-DLO, The Hague, The Netherlands.

Hutson, J. and R.J. Wagenet, 1992. LEACHN, a process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Technical report, Cornell University, Ithaca, New York.

IKC-L, 1997. MINAS brochure maart-april 1997. IKC-L, Ede, The Netherlands.

Jury W.A., W.R. Gardner and W.H. Gardner. 1991. Soil Physics. Fifth edition, John Wiley and Sons Inc. 328 pp.

Meeuwissen, P.C., 1987. De depositie van N via natte en droge neerslag in Nederland. Interne notitie CAD voor Bodem-, Water- en Bemestingszaken in de Akker- en Tuinbouw, Wageningen, The Netherlands.

Neeteson, J.J., D.J. Greenwood and A. Draycott, 1987. A dynamic model to predict yield and optimum nitrogen fertilizer application rate for potatoes. Proceedings 262 of The Fertilizer Society, 31pp.

PAGV, 1989. Handboek voor de akkerbouw en de groenteteelt in de vollegrond. Publication 47, PAGV, Lelystad, The Netherlands.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge and A.H. Bakema, 1988. Simulation of eco-physical processes of growth of several annual crops. Simulation Monographs, PUDOC-IRRI, Wageningen, The Netherlands.

Roberts, W.S. and S.M. Swinton, 1996. Economic methods for comparing alternative crop production systems: A review of the literature. *American Journal of Alternative Agriculture* 11: 10-17.

Smit A.L. and A. Van der Werf, 1992. Fysiologie van stikstofopname en –benutting: gewas- en bewortelingskarakteristieken. In: H.G. van der Meer and J.H.J. Spierz (Eds.). Stikstofstromen in agro-ecosystemen. Agro-biologische thema's 6, CABO-DLO, Wageningen, The Netherlands.

Spitters, C.J.T., H. van Keulen and D.W.G. van Kraalingen, 1989. A simple and universal crop growth simulator: SUCROS87 In: R. Rabbinge, S.A. Ward and H.H. van Laar (Eds.). Simulation and systems management in crop protection. Simulation monographs 32, Pudoc, Wageningen, The Netherlands.

Spitters, C.J.T. and A.H.C.M. Schapendonk, 1990. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. *Plant and Soil* 123: 193-203.

Stolte, J., J.G. Wesseling and J.H.M. Wösten, 1996. Pedotransfer functions for hydraulic and thermal properties of soil and the tool Hercules. Report 126, SC-DLO, Wageningen, The Netherlands.

Vanclooster, M., 1995. Nitrogen transport in soils: theoretical, experimental and numerical analysis. Ph.D. thesis 278, Faculty of Agricultural and Applied Biological Sciences, Catholic University Leuven, Leuven, Belgium.

Vanclooster, M., P. Viaene, K. Christiaens and S. Ducheyne, 1996. Water and Agrochemicals in Soil and Vadose Environment: Release 2.1. Institute for Land and Water Management, Catholic University Leuven, Leuven, Belgium.

Van Loon, C.D. A. Veerman and C.B. Bus, 1993. Teelt van consumptie-aardappelen. Publication 57, PAGV, Lelystad, The Netherlands.

Verhagen, J. and J. Bouma, 1997. Modelling soil variability. In: F.J. Pearce and E.J. Sadler (Eds.). The state of site specific management for agriculture. ASA Misc. Publ., ASA, CSSA and SSSA, Madison, WI: 55-67.

Wesseling, J.G., 1991. Meerjarige simulatie van grondwaterstroming voor verschillende bodemprofielen, grondwatertrappen en gewassen met het model SWATRE. Report 125, SC-DLO, Wageningen, The Netherlands.

Wijnands F.G. and P. Vereijken, 1992. Region-wise development of prototypes of integrated arable farming and outdoor horticulture. *Netherlands Journal of Agricultural Science* 40: 225-238.

Wossink, G.A.A., 1993. Analysis of future agricultural change; a farm economics approach applied to Dutch arable farming. Ph.D. thesis, Department of Farm Management, Wageningen Agricultural University, Wageningen, The Netherlands.

Yiridoe, E.K., R.P. Voroney and A. Weersink, 1997. Impact of alternative farm management practices on nitrogen pollution of groundwater: evaluation and application of CENTURY model. *Journal of Environmental Quality* 26(5): 1255-1263.

Appendix

Soil characteristics

Parameter		Unit	Horizon[30]				
			1 (0-25 cm)	2 (25-40 cm)	3 (40-65 cm)	4 (65-90 cm)	5 (90-160 cm)
Soil composition (Eilander *et al.*, 1990, profile 5, map Mn35A-VI; bulk density: Stolte *et al.*, 1996)							
Humus[31]		%	2.6	3	3.8	3.1	7.9
Lutum		%	33	35	25	13	15
Bulk density		kg l^{-1}	1.2	1.2	1.3	1.4	1.2
Hydraulic properties (Stolte *et al.*; 1996)							
Residual water content		%	0.01	0.01	0.00	0.00	0.00
Saturated water content		%	0.49	0.50	0.49	0.45	0.52
Inverse air entry value	α	cm^{-1}	0.0853	0.0859	0.0629	0.0491	0.0221
Shape parameters	n (m)	-	1.103 (0.093)	1.099 (0.090)	1.126 (0.112)	1.202 (0.168)	1.219 (0.180)
Saturated hydraulic	Ksat	cm day^{-1}	103.9	109.6	94.6	53.4	55.6
Slope	l	day^{-1}	-5.789	-5.867	-4.787	-2.412	-1.439

Transformation constants

Parameter		Unit	Layer				
			0-15 cm	15-30 cm	30-60 cm	60-100 cm	100-160 cm
Potential transformation rate constants							
Nitrification constant	k_{nitri}	day^{-1}	0.7	0.4	0.4	0	0
Denitrification constant	k_{denit}	day^{-1}	0.04	0.02	0.02	0.02	0
Volatilisation constant	k_{vol}	day^{-1}	0.03	0	0	0	0
Potential decomposition rates							
From litter pool	K_{lit}	day^{-1}	0.008	0.008	0	0	0
From manure pool	K_{man}	day^{-1}	0.008	0.008	0	0	0
From humus pool	k_{hum}	day^{-1}	0.00001	0.00001	0	0	0

---

[30] Soil profile 5 in map Mn35A-VI (bodemkaart van Nederland) shows a shell containing layer between between 37 and 42 cm depth. For reasons of representability, this layer is omitted here.

[31] WAVE requires a definition of the organic pool that is specified for carbon and nitrogen and for depth. For this, it is assumed that the weight of carbon equals 58% of the organic matter weight (Kuipers, 1984). The C/N quotient is assumed to have a value of 10 for all types of organic matter. Further, the proportion between manure/litter/humus in the soil is set at 1/1/98 for the upper 30 cm; 0.5/0.5/98 for 30-75 cm and 0/0/100 for a depth of 75 cm and more.

Crop development parameters

Crop stage	date	Tsum DVS^{-1}	KC
sowing	7-4	0	1.00
emergence	15-5	0	1.00
end initial stage	17-5	20	1.00
start tuber growth / GPD	5-6	170	1.05
maturity	16-7	625	1.05
harvest	7-9	1200	0.70

sources: De Jong, 1985 (dates); PAGV, 1989 (Tsum); Vanclooster *et al.*, 1996 (DVS, KC).

Air temperature	[°C]	3	10	15	20	30	35
Reduction factor		0.01	0.75	1.00	1.00	0.75	0.01

Main crop parameters

Parameter		Unit	Value	Source
Crop			potatoes	
Crop maturity class			6.5	
Number of plants		m^{-2}	4	
Base temperature for crop growth	TB	°C	2	Vanclooster *et al.*, 1996; Spitters and Schapendonk, 1990
Leaf development during juvenile stage	k_L	$m^2\ m^{-2}\ °C^{-1}\ day^{-1}$	0.012	Boons-Prins *et.al*, 1993; Spitters *et al.*,1988
Specific leaf area	SLA	ha leaf · kg leaf^{-1}	0.003	
Leaf CO_2 assimilation rate at light saturation (T = 20°C)	AMAX	kg ha^{-1} hour^{-1}	30	Penning de Vries *et al.*, 1988; Boons-Prins *et.al*, 1993; Spitters *et al.*,1988
Initial light use efficiency (T = 20°C)	ε	$(kg\ ha^{-1}\ hour^{-1})\cdot(J\ m^{-2}\ s^{-1})^{-1}$	0.45	
Extinction coefficient for diffuse light within the canopy	kdf	m^{-1}	1.00	Boons-Prins *et.al*, 1993; Spitters *et al.*,1988
Scattering coefficient	σ	%	0.20	
Maintenance factor for storage organs		kg CH_2O kg^{-1} DM day^{-1}	0.0045	
Assimilation requirement for storage material conservation		kg CH_2O kg^{-1} DM	1.28	Penning de Vries *et al.*, 1988
Critical leaf area for leaf death due to self shading		m^2 leaves · m^{-2} soil	4.0	Vanclooster *et al.*, 1996; Spitters and Schapendonk, 1990
Initial leaf area of the seedling		m^2 leaves · m^{-2} soil	0.062	Van Keulen and Van Kraalingen, 1989

7 Using experimental economics to assess farmers' decision making on weed control

Abco J. de Buck, Ada Wossink [a], Jan A. Renkema

For submission to *Netherlands Journal of Agricultural Science*

Abstract

An economics experiment was used to investigate farmers' response to a fine on excess herbicide use. Thirteen arable farmers differing in the degree of sustainability of their farming were examined, to discover their behaviour when choosing among various weed control strategies and measures. Weed control situations with stochastic features were simulated by the computerised model 'BESTWINS' and presented to the farmers. Prior to the introduction of the fine, three participants had opted for a more sustainable strategy, which they persisted with, regardless of this fine. Two farmers responded by persisting with their conventional strategy and eight responded by changing to a more sustainable weed control strategy. The herbicide use of farmers in the experiment correlated with their weed control practices in real life. This correlation makes it plausible that the results of the experiment (treatment effects included) will transfer to farming practice. If this transfer occurs, the experiment will have shown its worth for ex-ante evaluation of the prospects for new farming practices to be adopted under changing settings of environmental regulations.

Keywords: risk perception, herbicide use, experimental economics

---

[a] *NC State University, Department of Agricultural and Resource Economics, Raleigh, NC, USA and Farm Management Group, Wageningen University*

7.1 Introduction

In the last twenty years, new systems for crop production have been developed in the Netherlands in response to growing environmental concerns (Wijnands and Vereijken, 1992). These sustainable farming systems integrate economic and environmental goals in crop production to comply with the agreements between the arable sector and the Dutch government on the reduction of pesticide use (Falconer, 1998). However, farmers are slow to take up sustainable farming systems. De Buck *et al.* (2000) argue that this reluctance is attributable to insufficient economic incentives and to the farmers' perception of large risks and their lack of knowledge and skills with regard to sustainable farming methods. To investigate the prospects of sustainable weed control being adopted, a study was conducted in which current weed control management of arable farmers and the impact of a fine on their choice of weed control strategies and measures were investigated.

To adopt a new farming system (such as sustainable farming) means having to make a decision surrounded by uncertainty, in which farmers' perceptions and attitudes are influential. The risks attributed to this decision include labour requirements, pesticide costs, crop yields and the possibility of controlling biological processes (*e.g.* weed development) in the farming system. However, other factors, such as societal pressures, will also influence the choice made. The factors that determine the choice of a farming system are usually too complex for systematically conducting a field study (De Buck *et al.*, 2000).

In such a complex decision environment, methods from experimental economics offer possibilities for analysing the behaviour of decision-makers. The main advantages of experiments compared to other empirical methods, such as survey studies, are that the influential parameters can be better controlled and fewer historical data are required.

In accordance with the principles of experimental economics (Davis and Holt, 1992), we formulated a decision problem in weed control as a computerised experiment. Practical decision-makers –in this case farmers with different experiences with sustainable farming systems – were invited to participate. In order to mimic more restrictive regulations on the use of pesticides, in the experiment excess herbicide use was penalised.

As applications of experimental economics in agriculture are scarce, a pilot experiment was conducted. Another reason for running a pilot experiment was the novelty of combining the economic problem of investment and operational decisions with the agro-ecological features of weed control measures. If this approach proves it worth, experiments could be used for the ex-ante evaluation of the prospects of the adoption of new farming practices, where no historical data is available (Verstegen *et al.*, 1998).

This paper continues with a description of the theoretical background of experimental economics and of the decision problem of weed control. Then, the outline of the experiment is presented, including the participants' interactive use of the computer model, the procedure for selecting the participants and the experimental design. Subsequently, the results of the pilot experiment are presented, followed by a discussion of the method and the results, and the conclusions of this paper.

7.2 Theoretical framework

7.2.1 Experimental Economics

Two methods commonly used to find evidence to support theoretical models such as economic decision models, are the analysis of historical panel data, or survey studies based on interviews. An alternative approach is to use experimental economics; this is a powerful approach enabling the determining variables to be controlled, which overcomes some of the practical limitations (such as intervening variables and high labour and money requirements) of field experiments (Verstegen *et al.*, 1998). Economics experiments are typically conducted in a laboratory environment and their results can be extrapolated to the more complex natural environment (Davis and Holt, 1993). Economics experiments have some basic properties (Smith, 1982 and 1994). Firstly, abstract decision problems are used to control for information available to the participants. The key elements of this decision problem should be incorporated in the experiment and they should act as in the natural decision environment. For example, when in real life the making of a sound decision requires an effort to be made to obtain additional information, this should also be the case in an experiment. If the participant recognises the abstract decision problem as a natural decision problem, the participants' knowledge and experience play a role in decision making. The researcher should be aware of this. Secondly, the participants are stimulated to make economically motivated decisions by a real monetary incentive; the level of which varies in accordance with the financial results of their decisions.

7.2.2 The decision problem

The experiment was conducted with a computerised numerical presentation of the decision problem of weed control in sugar beet, which consists of two levels: choosing a strategy and making operational decisions during the growing season (De Buck *et al.*, 1999). In order to obtain lifelike decisions, in the experiment, the typical complex, agro-ecological decision environment of weed control was designed as a decision problem that was recognisable to the farmers. Hence, the farmers' knowledge and experience implicitly, but deliberately, influenced their decisions in the experiment.

In this experiment, a strategy determined the investments in weed control machinery and the control measures that were available to the participant. When there was no change in strategy, weed control was resumed in a new growing season with the same set of measures. The experiment included the annual costs of investments involved in strategy choice, and also the costs of operational weed control decisions.

In the experiment, decisions about weed control were based on a model for weed control in sugar beet (De Buck *et al.*, 1999). Within one growing season, weed control is an iterative process divided into decision stages (Figure 7.1). At each stage, the state of the system is monitored by the decision-maker. The state of the system includes weed population (number, location and development stage), development stage of the crop and meteorological conditions.

At each decision stage, there is uncertainty about the future state of the system because of the stochastic character of weather parameters. Weed control is to prevent the system from

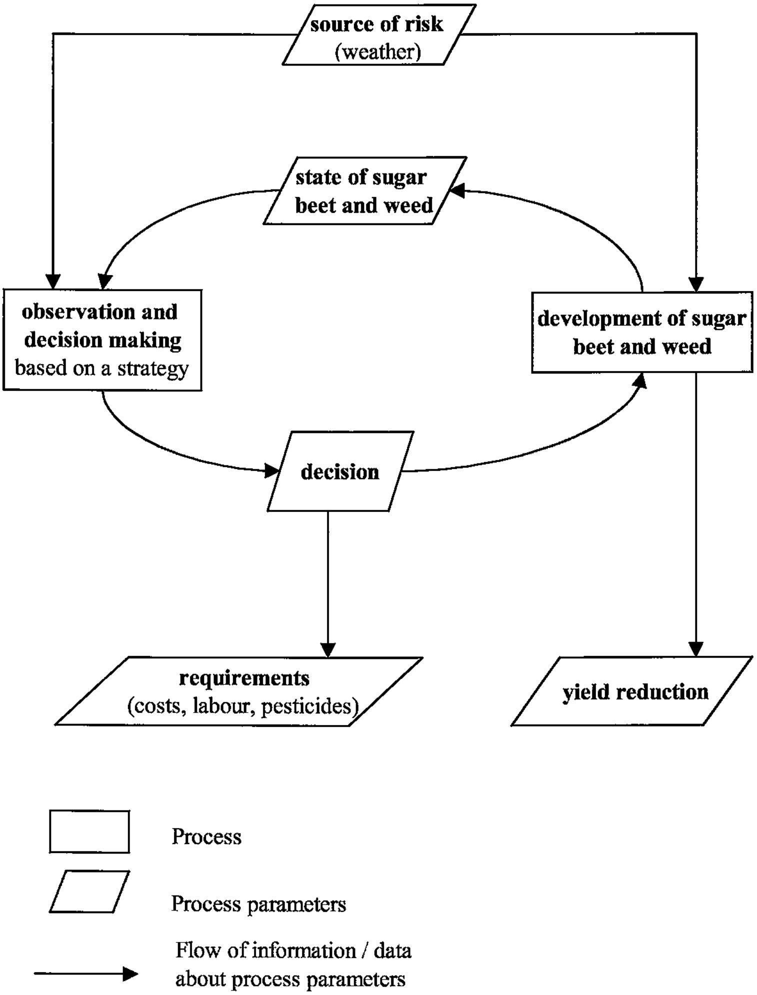


Figure 7.1 Outline of the stochastic, multi-stage decision problem of weed control in sugar beet during one growing season (after De Buck et al., 1999).

having to cope with an excessive weed population, which would lead to serious costs because yield is reduced and additional weed control is necessary. Based on the current state of the system, knowledge and experience, the farmer estimates the future state of the system and decides on a weed control measure, in which direct costs of herbicide, labour and machine input are involved. In the experiment, the quality of decision making was measured as the total of direct costs, annual costs of investments and costs of yield reduction.

7.3 Outline of the experiment

7.3.1 Simulation of a weed control season

The experiment was carried out with a user version (programmed in Borland Delphi 2) of the Bio Economic model on STrategy choice in Weed control IN Sugar beet (BESTWINS; see De Buck *et al.*, 1999 for a comprehensive description).

In the experiment, six weed control strategies were available. Strategy 1 was based on full field spraying of herbicides, while strategy 6 fully depended on mechanical methods like harrowing and hoeing (Table 7.1). Going from strategy 1 to 6, 'conventional' full field spraying was gradually replaced by 'sustainable' mechanical methods and/or row spraying. Annual costs of investments for each of the six strategies (that is extra costs of additional machinery; Tables 7.1 and 7.2) were presented to the participant (in Dutch currency) in the first window on the computer screen.

Table 7.1 Machinery inventory for the six weed control strategies in sugar beet.

Strategy	Machinery inventory
1	Full field sprayer
2	Full field sprayer, hoe with ridgers
3	Full field sprayer, harrow, hoe with ridgers
4	Row sprayer, hoe with ridgers
5	Row sprayer, harrow, hoe with ridgers
6	Harrow, hoe with ridgers

A second window presented direct costs (of herbicide, labour and machine input) and the quantity of herbicide and labour input of each measure (Table 7.3). Spraying was based on the Low Dose system (LD system, which is commonly applied in the Netherlands), where the standard load per application is increased by a factor of 1.5 or 2 if the development stage of the weed population requires this (Table 7.3; De Buck *et al.*, 1999). Each half-weekly decision stage, the third window (Figure 7.2) updated the participant with information on total weed control costs (direct and annual costs of investments), total chemical active ingredient (*a.i.*) use, crop development stage and actual meteorological and soil status (no forecast was given). The meteorological data were derived from records of a local weather station.

Table 7.2 Equipment required for the execution of measures 1-6, and annual costs of investment, ascribed to sugar beet (Spigt and Janssen, 1997).

Equipment	Replacement value	Measures	Annual costs		
			Total	Ascribed to sugar beet	
	(1) €	(2)	(3) % of (1)	(4) % of (3)	(5) €
Full field sprayer	15000	1-5	13.1	25	491
Row sprayers (additional to full field sprayer)	1850	4,5	13.3	50	123
Hoe	6000	2-6	11.1	50	333
Ridgers (additional to hoe)	750	2-6	11.1	100	83
Harrow	4150	5,6	11.1	50	230

Table 7.3 Direct costs of herbicide, labour and machine input and requirements (labour and chemical active ingredient, or *a.i.*) of the weed control activities; all per application of a single measure.

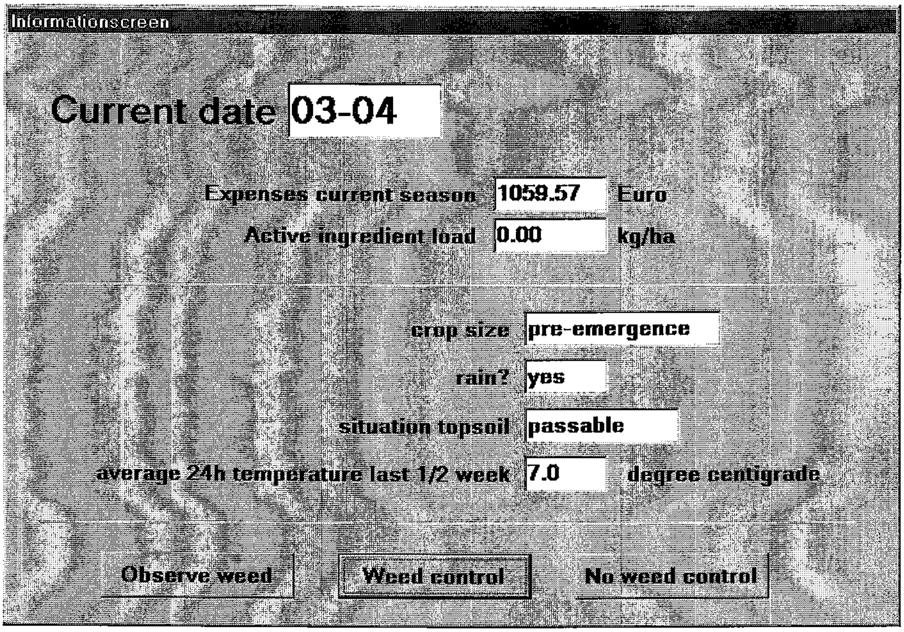
	Measure	Direct costs	Requirements	
			a.i.	Labour
		€ ha^{-1}	kg ha^{-1}	h ha^{-1}
1	Full field spraying LD	75.80	0.53	0.41
2	Full field spraying 1.5 LD	109.53	0.79	0.41
3	Full field spraying 2 LD	144.57	1.06	0.41
4	Row spraying LD	51.30	0.25	1.10
5	Row spraying 1.5 LD	68.17	0.38	1.10
6	Row spraying 2 LD	85.04	0.51	1.10
7	Hoeing	17.15	0	1.00
8	Ridging	17.15	0	1.00
9	Harrowing	8.40	0	0.49
10	Manual weeding	450[a]	0	30[a]
11	Field inspection	2.00	0	0.13

[a] At least; depends on weed population

General information, as presented in the third window, was available for free (Figure 7.2). Information on the weed population had to be paid for (€ 20 per 10 ha), as field inspection requires time and money. At each decision stage there was an opportunity to call up information on the current weed situation via a fourth window on the computer screen[32]. The

---

[32] Monitoring the weed population could be employed as a check of the effectiveness of a previous weed control measure. The decision-maker has to compare the costs of monitoring and the effort involved with the expected benefits of the additional information acquired on the weed population. This information was useful to avoid yield reduction (due to excessive weed occurrence) or costly 'emergency' measures.



Current date 03-04

Expenses current season 1059.57 Euro

Active ingredient load 0.00 kg/ha

crop size pre-emergence

rain? yes

situation topsoil passable

average 24h temperature last 1/2 week 7.0 degree centigrade

Figure 7.2 Information that was presented to the participants (in Dutch); the buttons effectuate the decision to do field observations, to execute a weed control activity or to continue without any action.

weed situation was presented as numbers of plants per m^2 in four development stages, located within and between the crop rows. In the model, 'bad management' led to a yield reduction of € 1000 for the whole field for every decision stage the weed population surpassed a fixed threshold and the need for expensive (emergency) measures. Participants were given advance warning of this most unlikely event and, if it occurred, received a warning message in the third window (Figure 7.2).

7.3.2 Selection and characteristics of the participants

Participants were recruited via farmers' groups set up by the extension service to study agronomic or management themes (not specifically weed control). When contacted by telephone, fifteen farmers who grew sugar beet were willing to co-operate and were sent a letter of invitation; thirteen of them ultimately participated in the experiment.

At the start of the experiment the participants' weed control practices were inventoried by means of a short questionnaire. The participants were asked to mark the frequency in which they used five machine combinations for weed control in sugar beet, listed in Table 7.2. We scored these five answers in terms of environmental sustainability[33], and summed them for

---

[33] When a machine combination was 'never' used, it was '1'; 'rarely' was '2'; 'now and then' was '3'; 'often' was '4' and 'as much as possible' was '5'. These numbers were inversely related to the scores we assigned for

the five machine combinations. The total score for each participant indicated the environmental sustainability of his weed control, which we classified into three ***sustainability grades*** (*SG*)[34], that can be characterized as follows: *SG* = 1 when weed control in sugar beet was based on full field spraying, *SG* = 2 when row spraying was applied or when spraying was combined with mechanical techniques and *SG* = 3 when weed control was based on mechanical techniques with only emergency sprayings. *SG*s of the participants were expected to be related to the outcomes of the experiment.

7.3.3 Experimental design and procedure

The laboratory consisted of a college lecture room in Dronten, the Netherlands (near the farms of all participants) with 17 PCs and a whiteboard. The experiment was held on March 16, 1998 from 7.00 to 10.00 p.m.[35]

To ensure that the experiment mimicked real life as much as possible, the participants were asked to execute weed management for the situation of a representative farm in their area (written information about this hypothetical farm was handed out before the start of the experiment)[36]. The participants were introduced to the model verbally and by means of a preliminary simulation run of two weed control seasons.

The experiment was conducted in three rounds of two weed control seasons (or: years), represented by the meteorological data of six randomly selected, different years over 1954-1995. All participants were exposed to the same selection. In the first round, strategy 1 was pre-set for all participants, so that the differences in operational decisions between them could be observed. In the second round, farmers were free to choose and invest in new strategies. The annual costs of investments in machinery were irreversible during the experiment. Before the third round, as an economic incentive to reduce herbicide use, a fine was announced on excess herbicide use (> 2.25 kg *a.i.* ha^{-1} $year^{-1}$).

---

environmental sustainability. For instance, a 5 for a full field sprayer was scored 1 and a 4 or 5 for a harrow was scored 3.

[34] *SG* = 1 when 5 ≤ score ≤ 7 (lowest possible score was 5); *SG* = 2 when 8 ≤ score ≤ 9 and *SG* = 3 when 10 ≤ score ≤ 11 (highest possible score was 11).

[35] The user shell and the procedure of the experiment were approved after a pre-test with a group of eight researchers and PhD students in a similar laboratory environment.

[36] Information was provided on the crops that were grown: sugar beet (10 ha), ware potatoes (10 ha), winter wheat (10 ha), ware onions (5 ha) and grass seed (5 ha). Further, information was presented on the efficacy of a measure –specified per development stage of the weed population– as well as information on the minimum development stage of the crop for successful application of the measures.

In order to let each participant position himself within the group, after each round the results of the participants (costs and *a.i.* use) were presented on a whiteboard and discussed with the participants. At the end of the game, the participants were paid according to[37]:

$$payment = 80 - \sum_{m=1}^{M} costs_m - fine \qquad (1)$$

with :

m = round

$costs$ = direct and investment costs of weed control

As an economic incentive to reduce herbicide use, a multi-level fine on *a.i.* use was introduced:

$fine = 0$ when $\overline{a.i.}_{m=3} < 2.25$ kg ha^{-1} year^{-1}

$fine = 5$ when $2.25 \leq \overline{a.i.}_{m=3} < 2.75$ kg ha^{-1} year^{-1}

$fine = 10$ when $\overline{a.i.}_{m=3} \geq 2.75$ kg ha^{-1} year^{-1}

The lowest payment was expected to cover the participants' travel expenses and time. The aim was for the maximum difference between the lowest and the highest payment to be € 25.

7.4 Results

In Table 7.4, the participants are ranked according to (a) SG; (b) strategy choice in round 2 and (c) strategy choice in round 3. Nine of the thirteen participants combined spraying with mechanical techniques on their own farm (SG = 2); four of them based weed control on full field spraying (SG = 1). No farmer based weed control solely on mechanical techniques.

The SG, reflecting the environmental sustainability of weed management on the participants' own farms, was expected to be inversely related to herbicide use in the experiment. Table 7.4 shows *a.i.* use for each participant in round *m*. The SG was negatively correlated ($\alpha = 0.11$) with *a.i.* use, summed over all rounds (Table 7.5). Hence, compared with SG = 1, farmers with SG = 2 showed a lower herbicide use, but this was not found consistently in the three game rounds.

In the second round, when strategy choice was free, all participants with SG = 1 chose 'conventional' strategy 2, based on full field spraying and hoeing (Table 7.4). Of the participants with SG = 2 six participants chose a conventional strategy (1 or 2) and three chose a more sustainable strategy with row spraying and hoeing. In the third round, participants with SG = 2 showed a tendency to choose more sustainable strategies; two participants

---

[37] The formula calculates the payment in Euro (€), but the participants were actually paid in Dutch currency: it was assumed that NLG 2 = € 1

Table 7.4 Sustainability grade (SG) of the participants, results of the experiment (average yearly costs and *a.i.* use and strategy choice in the three rounds *m* of the experiment) and ultimate payment to the participants.

Participant		$m = 1$ (strategy 1)		$m = 2$ (free strategy choice)			$m = 3$ (free strategy choice, fine on excess *a.i.*)			*payment*
		costs	*a.i.*	strat.	*costs*	*a.i.*	strat.	*costs*	*a.i.*	
number	SG	€ ha^{-1}	kg ha^{-1}		€ ha^{-1}	kg ha^{-1}		€ ha^{-1}	kg ha^{-1}	€
9	1	649	2.6	2	779	0.8	2	511	2.6	36
3	1	493	2.8	2	583	2.4	4	588	1.4	47
4	1	467	3.7	2	466	1.9	4	835	1.6	45
11	1	489	3.0	2	498	2.8	4	614	0.9	48
7	2	567	2.9	1	561	2.7	4	1142	2.4	30
10	2	430	2.5	2	439	2.1	2	601	1.7	51
2	2	532	2.9	2	741	2.5	4	602	1.5	43
5	2	506	3.6	2	437	1.1	4	747	0.9	46
1	2	489	3.2	2	1000	2.0	5	549	1.4	39
6	2	400	2.0	2	580	2.0	6	696	0.0	47
12	2	497	2.4	4	1013	0.8	4	451	1.1	41
13	2	462	2.8	4	493	1.3	4	468	1.3	52
8	2	458	1.7	4	589	2.0	4	865	1.1	42
Average:		495	2.8	2.4	629	1.9	3.9	667	1.4	43

decided to invest in a harrow (strategy 5 and 6). In both rounds two and three, SG and strategy number tended to be positively correlated ($\alpha = 0.18$), meaning that participants with a high SG tended to choose more sustainable strategies.

Prior to the fine on excess herbicide use, three participants had already opted for a sustainable strategy. The announcement of the fine appeared to be an ample stimulus for the majority to follow suit, as eight responded by shifting towards a more sustainable weed control strategy. Two participants persisted with their conventional strategy as a response to the fine. Altogether, eleven participants ended up with a more sustainable strategy. Given that timeliness greatly determines efficacy of weed control, more sustainable strategies have the theoretical advantage of a larger stock of machinery which is deployable under a broader range of conditions. Eventually, only two participants exceeded the *a.i.* use threshold of 2.25 kg *a.i.* ha^{-1} $year^{-1}$: participant 9 who persisted in 'conventional' strategy 2 and participant 7 who chose a more 'sustainable' strategy 4 (Table 7.4).

Participant 10 succeeded in reducing herbicide use below the threshold level at low costs with strategy 2, showing that reduction in herbicide use was possible with good management of a 'conventional' strategy. Participant 13 with 'sustainable' strategy 4, received the highest payment due to low costs and low *a.i.* use.

The results show that both in 'conventional' and in 'sustainable' strategies, poor management can result in the use of large quantities of herbicides, for instance due to additional 'emergency' sprayings to kill an excessive weed population. However, we found that the more

Table 7.5 Correlation matrix of the outcomes of the experiment (Pearsons correlation test: number of observations =13, r=correlation coefficient).

		Correlation with (r)			
		SG	*a.i.*		
			$m = 1$	$m = 2$	$m = 3$
Strategy	$m = 2$	0.28	-0.48[c]	-0.5[c]	-0.3
	$m = 3$	0.28	-0.06	0.24	-0.72[c]
costs	$m = 1$	-0.33[a]			
	$m = 2$	0.17			
	$m = 3$	0.11			
a.i.	$m = 1$	-0.33[a]	1	0.04	0.25
	$m = 2$	-0.1	0.04	1	-0.05
	$m = 3$	-0.28	0.25	-0.05	1
$\sum_{m=1}^{3} a.i.$		-0.37[b]			

[a] statistically significant at $\alpha = 0.14$ (one-tailed)

[b] statistically significant at $\alpha = 0.11$ (one-tailed)

[c] statistically significant at $\alpha \leq 0.05$ (one-tailed)

sustainable strategies in general were successful in reducing herbicide load: over the whole experiment there was a significant and strong negative correlation between strategy number and *a.i.* use (Pearsons' coefficient equals 0.50 and 0.72 in rounds 2 and 3 respectively, with $\alpha \leq 0.05$).

Costs in Table 7.4 include total annual costs of investments, direct operational costs and costs incurred from yield reduction per year for the whole area of 10 ha of sugar beet. This composition of the parameter *costs* does not allow clear-cut conclusions to be made about correlations with other variables.

7.5 Discussion

Having identified weed management as a bio-economic decision problem in an agro-ecological environment with stochastic features, this study shows that methods from experimental economics were a suitable tool to analyse weed control decisions of farmers. Generally, our impression of the farmers' behaviour during the preliminary round was that they were familiar with a PC and understood the model. The results showed that participant 7 might be an exception. However, excluding participant 7 from the analysis of the results did not change the conclusions from the Pearsons' correlation test.

Describing the weed population in numbers of plants per m^2, in plant location (within and between the crop rows) and in weed development stage (a rather complex abstraction) appeared to coincide well with the way farmers observe weeds in the field. So, it was not necessary to visualise the weed population (in the form of pictures, for instance).

Our results showed parallels between the decision behaviour of the participants in the experiment and in real life: farmers with SG = 2 showed a lower herbicide use in the experiment than farmers with SG = 1 and tended to choose more sustainable strategies. This correspondence makes the extrapolation of the results of the experiment (treatment effects included) to farming practice plausible. However, the limited size of this pilot experiment would require our findings to be confirmed by replications. If this transfer occurs, the experiment will have proved its worth for the ex-ante evaluation of the take-up prospects of new farming practices. It can then be used in the design of policy measures and extension programmes that aim to improve the environmental performance of the farming sector.

In an LP study on fixed levies per unit *a.i.*, Wossink *et al.* (1992) report a change to low-herbicide sugar beet variants in the optimal solution at relatively low levies. In our economics experiment, where the conditions of rationality and optimality were not necessarily met, we also found that an economic incentive made farmers change to low-herbicide variants. In another laboratory experiment, other options could be investigated on how to achieve the targeted reductions in pesticide use in the Netherlands that are agreed upon by the arable sector and the government (Falconer, 1998).

In our experiment, decision quality was addressed by the aggregate parameter of costs. No strategy was particularly cost saving, as we found no unambiguous correlations with the parameter of *costs*. The experimental design offered the opportunity to gather data on more parameters that could describe farmers' decision-making (for instance, describing the quality of the decisions). A more refined specification of this compound parameter of *costs* (including annual costs of investments, operational costs and costs for yield reduction) would allow a more detailed correlation analysis. Other parameters that could describe decision-quality include the weed density at which farmers decided to control weeds, or the weather when weed control took place. Obviously, more detailed records are only useful in an experiment with a sufficient number of observations.

7.6 Conclusions

This paper has demonstrated the potential of conducting an economics experiment on the bio-economic decision problem of weed control, which has stochastic features. The participants recognised the abstract representation of the biological system as a real situation in weed control.

It can be concluded that decision behaviour in the experiment reflected real life choices, because, compared to participants with SG = 1, participants with SG = 2 used less herbicide and tended to choose more sustainable strategies in the experiment.

Before the fine on excess herbicide use was announced, three participants (of the total of 13) chose a more sustainable strategy, which they persisted with, regardless of the imposition of this fine. As a response to the fine, two participants persisted with their conventional strategy and eight shifted towards a more sustainable weed control strategy.

The set-up as a pilot study makes it necessary to confirm the results by replicate experiments. This paper shows the promising prospects for conducting such a more large-scale experiment, which offers possibilities of investigating the herbicide-reducing effects of other changes (besides a fine) in the agronomic and institutional environment of crop production.

Acknowledgements

The authors are indebted to J.A.A.M. Verstegen for his suggestions regarding the design of the experiment and his comments on an earlier version of the manuscript. The authors thank J. Oenema for assistance on computer software and hardware and J. Burrough for correcting and editing the English.

References

Davis, D.D. and C.A. Holt, 1993. *Experimental economics.* Princeton NJ: Princeton University, 572 pp.

De Buck, A.J., H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens, 1999. Risk of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model, Agricultural Systems 59: 283-299.

De Buck A.J., I. van Rijn, N.G. Röling, and G.A.A. Wossink, 2000. Farmers' reasons for changing or not changing to more sustainable practices: an exploratory study of arable farming in the Netherlands. (submitted).

Falconer, K.E., 1998. Managing diffuse environmental contamination from agricultural pesticides: an economic perspective on issues and policy options, with particular reference to Europe. *Agriculture, Ecosystems and Environment* 69: 37-54.

Smith, V. L., 1982. Micro-economic systems as an experimental science. *American Economic Review* 72: 923-955.

Smith, V. L., 1994. Economics in the laboratory. *Journal of Economic Perspectives* 8: 113-131.

Spigt, R.M. and T.L.J. Janssen, 1997. Kwantitatieve informatie akkerbouw en vollegrondsgroenteteelt. Publication nr.85, *Applied Research for Arable farming and Field production of Vegetables* (PAV), Lelystad.

Verstegen, J.A.A.M., J. Sonnemans, R.B.M. Huirne, A.A. Dijkhuizen and J.C. Cox, 1998. Quantifying the Effects of Sow-Herd Management Information Systems on Farmers' Decision Making Using Experimental Economics, *American Journal of Agricultural Economics* 80(4): 821-829.

Wijnands F.G. and P. Vereijken, 1992. Region-wise development of prototypes of integrated arable farming and outdoor horticulture. *Netherlands Journal of Agricultural Science* 40: 225-238.

Wossink, G.A.A., T.J. de Koeijer and J.A. Renkema, 1992. Environmental economic policy assesment: a farm economic approach. *Agricultural Systems* 39: 421-438.

8 General discussion

8.1 Introduction

The overall research goal of this study was to determine to what extent production risks obstruct the introduction of more sustainable production systems in arable farming. The research outline derived from this goal combines normative and descriptive methods. In the descriptive part of the research (Chapter 2), we assessed farmers' perceptions of sustainable farming, with emphasis on production risks. The normative part of the research (Chapters 3-6) showed the differences in risk attributes between 'conventional' and 'sustainable' production alternatives. In order to assess differences in decision behaviour between farmers in different stages of adoption, Chapter 7 presented a laboratory experiment in a simulated production environment.

The objective of this General Discussion is to compare and integrate the results of the normative and the descriptive research. Section 2 presents the main conclusions of the research. Section 3 elaborates on the descriptive approach to *innovator*-specific characteristics. Section 4 relates the main outcomes of the normative model calculations to the outcomes of the descriptive research. Section 5 discusses the methodological issues of addressing production risks from the perspective of the *innovator* and/or of the *innovation*. Throughout this General Discussion, the implications of the research findings for the arable farming community are highlighted and recommendations for future research are made. Section 6 recommends a further development of *bio-economic models* of the type described in this study and discusses the possibilities to insure the risks involved with environmentally sustainable arable farming practices. Finally the chapter presents the prospects for the dissemination of more sustainable farming systems under future scenarios for arable farming in the Netherlands, in the light of upcoming environmental legislation and market conditions.

8.2 Main conclusions

Based on the results of this research, fourteen conclusions can be drawn:

1. IAFS cannot be considered as a single innovation; interviews showed that farmers adopted only those components of IAFS that had economic advantages in addition to environmental advantages.
2. Without guidance through an introduction project, farmers will not be motivated to adopt IAFS as a single innovation.
3. Herbicide-saving, 'integrated' strategies in sugar beet imposed lower environmental risks of herbicide use (based on simulated average load and peak loads).

4. Herbicide-saving, 'integrated' strategies (especially those based on row spraying) in sugar beet imposed larger organisational risks (based on the simulated requirements for skilled labour) than the strategy of full field spraying.
5. The herbicide-free, 'organic' strategy in sugar beet imposed much larger organisational risks than the other strategies; however, under 5% of the most unfavourable conditions, the requirement of unskilled labour converged for all strategies
6. There was no economic advantage of a spraying scheme with variable intervals (vs. fixed intervals) in Late Blight control in ware potatoes; the additional costs of the equipment required outweighed the simulated savings on fungicide use.
7. Based on bio-economic simulation results, variable vs. fixed spraying intervals in Late Blight control in more resistant potato cultivars reduced environmental risks of fungicide use and did not increase epidemiological risks.
8. Farmers' reasons to refrain from adopting fungicide-saving Late Blight control were the perceived production risks arising from the more complex variable spraying interval schemes, and the perceived external socio-economic risks from uncertain market prospects for more resistant cultivars.
9. Nitrogen management in ware potatoes imposed considerable environmental risks; all the strategies investigated showed large simulated average values and peak values in nitrate leaching.
10. Manure application at the optimal moment did not impose larger environmental risks (based on the simulated average values and peak values in nitrate leaching) than the application of only synthetic fertiliser in ware potatoes.
11. Farmers can greatly reduce the risk of nitrate leaching by taking account of the nitrogen value of manure and by shifting from autumn to spring application of manure.
12. Production risks were not the major barrier for farmers to adopt IAFS, but were generally considered as an acceptable part of professional decision making.
13. External socio-economic uncertainties (government policy, the development of the market for arable products) were major constraints for farmers to adopt IAFS.
14. Experimental Economics proved to be a suitable method for investigating farmers' response to a tax on pesticides in a decision problem with uncertain agro-environmental features.

8.3 Farmers' perceptions of more sustainable arable farming practices

Chapter 2 reports that the researchers' construction of Integrated Arable Farming Systems (IAFS) as a package innovation to meet future environmental goals did not appear to match the farmers' demands for innovation. This issue was already being debated during the first introduction project (the so-called Innovation Project, Van Weperen *et al.*, 1998): should one introduce components of IAFS gradually, or should one introduce the package as a whole to the participating farmers? Our study supports the hypothesis of Röling and Jiggins (1998), that without guidance through an introduction project, farmers will not be motivated to adopt IAFS as a package.

Our study indicates that policy initiatives such as the Multi-Year Crop Protection Plan (MYCPP), and the development and promotion of the IAFS associated with it, have led to a new farming system that incorporates some IAFS techniques. Though most arable farmers seem to have converged on this new farming system, it has not led to the fulfilment of all environmental goals (Chapter 2). A fulfilment of the environmental goals can hardly be expected, because IAFS were developed as a package innovation to cope with future environmental demands. An earlier finding (Van Weperen *et al.,* 1998) that the conversion to IAFS required a change from the current paradigm of 'productivity' to a paradigm of 'environmental sustainability' was confirmed in the present study. The first introduction project showed that the communication and training efforts necessary to achieve such a paradigm shift are considerable (Chapter 2), which makes a large-scale autonomous diffusion of IAFS doubtful.

The farmers' experience that IAFS strategies in Late Blight control are increasingly being adopted (Chapter 2) contradicts earlier observations (Proost and Matteson, 1997; Janssen, 1996; Woittiez *et al.*, 1996) that the volume of fungicide use in the Netherlands is no longer decreasing. Farmers tended to overestimate the 'degree of sustainability' of Late Blight control practice in potato farming.

Farmers did perceive that fungicide-saving Late Blight control strategies were more complex and had large production risks. Normative calculations, however, showed that fungicide load could be reduced 'safely', provided that a more resistant cultivar were grown (Chapter 5). In this situation of farmers' perceptions being coloured by insufficient knowledge, communication and training efforts could support the change to fungicide-saving strategies, which is crucial to achieve the environmental goals (as stipulated in MYCPP; LNV, 1991; Falconer, 1998).

One of the key findings reported in Chapter 2 is that production risks do not feature very highly in farmers' perceptions. Farmers consider the trade-off between the positive and negative aspects of an innovation (and the accompanying uncertainty) to be a part of their profession. Farmers seem to converge on some new 'conventional' arable farming system, which uses less chemical inputs than the old one. Consequently, the presumed differences among farmers who had participated in projects to introduce IAFS, and 'conventional' farmers who had no such exposure, could not be established. This new farming system, however, is still a long way from the sustainable arable farming system that is considered feasible by IAFS researchers.

8.4 Production risks of more sustainable arable farming

Recall that in-depth interviews in a preliminary study with farmers, extension agents and researchers involved with the introduction of IAFS allowed the main attributes of production risks of IAFS to be specified. The selection criteria for the main issues in production risks of IAFS on the arable farm (Chapter 1) resulted in the following case studies of production risks of 'conventional' and 'sustainable' strategies:

- weed control in sugar beet, including strategies based on herbicide spraying according to the Low Dose System (LDS) in full field *vs.* row application, and strategies based on mechanical techniques (Chapter 4),
- Late Blight control in potatoes, including strategies based on short, fixed spraying intervals *vs.* variable spraying intervals applied on cultivars with a different degree of resistance (Chapter 5),
- nitrogen management strategies, with or without use of animal manure and a high *vs.* a moderate level of nitrogen input in ware potato cropping (Chapter 6).

In this section, the normatively calculated relative advantages and disadvantages of more sustainable production strategies are discussed and compared with the outcomes of the results of the descriptive research (Chapter 2). In line with our observation (Chapter 2) that IAFS are to be regarded as a collection of independent innovations, the risk attributes are discussed separately for each case of crop husbandry. The focus is on the main attributes of production risk: relative economic advantages, relative environmental advantages, epidemiological risks and organisational compatibility (which includes labour requirements and complexity).

8.4.1 Relative economic advantages

The relative economic advantage of the Low Dosage System (LDS, Chapter 4) for weed control in sugar beet compared to spraying full doses of herbicide explains its wide adoption (Chapter 2). As a result of adopting LDS, the arable sector has considerably reduced herbicide use for weed control in sugar beet. The small additional reduction in cost (the total of direct costs and annual costs of investment) of row spraying instead of full field spraying was apparently not sufficient motivation to switch to row spraying.

Bio-economic simulation showed that alternative strategies in Late Blight management had lower fungicide costs. However, the extra costs of a local weather station meant that generally there was no relative economic advantage in adopting a variable interval scheme (Chapter 5). Besides, farmers chose cultivars for reasons other than Late Blight resistance (the latter is a major factor in fungicide-saving Late Blight control); for example, farmers considered the market prospects for the susceptible cultivar 'Bintje' to be most certain and were not prepared to accept the market risk of growing a more resistant cultivar (Chapter 2).

There was no clear direct relative economic advantage of more sustainable strategies in nitrogen management (Chapter 6). Actually, shifting the application date of organic manure from autumn to spring might have a negative economic effect (which was not quantified), because spring application of manure can severely damage the soil structure. Especially in heavy clays under wet conditions this can severely reduce crop yield, while postponing manure application to wait for better conditions can also reduce yield.

8.4.2 Relative environmental advantages

Strategies that combine a clear relative economic advantage with a relative environmental advantage (such as LDS in weed control) have become part of current farming practice. Strategies that show a trade-off between an economic disadvantage and an environmental advantage (such as weed control based on row spraying *vs.* full-field spraying) were not adopted in practice. Relative environmental advantage was not found to be a sufficient single motive for changing to more sustainable strategies; it had to be accompanied by a relative economic advantage.

Only when more resistant cultivars are grown is it viable to reduce the use of fungicides for Late Blight control by switching from a scheme with fixed spraying intervals to one involving variable intervals. The market uncertainty surrounding these cultivars and the manageability and efficacy of a variable interval scheme were perceived as major disadvantages of more sustainable Late Blight strategies; the relative environmental advantages (as calculated in Chapter 5) were apparently not sufficient motivation for adopting these strategies.

As calculated in Chapter 6, differences in nitrate leaching between years caused by variable weather conditions were larger than differences between nitrogen management strategies in potato cropping. Manure applied in spring (instead of in autumn), or applying only mineral fertiliser, showed a notably lower environmental risk (based on average values and peak values of nitrate leaching). Shifting the application date from autumn to spring could reduce environmental risks for the largest group of farmers (43%) in the panel. Thirteen percent of the farmers in the panel could considerably improve environmental performance by merely adapting the mineral fertiliser rate to take account of the nitrogen content of manure. These measures to improve the exploitation of nitrate from organic manure could considerably reduce nitrate leaching in the study area.

As in the case of weed control and Late Blight control strategies, in the absence of a relative economic advantage, environmental advantages did not appear to be an argument for the adoption of more sustainable nitrogen management strategies. For those IAFS components actually adopted in practice, no trade-off was found between relative environmental advantages and relative economic advantages. So, the general conclusion is that to ensure that a strategy is adopted, an environmental advantage has to be associated with an economic advantage.

8.4.3 Epidemiological risks of alternative Late Blight management

The epidemiological and organisational risks of alternative Late Blight control strategies were perceived to be large (Chapter 2). The catastrophic consequences of a seriously infested crop are well known to every farmer. More sustainable Late Blight strategies require detailed meteorological and epidemiological information to determine the moment of spraying, which can be very critical. Given the perception of large risks, this complexity plays an important role in the non-adoption of alternative strategies. In Chapter 5, the epidemiological risk was quantified as the frequency of needing to replace a protective spraying by a curative or an eradicant spraying as a consequence of epidemiological conditions. Given this definition of epidemiological risk, a scheme with variable spraying intervals applied to more resistant cultivars appeared to be a 'safe' option for cutting down fungicide load (for the susceptible cultivar 'Bintje' the risk was not greater than a fixed schedule). Given the larger complexity of a strategy with variable spraying intervals, a farmer's (and advisor's) skills and knowledge are important to realise this safe reduction in fungicide load.

More aggressive pathotypes of *Phytophthora infestans* are evolving in the Netherlands. If Late Blight control is to be effective in the future, there will have to be a shift to resistant cultivars and intensive monitoring in the field; these are also the basis for the more sustainable strategies investigated in Chapter 5. However, more severe pathogen pressure might cancel out the fungicide-saving property of alternative Late Blight control. This makes it very unlikely that the MYCPP targets for fungicide use will be achieved. In all, the pressure to cut fungicide use for Late Blight control will become stronger, while the fungicide-saving effect of alternative control strategies might be cancelled out by more severe Late Blight outbreaks in the future. This demonstrated the urgency to develop not only cultivars with a lasting resistance but also new strategies to control Late Blight (for instance effective curative or eradicant measures that do not require large doses of harmful fungicides).

8.4.4 Organisational compatibility

At the start of the research project, there were two reasons for integrating the models at the crop level into a model at the level of the whole farm (Chapter 3). In the first place, a farm model was required to address the pre-supposed agronomic coherence amongst the various crop husbandry activities in the IAFS package. However, no concrete proof of this coherence could be elicited during this study. A second argument for constructing a farm model was to allocate limited farm resources (such as the available labour and equipment) to the different crop husbandry activities.

Labour is an example of an important limited resource that might be over-demanded in certain periods of the growing season. Variability in labour requirements of the various crops on the farm may cause peaks that go beyond the capacity available, which imposes organisational risks. This applies especially to more environmentally sustainable strategies that have a risk of a higher labour requirement. However, the activities generated by BESTWINS, BELABOR and the model for nitrogen management follow each other in the temporal schedule of farm activities. With this specific set of activities, no over-demand of labour was expected.

A farm is likely to comprise more activities than these three aspects of crop husbandry. To be able to calculate temporal labour demand accurately, a similar level of detail would be required for other farm activities. The labour demand of these activities would have to be assessed as a function of weather conditions; this could be achieved by generating data for these other activities, similar to the husbandry activities already modelled in this study

(Lambregts, 1996). This time-consuming exercise, together with the integration of the submodels to a farm model, remains a suggestion for future research. Such a model on farm level would allow other interesting issues to be investigated as well, such as the optimal allocation of a maximum permitted level of pollution (or level of input use) for the total farm to the crops in the rotation.

In summary, we did not address the organisational risks resulting from large labour requirements at the aggregated level of the whole farm. Instead, organisational risks were determined by means of the separate models for the three crop husbandry aspects analysed. The most significant risk was found in nitrogen management (Chapter 6). Organisational risks of fertilisation arise from the physical soil conditions in spring that can obstruct a timely application of animal manure. The calculated probability that an intended schedule for manure application could not be implemented was 40%. This confirmed the farmers' perceptions of organisational risks of spring application of manure on clay soils (Chapter 2). Deviation from the intended schedule leads to a postponed planting date, which probably causes a reduction of potato yield.

8.5 Methodological issues

The process of innovation is driven by the *relative advantage* (as put forward by Rogers, 1995) to be gained by adoption. An innovation can be described by a number of characteristics, or *attributes*. Whether an innovation will be adopted depends on the value of those attributes perceived by the decision-maker, rather than on the objective attribute values, and on the weighing of the attributes according to personal preferences. This study addressed the relative advantage of sustainable over conventional arable farming by means of a descriptive analysis of the attributes important to the innovator and by normative investigation of the risks of the innovation of sustainable farming.

8.5.1 Methods in descriptive research

As explained in Chapter 2, the exploration of the reasons for changing or not changing to sustainable farming practice required qualitative interviews with a semi-structured design. We applied this common technique in social sciences to construct tentative hypotheses about the adoption of sustainable farming practice. There is less likelihood that the respondents' answers are influenced by this type of interview than is the case with closed questions. Our research yielded some surprising hypotheses regarding the farmers' construction of IAFS and suggested that perceived production risks were not the assumed major barrier to conversion, but were just one of many attributes of professional farming.

It seems that an Innovation Adoption Lag (IAL) sets the speed of adoption of IAFS. Factors that determine this IAL include adjustment costs, farmers' motivations, attitude to risk, degree of information they have and their skills with new technologies. In order to address this IAL, the qualitative interviews that were conducted in this study (Chapter 2) require a quantitative follow-up, based on interviews with closed questions. The IAL can be reduced by a participatory approach to introduce sustainable farming. Changes in institutional settings and other externalities can change IAL-related factors. Longitudinal research on whether these IAL-related factors change over time can be helpful when designing a policy to introduce sustainable farming. Information about adopters (revealed preferences) and non-adopters (stated preferences) can be useful for making predictions about the diffusion of an innovation or of the IAL (Hubbell *et al.* 2000).

A well-known economic method to describe adoption behaviour is a time series analysis based on historical panel data. For our research, this method was infeasible, as historical data of recent innovations as IAFS are too limited to address production risks. Chapter 7 presented experimental economics as a promising alternative method to investigate the future behaviour of the potential *innovator*. For our purpose, the major advantage of experimental economics was that it allows an abstract and controllable representation of a complex and uncertain agro-ecological decision environment. As only a few decision parameters could be analysed in a single experiment, only one component of IAFS was investigated. The novelty of this application of experimental economics to agriculture justified a *pilot* experiment, particularly as no single experiment is known that integrates operational agro-ecological features into a combined operational and strategic (investment) decision problem.

8.5.2 Methods in normative research

The starting point for the normative analysis of production strategies was the principle of best technical means. The latter translates into a set of decision rules that ensures long-term agronomic feasibility while simultaneously achieving maximum profit. As an example, it is considered to be agronomically infeasible to build up a weed seed bank (which can be seen as a deterioration of agronomic production capacity) or to have a large incidence of Late Blight in a potato field.

The aim of the normative part of this research was to determine the nature and the size of the risks of sustainable arable production. To investigate this, several production strategies were formulated that range from conventional to sustainable. A strategy includes a specific decision rule that, based on agronomic knowledge, determines when a farmer should choose which measure from a strategy-specific set of measures.

Objective data on production risks of these strategies can be collected through field experiments, which are, however, generally time and money consuming. In this study, simulation was used as an alternative to data generation. Simulation models combine expert knowledge and data (derived from field experiments, for instance). The *bio-economic model* that was developed (Chapter 3) and applied (Chapters 4-6) in this research enabled comparison of more and less environmentally sustainable production strategies under a broad range of production circumstances.

As discussed in Chapter 3, our model can theoretically be represented as a dynamic network, which can be optimised with DP. However, the large dimensionality obstructed the implementation of DP. Instead, non-optimising decision rules were employed for selected aspects on crop husbandry: BESTWINS (Chapter 4), BELABOR (Chapter 5) and a model for nitrogen management (Chapter 6). With models of this type, normative decision rules generated good heuristic (not necessarily optimal) solutions at the crop level. In Chapter 3, an iterative LP procedure was also developed to generate activities that are efficient at the level of the whole farm. In doing so, the bio-economic model of Chapter 3 generates good solutions at both the crop and farm level.

8.5.3 Prospective on the combination of normative and descriptive research

Chapter 6 presents a synthesis of the normative and descriptive research for the case of nitrogen management in potatoes. The available panel data set was not large enough to assess production risks and was combined with objectively calculated parameters. This methodology enabled the empirical outcomes of a panel analysis to be completed with normative model calculations.

Another synthesis between normative and descriptive research was presented in an economics experiment (Chapter 7). An advantage of a laboratory experiment over a panel analysis is that differences in the decision environment between the decision makers are eliminated. We found indications that decision-making carried over to practice, which shows that methods from experimental economics are very useful for investigating cropping decisions in an agro-ecological environment.

One suggestion for a quantitative follow-up of the descriptive research on farmers' motivations (Chapter 1) is to assess farmers' preferences for the normatively calculated attributes of production strategies. A 'conjoint analysis' would be a suitable method, enabling the technology sets to be compared according to their overall expected utility (Schoorlemmer *et al.*, 1994). The prospects of a sustainable arable production strategy being adopted (as a technology set) can be assessed for different groups of farmers (for instance, farmers in a different phase in the process of learning about IAFS).

8.6 Practical implications

8.6.1 Outlook on sustainable farming systems

Farmers converge to a new conventional farming system that integrates the IAFS strategies that are cost saving, in addition to environmental advantages. IAFS, however, were primarily designed to achieve a better environmental performance of the arable farm, not a reduction in production costs. So, a large-scale introduction of IAFS needs to be supported by a drastic change of the socio-economic production environment.

It can be expected that future market and political conditions will re-define the production context for arable farming and will increasingly force the arable sector to move towards an environmentally sound way of producing.

The finding from this research that socio-economic risks –and not the pre-supposed production risks– are the main barrier for farmers to change to IAFS implies that government measures to support the change have not been very effective. This can be interpreted as a signal towards policy makers that the arable sector urgently needs a clear and consistent set of government measures to sustain the conversion to sustainable agriculture. Experimental economics offer a promising tool for the *ex-ante* evaluation of governmental regulations; our experiment indicated that a fine on excess herbicide use can support farmers to apply more sustainable crop husbandry.

Farmers did not identify production risks being the main constraint to adopt IAFS; in general, they accepted production risks as a part of their profession. Some production risks of IAFS, however, remain unacceptable in the perception of farmers. Farmers perceived production risks of the IAFS strategy of variable spraying intervals against Late Blight as unacceptably high. In cases where production risks of an IAFS strategy are perceived as unacceptable, teaching and training can give the farmer knowledge, skills and confidence to apply this new strategy.

Applied research for arable farming has a crucial role in finding solutions for the agronomic problems that are found in the implementation of IAFS. It is also important to investigate the applicability of technical innovations to IAFS (development of new pesticides, new 'traditional' cultivars or Genetically Modified Organisms (GMOs), biological control, or better mechanical control techniques). In this study, a tool was developed to assess the compatibility –with the focus on production risks– of these innovations on the farm.

Agronomic research has to anticipate on the increasing priority society gives to environmental stewardship. The discussion between representatives from agriculture and environmentalists need to be fed with scientific data on the determinants that guarantee a safe environmental quality and on the best possible performance of agriculture regarding these determinants. A safe environmental quality might impose such heavy restrictions that arable production becomes infeasible, even when the latest production techniques are applied. In order to keep sustainable agricultural production feasible, research also has to anticipate on the threat that resistant pest organisms evolve as a result of low input production systems and as a result of the shrinking assortment of pesticides that can be used legally.

There are lessons for 'Conventional' agriculture to learn from Organic farming on the implementation of pesticide-free solutions. In organic farming systems and in IAFS, crop rotation has to sustain crop protection and nutrient management. Hence, in a sustainable farming system with lower pesticide and fertiliser inputs, the intensive crop rotations that were considered self-evident in conventional farming may no longer be feasible.

8.6.2 An insurance for production risks

One practical implication of this thesis could be its contribution to the development of an insurance scheme for production risks of IAFS. Probability distribution functions (PDF) can be used to calculate premium and expected claim. The traditional approach in insurance settings to estimate PDFs from historical data can be difficult, as these data on IAFS are relatively scarce. Instead, the PDFs of net gain –or CDFs as derived from model simulations in this thesis– can be used.

Insurance covering some of the negative financial consequences of accidental agro-ecological circumstances would help farmers cope with production risks and could encourage them to convert to more sustainable production strategies. Examples of production risks associated with more sustainable strategies in this thesis are: 1) a reduction in potato yield due to Late Blight incidence, 2) increased herbicide and labour costs due to mechanical weed control or 3) yield reduction due to a delay of planting date after spring application of manure.

Production risks of IAFS affect net revenue. When deciding to adopt IAFS, a farmer may wish to have at least extreme losses of net revenue to be insured. The examples mentioned above show that the causes for a loss of net revenue differ per crop. A net revenue insurance at crop level is a specific product for each farmer. The insured revenue level can be established by a farmer's moving historical average revenue, corrected for yearly influences (these can be determined from historical regional data). As no output price effects of IAFS are expected, common market prices at harvest (instead of prices, obtained by individual farmers) can be taken as product prices.

A major question in a scheme for insuring net revenue for IAFS is to define what is damage due to an insured event and what is not. Indemnity is based on an unambiguous assessment of the amount of loss and the extent to which the loss was caused by an insured event (Meuwissen *et al.*, 2000). Ideally, this basis excludes moral hazard (*i.e.*, only losses occurring despite good agricultural practice are insured). A deductible bonus and a no-claim bonus are instruments in order to further safeguard an insurance scheme from moral hazard. In order to allow the cause and consequence in the case of IAFS to be verified, an insurance scheme would require a reliable and detailed registration of the production process, which would make it practicable only in an already intensively monitored and registered production process (such as in IAFS introduction projects, eco-labelling programmes, a quality care scheme, or a 'bookkeeping' scheme for minerals).

8.6.3 Other applications of the bio-economic models

Using the *bio-economic model* for investigating production risks of other farming systems or other elements of crop husbandry would justify the development of a more user-friendly general software structure, including an easy input of parameters and data and a clear and instant output. This would also offer possibilities for a *bio-economic model* to be a tool enabling extensionists or farmers to compare the production risks of a set of production strategies. As an example, in Chapter 7, a user-friendly version of the model for weed control in sugar beet was developed for use in an economics experiment.

A software shell containing the basic structure of the theoretical model with states, decision stages and a transformation function (Chapter 3) and a standardised input of model parameter values would improve the accessibility. This shell should enable interaction with existing, complex biological or physical models, such as the WAVE model for nitrogen management.

Though indicating several possibilities to improve the model's user-interface, the crucial task of estimating model parameter values will remain laborious. When the size and detail of the available input data are probably insufficient to generate reliable outcomes, it is no use to construct a *bio-economic model*. For example, prior to the construction of BELABOR the availability of a detailed, multi-year set of meteorological data had to be ascertained.

8.6.4 Closing remark

The increasing priority society gives to environmental stewardship will provide sustainable arable farming systems with a relative advantage, or probably even a 'licence to produce', that would increase the likelihood of their large-scale autonomous diffusion among farmers. Given constant output prices, however, more severe environmental restrictions in the future are likely to reduce farm income due to higher production costs, lower yields and less intensive crop rotations and to increase the production risks as calculated in this study. The continuation of arable farming in the Netherlands therefore seems to depend on the willingness of Dutch society to reward farmers for producing things other than cheap food.

References

Falconer, K.E., 1998. Managing diffuse environmental contamination from agricultural pesticides: an economic perspective on issues and policy options, with particular reference to Europe. *Agriculture, Ecosystems and Environment* 69: 37-54.

Hardaker, J.B., Huirne, R.B.M. and Anderson, J.R., 1997. Coping with Risk in Agriculture, Cab International, Oxford and New York.

Hubbell, B.J., M.C. Marra and G.A. Carlson, 2000. Estimating the demand for a new technology: Bt cotton and insecticide policies. *American Journal of Agricultural Economics* 82: 118-132.

Janssen, H., 1996. Oorzaken van verschillen in middelenverbruik tussen bedrijven. P. infestans in aardappelen. *LEI-DLO Publication 3.162*, The Hague, The Netherlands.

Lambregts, M.E.A.B., 1996. Bedrijfsrisico's bij verschillende teeltstrategieën in de akkerbouw. Een methode voor het kwantificeren van risico's m.b.v. een model. Scriptie vakgroep Agrarische Bedrijfseconomie, Landbouw Universiteit Wageningen, The Netherlands, 61 pp.

Leferink, J. and M. Adriaanse, 1998. Omschakelen: beren en bergen (onderzoek naar de redenen van akkerbouwers en vollegrondsgroententeler om niet om te schakelen naar biologische landbouw). IKC Landbouw, Ede, The Netherlands.

LEI/CBS, 1999. Landbouwcijfers 1999 (Agricultural figures 1999, in Dutch). Agricultural Economic Research Institute and Central Bureau of Statistics, The Hague, The Netherlands.

LNV (Dutch Ministry of Agriculture Nature Management and Fisheries), 1991. Multi-Year Crop Protection Plan. *Meerjarenplan Gewasbescherming; Regeringsbeslissing.* Ministry of Agriculture, Nature Management and Fisheries, Tweede Kamer, vergaderjaar 1990-1991, 21667, nr.3-4. Staatsuitgeverij, The Hague, The Netherlands.

Meuwissen, M.P.M., J.B. Hardaker, J.R. Skees, J.R. Black and R.B.M. Huirne, 2000. Conceptual considerations in developing an income insurance for European farmers. Chapter 4 in M.P.M. Meuwissen: Insurance as a risk management tool for European agriculture (PhD dissertation), Wageningen University, Wageningen, The Netherlands, 117 pp..

Proost, J. and P. Matteson, 1997. Reducing Pesticide Use in the Netherlands. *Journal of Pesticide Reform* 17: 2-8.

Rogers, E.M. (1995) Diffusion of Innovations. 4th ed. Free Press, New York.

Röling, N.G. and J. Jiggins, 1998. The ecological knowledge system. In: N. Röling and A. Wagemakers (Eds.) Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Schoorlemmer H.B, A.J. de Buck and G.A.A. Wossink, 1994. Risks and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.E. Pedersen, J. Christensen and S. Rasmussen (Eds.) Farmers' decision making, a descriptive approach, Proceedings of the 38th EAAE Seminar, Institute of Agricultural Economics, Copenhagen, Denmark, pp. 191-202.

Van Weperen, W., M.C.D. Proost and N. Röling, 1998. Integrated arable farming in the Netherlands. In: N. Röling and A. Wagemakers (Eds.) Facilitating Sustainable Agriculture. Participatory Learning and Adaptive Management in Times of Environmental Uncertainty. Cambridge University Press, Cambridge UK.

Vlek, C.A.J. and P.J.M. Stallen, 1979. Persoonlijke beoordeling van risico's: over risico's, voordeligheid en aanvaardbaarheid van individuele maatschappelijke en industriële activiteiten. State University of Groningen, Groningen, The Netherlands. Woittiez, R.D., G.H. Horeman and J. Baas, 1996. MJP-G emissie-evaluatie 1995: achtergronddocument. Commissie van Deskundigen Emissie-evaluatie MJP-G ,Ede, The Netherlands, 127 pp.

Summary

Introduction

In the twentieth century the agricultural production process underwent a tremendous intensification that involved large inputs of synthetic nutrients and pesticides. Environmental pollution, as one negative effect of this intensive way of farming, became a matter of public concern. Consequently it became a major item on the political agenda and led to agro-environmental policies. Extensive research and introduction programmes have been conducted in the Netherlands to develop more sustainable arable farming systems in order to meet the environmental objectives set by these policies. The resulting Integrated Arable Farming Systems (IAFS) integrate economic and ecological goals. In IAFS, all aspects of crop rotation, crop protection and nutrient management are used to minimise the use of polluting pesticide and fertiliser inputs.

Though the technical and economic results of IAFS experiments and pilot projects were promising, adoption by Dutch farmers has been disappointing. This farmer reluctance is of major concern, as IAFS were intended to play a major role in meeting political and societal demands for protection of the environment. Production risk was expected to be an important factor in explaining the lack of adoption. This instigated the present research programme, in which the nature and the size of production risk and farmers' perceptions of sustainable farming practices were investigated.

The overall goal of this study was to determine the role of production risks in the conversion to more sustainable production systems in arable farming. More specifically, the objectives were:

1. to specify the typical production risks that prevent farmers from changing to more sustainable farming,
2. to develop a method to quantify the size of these production risks,
3. to apply that method in order to quantify the risks involved in sustainable arable farming practices as compared to those involved in conventional practices, and
4. to assess farmers' behaviour when choosing from sustainable and conventional farming practices.

To achieve these objectives, descriptive research was done on the properties of the *innovator* (objective (1)) and normative research was done on the properties of the *innovation* (objectives (2) and (3)). Furthermore, an experimental analysis of adoption behaviour in a simulated, uncertain agro-ecological environment was conducted to integrate *innovator*-specific and *innovation*-specific properties (objective 4).

In this dissertation, production risk was defined as the consequences of the exposure to uncertain conditions, particularly those consequences that are unfavourable to the decision maker, in this case the farmer. The main sources of risk in agriculture are: personal conditions, external socio-economic conditions, and the physical production environment.

Production risk can be represented as the statistical distributions of stochastic parameters (such as specific costs, pesticide use, nitrate leaching and labour requirements) resulting from variation in the physical environment.

Farmers' perspective on the change to sustainable farming

In the descriptive part of the research, farmers' motives for changing to sustainable farming were investigated, using qualitative interviews of a semi-structured design. This type of interview makes it less likely that the respondents' answers will be influenced than is the case with closed questions. Production risks, as perceived by the respondents, were placed in the context of other risks that play a role in the conversion to sustainable farming.

The interviews suggested that perceived production risk is not a satisfactory explanation for the low take-up of IAFS. Both conventional and IAFS farmers considered dealing with production risks to be part of farming professionalism. In general, production risks such as weather-dependent problems with weeds, pests and diseases had not been a reason for avoiding a specific crop husbandry strategy.

A remarkable finding was that IAFS had been adopted not as a single package (as was intended by its developers), but as a collection of separable methods that resulted from IAFS research. Within three groups of interviewed farmers, a continuum of gradual adoption of IAFS methods, mainly for economic reasons, was observed.. It appeared that without guidance through an introductory project, farmers were not motivated to adopt IAFS as a single innovation.

For commerical enterprises such as farms, a new farming system's attribute of relative economic advantage is a major reason for adopting that system. Further, uncertainties emanating from market conditions and environmental policy were found to be important considerations. This indicates the arable sector's need for a clear and consistent policy to sustain the conversion to sustainable agriculture.

Other attributes of a new farming system that were found to be a barrier to its adoption were: complexity, organisational aspects (such as labour requirements and marketing) and production risks. Finally, the interviews showed that the relative environmental advantages of IAFS were not a major consideration in the decision to adopt IAFS.

A theoretical model to analyse production risks

Variable physical conditions (such as the weather) greatly determine the agro-ecological production environment of arable farming and lead to production risks. Agro-ecological factors include crop and soil characteristics and the incidence of pests, diseases and weeds. These factors affect the ultimate quantity and quality of yields, as well as the kind and timing of crop husbandry measures. Variability in yield and in inputs that are required to carry out crop husbandry impose production risks on the farmer. Production risks were specified as financial risks, yield risks, organisational risks (induced by peaks in labour demand), epidemiological risks and environmental risks. The use of polluting inputs such as pesticides and fertilisers causes environmental risks.

To assess risks caused by weather conditions, the major aspects of crop husbandry in various crops were analysed by different *bio-economic models*. A *bio-economic model* can be represented as a stochastic dynamic directed network, having the following components:

- *state variables* (describing crop status; pest, weed or disease status; the nutrient status of the soil),
- a series of *decision stages*, and
- *a transition function* (describing the change in the state variables from one decision stage to the next).

A specific bio-economic model includes various husbandry strategies that range from conventional to environmentally sustainable. Each strategy represents a specific farming system such as conventional farming, integrated farming, or organic farming, and comprises a specific decision rule and a set of crop husbandry measures. Using this decision rule and weather uncertainty as input, the model calculates statistical distributions of resource requirements. Weather uncertainty was estimated using weather data sets, mostly at the daily level, covering 20 to 43 years. Simulations with the *bio-economic model* compared the production risks of the different strategies.

Weed control in sugar beet, Late Blight control in ware potatoes and nitrogen management in ware potatoes were selected to be investigated by bio-economic modelling. The main selection criteria were that the specific crops contribute considerably to farm income and that the conventional management practice causes considerable environmental pollution.

From a farm management perspective, all the aspects of crop husbandry in the various crops should be taken into account jointly. Given the weather conditions, all simulated crop husbandry activities were combined in an LP model of the whole farm, where they competed for limited resources. Information provided by the LP solution was used to re-assess the crop husbandry decisions by means of bio-economic simulation. This procedure was applied iteratively, hence enabling production risks of conventional and integrated farming systems to be compared, considering fixed, allocatable resources for the whole farm enterprise.

Production risks of weed control strategies in sugar beet

In conventional farming in the Netherlands, weed control in sugar beet is based on several consecutive full-field applications of herbicides. Commercial farmers have adopted the so-called Low Dose System in herbicide spraying, because it is effective and saves costs. In integrated weed control this system is combined with mechanical techniques, or replaced either by row spraying or by mechanical control. The most important risks associated with these new strategies are to do with manageability and effectiveness of control in relation to the weather.

A Bio-Economic model on sTrategy choice in Weed control IN Sugar beet (BESTWINS) was developed and employed to compare the risks of conventional, herbicide-saving ('integrated') and herbicide-free ('organic') strategies. Risk is measured by the statistical distributions of specific costs, labour required and active chemical ingredient.

Compared to full-field spraying, 'integrated' strategies of row spraying and/or mechanical techniques resulted in smaller environmental risks from herbicide use (based on average load and peak loads) and larger organisational risks from labour requirements for intensive tractor use. In the herbicide-free, 'organic' strategy in sugar beet, no mechanical measures are available to 'repair' a failed mechanical weed control action within the crop rows. This resulted in the requirement of large quantities of unskilled labour for hand weeding. Hence, the 'organic' strategy in sugar beet resulted in much larger organisational risks than the other strategies; however, for all strategies, the requirement for unskilled labour was the same under 5% of the most unfavourable conditions.

Only when equipment for mechanical weed control and a full-field sprayer were already present on the farm was there a very modest economic incentive to purchase additional row spraying equipment. The savings in specific costs for herbicides and tractor operation outweighed the additional machinery costs for the row-spraying equipment. The ‘organic’ strategy is labour-demanding but entails few specific costs and investments.

Besides demonstrating the absence of a substantial economic incentive to adopt more sustainable weed control in sugar beet, the interviews showed that the main factors causing farmers to refrain from adopting it were the small herbicide savings, the perceived complexity and the soil type of the farm.

Production risks of Late Blight control strategies in potatoes

Late Blight control in potatoes in The Netherlands is characterised by large amounts of fungicide use, great variability in use between years and large epidemiological risks. This makes Late Blight control a major obstacle to converge to more sustainable arable farming. The Bio-Economic model of LAte Blight control Options and Risk (BELABOR) was developed and employed to investigate the economic, environmental and epidemiological risks of more sustainable strategies. Fixed interval spraying of fungicides was compared with weather-based variable interval spraying for potato cultivars differing in Late Blight resistance.

The results showed that fungicide load was dependent more on weather conditions than on control strategy or cultivar. When spraying was at fixed intervals, a ‘premium’ was paid in the form of protective applications to preclude the risk of Late Blight infestation that would necessitate curative or eradicant sprayings. Model simulations showed that in more resistant potato cultivars variable rather than fixed spraying intervals in Late Blight control reduced environmental risks of fungicide use and did not increase epidemiological risks. Epidemiological risks were measured as the average number of curative or eradicant sprayings required for Late Blight control in one season. For a susceptible cultivar, however, a variable interval scheme showed a large probability of a large fungicide requirement, denoting a large environmental risk.

The lowest fungicide costs for Late Blight control were achieved with a strategy of variable spraying intervals and the most resistant cultivar. To be able to use a spraying scheme with variable intervals, the farmer must have data from a local local weather station. The simulation results showed that on average, the additional costs of this equipment outweighed the savings on fungicide use.

As well as revealing the absence of an economic incentive to adopt IAFS, the interviews showed that the perception of risks of a Late Blight infection was a motive to refrain from adopting a more complicated strategy based on spraying at variable intervals. Farmers also perceived uncertain market prospects for more blight-resistant cultivars.

Production risks of nitrogen management strategies in potatoes

Manure is important for maintaining soil fertility in crop production on clay soils but carries the risk of nitrate contamination of the groundwater. For ware potatoes, six nitrogen fertilisation strategies were compared on the risks of yield reduction, nitrate leaching to groundwater, organisational compatibility, nitrogen release from manure and fertiliser costs. The six strategies covered conventional and integrated nitrogen management and varied according to whether or not pig slurry was applied, application date of the manure and additional amount of nitrogen fertiliser used.

The risk entities were determined by model calculations using 43 years of weather data. The results showed that for all six strategies, stochastic environmental conditions caused a wide distribution of leaching values with peaks of 200 kg N ha^{-1}. This demonstrates that nitrogen management in ware potatoes imposed considerable environmental risks due to leaching. This is especially true of manure application in the autumn. When manure was applied in spring, it did not result in larger environmental risks than the application of artificial fertiliser only. There were just small differences between the strategies in average values and peak values in fertilisation costs.

Model calculations showed that spring application of manure on clay soils imposed organisational risks. Organisational risks of fertilisation arose from the physical state of the soil that hamper spring application of animal manure. It was calculated that there was a 40% probability that spring application of manure would conflict with sowing and cultivation activities –intended planting dates would have to be postponed, probably leading to a yield reduction.

As well as the normative simulation, current nitrogen management practices were investigated in an empirical analysis of 136 pooled farm-year records. Most arable farmers (83% of those on the panel) applied manure and it was mostly (75%) applied in the autumn. Most of the farmers on the panel who applied manure, applied more nitrogen than the standard recommendations; 13% of the farmers even applied manure in addition to a nitrogen fertiliser dose that was already larger than or equal to the current recommendation. These figures show that farmers can greatly reduce the risk of nitrate leaching by taking account of the nitrogen value of manure and by shifting from autumn to spring application of manure.

Experimental analysis of farmers' adoption behaviour

To adopt a new farming system (such as sustainable farming) means having to make a decision surrounded by uncertainty, in which farmers' perceptions and attitudes are influential. The uncertainty attributed to this decision include labour requirements, pesticide costs, crop yields and the effectiveness of controlling biological processes. In such a complex decision environment, methods from experimental economics offer possibilities for analysing decision behaviour of decision-makers. The main advantage of experiments compared to other empirical methods is that the influential parameters can be better controlled. In the case of investigating new farming systems, an experiment also has the advantage of requiring fewer historical data.

An economics experiment was conducted to investigate farmers' response to a fine on excess herbicide use. Thirteen arable farmers differing in the environmental sustainability of their farming were examined, to discover their behaviour when choosing from various weed control strategies and measures. Weed control situations with stochastic features were simulated by the computerised model BESTWINS and presented to the farmers in a PC laboratory setting. For several seasons, the participants were asked to enter their decisions into the model. The strategies that were presented to the participants ranged from conventional, based on full-field spraying, to herbicide-free, based solely on mechanical techniques.

Before the fine on excess herbicide use was announced, three participants chose a more sustainable strategy, which they persisted with, regardless of the imposition of this fine. As a response to the fine, two participants persisted with their conventional strategy and eight shifted towards a more sustainable weed control strategy. Only two participants exceeded the threshold for herbicide use; one with a conventional strategy and one with a more sustainable strategy.

The strategies chosen and the amount of herbicide applied by farmers in the experiment correlated significantly with their control activities in real life, which is a strong argument for the usefulness of the results of the experiment. The pilot study clearly showed the potential of economic experiments for the *ex-ante* evaluation of innovation adoption under changing settings of environmental regulations.

Closing remarks

IAFS were developed as a package innovation to enable the arable farming sector to meet future environmental regulations. This study showed that IAFS cannot be considered as a single innovation, because farmers have adopted only those components of IAFS that had economic as well as environmental advantages. Farmers seem to prefer to converge on a new 'conventional' arable farming system that uses less chemical inputs than the old one. This new farming system, however, is still a long way from IAFS and the environmental sustainability that researchers consider to be feasible. A large-scale introduction of sustainable farming systems needs to be supported by a drastic change of the socio-economic environment of the farm enterprise.

The type of *bio-economic model* that was developed in this dissertation provides crop specialists or farmers with a tool for comparing the production risks of a set of production strategies. Other problems in crop husbandry could also be assessed using the principle of this model.

Another practical implication of this dissertation could be its contribution to the development of an insurance scheme for production risks of sustainable farming. Insurance covering extreme losses of net revenue of incidental agro-ecological circumstances would help farmers cope with production risks and could encourage them to convert to more sustainable farming systems. In the design of insurance schemes, probability distribution functions (PDF) are used to calculate premium and expected claim. The traditional approach in insurance settings to estimate PDFs from historical data can be difficult, as these data on new farming systems are relatively scarce. Instead, the PDFs or CDFs, generated by model simulations (as demonstrated in this study) could be used. In order to be able to verify the cause and consequence in the case of IAFS, an insurance scheme would require a reliable and detailed registration of the production process, which would make it compatible with eco-labelling programmes, quality care schemes, or 'bookkeeping' schemes for minerals.

The increasing priority society gives to environmental stewardship will provide sustainable arable farming systems with a relative advantage, or probably even a 'licence to produce', that will increase the likelihood of their large-scale autonomous diffusion among farmers. More severe environmental goals, however, are likely to reduce farm income due to higher production costs, lower yields and less intensive crop rotations, and to increase the production risks as calculated in this study. Output prices that tend to fall will drastically limit the farmers' possibilities to achieve these goals. The continuation of arable farming in the Netherlands would therefore seem to depend on the willingness of Dutch society to reward farmers for producing 'goods' other than cheap food.

Samenvatting

Introductie

De ontwikkeling van de landbouw gedurende de twintigste eeuw kenmerkte zich door een enorme intensivering van het productieproces. Dit ging gepaard met een gebruik van veel kunstmest en bestrijdingsmiddelen. De vervuiling van het milieu –als een negatief effect van deze intensieve wijze van landbouw– werd een onderwerp van maatschappelijk belang. Zorg voor het milieu werd vervolgens een belangrijk onderwerp op de politieke agenda, wat leidde tot de huidige milieuwetgeving. Om aan de door het beleid gestelde doelen te voldoen zijn in Nederland grootschalig onderzoeks- en introductieprogramma's opgezet ter ontwikkeling van meer duurzame bedrijfssystemen. Dit resulteerde in Geïntegreerde Bedrijfssystemen (of: Integrated Arable Farming Systems, afgekort tot IAFS), welke economische en ecologische doelen integreren. In IAFS worden alle aspecten van vruchtwisseling, gewasbescherming en nutriëntenmanagement aangewend om het gebruik aan vervuilende bestrijdingsmiddelen en meststoffen te minimaliseren.

Ondanks de veelbelovende technische en economische resultaten van IAFS, was de verspreiding ervan onder akkerbouwers teleurstellend. De geringe opgang die IAFS in de praktijk maakt is zorgwekkend, omdat er een belangrijke rol van werd verwacht om aan politieke en maatschappelijke eisen ten aanzien van de milieubescherming te voldoen. Dit was de aanleiding voor het in deze dissertatie beschreven onderzoeksproject met als onderwerp de aard en de omvang van productierisico's van duurzame methoden in de akkerbouw, alsmede de perceptie daarvan door boeren.

De algemene doelstelling van deze studie was het bepalen van de rol van productierisico's in de omschakeling naar meer duurzame bedrijfssystemen in de akkerbouw. Deze doelstelling is uitgwerkt in de volgende doelen:

1. het specificeren van de productierisico's die de boer weerhouden van de keuze voor meer duurzame methoden in de akkerbouw,
2. het ontwikkelen van een methodiek om de omvang van deze productierisico's te kwantificeren,
3. het toepassen van die methodiek ter bepaling van de omvang van de productierisico's van duurzame methoden in de akkerbouw in vergelijking met die van gangbare methoden, en
4. het bepalen van het gedrag van boeren in de keuze voor duurzame en gangbare methoden in de akkerbouw.

Om deze doelen te bereiken is beschrijvend onderzoek naar de eigenschappen van de *innovator* (doel (1)), alsmede normatief onderzoek naar de eigenschappen van de *innovatie* (doel (2) en (3)) uitgevoerd. De eigenschappen van de *innovator* en de eigenschappen van de *innovatie* worden integraal onderzocht in een economisch experiment met een gesimuleerde, onzekere agro-ecologische omgeving (doel (4)).

In deze dissertatie zijn productierisico's gedefinieerd als de consequenties van de blootstelling aan onzekere omstandigheden, in het bijzonder die omstandigheden welke ongunstig zijn voor de beslisser, in dit geval de boer. Voor de akkerbouw zijn de belangrijkste bronnen voor risico: persoonlijke condities, externe socio-economische condities en de fysieke omgeving van de productie. Productierisico's kunnen worden voorgesteld als de statistische kansverdeling van stochastische parameters (zoals toegerekende kosten, gebruik van bestrijdingsmiddelen, uitspoeling van nitraat en behoefte aan arbeid) ten gevolge van de variatie in fysieke omgevingsparameters.

Omschakeling naar duurzame landbouw vanuit het perspectief van de boer

In het beschrijvende deel van het onderzoek zijn de motivaties van boer om al dan niet om te schakelen naar duurzame landbouwmethoden onderzocht. Voor dit onderzoek zijn kwalitatieve enquêtes met een semi-gestructureerde opzet uitgevoerd. Ten opzichte van een interview met gesloten vragen, verkleint dit type interview de kans beïnvloeding van de antwoorden. Productierisico's, zoals gepercipieerd door de boer, zijn hier beschouwd in de context van andere risico's die een rol spelen in de omschakeling naar duurzame methoden in de akkerbouw.

De interviews suggereerden dat gepercipieerde risico's de geringe verspreiding van IAFS in de praktijk onvoldoende verklaren. Het omgaan met productierisico's werd zowel door gangbare als door IAFS akkerbouwers gezien als een onderdeel van professioneel ondernemerschap. In het algemeen werden productierisico's niet genoemd als reden om af te zien van de toepassing van een specifieke teeltstrategie.

Het was opmerkelijk dat IAFS niet in zijn geheel werd overgenomen (zoals beoogd door onderzoek en voorlichting), maar als een pakket van afzonderlijk toe te passen methoden, die voortkwamen uit onderzoek naar IAFS. In drie groepen geïnterviewde boeren werd een continue gradatie van toegepaste IAFS methoden gevonden. Zonder begeleiding door een introductieproject waren boeren niet gemotiveerd om IAFS in zijn geheel over te nemen.

Voor commerciële ondernemingen zoals het boerenbedrijf, wordt de keuze voor een nieuw bedrijfssysteem in belangrijke mate bepaald door het attribuut relatief economisch voordeel. Verder werden onzekerheden die voortkomen uit marktcondities en milieubeleid genoemd als belangrijke overwegingen. Dit geeft aan dat er behoefte is aan duidelijk en consistent beleid ter ondersteuning van de omschakeling naar meer milieuvriendelijke methoden in de akkerbouwsector.

Andere eigenschappen van nieuwe bedrijfssystemen die als belemmerend werden ervaren zijn: complexiteit, organisatorische aspecten (zoals arbeidsbehoefte en marketing) en productierisico's. Tenslotte toonden de interviews aan dat de eigenschap van relatieve milieuvoordelen van ondergeschikt belang was in de keuze voor IAFS.

Een theoretisch model voor de analyse van productierisico's

Variabele fysische omstandigheden (zoals het weer) bepalen in sterke mate de agro-ecologische omgeving van de productie in de akkerbouw, wat leidt tot productierisico's. Agro-ecologische factoren zijn bijvoorbeeld gewas- en bodemeigenschappen en het vóórkomen van ziekten, plagen en onkruiden. Deze factoren beïnvloeden de uiteindelijke opbrengst in kwantitatieve en in kwalitatieve zin, evenals de aard en het tijdstip van de uit te voeren teeltmaatregelen. Zowel variabiliteit in de opbrengst als in de middelen die het uitvoeren van teeltmaatregelen vergt, brengen productierisico's voor de boer met zich mee. Productierisico's zijn onder te verdelen in financiële risico's, opbrengstrisico's, organisatorische risico's (geïnduceerd door pieken in de arbeidsbehoefte), epidemiologische risico's en milieutechnische risico's. Gebruik van vervuilende inputs zoals bestrijdingsmiddelen en meststoffen veroorzaakt milieutechnische risico's.

Ter bepaling van de risico's, veroorzaakt door weersomstandigheden, zijn de belangrijkste aspecten van de teelt van verschillende gewassen geanalyseerd met verschillende *bio-economische modellen.* Een *bio-economisch model* kan worden voorgesteld als een stochastisch dynamisch gericht netwerk met de volgende componenten:

- *toestandsvariabelen* die de status beschrijven van het gewas, van het onkruid, van de ziekte of plaag, of van de nutriëntentoestand van de bodem,
- een reeks *beslisstadia,* en
- een *transitiefunctie* die de verandering in toestandsvariablen van het ene beslisstadium naar het volgende beschrijft.

Een *bio-economisch model* voor een specifiek teeltaspect bevat een aantal teeltstrategieën die variëren van gangbaar tot duurzaam. Elke strategie vertegenwoordigt een bepaald bedrijfssysteem, zoals een gangbaar systeem, een geïntegreerd systeem of een biologisch systeem. Een strategie heeft een specifieke beslisregel, welke een specifieke set maatregelen aanstuurt. Deze beslisregel en onzekerheid ten aanzien van het weer vormen de input van het model, wat de statistische kansverdeling berekent van de benodigde middelen. De onzekerheid ten aanzien van het weer is geschat met meteorologische datasets, bestaande uit overwegend dagelijkse metingen gedurende 20 tot 43 jaar. De met het *bio-economisch model* gesimuleerde productierisico's zijn voor verschillende strategieën vergeleken.

Onkruidbestrijding in suikerbieten, de bestrijding van Phytophthora in consumptie-aardappelen en stikstof-management in consumptie-aardappelen zijn geselecteerd voor bio-economische modellering. De criteria voor selectie waren de grote bijdrage aan het bedrijfsinkomen van de betreffende gewassen en de aanzienlijke milieubelasting indien een gangbaar management wordt toegepast.

Vanuit het gezichtspunt van de bedrijfsvoering dienen alle teeltaspecten tezamen te worden beschouwd. Alle voor identieke weerscondities gesimuleerde teeltaspecten zijn gecombineerd in een LP model van het hele bedrijf, waar zij aanspraak maken op beperkte middelen. Informatie uit de LP oplossing is gebruikt om de teeltbeslissingen opnieuw te bepalen door middel van de *bio-economische modellen*. Deze procedure is iteratief toegepast. Op deze wijze kunnen de productierisico's van gangbare en geïntegreerde bedrijfssystemen worden vergeleken, rekening houdend met te alloceren, beperkt op het bedrijf aanwezige middelen.

Productierisico's van onkruidbestrijdingsstrategiën in suikerbieten

Onkruidbestrijding in de gangbare akkerbouw in Nederland is gebaseerd op een aantal achtereenvolgende volveldse bespuitingen met herbiciden. Het zogenaamde Lage Doserings Systeem is wijd verspreid in de praktijk vanwege de goede technische resultaten en de besparing op herbicidekosten. In geïntegreerde onkruidbestrijding wordt dit systeem gecombineerd met mechanische methoden of wordt dit systeem vervangen door rijenbespuiting in combinatie met mechanische methoden, dan wel volledig vervangen door mechanische bestrijding. De uitvoerbaarheid en de effectiviteit van bestrijding in relatie tot het weer zijn de belangrijkste risico's van deze nieuwe strategieën.

Het bio-economisch model voor strategiekeuze in onkruidbestrijding in suikerbieten (BESTWINS) is ontwikkeld en toegepast om de risico's van gangbare onkruidbestrijding, herbicide-besparende ('geïntegreerde') onkruidbestrijding en 'biologische' onkruidbestrijding, zonder gebruik van herbiciden te vergelijken. Risico's zijn bepaald aan de hand van de statistische kansverdelingen van de toegerekende kosten en de behoefte aan arbeid en chemische actieve stof.

De resultaten tonen aan dat, vergeleken met volveldse bespuitingen, de 'geïntegreerde' strategieën met rijenbespuiting en/of mechanische methoden een lager milieukundig risico hebben ten gevolge van herbicidengebruik (gebaseerd op het gemiddelde gebruik en pieken in het gebruik) en een hoger organisatorisch risico hebben, vanwege de arbeidsbehoefte voor een intensiever gebruik van de trekker. De volledig mechanische, 'biologische' strategie van onkruidbestrijding biedt geen mogelijkheid om een mislukte bestrijding in de gewasrijen te 'repareren'. Dit resulteert in een grote behoefte aan ongeschoolde arbeid voor wieden. De ‘biologische’ strategie had dus een veel groter organisatorisch risico dan de andere strategieën; de behoefte aan ongeschoolde arbeid was echter voor alle strategieën gelijk onder 5% van de meest ongunstige omstandigheden.

Slechts wanneer de werktuigen voor mechanische onkruidbestrijding en een volveldse spuitmachine reeds op het bedrijf aanwezig zijn, biedt de aanschaf van aanvullende apparatuur voor rijenbespuiting een zeer bescheiden economisch voordeel. De besparing op de toegerekende kosten van gebruikte herbiciden en inzet van de trekker waren groter dan de additionele machinekosten van rijenbespuitingsapparatuur. De 'biologische' strategie is arbeidsintensief, maar de toegerekende kosten en de investeringsbehoefte zijn laag.

Ook uit de interviews bleek de afwezigheid van een substantieel economisch voordeel een belangrijke factor te zijn om af te zien van de keuze voor meer duurzame onkruidbestrijding in suikerbieten. Andere belangrijke factoren waren de geringe besparing op herbicidengebruik, de gepercipieerde complexiteit en het bodemtype van het bedrijf.

Productierisico's van strategieën in Phytophthora bestrijding in aardappelen

In Nederland wordt de bestrijding van Phytophthora in aardappelen gekarakteriseerd door gebruik van veel fungiciden met een grote variatie tussen jaren en door grote epidemiologische risico's. Dit maakt de bestrijding van Phytophthora tot een belangrijke hindernis in de omschakeling naar een meer duurzame akkerbouw. Het bio-economisch model voor Phytophthora bestrijding en risico (BELABOR) is ontwikkeld en toegepast om de economische, milieukundige en epidemiologische risico's van meer duurzame strategieën te onderzoeken. Voor aardappelcultivars met een verschil in de mate van resistentie tegen Phytophthora is het met vaste tijdsintervallen spuiten met fungiciden vergeleken met het spuiten volgens weersafhankelijke intervallen.

De resultaten lieten zien dat het fungicidengebruik meer afhankelijk is van weersomstandigheden dan van de bestrijdingsstrategie of de cultivar. Met vaste spuitintervallen werd een 'premie' betaald in de vorm van preventieve bespuitingen om het risico van Phytophthora infectie te voorkómen. Naarmate het tijdstip van infectie langer geleden is, worden middelen met een sterkere curatieve werking gebruikt. Voor meer resistente cultivars is gevonden dat variabele spuitintervallen (in vergelijking met vaste intervallen) de milieukundige risico's van het gebruik van fungiciden reduceerde en de epidemiologische risico's niet vergrootte. Epidemiologische risico's zijn gemeten als het gemiddeld aantal keren in één seizoen dat een curatief werkend middel nodig was voor de bestrijding van Phytophthora. Wanneer een spuitschema met variabele intervallen werd toegepast op een vatbaar ras, werd echter een grote kans op een grote behoefte aan fungiciden gevonden gevonden. Dit impliceert een groot milieukundig risico.

Met een strategie met variabele spuitintervallen en de meest resistente cultivar werden de laagste fungicidekosten bereikt. Toepassing van de strategie met variabele spuitintervallen is gebaseerd op de aanschaf van een locaal weerstation. De resultaten lieten zien dat de besparing in fungicidengebruik gemiddeld genomen niet opweegt tegen de additionele kosten van deze apparatuur.

Interviews toonden aan dat –naast het ontbreken van een economisch voordeel– de perceptie van de risico's op een infectie met Phytophthora een belemmering was in de keuze voor een meer gecompliceerde strategie met variabele spuitintervallen. Een andere belemmeringen was de perceptie van onzekere marktvooruitzichten voor meer resistente cultivars.

Productierisico's van stikstofbemestingsstrategieën in aardappelen

Organische mest is voor de akkerbouw in de Nederlandse kleigebieden belangrijk om de bodemvruchtbaarheid te handhaven. Na het gebruik van organische mest bestaat het risico van nitraatuitspoeling naar het grondwater. De risico's met betrekking tot opbrengstverlies, nitraatuitspoeling, inpasbaarheid in de arbeidsorganisatie, stikstofmineralisatie en bemestingskosten zijn vergeleken voor zes stikstof-bemestingsstrategieën in consumptie-aardappelen. Deze zes strategieën (van gangbaar tot geïntegreerd) verschilden in het al dan niet toepassen van varkensdrijfmest en de datum van toepassing daarvan en de additionele hoeveelheid toegediende stikstof in de vorm van kunstmest.

De risico entiteiten zijn bepaald aan de hand van modelberekeningen met de weerdata van 43 jaar. De resultaten lieten voor alle zes de strategieën een brede kansverdeling zien voor de uitspoeling van stikstof, met piekwaarden van 200 kg N ha^{-1}. Dit impliceert aanienlijke risico's voor stikstofuitspoeling door stikstofbemesting in consumptie-aardappelen. Dit geldt in het bijzonder voor de toepassing van dierlijke mest in de herfst. Toepassing van dierlijke mest in het voorjaar liet geen groter risico voor uitspoeling zien dan volledige bemesting met kunstmest. Er waren slechts kleine verschillen tussen de strategieën in gemiddelde waarden en piekwaarden in bemestingskosten.

Modelberekeningen toonden aan dat toepassing van organische mest in het voorjaar op kleigronden gepaard ging met organisatorische risico's. Organisatorische risico's ontstaan wanneer de fysische bodemgesteldheid de toepassing van dierlijke mest verhindert. De kans op een noodgedwongen uitstel van grondbewerking en poten door toepassing van dierlijke mest in het voorjaar was 40%. Uitstel van grondbewerking en poten leidt waarschijnlijk tot een lagere productie.

Ter aanvulling van de normatieve simulaties is een empirisch onderzoek verricht naar het stikstofmanagement op akkerbouwbedrijven. Een analyse van 136 gepoolde bedrijf-jaar waarnemingen toonde aan dat de meeste akkerbouwers dierlijke mest gebruikten (83% van de boeren in het panel) en dat het tijdstip van toepassing meestal viel in het najaar (75%). De meerderheid van de boeren in het panel die dierlijke mest gebruikten, wendden meer stikstof aan dan het standaard advies; 13% van de akkerbouwers bemestte zelfs met dierlijke mest, terwijl de kunstmestgift reeds groter of gelijk was aan het standaard advies. Deze uitkomsten tonen aan dat de uitspoeling van stikstof in de akkerbouw sterk kan worden teruggedrongen door rekening te houden met de stikstof-bemestende waarde van dierlijke mest en door uitstel van de dierlijke mestgift van het najaar naar het voorjaar.

Experimentele analyse van het keuzegedrag van boeren

De keuze voor een nieuw bedrijfssysteem (zoals duurzame landbouw) impliceert het nemen van een beslissing onder onzekerheid. Arbeidsbehoefte, kosten van bestrijdingsmiddelen, gewasopbrengsten en de mate van contoleerbaarheid van biologische processen zijn een aantal van deze onzekerheden. De perceptie en de houding van de boer zijn van invloed op de keuze voor een ander bedrijfssysteem. De experimentele economie biedt mogelijkheden om in een complexe omgeving als deze het beslisgedrag van beslissers te onderzoeken. Het belangrijkste voordeel van experimenten in vergelijking met andere empirische methoden is dat storende variabelen beter controleerbaar zijn. In het geval van een onderzoek naar nieuwe bedrijfssystemen is de geringe behoefte aan historische data ook een voordeel.

Een economisch experiment is uitgevoerd om de respons van boeren te onderzoeken op een boete op herbicidengebruik boven een vastgestelde drempel. Het gedrag van dertien akkerbouwers met een verschillende graad van ecologische duurzaamheid van hun bedrijf is onderzocht aan de hand van hun keuze voor strategieën en maatregelen in onkruidbestrijding. Met het model BESTWINS zijn situaties in onkruidbestrijding met stochastische eigenschappen gesimuleerd en via PC's individueel gepresenteerd aan de akkerbouwers. De deelnemers werd gevraagd om gedurende een aantal seizoenen beslissingen in te voeren in het model. De strategieën waaruit gekozen kon worden varieerden van gangbaar (gebaseerd op volveldse bespuitingen) tot 'biologisch' (volledig gebaseerd op mechanische methoden).

Vóór de aankondiging van de boete kozen drie deelnemers een meer duurzame strategie, welke zij ook ná aankondiging van de boete bleven volgen. Als respons op de boete hielden twee deelnemers vast aan de gangbare strategie; acht kozen voor een meer duurzame strategie voor onkruidbestrijding. Slechts twee deelnemers overschreden de drempel voor herbicidengebruik; één met een gangbare strategie en één met een meer duurzame strategie.

De gekozen strategieën en de hoeveelheid gebruikte herbiciden van de deelnemers aan het experiment vertoonde een significante correlatie met de onkruidbestrijding op hun eigen bedrijven. Dit duidt op een goede bruikbaarheid van de resultaten voor de praktijk. De mogelijkheden van experimentele economie voor de *ex-ante* evaluatie van de verspreiding van innovaties onder een veranderend milieubeleid zijn in dit kleinschalige experiment aangetoond.

Tenslotte

IAFS zijn ontwikkeld als dé innovatie voor de akkerbouwsector om te kunnen voldoen aan de eisen van het toekomstige milieubeleid. Deze studie toonde aan dat IAFS niet beschouwd kan worden als een enkele innovatie, omdat boeren slechts kozen voor díe componenten van IAFS waarmee een economisch voordeel te behalen is. Boeren lijken te convergeren naar een nieuwe 'gangbare' praktijk, waarin het gebruik van chemische inputs gereduceerd wordt. Er is echter nog een lange weg te gaan van dit nieuwe bedrijfssysteem naar een werkelijk duurzaam bedrijfssysteem met de ecologische duurzaamheid die onderzoekers haalbaar achten. Een grootschalige introductie van duurzame bedrijfssystemen vergt een drastische verandering van de socio-economische omgeving van het bedrijf nodig.

Uit deze studie kunnen een aantal mogelijke practische toepassingen voortkomen. De *bio-economische modellen* die in deze dissertatie zijn ontwikkeld kunnen fungeren als gereedschap voor gewasspecialisten of akkerbouwers om productierisico's van een aantal productiestrategiëen te vergelijken. Het principe van dit model kan ook gebruikt worden voor de uitwerking van andere teeltaspecten.

Een ander voorbeeld van een mogelijke toepassing is de bijdrage aan de ontwikkeling van een verzekering van de productierisico's van duurzame landbouw. De verzekering van tenminste de extreme verliezen in netto inkomen ten gevolge van incidentele agro-ecologische omstandigheden kan boeren helpen met het aangaan van productierisico's van het omschakelen naar meer duurzame bedrijfssystemen. Statistische kansverdelingen kunnen bij het ontwerp van een verzekering worden gebruikt bij de berekening van de premie en de verwachte claim. Traditioneel worden hiervoor statistische kansverdelingen geschat met historische data. In het geval van nieuwe bedrijfssystemen kan deze methode problemen geven, omdat weinig data beschikbaar zijn. In plaats daarvan kan de in deze studie beschreven *bio-economische modellering* worden gebruikt voor het genereren van data. Om oorzaak en gevolg van een dergelijke verzekering te kunnen verifiëren is een nauwgezette registratie van het prodctieproces noodzakelijk. Dit maakt het aantrekkelijk om de verzekering op te zetten in combinatie met een kwaliteitskeurmerk of een boekhoudsysteem voor mineralen.

Het toenemende maatschappelijke belang van de bescherming van het milieu zal duurzame landbouwsystemen een relatief voordeel, of zelfs een 'licence to produce', verschaffen. Dit kan de kansen voor de grootschalige, autonome verspreiding van duurzame systemen onder boeren vergroten. Sterengere wordende milieunormen zullen waarschijnlijk leiden tot maken lagere bedrijfsresultaten in de akkerbouw (vanwege hogere productiekosten, lagere opbrengsten en minder intensieve vruchtwisselingen) en tot grotere productierisico's, zoals berekend in deze studie. De dalende trend van de outputprijzen zullen de mogelijkheden van de akkerbouwers om deze doelen te bereiken drastisch inperken. De levensvatbaarheid van de akkerbouw in Nederland lijkt daarom afhankelijk van de bereidheid van de Nederlandse samenleving om boeren te betalen voor de productie van andere 'goederen' dan louter goedkoop voedsel.

Bibliography

Chapters of this dissertation for publication in refereed scientific journals

Chapter 2: A.J. de Buck, I. van Rijn, N.G. Röling, and G.A.A. Wossink. Farmers' reasons for changing or not changing to more sustainable practices: an exploratory study of arable farming in the Netherlands. *The Journal of Agricultural Education and Extension* (submitted).

Chapter 3: De Buck, A.J., E.M.T. Hendrix and H.B. Schoorlemmer, 1999. Analysing production and environmental risks in arable farming systems: a mathematical approach. *European Journal of Operational Research* 119: 416-426.

Chapter 4: A.J. De Buck, H.B. Schoorlemmer, G.A.A. Wossink and S.R.M. Janssens, 1999. Risks of post-emergence weed control strategies in sugar beet: development and application of a bio-economic model. *Agricultural Systems* 59: 283-299.

Chapter 5: A.J. De Buck, H.B. Schoorlemmer and G.A.A. Wossink. A bio-economic model for assessing the risks of Late Blight control strategies in ware potatoes. *Journal of Agronomy and Crop Science* (submitted).

Chapter 6: A.J. De Buck, T.J. de Koeijer, A.B. Smit, S.R.M. Janssens and J. Oenema. Risks and environmental sustainability of strategies in nitrogen management with or without manure in potato growing. *Agricultural Systems* (submitted).

Chapter 7: A.J. de Buck, G.A.A. Wossink and J.A. Renkema. Assessment of farmers' decision making in weed control using experimental economics. *Netherlands Journal of Agricultural Science* (submitted).

Other publications in refereed scientific journals

G.A.A. Wossink, A.J. de Buck, J.H. van Niejenhuis and H.C.M. Haverkamp, 1997. Farmer perceptions of weed control techniques in sugarbeet. *Agricultural Systems* 55: 409-423.

Conference papers

H.B. Schoorlemmer, A.J. de Buck and G.A.A. Wossink, 1994. Risk and risk perception in the conversion to sustainable production methods in arable farming. In: B.H. Jacobsen, D.E. Pedersen, J. Christensen and S. Rasmussen (Eds.) Proceedings from the 38th EAAE Seminar "Farmers' decision making - a descriptive approach", October 3-5 1994, Copenhagen, Denmark, pp.191-202.

A.J. De Buck, H.B. Schoorlemmer and G.A.A. Wossink, 1996. Analysis of production risks in sustainable arable farming on crop and whole farm level. In: Poster Paper EUNITA Seminar, Risk management Strategies in Agriculture: State of the Art and Future Perspectives, January 7-10, 1996, Wageningen, The Netherlands.

A.J. De Buck and G.A.A. Wossink, 1996. Production risks and the perception of risks in sustainable arable farming systems. In: Gerhard Schiefer (Ed.) Abstract Proceedings 1996 Bonn-Wageningen Workshop on Farm and Agribusiness Management Research March 15, Bonn, Germany, pp.11-12.

G.A.A. Wossink, A.J. de Buck, and J.H. van Niejenhuis, 1996. Farmers' perceptions of substainable production techniques: the case of weed control in sugarbeet. In: Proceedings IAAE Workshop on Economics of Agro-chemicals, April 24-28, Wageningen, The Netherlands.

A.J. De Buck, E.M.T. Hendrix, H.B. Schoorlemmer and G.A.A. Wossink, 1997. Analysing production risks in sustainable arable farming systems by combining LP with dynamic decision rules. In: EURO XV / INFORMS XXXIV joint international meeting, Barcelona, Spain, HB01.2: 170.

Other publications

H.N. Van Lier, C.F. Jaarsma, C.R. Jurgens and A.J. de Buck, 1994. Sustainable land use planning. Proceedings of an international workshop, 2-4 september 1992, Wageningen, The Netherlands. Elsevier, Amsterdam, etc.

A.J. De Buck, S.R.M. Janssens, A.T. Krikke, H.B. Schoorlemmer and G.A.A. Wossink, 1996. Risico's en risicoperceptie bij duurzame produktiemethoden op het akkerbouwbedrijf. Verslag fasen 1 en 2, Interne mededeling PAGV nr. 1297, Lelystad, The Netherlands, 93 pp.

A.J. De Buck, 2000. Risicoanalyse van minder milieubelastende teeltstrategieën in de akkerbouw. *Agro-Informatica* 13(1):2-4.

A.J. de Buck, F.J. de Ruijter, F. Wijnands, P.L.A. van Enckevort, W. van Dijk, A.A. Pronk, J. de Haan en R. Booij, 2000. Voorwaarts met de milieuprestaties van de Nederlandse open-teelt sectoren: een verkenning naar 2020. Rapport 6, Plant Research International, Wageningen, The Netherlands.

A.J. de Buck en M.J. Groot. De concurrentiepositie van de Nederlandse biologische fruitteelt in de EU. Fruitteelt Praktijk Onderzoek, Randwijk, The Netherlands (forthcoming).

Curriculum vitae

Abraham Jacobus de Buck werd geboren op 2 oktober 1966 te Zierikzee. In 1985 behaalde hij het diploma VWO aan de Christelijke Scholengemeenschap 'Blaise Pascal' te Spijkenisse. In 1985 begon hij de studie Landbouwplantenteelt bij de toenmalige Landbouwhogeschool te Wageningen. Deze studie werd in 1991 afgerond met de afstudeervakken Akkerbouw en Agrarische Bedrijfseconomie en met een onderzoeksstage in India onder supervisie van het International Potato Centre (CIP).

Na zijn afstuderen volgden een aantal tijdelijke betrekkingen. Van januari 1992 tot mei 1993 was hij als erkend gewetensbezwaarde militaire dienst aangesteld bij het toenmalige DLO-Staring Centrum te Wageningen. Van februari 1994 tot februari 1998 was hij als Assistent In Opleiding (AIO) verbonden aan de toenmalige vakgroep Agrarische Bedrijfseconomie van de Landbouwuniversiteit te Wageningen. Gedurende deze aanstelling is het onderzoek uitgevoerd, wat heeft geleid tot deze dissertatie. Een deel van deze periode was hij gedetacheerd bij het toenmalige Proefstation voor Akkerbouw en Groenteteelt in de Vollegrond te Lelystad.

Van juni 1999 tot maart 2000 was hij als Wetenschappelijk Onderzoeker Landbouwbedrijfssystemen verbonden aan Plant Research International. Bij de business unit Agro Systeemkunde werkte hij aan een project met als doel het ontwikkelen van duurzame bedrijfssystemen voor de Nederlandse open-teeltsectoren, die voldoen aan meest stringente milieutechnische criteria. Hij was ook belast met de opzet en de uitvoering van een onderzoek naar de stroom van grondstoffen en producten tussen de verschillende sectoren van de biologische landbouw in Nederland met als doel het totstandbrengen van kringlopen.

Sinds augustus 2000 is hij werkzaam als Wetenschappelijk Onderzoeker Economie en Management bij het Fruitteelt Praktijk Onderzoek (FPO) te Randwijk. Hij is daar belast met de opzet en de uitvoering van een aantal projecten die betrekking hebben op duurzame bedrijfssystemen in de fruitteelt.