Université de Toulouse

THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :
Institut National Polytechnique de Toulouse (INP Toulouse)

Discipline ou spécialité :

Agrosystèmes, Ecosystèmes et Environnement

Présentée et soutenue par :
Jérôme Dury

le : vendredi 9 décembre 2011

Titre :

The cropping-plan decision-making: A farm level modelling and simulation approach

---

Ecole doctorale :
Sciences Ecologiques, Vétérinaires, Agronomiques et Bioingénieries (SEVAB)

Unité de recherche :
UMR INRA-ENSAT 1248 AGIR

Directeur(s) de Thèse :
BERGEZ Jacques-Eric (INRA, Toulouse)
REYNAUD Arnaud (INRA, Toulouse)

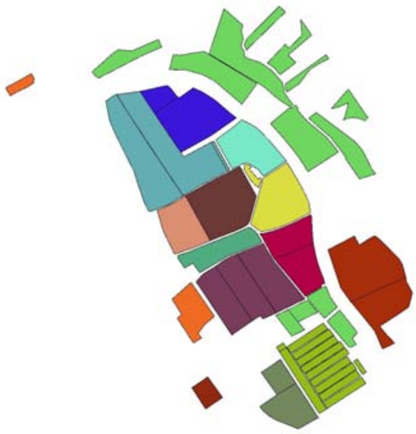
Rapporteurs :

DONATELLI Marcello (Joint Research Centre, European Commission, CRA, Bologna)
GARY Christian (INRA, Montpellier)

Membre(s) du jury :
GARY Christian (INRA, Montpellier)
BERGEZ Jacques-Eric (INRA, Toulouse)
DONATELLI Marcello (Joint Research Centre, European Commission, CRA, Bologna)
GUERRIN François (Cirad, La Réunion)
LEMARIE Stéphane (INRA, Grenoble)
NICOLETTI Jean-Paul, (ARVALIS - Institut du végétal, Paris)

THE CROPPING-PLAN DECISION-MAKING: A FARM LEVEL MODELLING AND SIMULATION APPROACH

Jérôme Dury



PhD

Institut National de la Recherche Agronomique (INRA-EA)
UMR INRA-ENSAT 1248 AGIR: Agrosystèmes et Agricultures, Gestion des ressources, Innovations & Ruralités

Université de Toulouse, Institut National Polytechnique de Toulouse

9 December 2011

SUPERVISOR:
Jacques-Eric Bergez (INRA, UMR 1248 AGIR, Toulouse)

CO-SUPERVISORS:
Arnaud Reynaud (TSE(LERNA-INRA), Toulouse)
Frédérick Garcia (UMR BIA, Toulouse)

REVIEWERS:
Marcello Donatelli (Joint Research Centre, European Commission, CRA, Bologna)
Christian Gary (INRA, Montpellier)

EXAMINATORS:
François Guerrin (Cirad Réunion)
Jean-Paul Nicoletti (ARVALIS-Institut du végétal)
Stéphane Lemarié (INRA, Grenoble)

FUNDINGS:
INRA EA, INRA SAE2, Arvalis Institut du végétal, CETIOM.

ABSTRACT

Evolutions of the institutional and environmental contexts are driving search for alternative cropping systems to reduce water use while maintaining high levels of productivity. This thesis is an account of the long tradition of research on cropping-plan choices at the farm level. It concerns the scope of modelling agricultural systems with an opening to economy. The objective of the research described in this thesis is to produce formalised knowledge on farmers' cropping-plan choices under uncertain environment (price and weather) by analysing and modelling their decision-making processes. Formalising and modelling decision-making processes is becoming a crucial point to develop decision support systems that go beyond limitations of formerly developed prescriptive approaches.

This thesis contributes to the development of a formalised and integrated methodology to study and model complex decision-making process. This methodology enables to fill the gap between field surveys and decision-model implementation. The methodology is drawn upon a theoretical background of the decision-making, and consistently combined tools to respectively survey, analyse, model and implement coupled agent and biophysical models. In this thesis, I address the question of uncertainty in two directions. I first analyse the spatio-temporal dynamic of individual farmers' decision-making process. Then I estimate farmers' aversion to risk by comparing stated and revealed elicitation methods. On the basis of field survey results, I develop a decision model called CRASH. The approach to develop the model stresses on explicit formalisation of the decision-making process in its temporal and spatial dimensions, and representation of the domain knowledge through generic concepts that are close to ones used by decision-makers. The implementation of developed models is carried out on the RECORD platform as trail blazing project. The originality relies on the use of dynamic models on both the biophysical and management processes.

This research opens new perspectives for developing farm specific decision support systems that are based on simulating farmers' decision-making processes. The modelling and simulating the cropping-plan decision-making processes should enable to design with farmers cropping systems that re-conciliate the required adaptive capacities and needs to maintain cropping systems productivity.

Keywords: cropping-plan, decision-making, coupled agent model, simulation, RECORD, uncertainty, farm scale

ACKNOWLEDGMENTS

Mes premiers remerciements vont bien évidemment à mes directeurs de thèse, Jacques-Eric Bergez, Arnaud Reynaud et Frédérick Garcia sans qui cette thèse n'aurait pas existé. Merci à vous d'avoir su me guider dans ce travail tout en me laissant une grande autonomie et même une grande liberté. Je voudrais remercier tout particulièrement Jeb pour son suivi quotidien et la confiance qu'il m'a accordé tout au long de cette belle aventure.

Je remercie les rapporteurs et les membres du jury qui m'ont fait l'honneur d'accepter de lire, d'évaluer et de commenter le travail de ces trois années de thèse: Marcello Donatelli, Christian Gray, François Guerrin, Lemarié Stéphane et Jean-Paul Nicoletti.

Je remercie les membres de mon comité de thèse, comité de suivie et de l'UMT eau qui ont su enrichir mes réflexions durant ces trois annnées par leurs remarques et commentaires avisés: Jean-François Amen, Christine Aubry, Luc Champolivier, Stéphane Couture, Jean Marc Deumier, Fritz van Evert, Bernard Lacroix, Jean Paul Nicoletti, Noémie Schaller et Sylvain Marsac.

Il est d'usage de remercier tous les collègues avec qui ont a partagé le travail. Je ne me risquerai pas à essayer de les citer tous ici, ils sont nombreux et je ne les oublie pas:

Je remercie tous les membres mon équipe d'accueil MAGE. C'est durant les réunions d'équipe du lundi matin que j'ai pu m'initier à une nouvelle langue: l'acronymie. Sans la maîtrise complète de cette langue, déconcertante pour le novice que je étais, tout effort de compréhension de la recherche et de son organisation était vaine. J'ai beaucoup progressé durant ces trois ans, mais dire que je suis aujourd'hui bilingue serait présomptueux. Ce fut un vrai plaisir que de partager avec les membres de l'equipe MAGE, et particulièrement Olivier Therond, des moments de réflexion et de bouillonnement conceptuel intenses durant nos réunion ontologie.

Un merci tout particulier à Mahuna Aplogan, Patrick Chabrier, Gauthier Quesnel et Ronan Trepos de m'avoir aider à faire face aux nombreuses *"segmentation fault"* et autres messages mystiques lancés sans préavis par un terminal qui n'a jamais fait de compromis. Vous avez fait preuve de beaucoup de patience avec un agronome souvent perdu dans les tréfonds du binaire: vous m'avez **beaucoup** appris, un grand merci à vous.

Un grand merci aussi à Yannick Genest et Stéphanie Chanfreau qui sont venus m'accompagner dans mon travail aux travers de leur stages de fin d'étude. Et comment ne pas remercier Dragan Amenga Mbengoue pour sa participation au développement de CRASH et surtout pour son sourire et sa bonne humeur légendaire. Ce fut une vrai belle expérience que de travailler avec vous trois.

Et puis une thèse ce n'est pas que du travail, c'est aussi et surtout des copains avec qui on partage d'autres choses, avec qui j'ai passé de très bons moments et qui ont su aussi être là dans les moments difficiles. Je pourrai les remercier de tant de choses, alors pour faire simple un **grand MERCI** à vous: Mahuna Aplogan, Laurent Bedoussac, Marion Casagrande, Caroline Gibert, Solenn Guillaume, Senthilkumar Kalimuthu, Guillaume Martin, Magali Willaume. Nos chemins vont se recroiser c'est sûr. En attendant, bon vent à vous et surtout n'oubliez pas de restez fou, c'est une question de survie!

Une thèse c'est aussi un bureau, un peu comme une deuxième maison qu'on partage avec des compagnons d'infortunes embarqués un an plutôt ou plus tard dans la même aventure de la thèse. Alors avec le temps on y prend ses petites habitudes: une petite discussion de politique nationale dès 8h du matin avec Marie-Hélène Bonnemé pour se gonfler à bloque, un petit *"M..., j'ai encore oublié d'arroser les plantes!"* quand une foi de plus Myriam Desanlis prend l'arrosoir pour sauver une énième foi les plantes promisent a un destin funèbre, un petit débogage de temps à autres de script R pour dépanner Solenn Guillaume, ou quand tous les matins je sors de ma bulle pour me rendre compte 2h après son arrivé que Toky Trakonton est là, toujours aussi discret et bienveillant.

Il y avait aussi ces pauses sur la place Arezki, du nom d'un célèbre pêcheur de truites Arezki Zerourou, avec ces interminables discussions politico informatico burlesques et passionnantes. Ce fut de vrais moments de relâche durant lesquels on a travaillé sans compter à refaire le monde. Mais à écouter la radio en ce moment, je me dis qu'on a peut être un peu déconné... On a du s'égarer dans notre analyse bayesio-pythonique de la crise, mais c'est peut-être juste un mauvais paramétrage du modèle, pas de panique on y travaille. Une devise: même si tout fout le camp ne rien lâcher!

Et puis, il y a la SNCF sans laquelle je n'aurai pas pu pu faire tous ces aller-retours le week-end, sans laquelle je n'aurai pas pu m'échapper dans le Berry pour me ressourcer. Et enfin et surtout, merci Laura pour avoir patienté ces trois ans, ça y est je suis là...

LIST OF PUBLICATIONS

PUBLISHED OR SUBMITTED TO PEER-REVIEWED JOURNALS

Bergez, JE., Leenhardt, D., Colomb, B., **Dury, J.**, Carpani, M., Casagrande, M., Charron, MH., Guillaume, S., Maton, L., Therond, O., Willaume, M., 2011a. Computer-model tools for a better agricultural water management: tackling managers' issues at different scales - A contribution from systemic agronomists. Computers and Electronics in Agriculture, Submitted.

Bergez, JE., Chabrier, P., Gary, C., Jeuffroy, MH., Makowski, D., Quesnel, G., Ramat, E., Raynal, H., Wallach, D., Debaeke, P., Durand, P., Duru, M., **Dury, J.**, Faverdin, P., Gascuel-Odoux, C., Garcia, F., 2011. RECORD: an open platform to build, evaluate and simulate integrated models of farming and agro-ecosystems. Environmental Modelling & Software, Submitted.

Dury, J., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2011. A case-based methodology for modelling decision-making processes: cropping-plan choices. Environmental Modelling & Software, Submitted.

Dury, J., Schallers, N., Garcia, F., Reynaud, A., Bergez, JE., 2011. Models to support cropping plan and crop rotation decisions: a review. Agronomy for Sustainable Development. DOI:10.1007/s13593-011-0037-x

Reynaud A., S. Couture, **Dury, J.**, Bergez, JE. 2011. Farmer's Risk Attitude: Reconciliating Stated and Revealed Preference Approaches? American Journal of Economic, Submitted.

Rufino, M. C., **Dury, J.**, Tittonell, P., Wijk, M. T. V., Herrero, M., Zingore, S., Mapfumo, P., Giller, K. E., 2011. Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. Agricultural systems 104 (2), 175–190.

ABSTRACTS AND PROCEEDINGS

Akplogan, M., **Dury, J.**, de Givry, S., Quesnel, G., Joannon, A., Reynaud, A., Bergez, JE., Garcia, F., 2011. A Weighted CSP approach

for solving spatio-temporal farm planning problems. In: Soft'11, 11th Workshop on Preferences and Soft Constraints. pp. 1–15.

Couture, S., Reynaud, A., **Dury, J.**, Bergez, JE., 2010. Farmer's risk attitude: Reconciliating stated and revealed preference approaches? In: Fourth World Congress of Environmental and Resource Economists. Montreal, Canada, p. 34.

Dury, J., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2010. Modelling the Complexity of the Cropping Plan Decision-making. In: and Software, E. M. (Ed.), International Environmental Modelling & Software Society. iEMSs, Ottawa, Canada, p. 8. (PhD paper award)

Dury, J., Genest, Y., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2010. The cropping plan decision-making in crop farms. In: AGRO2010. Montpellier, France.

Dury, J., Schallers, N., Akplogan, M., Aubry, C., Bergez, JE., Garcia, F., Joannon, A., Lacroix, B., Martin, P., Reynaud, A., Therond, O., 2009. Modelling crop allocation decision-making processes to simulate dynamics of agricultural land uses at farm and landscape level. In: Second Farming System Design. Monterey, CA.

Reynaud, A., Couture, S., **Dury, J.**, Bergez, JE., 2010. Farmer's Risk Attitude: Reconciliating Stated and Revealed Preference Approaches? In: Risk Elicitation and Stated Preference Methods for Climate Change Research. Trento (Italy), p. 25.

Rufino, M., **Dury, J.**, Tittonel, P., Van Wijk, M., Zingore, S., Giller, K., 2009. Competing use of organic resources, climate variability and interactions at village scale in a communal area of NE Zimbabwe. In: Integrated Assessment of Agriculture and Sustainable Development (AgSAP). Egmond aan Zee, The Netherlands.

CONTENTS

ACRONYMS

API Application Programming Interface

ARVALIS "*Arvalis institut du végétal*"

BDI Belief Desire Intention

CAP Common Agricultural Policy

CTA Cognitive Task Analysis

CETIOM "*Centre Technique interprofessionnel des Oléagineux Métropolitain*"

CRRA Constant Relative Risk Aversion

CRASH Crop Rotation and Allocation Simulator using Heuristics

DIESE DIscrete Event Simulation Environment

DEVS Discrete Event System Specification

DSS Decision Support System

EU European Union

INRA "*Institut National de Recherche Agronomique*"

STICS "*Simulateur mulTIdisciplinaire pour les Cultures Standard*

UML Unified Modelling Language

UMT eau Unité Mixte Technologique Eau

VLE Virtual Laboratory Environment

WCSP Weighted Constraint Satisfactory Problem

WFD Water Framework Directive

WTO Word Trade Organisation

Part I

GENERAL INTRODUCTION

It would be naive to suppose that the unsustainability problems humankind is faced with could be solved with current tools and methods (models!) that were applied - or seemed to work - in the past.

— J. Rotmans (Rotmans, 2009)

1 INTRODUCTION

1.1 GENERAL BACKGROUND

Agriculture is facing new challenges in the line of further changes occurring at the different levels of the whole society. The rising environmental concerns (Assessment Millennium Ecosystem, 2005) and likelihood of climate change (Pachauri and Reisinger, 2007) make necessary to adopt innovative farming practices to meet challenges of the future (McIntyre et al., 2008). In the same time, the socio-economic context of farmers is changing a lot with highly fluctuating crop prices combined with coming new regulations (e.g. Common Agricultural Policy (CAP) in European Union (EU), Word Trade Organisation (WTO) negotiation). In this broad context, most of the farming systems are highly exposed to the three main sources of risk in agriculture: production, market and institutional risks (Hardaker et al., 2004). All these elements question the vulnerability of the current farming systems and more over the need to strengthen their adaptative capacity to face an ever changing environment (Smit and Wandel, 2006; Darnhofer et al., 2010). Many crucial issues have emerged from this necessity to evolve that farmers, technical advisers, researchers and policies makers have to tackle. One of these issues concerns the evolutions of cropping systems in irrigated arable farms. These farms are particularly concerned and affected by the significant ongoing changes of economy, regulations and water scarcity (Amigues et al., 2006).

1.2 WHY BEING INTERESTED IN CROPPING-PLAN ONCE AGAIN?

1.2.1 *Prices, policies and cropping-plan*

Worldwide, cereal markets are regulated by global and local policies to maintain farmers' income and to protect them from highly variable crop prices as observed in the last decades (Figure 1.1). In Europe, these policies, also known as the CAP, was set up in 1962 consequently to the Rome treaty instituting the EU. The main objectives were to stimulate agricultural production and to ensure the European food production self-sufficiency. Consequently to this reform, most the European farming systems have been intensified and over specialised to successfully gain in productivity (Stoate et al., 2001). This policy has triggered a trend of cropping-plan simplification and encouraged development of mono-cropping in arable farms in France (Pointereau and Bisault, 2006).

In 1992, the CAP reform objectives have changed to maintain competitiveness of the European agricultural sectors. Crop prices have been used as a major factor to drive cropping-plan choices (Chavas and Holt, 1990) and has been used as a key driver by policy makers in reducing crop guaranteed prices and introducing compensatory payments. In France, high priority was given to irrigated crops for distributing subsidies at the expense of the rain fed crops. This certainly explains the increase of irrigated area in the period of 1994-2000 (Figure 1.2). As illustration of that, subsidies for irrigated crops were on average 30% higher than for rain fed crops in the region of Midi-Pyrénées in the period 1993-2003 (Teyssier, 2006). At the national level, subsidies for protein and oleaginous crops have also been decreased in this period resulting in a shift from these crops towards maize crop: the irrigated maize area has grown in France from 730 000 ha in 1994 to 915 000 ha in 2000 (Figure 1.2). In 2000, the irrigated grain maize was therefore largely the main irrigated crop in France with 50% of the irrigated cropping area.

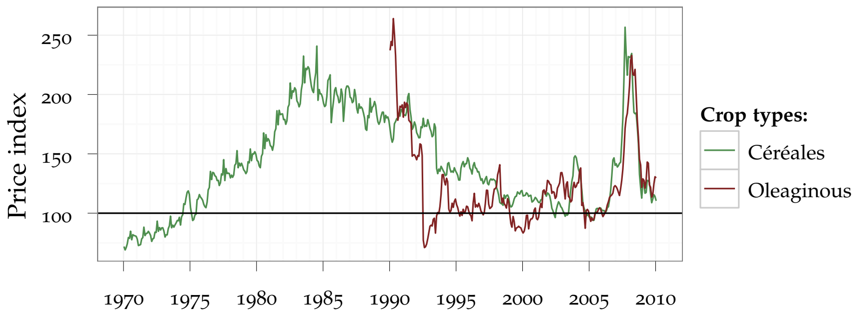


Figure 1.1: Price index for cereals and oleaginous based on 2005 (INSSE)

The CAP reform of 2003 introduced in 2006 the decoupling of 75% of the direct payments from production received by farmers. This shift from production-based subsidies to an income support program tends to lower the effect of the subsidies on cropping-plan farmers' decisions. As shown in Finland by Koundouri et al. (2009), this result is due to the increase in the non-random part of farm income generated by the policy. They also show that agricultural policies that are decoupled from production do affect input uses and cropping-plan choices through their effects on farmers risk attitudes (Koundouri et al., 2009). This reason has also been cited by Amigues et al. (2006) to explain the decrease of 7% of the irrigated maize area in France in 2006. As illustration in Midi-Pyrénées, an increase in rape seed has been estimated at 25% in 2007 (Agreste, 2007). With decoupling, water uses by farmers are not anymore driven by subsidy differences across crops (Berbel et al., 2007). In arable farms, the decoupling of payments also drives farmers to increase their farm size and consequently to simplify their cropping systems by reducing the number of crops to cultivate mono-crops despite agro-environmental incentive payments (Amigues et al., 2006). Further, the abolition of compulsory fallow in 2008 has freed nearly $400 \cdot 10^3$ ha (Agreste, 2008).

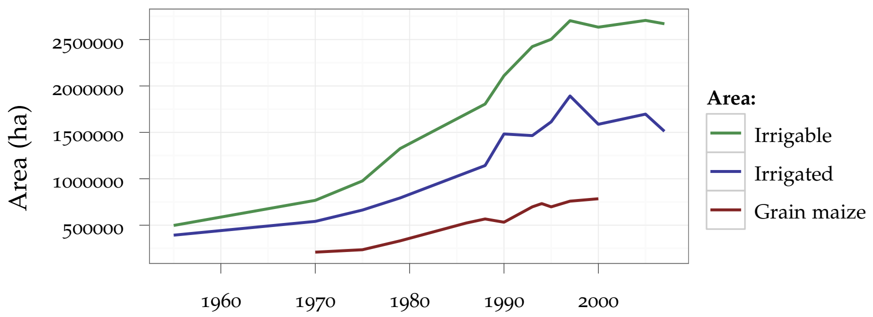


Figure 1.2: Irrigable and irrigated area for the period 1955-2007, and area of irrigated grain maize for the period 1970-2000 (Amigues et al., 2006; SOeS, 2011). The drought in 1976, 1989 and 1991 had a significant effect on the investments of irrigation equipments (Amigues et al., 2006).

As shown in the past, changes in regulation do affect cropping pattern choices heavily. The upcoming CAP reform in 2013 combined with a very uncertain crop price trends (Figure 1.1) is very likely to have important consequences on farmer's choices. Nowadays experts agree on the failure of the European policies to propose reforms that balance heterogeneous objectives not to detriment the environment and over use of resources (Stoate et al., 2001); water being the first concerned (Bartolini et al., 2007). The upcoming reform in 2013 is likely to reinforce the orientation of the CAP towards more environmental farming practices without renouncing to its initial productive objectives. This rise questions on the ways irrigated farms have to evolve to fit at best to the institutional context while reducing market risks as much as possible.

1.2.2 *Coping with scarce water resources*

1.2.2.1 *Water: a resource under pressure*

All around the word, water resources are under increasing pressure due to continuous population growth and to economic development (Assessment Millennium Ecosystem, 2005). Agriculture, and particularly irrigated cropping systems, strongly depends on direct withdrawals from natural resources such as rivers and aquifers. In France, the agricultural water withdrawals were estimated in 2003 at $4.8 \cdot 10^9 \mathrm{m}^3$ corresponding to 48% of the overall annual net water consumption considering other users. These water pumping can represent in summer up to 80-90% of the overall net water withdrawals. These figures have to be taken with caution because the water consumption by the agricultural sector is rather difficult to estimate due to the lack of reliable data (Amigues et al., 2006). These figures at the country scale should not hide very different situations among regions where water resources could be of different nature, and where quantitative water uses among users change. In this context, managing agricultural water withdrawals is a particularly sensitive issue in regions where irrigated crops cover a large area and significantly affect water resources (Figure 1.3).

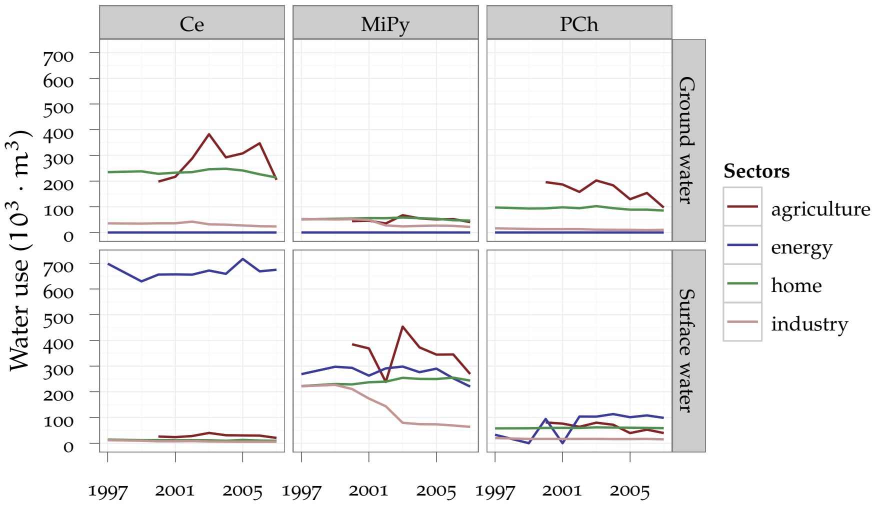


Figure 1.3: Water uses by sectors in three French regions where the issues of quantitative management of agricultural water are acute [Ce: Centre, PCh: Poitou-charentes, MiPy: Midi-Pyrénées] (MEDDTL, 2011)

In France, the agricultural withdrawals are managed in a fragmented manner between the different resource types and also between regions. The pricing systems vary from *average cost* to *marginal cost*, which are usually jointly used with systems of quotas. In the past, resources were not systemically subject to the volumetric monitoring, so that decisions made to meet demands of farmers typically failed to consider the impacts of those decisions on the other competing users and make difficult to known overall resource availabilities (Berbel et al., 2007). In a few locations where the volumetric management has been set up, some reductions of attributed quotas have already been effective. For instance, in the Beauce production basin in Centre region, the decrease in level by the aquifer since 2003, led to reduction water withdrawals of 45% in 2008 from the initial quota as negotiated in 1999 between farmers and the French government (Bouarfa et al., 2011). In France, the future of all irrigated systems will be heavily affected by the trends in European water and agricultural policy by the implementation of the European directive EC 60/2000 (Water Framework Directive (WFD)) (Bartolini et al., 2007). In France, the WFD translates into the generalisation to the volumetric management along with a global reduction objective of 20% of the water quotas for farmers. In Poitou-Charentes for instance, the *Boutone* river basin is one French area where problems of quantitative water resource management are the most acute (Bry and Holflack, 2004). In this area the application of the WFD could lead to a drastic reduction up to 84% of the authorisations delivered for agricultural withdrawals (Loubier et al., 2011).

1.2.2.2 *What are the options for farmers?*

In a context of limiting access to water, there is a need to embrace issues of quantitative water management by exploring alternative solutions. But options for farmers are not a lot, and none of them are perfect (Debaeke and Aboudrare, 2004):

Increasing the water use efficiency: In very short-terms, the main improvement path is optimisation of the irrigation doses and scheduling at the field scale (Wallace, 2000; Cognet et al., 2007). This can be achieved by the use of decision support systems that guide farmers to efficiently meet plant water demand all along the irrigation seasons. The development of decisions support systems are usually based on direct soil-plant monitoring in plots (Bouthier et al., 2003) and/or based on simulation models (de Juan et al., 1996; Ortega Álvarez et al., 2004; Bergez et al., 2001; Merot et al., 2008). The adoption of higher irrigation technology is also an option to increase the percentage of the water applied being used to meet agronomic objectives (Playán and Mateos, 2006). However, required investments for farmers are high (Marques et al., 2005). Wether these short-term solutions could lead to significant improvement (Bergez et al., 2001), they will not be sufficient to address the magnitude of quantitative water management issues.

Genetic improvement: The main expected genetic improvements of the crops for improving water use concern the adaptation of crop vegetative stage development to the period of drought, and the selection of less sensitive crop varieties to water shortage with high recovery potential after water stress (Debaeke and Aboudrare, 2004). Genetic improvement is a long-term process.

Building on water reserve capacities: Farmers demand for building water reservoirs filled in winter for summer uses to compensate the water quota reductions and prevent income drop down. The building of these substitution reservoirs for irrigation were shown to be not economically sustainable without governmental subsidies (Montginoul and Erdlenbruch, 2009; Loubier et al., 2011). Substituting uncertain water availability by a secured resource could lead to increase the water consumption (Loubier et al., 2011) because farmers make joint water and land use decisions for economic purposes partly based on water availability and reliability (Bartolini et al., 2007).

Designing innovative cropping systems: The design of innovative cropping systems is often presented as one of most the promising solutions (Amigues et al., 2006). This requires to deal with the whole complexity of the cropping system design by integrating the above mentioned options with others to take advantage of systemic synergies. In addition to the above mentioned solutions, the ways of improvement that are usually cited are:

- Crop diversity to increase the cropping system robustness to extreme conditions: 1) mix between rain fed and irrigated crops, 2) the mix of winter and summer crops.
- Integration of crops into crop rotations that are more tolerant to water deficit conditions.

The range of options available to farmers for managing the limiting water resource is the much broadest in the mid- and long-term perspectives. Major options for farmers are the adoption of cropping systems that combine high water use efficiency at field scale with robust cropping pattern selection fitting water resource availability and variability (Amigues et al., 2006). Conventionally, water management planning has been based on cropping pattern selection aiming at maximising the revenue from irrigation activities at different scales (e.g. Mainuddin et al., 1997; Ortega Álvarez et al., 2004; Sethi et al., 2006). In the real world however, several complexities make the cropping pattern selection a more complicated problem (Nevo et al., 1994; Tsakiris and Spiliotis, 2006) that have to be taken into account. Indeed, there is no any ideal cropping pattern to answer the question of the quantitative water management (Amigues et al., 2006). Uncertainty on drought characteristics and occurrences in relation to the site specific resource availabilities (e.g. water ,soil) govern the optimal cropping pattern and crop management schemes (Debaeke and Aboudrare, 2004). Further, the implementation of the WFD will introduce new quantitative constraints on water management that may make farmers rethinking their cropping-plan decision strategies as regard to this new context (Bartolini et al., 2007).

1.3 AN AGRO-ECOLOGICAL ENGINEERING APPROACH

Agro-ecology as a theory and approach of agro-ecological engineering plays a very important role in the design of farming systems (Dalgaard et al., 2003; Wezel et al., 2009). The complexity of a farming system consists of several interdependent components dynamically arranged (designed) by farmer in a coherent whole as regards to her/his objectives of productions and the agro-ecological, social and economic conditions (Liang, 1998). Agro-ecological engineering approaches aim to design and explore alternative land use systems at various scales and participate in identifying appropriate land use options. These approaches integrate and synthesis process-based agro-ecological knowledge usually in the form of mathematical representations while taking into account prevailing socio-economical knowledge. In agro-ecological engineering, the formalisation of concepts and processes is required to efficiently engineer alternatives that are consistent with farmers' production goals and the regime of resources under specific natural, social and economic conditions.

1.3.1 *Challenges for farming system designers*

Over the past, innovation in cropping systems has largely been promoted through changes in a single aspect of the systems. However, the design of innovative farming system must be addressed in the light of its own complexity (Meynard et al., 2001). Wery and Langeveld (2010) recalled the four main challenges that cropping systems designers have to face in order to propose innovative systems that fit with the rapid evolution of agricultural context:

1.3.1.1 *From technological packages to design methodologies*

The old fashion design methodologies were developed to produce generic turnkey technical solutions. The bottlenecks meet by these approaches call for developing methods and tools able to address site specific issues while being based on generic and scientific-sound methodologies (Vanloqueren and Baret, 2009).

1.3.1.2 *From mono- to multi-criteria design*

The prevailing concept of *agricultural sustainability* in most of the future oriented projects claims for a multidimensional approach to assess the newly designed cropping systems. (e.g. Bachinger and Zander, 2007; Sadok et al., 2009).

1.3.1.3 *From field scale to multi-scale design*

Resolution of agricultural issues requires the integration of biophysical and socio-economic data occurring at different levels of organisation and spatial scales (Hijmans and van Ittersum, 1996). This rises questions of up- and down-scaling data produced at the biophysical levels (e.g. field, landscape) to the ones at which decision-makers are operating (e.g. farm) without losing the integrity of the information (Dumanski et al., 1998).

1.3.1.4 *From stable to unstable environment*

An important challenge for agricultural system designer arising from changes in the whole society are the development of new methods for proposing adaptative farming systems (Darnhofer et al., 2010). The design processes have to integrate objectives of the resilience and the adaptability of the cropping systems (Smit and Wandel, 2006).

In addition to these four above mentioned challenges, some authors also point out the need of more effective integration of stakeholder decision-making within the process of farming systems design (e.g. Cox, 1996; Keating and McCown, 2001; Matthews et al., 2007; Liu, 2008; Bergez et al., 2010; Nuthall, 2010).

1.3.2 *Tools, methods and integrative approaches to design cropping systems*

Different tools and methods have already been developed to address the issue of farming system design. Loyce and Wery (2006) classified these tools and methods into three groups from which we can add a fourth. Wether the three groups are presented as separated methods, there are usually used in combination into coherent approaches (Sterk et al., 2007) following linear (e.g. Lançon et al., 2007) or iterative processes (e.g. Vereijken, 1997; Debaeke et al., 2009).

1.3.2.1 *Diagnosis*

Agronomic diagnosis have long been the basic methods to improve cropping system performances. They are implemented to identify limiting factors that might explain low system performances, and to identify technical options to alleviate these limitation (Doré et al., 1997).

1.3.2.2 *Prototyping*

Prototyping are empirical methodologies and were developed for the design of more sustainable farm systems (e.g. Vereijken, 1997; Lançon et al., 2007). In these approaches, farming systems are designed by experts. They involve application-oriented design and testing in pilot farms and/or field experiments, where scale, design and management are representative of a viable farm (Sterk et al., 2007). Recently, Debaeke et al. (2009) proposed an original approach were prototyping activities concern both the design of the cropping system itself but also the definition of the management rules to pilot this system.

1.3.2.3 *Model and simulation based approaches*

Given the complexity of the system to design, computer based simulation tools are commonly used to support the design and evaluation of innovative agricultural production systems (Bergez et al., 2010). Models provide means to formalise, expand, refine and integrate expert knowledge with scientific agro-ecological knowledge at the different scales of study (Matthews and Stephens, 2002). This approach allows to simultaneously quantify effects of different factors on the overall system performance (Boote et al., 1996).

1.4 Modelling and simulation approaches in agricultural studies

Considering the complexity of the systems to design, computer based simulation tools are nowadays used in almost all approaches to support the design and evaluation of innovative agricultural production systems.

1.4.1 *Crop soil simulation models*

Computer based simulation models are commonly used since De Wit (1965) to support the design and evaluation of innovative crop production systems (Bergez et al., 2010). Simulation models developed by farming systems researchers traditionally focus on the biophysical entities of the farming systems usually in the form of interacting crop-soil models (van Ittersum et al., 2003; Wallach et al., 2006). Crop-soil simulation models with their ability to integrate the results of research from many different disciplines and locations, offer a way of improving efficiency and/or explorative capability of researches (Rossing et al., 1997; Matthews and Stephens, 2002).

1.4.2 *Modelling management practices*

A farming system is a complicated, interwoven system in which decisions of human being are prominent. Agricultural productions result in fact of complex interactions between biophysical and man-controlled processes (Garcia et al., 2005). A classical approach to deal with the management of farmers in crop models was carried out under the concept of the *"best technical means"* as defined by van Ittersum and Rabbinge (1997) based on the work of de Wit (1992). This approach, also known as *"target oriented approach"* enables determination of the most efficient (i.e. optimal) combination of inputs to realise a particular production level in a certain physical environment and according to current level of knowledge and techniques (van Ittersum and Rabbinge, 1997). In this approach, there was no attempt to explicitly simulate farmer management practices.

When taken into account, farmer decision-making are usually characterised as operational, tactical and strategic decisions (Le Gal et al., 2011). Simulating management processes of the farming system is crucial as it helps in guiding necessary farming practice innovations (Le Gal et al., 2009). But in most of the simulation approaches, management processes were not or poorly accounted for (Garcia et al., 2005; McCown, 2002) constituting a major limitation of model-based farming systems approach (Keating and McCown, 2001). When taken into account, the simulation of crop management practices in crop models was mostly oriented and limited to the adjustment of inputs related to the production techniques used to control few production factors such as the level of nitrogen, water and/or pesticides (Bergez et al., 2010). Classical approach to represent decision-making into simulation models is to express decision behaviour through a set of decision rules. As presented in Listing 1.1, decision rules are elementary blocks of decision models that describe adaptive behaviour of the decision-making process (Bergez et al., 2010). The aggregation of elementary rules forms the structures of decision model. Rule-based models dynamically relate the state of simulated systems (Indicator in Listing 1.1) with decision-rules that trigger actions based on predefined conditions and threshold values. Rule-based models are a first attempt to take farmer management into account. This approach has mainly been applied on tactical decisions (e.g Aubry et al., 1998b; Bergez et al., 2001; Romera et al., 2004; Chatelin et al., 2005) and a few on strategic decisions (e.g. Aubry et al., 1998a; Cros et al., 2004; Navarrete and Bail, 2007; Donatelli et al., 2006b).

```
if(Indicator operator Threshold)
    {
        Action1
    }
else
    {
        Action2
    }
```

Listing 1.1: Elementary decision rule

The rule-based approach becomes awkward as rules quickly grows over an unmanageable number when attempt is to represent detail and complex decision-making as usually encountered in farming systems (Martin-Clouaire and Rellier, 2009). Activity-based approaches are another way of representing decision-making where management strategies are represented through a plan of activities that reflect the scheduling, priorities of activities in time and space. Activity-based approaches deal with the planning and coordination of activities whereby the farmer controls the biophysical processes (Martin et al., 2011). Activity-based approach make possible planning while considering more complex decision-making processes and systems. Planning is a deliberative decision-making process to purposely select and schedule activities anticipating their effects, and engaging decision-maker to execute them. The result of a planning process is a plan of activities more or less completed and structured which can be performed as sequence of activities.

Sebillotte and Soler (1988) already argued in the eighties that any decision-aid approaches should rely on a theory of the decision-maker's behaviour. They developed the concept of *"modèle général"* seen as a conceptual framework for modelling farmer's decisions. They addressed the dynamic of the decision-making process through an iterative approach of planning and adaptation phases. This initial work has been extended and used as basis of many studies interested in farmer's decisions (e.g. Duru and Hubert, 2003; Cros et al., 2004). Management (or decision) models have been therefore linked with biophysical models for more appropriate analysis of practice evolutions due to contextual changes than standalone biophysical models (e.g. Keating and McCown, 2001; Chatelin et al., 2005; Bergez et al., 2006). In recent developments, the farming system was represented as three interacting sub-systems (Figure 1.4): *"manager"*, *"operating"* and *"biophysical"* sub-systems (e.g. Martin-Clouaire and Rellier, 2000; Le Gal et al., 2009; Martin-Clouaire and Rellier, 2009). A key feature of these systems is that they link crop-soil and decision models in a single operating system allowing for a better understanding of interactions between the production systems and its management by the farmers (Bergez et al., 2010).

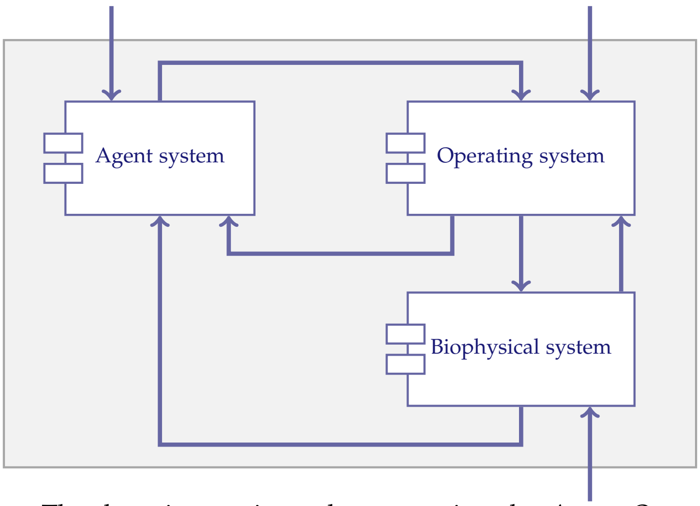


Figure 1.4: The three interacting subsystems, i.e. the *Agent*, *Operating*, and *Biophysical systems*, of any agricultural systems as described by Martin-Clouaire and Rellier (2009); Le Gal et al. (2009).

2 THESIS PROJECT

2.1 THESIS CONTEXT

2.1.1 *The joint research-development unit: UMT eau*

Several reports (e.g. Amigues et al., 2006; Cognet et al., 2007) have highlighted the need for coordinate research and development on the theme of quantitative water management in agricultural systems. To answer some of the questions raised in these reports, the "*Institut National de Recherche Agronomique*" (INRA), "*Arvalis institut du végétal*" (ARVALIS) and "*Centre Technique interprofessionnel des Oléagineux Métropolitain*" (CETIOM) established a joint research-development unit, called the *"Unité Mixte Technologique Eau (UMT eau)"* [1]. The UMT eau team works on tools and methods for quantitative water management at different scales (Figure 2.1).

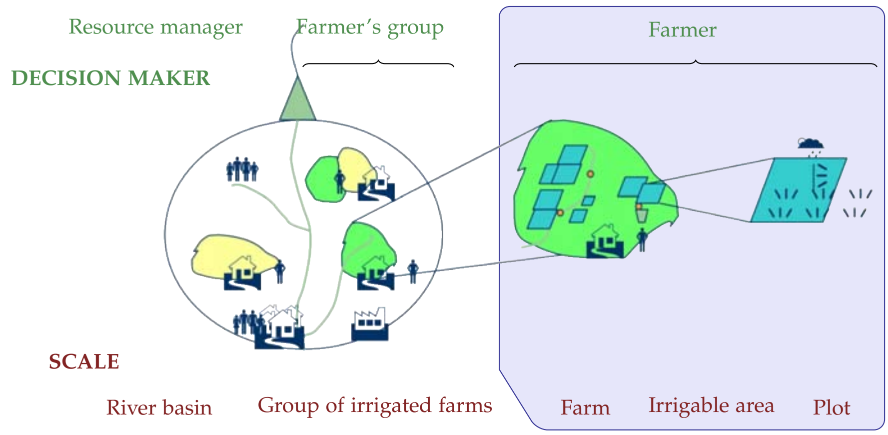


Figure 2.1: Decision makers and corresponding scales at which the joint research-development unit UMT eau is working on to address issues of quantitative irrigation water management. [Focus of this thesis: □].

Within UMT eau, questions of quantitative management are divided into three actions addressing the issues at the different scales as shown in Figure 2.1:

- *Action 1:* Analysis and modelling of cropping systems on irrigable areas at the farm scale. This action is subdivided in two items:

1. UMT eau: outils et méthodes pour la gestion quantitative de l'eau du bloc: d'irrigation au collectif d'irrigants

– Tools and methods to support farmers in their cropping-plan decisions
– Improvement of multi-crop irrigation strategies

- *Action 2:* Improvement of irrigation dose and scheduling strategies for the main irrigated crops in arable farms: maize, cereal crops, potatoes, sunflower, soya beans and sorghum.
- *Action 3:* Analysis and decision support for groups of irrigating farmers sharing a common water resource

The thesis objectives precisely fit into this collaborative research-development project by addressing the issue of cropping-plan decision-making in irrigated arable farms, i.e. action 1 item 1. The work of this thesis mostly focus on the farmer's decisions at farm scale, but also concerns farmer's decisions occurring at the irrigable area and plot scales (☐ in Figure 2.1).

2.1.2 *The RECORD-VLE platform*

The development and use of farming system models usually involve different domain knowledge and methods coming from very different scientific background (Poch et al., 2004; Liu, 2008; Quesnel et al., 2009). This translates into a real challenge to integrate all necessary components for modelling complex farming systems in a comprehensive and scientifically sound approach. In this context, the RECORD project driven by the INRA has been set up to tackle this challenge by implementing a modelling platform allowing for better sharing and reuse of modelling works.

The implementation of developed models in this thesis were carried out on the RECORD-VLE platform as a trail blazing project. The RECORD-VLE is a platform specifically designed for modelling and simulating cropping systems (Chabrier et al., 2007; Bergez et al., 2009). RECORD-VLE is based on a multi-modelling and simulation environment of complex dynamic systems: Virtual Laboratory Environment (VLE) (Ramat and Preux, 2003; Quesnel et al., 2009). VLE is a complete software environment dedicated to events driven modelling and simulation approaches. VLE provides a set of tools and libraries for coupling and simulation of heterogeneous models specified in different formalisms. It is designed on the Discrete Event System Specification (DEVS) formalism as defined by Zeigler et al. (2000). DEVS is a formal simulation framework based on discrete events.

2.2 RATIONALE

Every year farmers have to allocate their fields to different crops with their corresponding crop management option. Far from being obvious, these decisions are difficult and have considerable effects on farm productivity and profitability in the short- and long-term horizons (Aubry et al., 1998a; Dogliotti et al., 2004). As main land use decisions occurring at the farm level, these decisions are the core of the farm management strategies and have strong impacts on resource use efficiency at the farm and larger scales.

Independently to farm location in time and space, cropping-plan decisions and related crop management options always involve short- and long-term commitments of resources in order to convert them into production outputs. However, under similar production conditions, farms are not necessarily managed in the same way (e.g. Baudry and Thenail, 2004) and contrast to the common view that only economic context and technology determine management practices (van der Ploeg et al., 2009). Economic and technological contexts only constitute the space in which farmers take not uniform but individual decisions (van der Ploeg and der van Ploeg, 1994; Wilson, 1997). Because there is no general rule for answering the question of the best cropping-plan, a deeper understanding of individual cropping-plan decision-making processes at farm level is a beginning to model and design adaptative and environmental-friendly cropping systems. Crop choices, acreages and allocations are an important part of farmer's decisions that have to be modelled (Cox, 1996; Bacon et al., 2002), and a formalised approach should enable the development of operational tools. Modelling cropping-plan decisions at the farm scale will be very helpful to:

1. Understand and model relationships between the different types of decisions and the time farmers take them.
2. Support farmers in their annual and long-term joint crop and water allocation strategies.
3. Support the design of environmental public policies by simulating their effects on individual land use decisions

This thesis aims at producing knowledge on the way farmers choose their cropping-plan in irrigated arable farms by analysing and modelling their decision-making processes. We hypothesised that i) farmers design cropping-plan to fit at best their production projects accounting for farm constraints and their risk preference, and that ii) cropping-plan decision-making is a dynamic process, incorporated into a succession of other hierarchical and planned decisions at different time scale horizon.

2.3 OBJECTIVES

The thrust of this study was to investigate the farmer's cropping-plan decision-making process considering the uncertain environment (weather and price) and to propose an innovative modelling and simulation approach to explore and simulate the cropping-plan decision-making at the farm scale. This thesis concerns the scope of modelling agricultural systems with an opening to economy. The originality relies on the use of dynamic models on both the biophysical and management processes.

The specific objectives were as follows:

1. A better understanding of the processes of cropping-plan choices by farmers and the determinants of these choices, including risk aversion and the ability of farmers to manage uncertainty through crop choices.
2. A more realistic and efficient representation of the decision-making processes given scientific advances in modelling decisions.
3. The biophysical representation of crops in the light of advances in biophysical dynamic modelling.
4. An integration of multi criteria objectives in cropping-plan evaluation and selection.
5. An implementation of a prototype in the environment of the VLE simulation platform.

2.4 OUTLINE

In this thesis, I purposely did not address all aspects of the cropping-plan decision-making process, some well-known decision factors have already been extensively treated in the literature (economy, work, irrigation water) (see Chapter 3). I rather focused on presenting new and complementary insights on this topic: 1) a methodology to study and model complex decision-making processes such as cropping-plan decision-making, 2) an analysis describing spatio-temporal interactions of the cropping-plan decision-making process, 3) a comparison of measurement methods and an estimate of farmers risk preferences, and 4) a new modelling approach taking into account spatio-temporal interactions of the farmer's decision-making process. To address the issue of cropping-plan decisions the general approach of the thesis has its roots in case study research that we extend with modern and integrative modelling methods. Case study research is an approach which focuses on understanding the dynamics present within single settings (Eisenhardt, 1989). Doing so, our modelling approach mostly focused on representing knowledge structures and contents rather than focusing on representing statistical relationships between factors and outputs. In this thesis, the modelling cover all phases of modelling and simulation as described by Schlesinger (1979) (in Bellocchi et al., 2011) except model validations that we did not conduct yet (Figure 2.2).

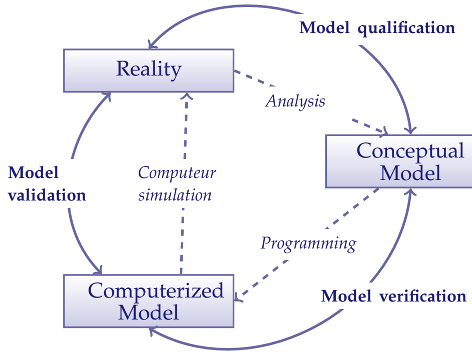


Figure 2.2: Phase of modelling and simulation (Adapted from Schlesinger, 1979 in Bellocchi et al., 2011)

Since the chapters of this thesis are based on published/submitted journal papers or proceedings, some repetitions among them can be apparent, but it ensures that chapters can be read independently. The bibliography of all chapters is gathered at the end of the document.

Chapter 3: This Chapter is a review of more than 120 references where the concepts of cropping-plan and crop rotation decision have been incorporated into models. Our aim was to review how these two concepts have been formalised and used in agronomic, economic and land use studies. This Chapter shows that cropping-plan selection modelling have already been treated with a great variety of approaches based on different objectives and handled at very different scales. The cropping-plan models were mainly based on two seminal concepts, the cropping-plan **or** the crop rotation selections. We argued that cropping-plan and crop rotation decisions are part of the same decision-making process because they are the core of the cropping systems design at the farm scale. Further, these decisions are not single decision, they are on the contrary dynamic processes incorporated into a succession of other planned and adaptive decisions made at annual and long-term horizons. To support farmers in their decisions, new cropping-plan decision models require new modelling paradigm based on simulation of the decision-making processes rather than on single normative approaches.

Chapter 4: The scope of this chapter is to present ways in which farmers' representations were elicited, formalised and used as a basis for designing decision models based on theories of decision-maker behaviour. We propose a step approach that combines decision-making analysis with a modelling approach inspired by cognitive sciences and software-development methods in order to study and formalise the complexity of decision-making processes. Through this methodological proposition, we argue that the complexity of decision-making in farming system should be investigated in light of procedural rationality, particularly when the objective is to support farmers as decision-makers. We conducted a cognitive task analysis based on semi-structured farmer' interviews (n=30) to analyse decision-making in relation to farmer' strategies and constraints that affect cropping-plan choices. We identified objects/concepts that farmers use to decide cropping-plans and gathered them into an ontology. We constructed individual decision models using abductive reasoning to capture the decision-making dynamic. All individual decision models were used as hypotheses to build a more generic cropping-plan decision model through an inductive and iterative integration. We considered that farmers' decisions involve anticipation, uncertainty and risk.

Chapter 5: This chapter describes the analysis we conducted on farmer cropping-plan decision making. We focused on the spatio-temporal dimensions of the decision-making. We surveyed 30 farmers to study the dynamics of the cropping-plan decision-making of farmers in irrigated arable farms. Using methods of the cognitive sciences, we analysed the ways farmers managed uncertainty through planning and reactive decisions. We showed in this study that representing the cropping-plan selection as a single problem of resource allocation or as a problem crop rotation design is not sufficient to account for the decision-making processes of farmers. Indeed, we showed that the cropping-plan decision-making does not occur once a year or once a rotation as usually represented into models but is a continuous process mixing design and adaptive activities. We characterised the concepts that farmers use to plan their cropping-plan in times. We also highlighted the importance of the spatial organisation of the farmland into crop management block as major determinant of the cropping-plan strategies. We argued that a deep understanding of these processes at the farm level is required before it is possible to model and design flexible and environmental-friendly cropping systems that fit with farmer reality.

Chapter 6: In this chapter, we empirically assessed consistency of risk preference measures across different elicitation methods. In order to elicit risk preferences of French farmers, we first used an experimental approach based on two different lottery tasks (the Holt and Laury (2002) procedure and a variation of the Eckel and Grossman (2008) procedure). Second, we developed a farm-level land allocation model under climatic risk from which farmer's risk preferences were assessed. The comparison of the two different approaches revealed that the stability of risk preferences varies crucially according to the type of lottery task implemented in the experimental approach.

Chapter 7: This chapter describes the system-based modelling framework Crop Rotation and Allocation Simulator using Heuristics (CRASH) developed with the objective to improve farmers' managerial support in their cropping-plan decisions. CRASH integrates a set of tools to plan, simulate and analyse the choice of cropping-plan and crop managements. Our approach to support farmers particularly focused on explicit representations of the decision-making process in the temporal and spacial dimensions. It was based on a well structured representation of domain knowledge through generic concepts that were close to ones used by decision-makers. Modelling a decision-making process to support such complex farmers' decisions required to consider planning of crop allocation over a finite horizon, and to explicitly consider the sequence of problem-solving imposed by the changing context (e.g. weather, price). Results shown in this chapter concerned components of the CRASH framework that have already been implemented. These results just sketch up capabilities of CRASH to simulate realistic crop production process as well as the ability to simulate planning of the cropping-plan decision-making process of farmers.

3 MODELS TO SUPPORT CROPPING-PLAN AND CROP ROTATION DECISIONS: A REVIEW

Why this chapter?

This Chapter is a review on the ways cropping-plan and crop rotation were formalised and incorporated into agronomic, economic and land-use models. This chapter identifed lacks in literature on this topic and justified the need to renew approach and methods to deal with cropping-plan and crop rotation modelling.

This chapter was published as:

Dury, J., Schallers, N., Garcia, F., Reynaud, A., Bergez, JE., 2011. Models to support cropping plan and crop rotation decisions: a review. Agronomy for Sustainable Development. DOI:10.1007/s13593-011-0037-x

Agriculture, being the main type of land-use in Europe, accounting for 45% of European land cover (Rounsevell et al., 2003) being increasingly questioned on the environmental side effects of its activities. Water use, soil erosion, biodiversity and landscape design are some of the issues that agriculture now has to deal with; rural employment and energy production also have to be accounted for without compromising the primary objective of agriculture, which is food production to these concerns, the expected climate change (Pachauri and Reisinger, 2007), market variation and regulation changes for more sustainable resource management compel farmers to continuously adapt their practices. These new practices should address the challenges related to the environment, resource use efficiency and the economic sustainability of farms simultaneously (Meynard et al., 2001). As chemical inputs are increasingly forbidden (European Parliament Council, 2006), the use of more agro-ecological concepts is required not only in farm production processes, but also during the design phase of innovative cropping systems (Griffon, 1999; Dalgaard et al., 2003). The renewed popularity of crop rotation as a key concept for designing cropping systems is an illustration of such changes (e.g. Vereijken, 1997; Dogliotti et al., 2004; Sadok et al., 2009). The adoption of innovative cropping systems is a challenging goal for the agricultural sector and lead researchers to requestion the methods and concepts on which the developments of these innovative systems are based. *"It would be naive to suppose that the unsustainability problems humankind is faced with could be solved with current tools and methods (models!) that were applied - or seemed to work - in the past"* (Rotmans, 2009).

Given the complexity of farming systems and the large number of possible adaptation options, model-based exploration tools are commonly used to supplement traditional empirical approaches (e.g. Vereijken, 1997) for designing and evaluating innovative agricultural production systems. Despite some difficulties in transferring results to farmers and extension advisers (Keating and McCown, 2001; Bergez et al., 2010), the usefulness of such model-based approaches has now been proven (Rossing et al., 1997).

The choice of crops and their allocation to plots is at the core of the farming system management. These decisions concentrate all the complexity involved in cropping system design and selection at the farm level because of their many involvements at different stages of the crop production processes (Nevo et al., 1994; Aubry et al., 1998a; Navarrete and Bail, 2007). Cropping-plan decisions are indeed crucial steps in crop production processes and have considerable effects on the annual and long-term productivity and profitability of farms. A suitable cropping-plan must satisfy multiple and conflicting objectives, and take into account a large number of factors and their interactions (Nevo and Amir, 1991). Many models dealing with cropping system design have been based on cropping-plan selections represented through the choice of cropping-plan or that of crop rotation. These two concepts, i.e. Cropping-plan and crop rotation, describe the cropping-plan decision problem in space and time respectively. Not all models that we reviewed were developed to support and/or imitate stakeholder decision. However, all these models allow the selection of one or several cropping-plans within a given context and objectives which some how represent a decision (not necessarily that of the farmers). To avoid confusion, we use *"cropping-plan selection models"* as generic term to designate the models we reviewed. We use *"cropping-plan decision model"* when the authors explicitly refer to decision-maker behaviour (e.g in the field of agricultural economics).

The modelling of cropping-plan selection has been treated using a variety of approaches based on different objectives and handled at very different scales. More than 120 scientific references on this topic have been found. This paper reviews how cropping-plan and crop rotation are formalised and incorporated into agronomic, economic and land-use models. We do not review how these models were used into research project although it is another crucial issue in model-based decision-aid. In the first section, we focus on the concept of cropping-plan decision-making and clarify terminology. In the second section, we survey cropping-plan selection models with a focus on arable farm and categorise the how and why of these models. In the third section, we discuss the issue of scale and the dynamic aspects of existing approaches and highlight some of their limitations.

3.2 Terminology, definitions and concepts

Before reviewing the modelling approaches dealing with cropping-plan selections or any similar topics, we wish to clarify the terminology and definitions used in cropping-plan and other related concepts. Clarification is not only useful for specifying the meanings of words, but also important for realising and understanding the consequences of the use of particular concepts in cropping-plan models.

3.2.1 *Cropping-plan*

A cropping-plan refers to the acreages occupied by all the different crops every year (Wijnands, 1999) and their spatial distribution within a farming land (Aubry et al., 1998b). This definition includes two concepts widely used in papers on farm planning and land-use/cover

(Figure 3.1). The first, crop acreage, refers to the area on a farming land normally devoted to one or a group of crops every year (e.g. x ha of wheat, y ha of winter barley); the second, crop allocation, is the assignment of a particular crop to each plot in a given piece of land. Allocation can be spatially explicit (e.g. Rounsevell et al., 2003; Joannon et al., 2006) or characterised by land area attributes such as soil type (e.g. Annetts and Audsley, 2002; Bachinger and Zander, 2007). A cropping-plan can be expressed at the farm level where most of the decisions are made (e.g. Stone et al., 1992), or at a higher level in order to address collective issues (e.g. resource uses, landscape, economy) (e.g. Rounsevell et al., 2003).

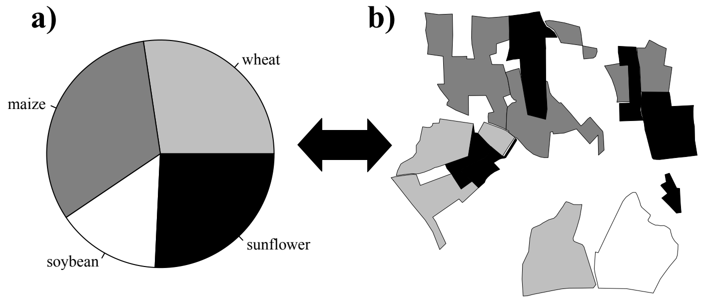


Figure 3.1: Crop acreage and crop allocation are the two interlocking elements of a cropping-plan. a) Crop acreage can be simplified as the crop area distribution, represented here by means of a pie chart, while b) crop allocation calls for the explicit representation of land units, in a map for instance, or their characterisation in terms of various land attributes.

3.2.2 *Crop rotation*

Crop rotation is defined as the practice of growing a sequence of plant species on the same land (Bullock, 1992). Crop rotation is characterised by a cycle period, while crop sequence is limited to the order of appearance of crops on the same piece of land during a fixed period (Leteinturier et al., 2006). Crop rotation is along used concept in models to represent the temporal dimension of cropping-plan decisions (Heady, 1948). Because the succession of crops in a given area has effects on production and consequently on cropping-plan decisions, the traditional approach developed by agronomists was to derive cropping-plans from the crop proportions in crop rotation. Some authors (e.g. Maxime et al., 1995; Dogliotti et al., 2003) have argued that the reproducibility of a cropping system over time is only ensured when crop choices are derived from crop rotation. Cropping-plan decisions consequently require one to look back and forth in time (Figure 3.1). Crop rotation as a particular crop sequence is therefore a natural starting point in designing cropping systems that are stable over time (Vereijken, 1997). Crop rotation is considered as being essential for integrated farming (Stoate et al., 2001) and is in contradiction with mono-cropping as a sustainable solution for farms (Leteinturier et al., 2006). The concept of crop rotation is an interesting means of obtaining a succession of crops year after year on a specific piece of land. It offers the potential of attenuating the environmental impacts of agriculture while maintaining production and achievements over the years (Vandermeer et al., 1998). Crop rotations are also used for breaking weed and disease cycles, and for reducing dependence on external inputs (Bullock, 1992). However, the concept of crop rotation provides very limited insight into the organisation of crops among different and heterogeneous pieces of land.

3.2.3 *Cropping-plan decisions*

cropping-plan decisions are the main land-use decisions in farming systems and involve, at the very least, the choice of crops to be grown, their acreage and their allocation within a particular farmland (Nevo et al., 1994). These decisions mostly occur at the farm level and are consequently part of the global technical management of farm production (Aubry et al., 1998a). A cropping-plan decision is the result of a decision-making process where farmers weigh up the various objectives and constraints fitted into different spatial and temporal dynamics. Because of the fact that production decisions are almost always made under uncertainty (weather, market) and that there may be several sowing seasons per year, cropping-plan decision-making does not merely involve a single decision but is a continuous process occurring all throughout the year (Aubry et al., 1998b; Nuthall, 2010). The decisions to choose certain crops and allocate them to certain areas within the farmland interact with one another at different levels of farm management, usually presented as two dimensions: a strategic dimension related to long-term production organisation (equipment funding, crop rotation, etc.), and a more tactical dimension linked to the possibilities of (intra-)annual adjustments in response to the changing and uncertain environment and to the organisation of work (Figure 3.2).

3.3 WHY AND HOW CROPPING-PLAN SELECTION HAVE BEEN MODELLED

3.3.1 *Model-based exploration*

Given the large spectrum of consequences of cropping-plan decisions at the farm and higher levels, the assessment and/or designing of cropping-plans using models is driven by many different motivations. Cropping-plan selection models are mostly used to support farmers, policy maker and other stakeholders in defining strategies

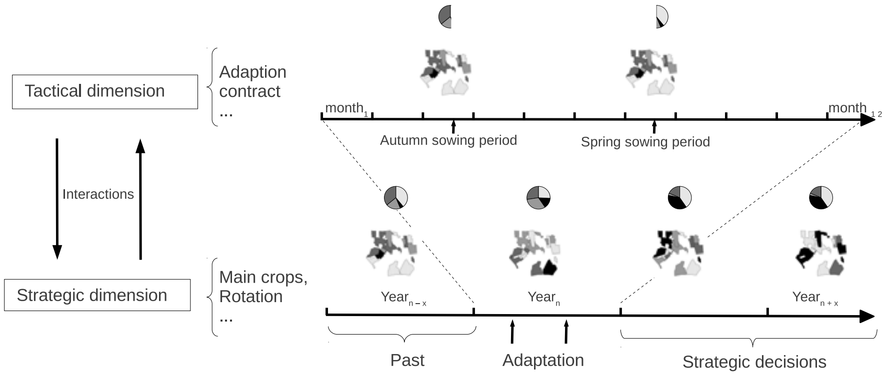


Figure 3.2: cropping-plan decision-making is a combination of planned activities and dynamic decision-making for achieving a control over a dynamic system in order to produce a desired output, rather than as an unique resolution of choice dilemma. Cropping-plan decisions are incorporated into strategic and tactical dynamic decision-making processes as interactions.

to allocate scarce and competing resources more efficiently, assess landscape changes, and also design policy options and anticipate their effects at different time scale horizons. Cropping-plan selection models are used in research project aiming at different outcomes (Matthews et al., 2011) and are differently used within these projects. However, these models share comparable outputs, i.e. the selection of one or more cropping-plans and/or rotations. We did not reviewed cropping-plan models in terms of outcomes of projects in which they were involved but rather how these models allow the selection or the design of cropping-plan. We have summarised the various approaches as two broad issues: i) cropping-plan selection for better resource allocation and more efficient resource use, and ii) cropping-plan decisions to assess large-scale changes (landscape, policy). Although this distinction is useful for presenting the existing literature, we recognize that there are in fact strong relationships between these two issues.

3.3.1.1 *Problem formalisation*

cropping-plan selection models are mostly developed by agronomists to carry out exploration studies for better resource allocation and uses. The approaches aim at designing and exploring alternative land-use systems at various scales and may support the identification of appropriate crop combinations and resource allocation options. The approaches combine the knowledge of the biophysical processes underlying agricultural production, stakeholder objectives and farm constraints. The main goal is to support the strategic thinking of farmers and other stakeholders during the design phase of farming systems. Modelling cropping-plan requires a formal representation of the cropping-plan selection. The boundaries of the farm system and the level of detail in the representation of the design process greatly depend upon the objectives of the study. The formalisation of cropping-plan selection are mostly represented in models as a static and deterministic problem of resource allocation. The cropping-plan selection problem is often addressed as the search for the best land-crop combination under some known constraints. Depending on the objective of the study, the search for solutions is sometimes carried out at the rotational level and other times at the annual level, but in most cropping-plan selection models, the decision process is represented as a single decision occurring (i) once a rotation or (ii) once a year:

(i) In a number of studies, cropping-plan selection are directly derived from crop rotation selection used as a seminal concept in the design of cropping systems. Implementation of crop rotations into cropping-plan models is often based on expert knowledge using different crop sequence representations (Table 3.1). Fixed recommended crop rotations (Stockle et al., 2003) or fixed computed crop rotations (Dogliotti et al., 2003; Bachinger and Zander, 2007) take into account crop succession requirements. But as a consequence, there is little leeway for contextual adaptation and for choosing production plans for the following years (Kein Haneveld and Stegeman, 2005). To overcome the limitations of the static rotational approach, several authors have introduced yearly flexibility by focusing on complex and flexible crop sequences/rotations (Tsai et al., 1987; Kein Haneveld and Stegeman, 2005; Detlefsen and Jensen, 2007; Castellazzi et al., 2008). Castellazzi et al. (2008) describe three types of flexible crop rotations: 1) cyclical with fixed rotation length, 2) cyclical with variable rotation length and 3) less structured cyclical with highly variable rotation length. Different mathematical formalisations have been used to represent such complex and flexible crop rotations in models, for example network flow problems (Tsai et al., 1987; Kein Haneveld and Stegeman, 2005; Detlefsen and Jensen, 2007) and Markov chains (Castellazzi et al., 2008). An interesting feature of the approaches introducing flexible crop rotations into cropping-plan selection models is the given opportunity of representing annual adjustments in the cropping-plan in relation to the changing context. However, clear and explicit methods of achieving this are still lacking.

(ii) In studies interested in cropping-plan selection made on an annual basis, the crop succession requirements are either ignored (e.g. Abdulkadri and Ajibefun, 1998; Leroy and Jacquin, 1991) or incorporated into models as predefined factors reducing crop yields (e.g. El-Nazer and McCarl, 1986; Annetts and Audsley, 2002; Garcia et al., 2005). Crop yield reduction factors are either defined by experts

(Garcia et al., 2005) or based on a regression analysis of historical records (El-Nazer and McCarl, 1986). In such annual approaches, the cropping-plan selection is seen as a static and single decision of resource allocation. None of the approaches take into account infra-annual decisions and/or sequences of decisions in the problem formalisation. Considerations of the uncertainty of information (price, weather) and decision-makers' behaviours towards risk are indeed poorly dealt with by agronomists. These aspects are studied in much greater detail in the field of agricultural economics (see: Chavas and Holt, 1990; Itoh et al., 2003).

3.3.1.2 *Mono- vs multi-attribute objectives selection*

cropping-plans are very often selected based on a single monetary criterion, i.e. profit maximisation (e.g. Heady, 1948; Leroy and Jacquin, 1991; Audsley, 1993; Itoh et al., 2003). Single-criterion models mainly differ from multi-criteria ones in the way in which the cropping-plan decision problem is formalised (annual or rotational) and in the set of constraints that are considered for restricting profit maximisation. Although it is commonly acknowledged that cropping systems must generate incomes for farmers, some authors point out the limitations of an approach that focuses exclusively on return maximisation. They argue that the decisions to do with cropping-plans involve the meeting of multiple and competing objectives that have to be explicitly accounted for (Stone et al., 1992; Piech and Rehman, 1993; Foltz et al., 1995; Bartolini et al., 2007). Besides, growing environmental concerns have led researchers to explicitly target objectives other than profitability (Rehman and Romero, 1993; Foltz et al., 1995; Dogliotti et al., 2005; DeVoil et al., 2006). Objectives that influence the selection of a cropping-plan have to reflect the different goals, perspectives and values of the decision-makers. We summarize the objectives taken into account in multi-attribute cropping-plan decision models into three groups (Table 3.2).

Apart from the objectives that determine the selection of a cropping-plan, models also differ in terms of the type of constraints that restrict the selection and how these constraints are taken into account. Limiting resources that are easily quantifiable are the constraints that receive the greatest consideration in cropping-plan decision models. As a typical example, irrigation water resource management is traditionally based on cropping pattern selection at the field (e.g. Tsai et al., 1987), irrigation block (e.g. Leroy and Jacquin, 1991), farm (e.g. Huang et al., 1974) or regional level (e.g. Gupta et al., 2000; Kipkorir et al., 2002; Ortega Álvarez et al., 2004; Tsakiris and Spiliotis, 2006; Bartolini et al., 2007). These studies focus particularly on maximising revenue from irrigation activities while respecting water availability over the seasons. Other resource availabilities such as labour (e.g.

Table 3.1: Crop succession representations in cropping-plan models based on the rotational approach

Crop succession representations	Crop succession requirements	Authors
Predefined by expert		Stockle et al., 2003; Sadok et al., 2009
Rules and agronomic filter	- Rules controlled by model's users using parameters that describe timing, sequence, frequency and farm-specific constraints.	Dogliotti et al., 2003
	- Predefined forbidden crop sequences.	Kein Haneveld and Stegeman, 2005
	- Timing and preceding crop supply/demand constraints, exclusion rules.	Bachinger and Zander, 2007
	- Predefined allowed crop sequences (maximum 2 years).	Detlefsen and Jensen, 2007
Indicators	- Effects of previous crop on the subsequent crop (soil structures, diseases, pests, weeds and nitrogen), recurring crops and their respective recommended minimal return time, crop diversity.	Leteinturier et al., 2006
Probability of crop occurrence	- Probabilities based on observed crop rotations.	Castellazzi et al., 2008
Reducing factors	- Regression analysis to estimate yield influence of preceding crop.	El-Nazer and McCarl, 1986
	- Timing and sequencing constraints, disease classes associated with yield reduction penalties	Annetts and Audsley, 2002
	- Predefined yield reducing factors	Garcia et al., 2005

Abdulkadri and Ajibefun, 1998; Itoh et al., 2003), machinery and operation timing (e.g. Annetts and Audsley, 2002; Dogliotti et al., 2005) are also incorporated into models in order to constrain cropping-plan decisions.

3.3.1.3 *Problem resolution*

Optimisation: A number of techniques are used to plan crop production while accounting for known operational constraints. Mathematical programming is widely used in this area (Glen, 1987). Linear programming (LP) is by far the most common optimisation procedure since Heady (1954) that has been used to solve the cropping-plan decision problem (e.g. McCarl et al., 1977; Leroy and Jacquin, 1991; Sarker et al., 1997). The LP model has the advantage of simplicity and of capturing the conflict between different choices (Hazell and Norton, 1986). Some of the problems associated with the use of this technique include the difficulties in formulating the model (objectives and constraints) and interpreting its results (Nevo et al., 1994). The original LP framework has gradually been extended in several respects to reduce its limitations (Kennedy, 1986). Simple optimisation techniques have been enriched in many ways by exploring alternative sub-optimal solutions (e.g Abdulkadri and Ajibefun, 1998), by integrating fuzzy logic techniques to take into account flexibility in decisions (e.g Itoh et al., 2003) and qualitative factors (e.g Nevo et al., 1994), and stochastic variables to deal with uncertain factors (e.g Sethi et al., 2006).

Goal programming or multi-objective linear programming is another extension of LP models and is employed to solve cropping-plan decisions formalised as a multi-objective decision-making problem (e.g Piech and Rehman, 1993; Sarker and Quaddus, 2002; Annetts and Audsley, 2002; Tsakiris and Spiliotis, 2006; Bartolini et al., 2007). Depending in the study, different objectives are explicitly formulated in multi-attribute function within cropping plan models (Table 3.2). For instance, Annetts and Audsley (2002) developed a multi-criteria optimisation tool, the "Silsoe Whole Farm Model, for environmental farm planning based on the cropping-plan model of Audsley (1993). The multi-criteria optimisation tool allows us to explore whether a reduction in environmental impact is possible with a small decrease in profitability. Various multi-criteria techniques are used in cropping-plan decision models to aggregate various objectives; Hayashi (2000) has written a detailed review for their application to agricultural resource management. A major difficulties of the multi-criteria approach is to elicit objectives and to attribute them a weights (Sumpsi et al., 1996).

The LP framework is not only employed for annual solutions but also for solving the cropping-plan problem when formalised as a crop

Table 3.2: Objectives explicitly formulated in multi-attribute cropping-plan models [↑: maximisation, ↓:minimisation].

Categories	Objectives	Indicators	Authors
Socio-economic	Profit	↑: gross margin, annual profit, income, net benefit	Piech and Rehman, 1993; Foltz et al., 1995; Mainuddin et al., 1997; Gupta et al., 2000; Annetts and Audsley, 2002; Tsakiris and Spiliotis, 2006; Dogliotti et al., 2005; Bartolini et al., 2007; Sarker and Ray, 2009; Louhichi et al., 2010
	Equipment	↓: investment	Gupta et al., 2000
	Labour	↓: total labour, casual labour, cost	Piech and Rehman, 1993; Gupta et al., 2000; Dogliotti et al., 2005; Bartolini et al., 2007; Sarker and Ray, 2009
Agronomy	Irrigation	↑: irrigated area	Mainuddin et al., 1997; Gupta et al., 2000; Tsakiris and Spiliotis, 2006
Environment	Energy	↓: calories	Gupta et al., 2000
	Nutrient	↓: nitrogen and phosphorus uses, losses	Foltz et al., 1995; Annetts and Audsley, 2002; Dogliotti et al., 2005
	Pesticide	↓: herbicide use, losses, pesticide exposures	Foltz et al., 1995; Annetts and Audsley, 2002; Dogliotti et al., 2005
	Soil	↓: erosion, ↑: organic matter rate of change	Dogliotti et al., 2005

rotation problem . Kein Haneveld and Stegeman (2005) use a standard LP model applied within a max-flow network representing the crop sequence. Pre-calculated crop sequences that are not admissible from an expert point of view are used as constraints. In a slightly different way, Detlefsen and Jensen (2007) have taken advantage of the special structure of the network representation of the rotation to use network flow modelling tools. Both these methods allow the proposal of flexible crop rotations while considering crop succession requirements over several years. Dogliotti et al. (2005) solve the crop rotation problem using mixed integer linear programming (MILP) as an interactive multiple-goal linear program. The original feature of this lies in the fact that both the complex temporal interactions of rotation and the spatial heterogeneity of soil types of the farmland are considered in the resolution of the cropping-plan decision problem.

More recently, evolutionary optimisation algorithms have been used for solving multi-objective cropping-plan decisions at farm level (e.g. Garcia et al., 2005), regional scale (DeVoil et al., 2006), and at national level (e.g. Sarker and Ray, 2009). The main advantage of using genetic algorithms is to produce a set of compromise solutions along the Pareto's frontier (DeVoil et al., 2006). Such algorithms are well suited for expressing solutions in a multi-objective problem context. Although the algorithms are different from LP techniques, the formalisation of the selection problem is very similar , i.e. the cropping-plan is seen a static planning problem. Other mathematical programming tools have also been used to solve the cropping-plan decision problem. Howitt (1995) and Louhichi et al. (2010), for instance, proposes a non-linear optimisation approach based on positive mathematical programming (PMP). PMP employs both programming constraints and "positive" inferences from base-year crop allocations.

Expert systems: Some authors (Stone et al., 1992; Nevo et al., 1994) have argued that using quantitative and deterministic methods alone is not enough to achieve satisfactory cropping-plans due to the nature of the information that is required, as such information is often incomplete, qualitative and uncertain. Nevo et al. (1994) complement the traditional linear optimisation approach with an expert system technology that provides a solution to these limitations. The expert system approach has the advantage of providing some consistent ways of pruning the search space and reducing the number of allocation alternatives. The expert system also includes a set of adjustment rules allowing the quantification of the effect of actual production conditions on the profit from potential crop production. These rules are based on expert knowledge and are “quantified” using fuzzy logic techniques for logical conclusion or Bayesian theory to deal with uncertain processes. Stone et al. (1992) and Buick et al. (1992) tackle the cropping-plan decision as a planning problem, such as that developed in the field of artificial intelligence, without using traditional optimisation techniques. One limitation of model-based expert systems is that they tend to reproduce the current situation and strong restrictions arise whenever one aims to propose alternatives and innovative cropping-plans.

Evaluation procedure: Another approach to the handling of the cropping-plan selection problem consists in evaluating alternative cropping-plans based on indicators, rather than merely selecting one solution. Multi-criteria decision-aid methods make it possible to take into account the conflicting objectives underlying the economic, social and environmental dimensions of sustainability (Sadok et al., 2009). Bachinger and Zander (2007) propose a static approach to generate, evaluate and select crop rotations adapted for organic farming. Crop rotations are selected according to exclusion criteria (i.e. thresholds for N balance, weed and pest infestation risks and chronological restrictions) and ranked according to economic performance. Foltz et al. (1995) use dynamic crop simulation models to obtain values for calculating indicators, then use multi-attribute ranking to select suitable cropping plans. Using an original approach, Sadok et al. (2009) developed a qualitative multi-attribute decision model for an ex-ante assessment of the sustainability of cropping systems (MASC). The MASC model integrates quantitative indicators and informal knowledge at the same level within a qualitative DEXi decision tree (Bohanec and Rajkovic, 1990).

3.3.2 *Policy and land-use assessments*

cropping-plan choices can also be considered as part of the agricultural sector and/or regional planning, where the effect of policies on patterns of land-use is studied. In this approach, the objective is not to answer "What is the best cropping-plan? ", but rather, to explore how a particular trend could evolve given the understanding of crop allocation decision-making. Trend analyses belong to the field of agricultural economics and more recently to the field of landscape ecology. The aim of this section is to outline the major trends involving cropping-plan decisions in these two disciplines. These disciplines are usually interested in studying cropping-plan decisions on a large scale. Our review of the existing literature will be restricted to papers that deal directly with the cropping-plan decision problem.

3.3.2.1 *Policy assessment*

Farmers' reaction to the changing context: On a large scale, the collective dynamics of farmers are generated by all individual farmer decisions mediating the impact of policy and market changes on land-uses (Winder et al., 1998). This issue has been particularly treated in agricultural economics on a large scale. The primary interest of economists has been the estimation of single-crop supply response in order to develop elasticity estimates, presumably for use in policy analysis and forecasting (Holt, 1999). The econometric approach of the single-crop acreage problem has been widely used in the past based on Nerlove' model (Askari and Cummings, 1977), which assumes that farmers' reactions may be represented in terms of crop acreage adjustments based on price expectations. Farmers are usually assumed to be profit maximisers and are therefore likely, at best, to fit their practices to the economical context. The consideration of crop production jointness has accelerated the development of multi-crop models (e.g. Just et al., 1983; Chambers and Just, 1989; Bel Haj Hassine and Simioni, 2000). The interdependences of crops are partly explained by fixed allocatable inputs such as land or water (Shumway et al., 1984). The basic acreage response framework has been extended to include risk effects due to price and production uncertainties (e.g. Chavas and Holt, 1990; Baltas and Korka, 2002; Itoh et al., 2003; Olarinde, 2008), among other things. The original feature of this lies in the explicit incorporation of farmers' behaviours towards uncertainty and risk as a factor influencing land allocation decision-making. The Econometric approaches usually do not account for the large behavioural heterogeneities across individuals.

The assumption of profit maximising behaviour is not confirmed in all studies. For instance, Vavra and Colman (2003) conclude for UK case studies that observable economic variables are unsuitable for explaining crop acreage changes at the farm level. They suggest that farmers do not necessarily share the same objectives while managing their farms. Furthermore, difference in cropping-plan responses between farmers may be explained by the fact that every farm is captured at a different stage in its investment, marketing and rotation cycle. Other approaches assume that farmers do not maximise short-run profits, but rather, consider future incomes when deciding on crop allocations. Orazem and Miranowski (1994) and Thomas (2003) have incorporated agronomic considerations into their economic models. In both models, the approach consists in "an economic interpretation of the crop rotation"(Thomas, 2003) and considers multi-annual economic constraints.

3.3.2.2 *Landscape ecology*

In the past 30 years, the concept of landscape has emerged in ecology: the central paradigm in landscape ecology is that the spatial structures of a landscape have an effect on the movements of individuals and the flow of matter (Burel and Baudry, 2003). Cropping-plan decisions, even if made at the farm level, also impact the landscape level by contributing to crop-mosaic patterning (Thenail et al., 2009). Thenail and Baudry (2004) showed that farm characteristics, especially the structure of the farm territory, have a major influence on land-use allocation on farms, which in turn influences landscape structures and the associated natural processes (Joannon et al., 2006, 2008). As a consequence, some studies aim at improving the understanding of the causes and effects of cropping-plan changes to support sustainable landscape development (Mottet et al., 2006). We give here a brief overview of the different methods used for assessing landscape changes as affected by cropping-plan decisions.

Landscape trend analysis: Most studies in landscape ecology are aimed at describing the evolution of land-use in landscapes through statistical trends or spatial patterns without accounting for the farm level. Benoit et al. (2001) and Le Ber et al. (2006) developed data mining techniques using a land cover database, namely Ter-Uti to describe the spatio-temporal changes in crop sequences. In a similar vein, Lazrak et al. (2010) developed a landscape description tool using hidden Markov models capable of identifying statistical time-space regularities of land-use successions at the regional level. Using a similar data-mining approach, Mignolet et al. (2007) statistically mapped homogeneous agricultural regions at the regional level. Castellazzi et al. (2007) devised statistical measures and tests for the spatial and temporal patterns of crops in order to assess the non-randomness of spatial patterns and the temporal or spatio-temporal heterogeneity of agricultural landscapes at the regional or national level. All these statistical methods require access to a large amount of land-use data over time. Even if interactions between farming systems and landscapes are considered in most studies, scientific literature shows that farm management and farmers' cropping-plan choices are not widely explored as a factor of the spatial and temporal dynamics of landscapes (Thenail and Baudry, 2004; Thenail et al., 2009). Only a few authors (e.g. Pocewicz et al., 2008) have combined the statistical trends of landscape changes and the local practices of landowners identified through surveys.

Such statistical approaches are also used for anticipating the cropping decisions made by farmers that affect resource uses. An early decision about crop acreage for the coming year is a typical piece of information that can help to manage water at the catchment or regional level (Leenhardt et al., 2005). The prediction of crop sequences for the coming years are based on the occurrence probability of the previous crop succession (Leenhardt et al., 2005), determined using the data mining tools developed by Benoit et al. (2001) and Le Ber et al. (2006). It is therefore assumed that the observed land pattern, both in terms of space and time, may be representative of farmers decisions' and is viewed here as a black box.

From farm to landscape: Several authors (e.g. Winder et al., 1998; Rounsevell et al., 2003; Le Ber et al., 2006; Joannon et al., 2006; Louhichi et al., 2010) argue that decisions made at the farm level must be the focal point for effectively addressing issues of a larger scale. Analyses of farmers' practices are carried out to identify the local drivers of land-use changes and their underlying causes (Lambin et al., 2003; Mottet et al., 2006). Such investigations are mostly local case studies and succeed in accounting for the diversity of farmers' management choices; however, they have the disadvantage of not being generic. In the approach advocated by Rounsevell et al. (2003), land-use issues are converted into farming system questions in which farmers' decisions and their management strategies are central to the simulation of crop allocation across landscapes. The model initially developed for farm level analysis (Audsley, 1993) is incorporated into a regional modelling framework. Aggregation at the regional level is carried out based on gridded soil and climate data. Similar aggregation at European level was carried out in the SEAMLESS project where geo-referenced farm type were distributed along landscapes (Louhichi et al., 2010). In such farm-oriented approaches, the models are similar to those presented in the previous section, and their original feature lies in the way in which they allow processes to be extended beyond the farm level to a much larger scale.

3.4 DISCUSSION

3.4.1 *Cropping-plan decision-making as a dynamic process*

Significant efforts have been made to integrate the many constraints that limit or influence the achievement of a plan in a specific situation. These constraints are mostly described within a static framework where economic return, and sometimes other objectives, are optimised. The few authors who combined optimisation procedures with dynamic models (Tsai et al., 1987; Foltz et al., 1995; Louhichi et al., 2010) do so by using dynamic models for the assessment of cropping-plans rather than the representation of the dynamics of cropping-plan decision-making processes. In such approaches, the dynamics of the mechanisms involved in the decision-making processes occurring at the farm level are not accounted for (Aubry et al., 1998b), even if they are an important part of the farmers' decision-making that must be modelled (Cox, 1996; Bacon et al., 2002; Garcia et al., 2005). cropping-plan decisions are not treated by agronomists as a continuous process incorporated into a succession of other planned and adaptive decisions made at annual and long-term horizons. Only few authors explicitly formalised into details the processes of decision-making by farmers (e.g. Aubry et al., 1998b; Navarrete and Bail, 2007). In approaches developed in agricultural economics, more interest is paid to the description of the dynamics of the decisions but farmers' decision-making processes are not made explicit (e.g. Thomas, 2003).

One important challenge in modelling farming system production does not only rely on making of more accurate biophysical models but also on being more relevant to their application in real situations of decision-making (Keating and McCown, 2001; Carberry et al., 2002). Part of the technical solution could be the use of coupled and distinct management and biophysical simulation models (Le Gal et al., 2009; Martin-Clouaire and Rellier, 2009). The introduction of management models allows a more appropriate analysis of the evolutions of farmers' practices arising from contextual changes than that provided by stand-alone biophysical models (Bergez et al., 2010); such management models also improve farmers' managerial support (Cox, 1996; Attonaty et al., 1999). The development of a cropping-plan management model will require the study of the decision-making process dynamic of farmers and a better understanding of the objectives that drive their decisions (Sumpsi et al., 1996; Ohlmer et al., 1998).

3.4.2 *Uncertainty and risk management*

While risk and uncertainty are clearly important determinants of cropping patterns (Chavas and Holt, 1990), they are largely ignored in cropping-plan decision models, particularly when they are formulated as an LP problem (e.g. Itoh et al., 2003; Sethi et al., 2006). In agricultural economics, risks are mostly taken into account by using stochastic variables (e.g. Itoh et al., 2003; Baltas and Korka, 2002; Olarinde, 2008) to better predict the non-deterministic aspect of decision-makers' behaviours. The uncertainty of information used in the decision problem is defined as the probability of occurrence. The probability is often kept static whatever the decision-makers' knowledge regarding the evolutionary dynamics of the constraints. In most decision-making problems, farmers have the opportunity to make sequential decisions to adjust their choices as a season progresses and more information becomes available (Dorward, 1999; Nuthall, 2010). The risk is therefore not only a matter of probabilities or stochasticity but also a matter of tactical responses (Dorward, 1999) to the so-called embedded risk (Hardaker et al., 1991). Farmer attitudes to risk, differing views on future prices and profitability, and the effect of time lags on decisions have also to be taken into account in a cropping-plan decision model (Rounsevell et al., 2003).

An important aspect that is not covered in the cropping-plan decision models developed for design purposes is the consideration of possible adaptations to changing circumstances (Dorward, 1999). The majority of the models developed by agronomists propose normative and prescriptive solutions based on a static description of the decision problem (e.g. Sarker and Ray, 2009). Although agronomists strive to develop models that strengthen the strategic thinking of farmers (e.g. Dogliotti et al., 2004), they implicitly base their solutions on the assumption that the world is stable and somehow predictable. If we consider this in a context of continuous and barely predictable change, there are no single optimal solutions, but certainly a trade-off between short-term optimisation and a long-term adaptive response to unpredictable changes (Rammel and van den Bergh, 2003). Such normative modelling approaches are very useful for exploring alternative solutions (Rossing et al., 1997; Dogliotti et al., 2005) but are of little use for supporting the decision makers because of the decision problem formulation (Cox, 1996; Ohlmer et al., 1998; Mackenzie et al., 2006). Further, normative and prescriptive modelling approaches are useful to support decision-making when used in decision-making situations that are well structured (Mackenzie et al., 2006) which is not the case for most of farmers' decision-making problems (Ohlmer et al., 1998; McCown, 2002; Mackenzie et al., 2006). Helping farmers to improve their adaptive capacity appears to be more relevant for strengthening the strategic thinking of farmers than the prescription of turnkey solutions (Darnhofer et al., 2008). Innovative cropping-plan decision models could help to develop farmers' ability to address changing and uncertain conditions if they are formalised as an adaptive and continuous process (Smit et al., 1999).

3.4.3 *Spatial representation and scale issues*

The extent of spatial detail used to represent the cropping-plan should be determined by the objectives of the study and the appropriate scale for presenting the results (Leenhardt et al., 2010). Crop allocation processes are treated at various scales involving different spatial representations of land heterogeneity for the systems under investigation. In most of the modelling approaches, the cropping-plan is not spatially represented and is summarised as simple crop acreage distributions across various land types. At the farm level, the heterogeneity of a farm territory is generally described using soil type as the sole criterion. Soil types are linked to crop-specific production functions or models in order to differentiate between them. Some authors, focusing on resource uses, introduce other variables, for instance water availability, to distinguish irrigated from non-irrigated lands (Leroy and Jacquin, 1991). The main advantages of the acreage approach lie in the genericity offered by the models and the ease of use in mathematical models. A few authors (Stone et al., 1992; Joannon et al., 2006; Nevo et al., 1994; Garcia et al., 2005; Dogliotti et al., 2005) do not describe farming land as continuous lands but have introduced discrete management units. In such cases, management units are usually reduced to the plot unit, even if such units are in reality much more complex (Aubry, 2000; Papy, 2001; Navarrete and Bail, 2007). Spatial constraints related to the farming land (e.g. field accessibility, spatial distribution) are hardly taken into account (Joannon et al., 2006; Navarrete and Bail, 2007) despite their effects on the organisation of work from season to season, as shown by Morlon and Trouche (2005a).

Many methods set aside the farm level and directly address the crop allocation problem on a larger scale. In some regional studies, the population of farmers is viewed as a single unit and not as a diverse group of actors spread across the landscape (Winder et al., 1998). The farming land under investigation is mostly assumed to be a continuous aggregate of homogeneous pieces of land and is somehow likened to one big farm. Other approaches, which are farm-oriented, are grounded on the assumption that the region can be represented by the proportional sum of different farm types (e.g. Rounsevell et al., 2003; Bartolini et al., 2007). In such approaches, the crop allocation processes are usually very simplified and the distinction between land units is based on soil type and water accessibility. Much of the spatial variation is obscured when land evaluation units are aggregated to form large units (Hijmans and van Ittersum, 1996), despite the fact that farm structures do actually have a major influence on land-use allocation (Thenail and Baudry, 2004; Morlon and Trouche, 2005a; Thenail et al., 2009). As a consequence, in order to improve the understanding of the processes and patterns taking place at different levels of analysis, there is a need for an improved linkage of micro-studies, which explain local processes but cannot easily be extended to larger scales, and macro-studies, which give global trends but do not guarantee any causality between processes (Verburg and Veldkamp, 2001). A better knowledge about the temporal dimension of farmers' cropping-plan decision-making would also be a key-step for helping managers of rural spaces in designing appropriate policies for local environmental issues. Many of these environmental issues are indeed strongly impacted by the landscape spatial organization, for instance risk of spatial dissemination between GM and non-GM maize at the level of supply basins, (Le Bail et al., 2010), risk of soil erosive run-off at the catchment level, (Joannon et al., 2006); risk of phoma stem canker dissemination on oilseed rape at the landscape level, (Lô-Pelzer et al., 2010). In order to favourably orientate the crop spatial organization at the landscape level, it would be necessary to coordinate individual farmer cropping-plan decisions or at best, to chose concerted cropping-plans at the landscape level. To do so, one needs to know exactly when farmers make their decisions and until when the planned decisions can be adjusted.

3.5 CONCLUSION

To take the decision support modelling approaches a step further, the formalisation of the cropping plan decision-making problem should be carried out within an integrative modelling framework that takes into account the various levels of the temporal and spatial dimensions of the decision-making problem rather than formulated as a static and deterministic procedure. Innovative models tackling the issue of cropping-plan decisions require new modelling paradigm based on the simulation of the decision-making processes rather than on single normative approaches. The modelling of cropping-plan decision-making processes occurring at the farm level needs to explicitly consider interactions between a set of constraints of very different natures represented in their different time scale dynamics. To achieve this, there is a need to better understand and formalise the dynamics of the processes of cropping-plan decision-making by farmers and the determinants of their decisions including risk aversion, for instance price and weather conditions. The use of integrated biophysical and decision models is now recognised as an advance in farming system design and could be an interesting solution to structuring all the elements that constitute the complexity of the cropping-plan decision-making problem. Rethinking the cropping-plan decisions as a decision-making process at farm level is a means of reconciling the flexibility to increase the adaptive capacities of crop choices and the need to maintain cropping system robustness in farm production over time.

Part II

BUILDING DECISION-MODEL FROM CASE STUDY RESEARCH

Science do not deal with the reality but with the representation of an agreed-upon perception of the reality. Any formalization provided by hard science starts from a given narrative about the reality.

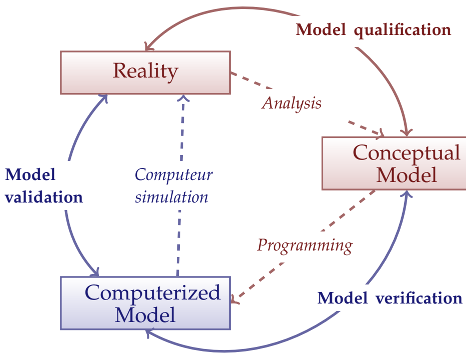
— Mario Giampietro (Giampietro, 2004).

4

A CASE-BASED METHODOLOGY FOR MODELLING DECISION-MAKING PROCESSES: CROPPING-PLAN CHOICES

Why this chapter?

This Chapter presents the methodology we developed to study, analyse and model real case-based decision-making in a scientific sound and reproducible approach. This methodology enables to build decision-model that is based on generic and formal concepts. In **red**, phases of modelling and simulation that are concerned by this chapter.



(Adapted from Schlesinger, 1979 in Bellocchi et al., 2011)

This chapter is under review as:
Dury, J., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2011. A case-based methodology for modelling decision-making processes: cropping-plan choices. Environmental Modelling & Software, Submitted.

Parts of this chapter were presented as:
Dury, J., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2010. Modelling the Complexity of the Cropping Plan Decision-making. In: and Software, E. M. (Ed.), International Environmental Modelling & Software Society. iEMSs, Ottawa, Canada, p. 8.

Agronomist tools and methods involved in the study and design of new farming systems must evolve to meet the challenges imposed by recent concerns with agricultural sustainability (Cox, 1996; Rotmans, 2009).

Computer-based simulation models have been used since De Wit (1965) to support the design and evaluation of innovative agricultural production systems. Simulation models developed by farming systems researchers traditionally focus on the biophysical entities of farming systems usually in interacting crop-soil models (Matthews and Stephens, 2002). Crop management practices in most models are mostly oriented and limited to technical operations used to control a few production factors such as the level of nitrogen and water. Farmer' practices are generally represented at the field level through management rules using expert-based or optimisation-based threshold values (Bergez et al., 2010). An inadequate consideration of the management-process dynamics in most simulation approaches (Garcia et al., 2005; Edwards-Jones, 2006) is a major limitation of model-based farming system design (Shaffer et al., 2000; Keating and McCown, 2001). The introduction of management (or decision) models as reprentations of human action (Le Gal et al., 2009; Martin-Clouaire and Rellier, 2009) allows a more appropriate analysis of farmer-practise evolutions due to contextual changes than biophysical models (Bergez et al., 2006) and improves managerial support for farmers (Cox, 1996; Ohlmer et al., 1998). A key feature of these models is that they link biophysical and decision models in a single operating model often called a bio-decisional model (Bergez et al., 2010). Regardless of whether the use of a bio-decisional model is currently recognized to be an advance in farming system design (Bergez et al., 2010; Nuthall, 2010), we explore the insufficient use of methodology dedicated to the study and formalisation of decision-making problems in developing computer models in the field of agronomy.

Techniques for analysing decision-making over the past few decades have encouraged the developement of the naturalistic decision-making framework (Klein, 1993) which provides insight for studying and improving decision-making in real-world settings (Klein and Klinger, 1991). This framework postulates that the structure and content of the decision-making processes are defined by the organisation of the domain in which the decision maker is acting. From this theoretical viewpoint, it is futile to develop decision model or decision-support systems without detailed understanding and formal representation of the relationship between decisions and expert knowledge in a specific domain. However the naturalistic decision-making framework does not provide an efficient method suitable for fitting all problem-solving situations and domains (Zachary et al., 1998). In parallel with the emergence of a naturalistic decision-making framework, software development and cognitive-science researchers developed powerful methods to analyse decision-making, namely cognitive-task analysis methods (see Hollnagel, 2003). The objectives of these methods are to analyse and model the cognitive processes that underlie human action and serve as foundation for designing computer-based learning and decision support systems (Miller and Woods, 1997).

The scope of our paper is to present ways in which farmer representations may be elicited, formalised and used as basis for designing decision models based on theories of decision-maker behaviour. This paper describes the process of building a decision model based on case studies, from specifying the decision-making problem to the development of the model. Our approach focuses on dynamic decision-making problems (Edwards 1962 cited in: Brehmer, 1990) that characterise farmers' decision-making problems in agricultural production systems (Ohlmer et al., 1998). The methodology presented provides a consistent step approach to support the development of a decision model with tools to analyse, formalise and model real-world decision-making problems. We illustrate our methodological proposition with cropping-plan decision-making processes on arable farms. The paper does not describe a bio-decisional model but rather focuses on methodology used to develop such a model.

The paper does not follow the traditional plan of a scientific paper and is organised as follow. Section 4.2 presents the cropping-plan decision-making problem and justifies the need to consider the dynamics of decision-making to develop a bio-decisional model dealing with cropping-plan decisions. Section 4.3 explains the theoretical foundation of our methodology and justifies the use of Belief Desire Intention (BDI) framework for structuring the decision-making problem from knowledge-elicitation step to model implementation. Section 4.4 presents the main steps of our methodology in building a decision model based on case-study analysis. These steps fill the gap between field observations and decision-model design. Section 4.5 illustrates our methodological proposition by presenting aspects of the cropping-plan decision-making processes on irrigated arable farms in France. Lastly, we discuss and draw conclusion about the appropriateness and limitations of our approach.

4.2 THE CROPPING-PLAN DECISION: SHAPING THE PROBLEM

A cropping-plan is the acreages occupied by different annual crops and their spatial distribution within farm-land. Cropping-plan decisions occur mostly at the farm level and are part of the global technical management of farm production. As main land cover/use decisions in farming systems, cropping-plan decisions depend on multiple spatial and temporal factors, farmer strategy and risk behaviour, and interact at different temporal levels in farm management (strategic, tactical). Since Heady (1948), the cropping-plan decision was represented in most modelling approaches as the search for the best land-crop combination allowing optimal use of farm resources (e.g. Dogliotti et al., 2003; Kein Haneveld and Stegeman, 2005). The cropping-plan decision is usually represented in models as a single decision occurring once per year or once per crop rotation. Objectives in achieving a suitable cropping-plan often are based on a complete rationality paradigm using a single monetary criteria optimisation and sometimes multi-attribute optimisation (e.g. Annetts and Audsley, 2002) or assessment procedures (e.g. Bachinger and Zander, 2007). Such normative modelling approaches are used mainly for exploring alternative solutions (Rossing et al., 1997; Dogliotti et al., 2005).

Normative and prescriptive modelling approaches are useful to support decision-making when used in decision-making situations that are well structured (Mackenzie et al., 2006). Conversely, the cropping-plan decision problem is a typical *ill-structured* problem as defined by Simon (1973). Ill-structured problems are characterised by ambiguous goal specification, multiple solutions and solution paths with no consensual agreement, multiple criteria for evaluating solutions, and uncertainty about concepts, rules and principles that are necessary for finding solutions (Jonassen, 1997). The achievement of a cropping-plan must satisfy multiple and sometimes conflicting objectives that are not always easy to elicit. Achieving a suitable cropping-plan is also highly context-dependent (on and off-farm) and difficult due to the large number of factors involved and the complexity of their interactions (Figure 4.1). These factors span several domains (i.e. agronomic, economic and social), and sometimes are difficult to quantify (e.g. crop-succession effect) or uncertain (e.g. weather, markets) (Stone et al., 1992; Nevo et al., 1994) (Figure 4.1). Ill-structured problems typically are situated in a specific context that require the integration of several content domains (Jonassen, 2000).

Aubry et al. (1998b) and Ohlmer et al. (1998) also argued that the normative and static formulation of the cropping-plan decision problem failed to address the dynamics of mechanisms involved in the processes of farmer's decision-making. A initial reason is that decision indicators such as water availability, prices and weather vary dayly, and a successful decision-making process is must be dynamic to keep up with the most up-to-date information (Hardaker et al., 1991; Dorward, 1999; Nuthall, 2010). A second reason is that farmer

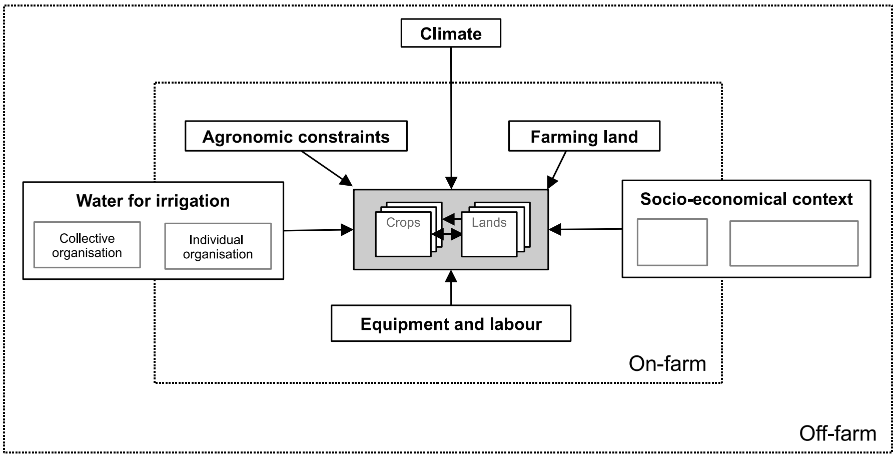


Figure 4.1: The analytical framework is an a priori construct based on information found in the literature. In the initial stage of the methodology, the analytical framework provides an initial base that shapes the decision-making problem and identifies the nature of factors involved. This figure is a static view of groups of factors that might be involved in the cropping-plan decision-making process.

decision-making involves both planning and adaptive phases (Bergez et al., 2004; Garcia et al., 2005). Modelling decision-making in order to support farmer decisions therefore requires consideration of farmers' strategic planning, and explicit consideration of problem-solving sequence imposed by an uncertain and changing context (Cox, 1996; Bacon et al., 2002), since both are interrelated.

Based on this problem description, the cropping-plan is seen as a dynamic decision-making problem (Ohlmer et al., 1998; Brehmer, 1990) embedded within a design problem at the strategic level. Design problems are a sub-type of ill-structured problems (Simon, 1973; Jonassen, 2000) and require application of general and domain-specific schemas as well as procedural knowledge (Dorst, 2003; Jonassen, 2000). Additionally, the cropping-plan decision problem combines the three common features of dynamic decision-making problem as defined by Edwards in 1962 (cited in: Brehmer, 1990):

1. A series of decisions taken over time to achieve an overall goal
2. The decisions are interdependent
3. The environment changes over time, both autonomously and as consequence of decision maker's actions.

Orasanu and Connolly (1993) list eight factors to characterise naturalistic settings: 1) ill-structured problems, 2) uncertain dynamic environments, 3) shifting, ill-defined, or competing goals, 4) action/feedback loops, 5) time stress, 6) high stakes 7) multiple players and 8) organisational goals and norms. Not all factors are present in every naturalistic setting, but each adds complexity to the problem (Norling et al., 2001). Regarding this framework, cropping-plan decision-making is concerned with all factors except in most cases multiple decision-makers.

Cropping-plan decision-making is consequently seen as a combination of design activities and dynamic decision-making for achieving a control over a dynamic system to produce a desired output, rather than as unique resolution of choice dilemma. According to this conception, simulation models based on the reasoning processes of the decision-making agent are suitable approaches to study and model such decision-making processes to support decision makers.

4.3 DECISION-MAKING THEORETICAL FRAMEWORK

The main paradigm of design methodology, in which design is seen as a rational problem-solving process, was introduced by Simon in the early 1970's. He based his paradigm on the concept of *bounded rationality* to express the idea that human decision-making is limited by available information over time and the information-processing ability of the decision-maker (Simon, 1947). Simon (1976) also stressed the reasoning processes of decision-making based on the agent's procedural rationality, which includes the rationality of the procedure used to reach a decision rather than the rationality of the decision itself, as is usually assumed in decision theory. The novelty of considering the cropping-plan decision-making problem in light of procedural rationality creates the possibility of combining proactive and reactive decisions within a dynamic and uncertain environment. Reactivity denotes the decision-making agent perceives the environment and appropriately reacts to changes. Pro-activeness conveys that behaviour is also driven by internal goals. The theoretical orientation of a naturalistic decision framework clearly fits within the sphere of bounded rationality (Miller and Woods, 1997; Todd and Gigerenzer, 2001).

The Belief-Desire-Intention framework is recognised as one of the most popular architectures for modelling decision-making of agents acting in complex and dynamic environments. The BDI framework also provides a sound theoretical background for rational decision-making processes (Bratman, 1987). BDI was inspired largely by developments in artificial intelligence and cognitive sciences (Rao and Georgeff, 1991) and is a solid framework for the formalising of decision-making problems (Becu et al., 2003). Drawing on studies of naturalistic decisions, Norling et al. (2001) demonstrated similarities between naturalistic decision-making theory and the BDI framework, since both approaches rely on goal-oriented decisions and are based on the concept of intentions. The BDI framework is organised into four structuring components:

1. Beliefs are the information and representations that the decision-maker has about the worlds, known as the problem space (Newell and Simon, 1972). We divided the belief into two main parts *structural knowledge* and *procedural knowledge*. Structural knowledge has two dimensions (i.e. content and structure). Content is the knowledge used in the decision-making process about concept and related variables of systems. Structure refers to the way concepts within a domain are organised and interrelated (Jonassen et al., 1993). Procedural knowledge is knowledge used in task performance. In our approach, procedural knowledge corresponds to the *plan library* of the Georgeff's Procedural Reasoning System (Georgeff and Ingrand, 1989) which is perceived as a subset of the agents beliefs (Haddadi and Sundermeyer, 1996).
2. Desires are objectives or situations the decision-maker would like to achieve and represent the agent's motivation. In any goal-directed sequence of cognitive operation, such as rational problem-solving, desires often are specified by goals (Jonassen et al., 1993). In the naturalistic decision-making framework, the decision maker's goal is satisficing, accepting satisfactory, as opposed to optimal, solutions (Zannier et al., 2007).
3. Intentions are partial plans for actions which the decision maker is committed to execute to achieve one or more goals or part of a goal (Rao and Georgeff, 1991). Intentions represent the deliberative state of the agent (i.e. what the agent has chosen to do immediately or at a later time).
4. The component Reasoner, aslo called *interpreter* (Wooldridge, 2002), represents the cognitive or deliberative processes that build and update the plan of action.

4.4 METHODOLOGY DESCRIPTION

4.4.1 *General approach*

We propose a step approach to elicit and formalise the complexity of the decision-making processes based on farmer interviews and on a modelling approach combining analysis methods from the cognitive and computer-software-development sciences. Our methodology provides coherent methods and tools that encompass the study of decision-making processes in real-world setting up to computer-model implementation (Table 4.1 and Figure 4.2). Following the cognitive perspective of naturalistic decision-making theory (Zsambok and Klein, 1997), we based our approach on the assumption that accessing farmers' knowledge and mental representations is a means to better understand the complexity of the decision-making problem. We followed steps similar to those described by Eisenhardt (1989) in his paper *"Building Theory from Case Study Research"*. Our methodological proposal has five main steps (Table 4.1). We focus on steps 1-4. Step 1, defintion of the problem and analytical framework has been presented in section 4.2. We did not detail step 5 because it is too specific to the computer platform that is used to implement the model.

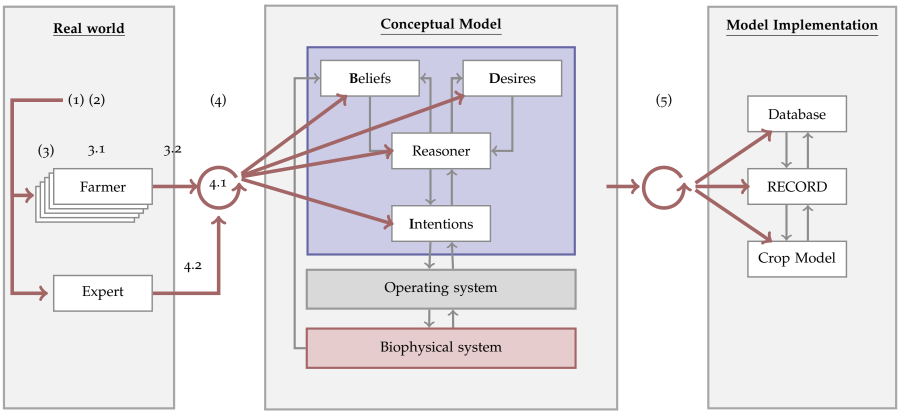


Figure 4.2: Schematic representation of the general approach we followed to develop a bio-decisional computer model from real-world setting to a computer model. The structure of the conceptual model is based on the description by Martin-Clouaire and Rellier (2009) and Le Gal et al. (2009) of an agricultural system divided into three sub-systems (i.e the agent: ☐, operating: ☐, and biophysical systems: ☐). The conceptual model of the agent is based on the BDI framework, described here through its four components: Beliefs, Desires, Intentions and Reasoner. The positions of each methodological step (Table 4.1) are indicated by number: (1) Problem definition, (2) Selecting cases, (3) Within case analysis, 3.1 Knowledge acquisition, 3.2 Transcription, (4) Shaping the conceptual model, 4.1 Case-based iterative design, 4.2 Ontological analysis, and (5) Model implementation.

Table 4.1: Process of building decision model based on case study analysis. Adapted from Eisenhardt (1989).

Step	**Activity**	**Reason**
1) Problem definition	Defining the decision-making problem	Specifying the type of the decision-making problem
	Defining the analytical-frame	Giving an a priori framework to the decision-making problem domain
2) Selecting cases	Choosing a population	Setting the validity domain of the decision model
	Non-probability sampling	Focusing on relevant cases
3) Within case analysis	Knowledge acquisition	Accessing farmer knowledge and representation
	Transcription	Formatting results into formal conceptual models that reveal underlying mental representations and problem solving strategies.
4) Shaping the conceptual model	Case-based iterative design	Generalisation of case findings
	Ontological analysis	Concept formalisation and relation
5) Model implementation	Computer model specification	
	Model implementation	

4.4.2 *Selecting cases*

Case selection is an important step in our approach. We used a **theoretical sampling** approach (Glaser and Strauss, 1967). Similar to probabilistic sampling methods the concept of population is important in theoretical sampling and helps define the limits or domain generalisation for finding used to develop the decision model. Therefore theoretical sampling differs from probabilistic sampling in the case selection. The sampling of cases from the chosen population is driven by the search for diversity rather than the search for representativeness. The goal is not to produce summary statistics regarding a set of observations but rather to provide deep understanding from a significant diversity of case studies likely to replicate and/or extend finding (Eisenhardt, 1989).

4.4.3 *Within case analysis*

Because decision models aim to support human action and rely on decision-making automation, special attention is given to the cognitive aspects of decision-making that are not accessible to direct observation (Schraagen et al., 2000). We used elicitation techniques from the knowledge-engineering community as a way to access farmer representations of the decision-making problem (Cooke, 1994; Wielinga et al., 1997; Milton et al., 1999). We used cognitive task analysis as a main approach (see: Hollnagel, 2003). Cognitive task analysis is defined as *"the extension of traditional task analysis techniques to yield information about the knowledge, thought processes and goal structures that underlie observable task performance"* (Chipman et al., 2000). The purpose of this approach is to analyse and model the decision-making processes underlying human task performance in specific domains. Cognitive task analyses are conducted for a wide variety of purposes, including the design of computer systems used to support decision-maker (Zachary et al., 1998).

Among the many types of methods in cognitive task analysis, our approach to elicit farmer knowledge is a mix between two methods (i.e. the *Work Domain Analysis* and the *Critical Decision Methods*) (Hoffman and Lintern, 2006). In Work Domain Analysis Methods, the focus is on the representation of specific knowledge domain while in Critical Decision Methods, the expert recalls and elaborates on previous cases. To stimulate the recall of experiences, we used a scenario based on past climat and crop-price data. The outcomes are a description of structural and procedural knowledge related to decision-maker objectives for each case. We follow the five common steps of cognitive task analyses (Table 4.2) as identified by Clark et al.

(2008). To present our methodology we combined them into two parts: knowledge acquisition and knowledge transcription.

Table 4.2: Common steps in most cognitive task analyses (Clark et al., 2008)

Steps
1) Collect preliminary knowledge
2) Identify knowledge representations
3) Apply focused knowledge elicitation methods
4) Analyse and verify acquired data
5) Format results for the intended application

Knowledge acquisition Cognitive task analysis uses variety of interview and observation strategies to capture a description of the knowledge which experts use to perform complex tasks (Cooke, 1994). Because of the ill-structured nature of the decision-making problem we encounter, preliminary interviews with key informants are especially useful in the initial phase of cognitive task analysis to identify specific boundary conditions of the decision-making problem (Clark et al., 2008). We conducted non-structured interviews with experts from local agricultural extension services (n=3) within the three surveyed area to capture the specificities of each regional context. Afterwards, we carried out semi-structured farmer interviews (n=30). The farmer questionnaire covered steps 2 and 3 of the cognitive task analysis (Table 4.2) and was structured into three complementary parts corresponding to the different components of the BDI framework:

- *1) Desire:* We questioned farmers about their productions (past, current and future) in relation to their objectives. We analysed ways objectives (desires) and goals impacted on the decision-making processes to assess farmers' modus operandi.
- *2) Belief:* We characterised the on- and off-farm constraints that affect cropping-plan decisions by accessing to farmers' mental representations (beliefs). We carrefully allowed free rein to evoke factors that could not be identified in advance by choosing open discussion over close-ended questions. We complemented questions with different media (e.g. farm map, warning bulletin for irrigation) to efficiently collect data and facilitate knowledge elicitation.
- *3) Intention:* Farmers were asked how they make decisions, what information they use and which activities undertaken when an option is selected. We determined the sequences of decisions in an annual cycle and the description of medium- and long-term plans. We prompted interviews with past scenarios on

climate, prices and water regulations adapted to each regional context to capture different decision-making options for various situations.

Transcription The transcription corresponds to the steps 4 and 5 of the cognitive task analysis (Table 4.2). Because our aim is to fill the gap between decision-making in real-world decision-making and decision-model implementation, we use the same formal language during the transcription process, generalisation (next section) and implementation (i.e. the Unified Modelling Language, UML). Unified Modelling Language (UML) is a standardised object-oriented modelling language in the software engineering field (Booch et al., 2000; Papajorgji and Pardalos, 2006). We also used UML as the formal language of transcription analysis because it provides standard graphical representations for representing knowledge (Milton et al., 1999) (Table 4.3).

We designed individual decision models using abductive reasoning. We first formalised structural knowledge through concepts that farmers used to decide their cropping-plan using individual thematic UML object diagrams. Next, the decision sequences (procedural knowledge), as described by farmers, were represented with UML activity diagrams. These diagrams were used to describe the infra-annual dynamics of decision-making and to identify events that disturb planned decisions. UML activity diagrams capture more information than simple task diagrams, and decision trees, they provides a simple means for capturing decision-making processes and sources of uncertainty impinging on those decisions (Hardaker et al., 1991). The sequence of decisions is regarded as a partial plan of action within the BDI framework. At this stage, object and activity diagrams were individual and solely based on farmer's mental representations derived from interviews.

Table 4.3: Correspondence between knowledge objects from Milton's classification (Milton et al., 1999) and UML formalism as proposed by Becu et al. (2003)

Knowledge object	**UML formalism**
Class	Concepts
Instance	Instance
Process (task, activity)	Operation or Activity
Rule	Methods
Relationship	Association, Aggregation or Inheritance

4.4.4 *Shaping the conceptual model*

In our methodology, the conceptual model developmnt has the same role as hypotheses construction in the approach of building theory from case studies (Glaser and Strauss, 1967; Eisenhardt, 1989). The conceptual decision model is based mainly on the transcriptions of information collected at the case-study level using inductive and iterative processes. The main idea of the highly iterative approach is that modellers constantly question and compare the model under design with all individual case study diagrams. The conceptual decision model therefore emerges from the analysis process itself. We enriched the initial inductive bottom-up approach (building from case studies) by combining a top-down approach in which external experts and modellers of the domain were involved in model design. They formalise the complex concepts which are commonly used in the domain but typically difficult to capture in a formal manner. This was performed during knowledge workshops with a limited number of experts and modellers. We also used UML language during these meetings. We applied this iterative approach to formalise structural and procedural knowledge which are the two dimensions of the Beliefs component of the BDI framework (Figure 4.3).

Structural Knowledge: The representation and access of well organised domain-specific knowledge is prerequisite for problem solving (Jonassen, 1997). *"An ontology is a formal specification of the concepts and relationships among these concepts within a particular domain"* (Beck et al., 2010) and efficiently represents knowledge. Through the iterative process, all farmer representation models (UML object diagrams) were used as hypothesss to build the ontology. The ontology should represent genericallly farmers' knowledge involved in cropping-plan decision-making. UML class diagrams were used to model the ontology as static models for depicting domain classes and their relationships (Kogut et al., 2002). The ontological analysis is primarily based on the transcription of information gathered under different forms from the various experts involved in cropping-systems management (Table 4.4). During the entire process, both the definition of concepts and their relationships were re-examined and refined.

Table 4.4: Expert and information sources for ontological analysis

Expert of the domain	Information sources
Farmers	interview
Advisers of agricultural services	interview, technical data sheet
Agronomists	personal communication, scientific papers
Agricultural system modellers	scientific literature, existing ontology

Procedural Knowledge: Procedural knowledge was formalised following two complementary methods. First, using the transcription of the sequence of decisions, we inferred the procedural knowledge that farmers used to make decision during the year. By analysing the individual UML activity diagrams, we identified events and associated information that motivates farmer decisions. We also enriched the structural knowledge with new classes and attributes regarding the knowledge required for these decisions.

The second method to formalise procedural knowledge was based on expert ontological analysis. Ontological analysis was conducted through an iterative cycle of knowledge workshops with a limited number of agronomists and modellers. We then completed the bottom-up integration with other essential concepts not necessarily included in the survey.

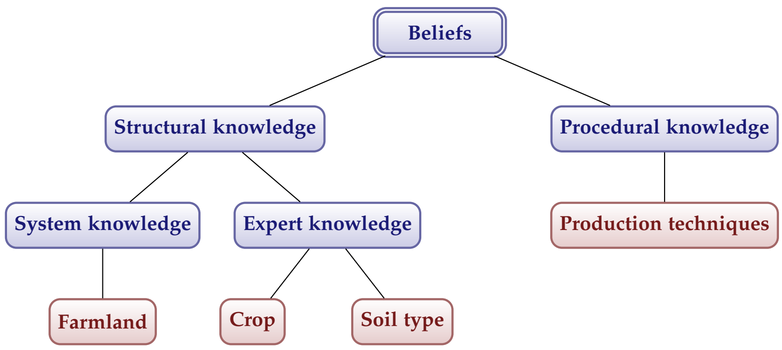


Figure 4.3: A simplified diagram of hierarchical organisation of concepts into the *Beliefs* component of the agent derived from the BDI framework (Rao and Georgeff, 1991; Haddadi and Sundermeyer, 1996). The higher levels of the diagram are shown in blue. The classes in red are examples of those classes mentioned in section 4.5.2. Several other classes were included in the *Beliefs* component in the final model. Horizontal relations between concepts are not evaluated in this figure.

4.5 ILLUSTRATION OF METHODOLOGY: THE CROPPING-PLAN DECISION-MAKING PROBLEM

This section does not aim to present a complete analysis of the 30 farms that were surveyed and the resulting decisional model but rather to illustrate our methodological proposal with relevant focuses.

4.5.1 *Case selection*

To study the cropping-plan decision-making processes, we focused on one population of farmers: crop farmers using irrigation. We used non probability sampling methods to choose crop farmers among lists provided by agricultural extension services and cooperatives. We choose cases using available key-variables likely to affect cropping-plan choices (i.e. type of crops, farm size, water resources and soil types). The key variables originated from the a priori analytic-framework designed in the first methodological step (Figure 4.1). To add contextual diversity, we performed field surveys in three regions in France, Midi-Pyrénées (MiPy.), Poitou-Charentes (PCh.) and Centre (Ce.).

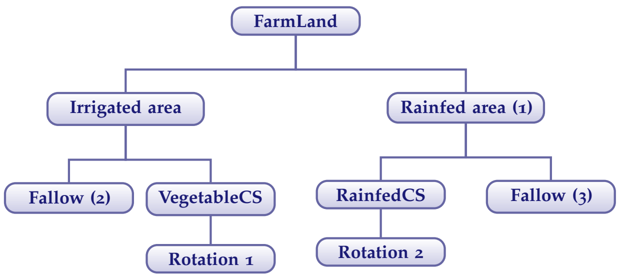
4.5.2 *Farmer representations: beliefs*

We first present the bottom-up approach with a close-up of knowledge acquisition (step 3.1), transcription (step 3.2) and generalisation (step 4) by analysing the spatial representation that farmers have about their own farmland. Using this example, we demonstrate the way UML language is very powerfull in identifying the main concepts involved in cropping-plan decisions and propose a formal representation in a readily implementable form through an ontology expressed in UML class diagrams.

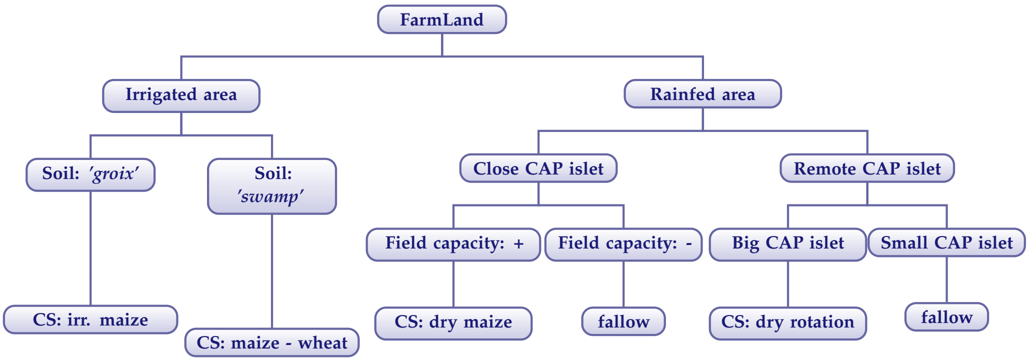
We then illustrate the top-down approaches by presenting the ontological analysis performed by experts during *knowledge workshops* regarding the concept of *production techniques* (Sebillotte, 1978; van Ittersum and Rabbinge, 1997) (step 4.2). We chose this example because it aptly demonstrate the way ontological analysis paid in the process of incorporating complex concepts into models formalised by expert while respecting the general structure of the *Beliefs* component (Figure 4.3) and the concept definition found in scientific literature.

Bottom-up approach: system knowledge During the survey, farmers described their farmland, and explained the factors that motivate different crop allocations among plots. We mediated this work by extensive use of farm maps. Along with farmers we constructed individual object diagrams that depict their own representation of their farmland organisation (Figure 4.4a & b). To illustrate, we show the resulting object diagrams as described by farmers Ce2 and PCh8 (Figure 4.4a & b).

For farmer Ce2, the main factor was the preferential installation of irrigation equipment on large plots close to the homestead. Based on the distinction between irrigated and rain-fed area, the farmer allocates two different cropping systems defined by their rotation. In both areas, small plots were left in fallow for simplicity. Based on this first description, the transcription analysis identified key concepts underlying the description of spatial organisation. This case revealed



(a) Object diagram, Ce2



(b) Object diagram, PCh8

Figure 4.4: a) and b) Organisation of farmland as described by farmers Ce2 and PCh8. This shows the heterogeneity of the land that farmer Ce2 considered when managing crop allocation: (1) small and remote plots, (2) parts of plots not easily accessible by irrigation equipment, (3) very small plot.

three concepts concerning the spatial allocation of crops (i.e. rain fed area, irrigated area and plot) and two concerning the description of production systems (i.e. Cropping system, crop rotation). During the description, farmer Ce2 also explicitly mentioned several decision indicators concerning these spatial units (e.g. plot size, distance to the homestead); others were implicit in the description and therefore were added by the modeller. For farmer PCh8, irrigation equipment also emerge as a main factor in justifying the spatial allocation of crops. However, his object diagram refers to concepts that were not mentioned by Ce2. For instance, soil properties were mentioned by PCh8 at a different stage of the diagram through the evocation of different soil types (*groie, swamp*) or through the *field capacity* indicator. The soil description reaches beyond the specificity of the spatial *soil unit* of each farm; therefore, the concept of *soil type* was included as a generic concept into the *expert knowledge* component (Figure 4.5).

We complemented this bottom up integration (from farmer) by a top-down concept integration (from the modeller) to ensure model consistency during the inductive processes. Following the same example, four concepts mentioned by farmer Ce2 were integrated into the ontology as four generic classes (light blue in Figure 4.5). The classes represented in white Figure 4.5 originated from either other farmer interviews (e.g. soil unit as described by farmer PCh8) or were introduced by the modeller (e.g. management unit) to enrich and retain the consistency and robustness of the model. The addition of abstract classes by the modeler brings a lower level of abstraction into the model. In this respect, the generalisation of classes is an important process in object oriented modelling (Papajorgji and Pardalos, 2006). These abstract concepts usually are not used by farmers but are of primary importance for implementation phases (step 5). For instance, the class *management unit* is a generalisation of (represented by ◁—) the plot, irrigated area and rain-fed area classes in Figure 4.5. Therefore, attributes concerning size and distance were introduced at this stage (Figure 4.5). In the final ontology, three more management units are presented in the Figure 4.4a & b: the CAP islet, irrigation block and crop-management block.

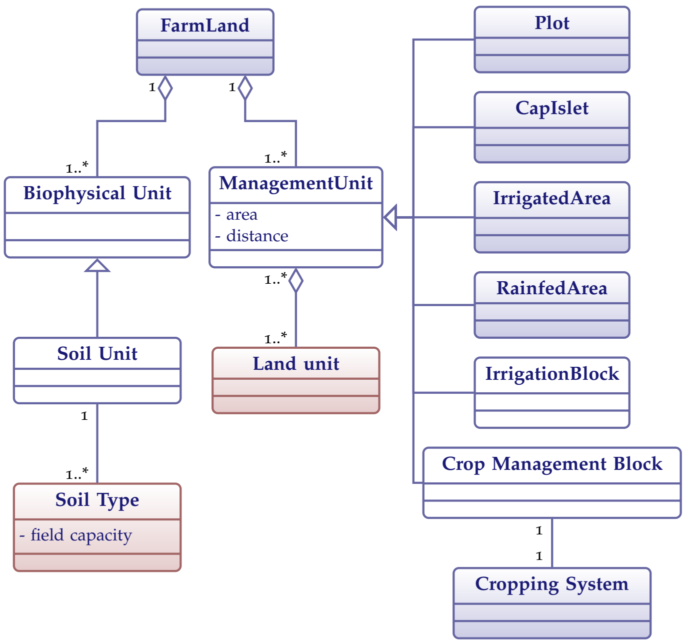


Figure 4.5: Part of the ontology that depicts farmers' farmland representation into management and biophysical units. The management units used by farmers Ce2 and PCh8 are in grey. In white, classes which originate other farmers' representations (e.g. crop management block) or were created for model consistency during the generalisation phases (e.g. management unit). Detail of the various biophysical units (e.g. soil unit) are not shown in this figure.

Similar modelling exercises were performed on different aspects of the cropping-plan decision-making problem representation (e.g. socio-economic context, water resources, agronomic constraints, farm land characteristics, equipment and labour). The farmer's knowledge involved in cropping-plan decision-making was therefore represented in more than 60 classes in the ontology.

Top-down approach: procedural knowledge In our simulation approach, we consider that farmers have technical expertise regarding the cultivation of crops. This knowledge must be represented in the procedural knowledge of the agent (Figure 4.3). The modelling of this knowledge as a partial plan of action rely solely on the ontological analysis performed by experts.One necessity was to express farmers' decision-making processes with regard to annual crop management techniques which are typical decisions repeated every year in a relatively similar planed pattern (Aubry et al., 1998b; Bergez et al., 2001).

The integration of a new concept such as *production technique* into the ontology necessarily started with a work on the concept definition (Table 4.5a).

Table 4.5: Definition of the concept of *production technique* and related concepts derived from its ontological analysis

	Concepts	Definitions
a)	Production technique	Production technique is a complete set of agronomic inputs to achieve a particular production level in a given physical environment (van Ittersum and Rabbinge, 1997). These agronomic inputs are provided to each plot through the logical combination of crop operations. It also refer to the type, crop sequence pattern and the implementation of rule-based crop operations (Sebillotte, 1990).
b)	Crop operation	A crop operation is a operational activity targeting modification of one or several states of the cultivated ecosystem. A crop operation is the basic unit of task management at the plot scale.
	Sequencing rule	Sequencing rules define the chronological order of crop operation at the field level (Aubry et al., 1998b).
	Activation rule	Activation rules defines all conditions necessary to trigger a crop operation on a field (adapted from Aubry et al., 1998b).
	Predicate	A predicate is an atomic condition accounting for a particular state of the cultivated ecosystem under control.
	Effect	Effects correspond to the input provided by the crop operation (e.g.fertilizer, water...) that modifies one or several states of the cultivated ecosystem.

During knowledge workshops, related concepts were identified, defined (Table 4.5b) and associated with each other using relation types provided in the UML standard (i.e. inheritance, association, composition and aggregation) (Figure 4.6). To express the complexity of the

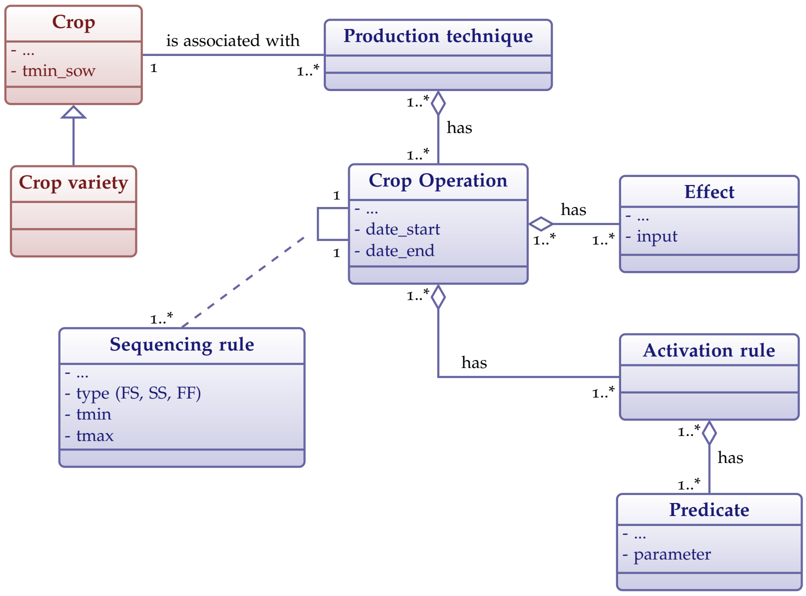


Figure 4.6: UML class diagram of the concept of *production techniques* and related classes. Classes in blue are part of *procedural knowledge*, and classes in red are part of *expert knowledge*. For simplification, we did not include all attributes describing each classe.

definition (i.e. *"logical combination of crop operation"* and *"derived from decision rules"*), we carefully defined the concept of *crop operation*. In our approach, crop operations were seen as basic activities or tasks to be performed at the plot level. The activation of a crop operation occurs within a pre-defined time window (see *date_start* and *date_end* in Figure 4.6) and must respect two types of decision rules (Aubry et al., 1998b):

- The sequencing rules specify the chronological order in which two crop operations must be performed.
- An activation rule is a conjunction of predicates. To be valid, all predicates belonging to the rule must be valid. A predicate is therefore a precondition of an activation rule. It is implemented as a test returning a Boolean value that compares a decision indicator (a state of the system) with a decision threshold. Decision indicators are part of *system knowledge* and are dynamically updated when the state of the system changes; and decision thresholds are parts of *expert knowledge*.

The representation in classes of the concept of *production techniques* is usable by the component *Reasoner* for generating a plan to simulate crop managements at the plot level (Figure 4.6).

4.5.3 *Farmer plan: Reasoning and Intention*

We studied ways in which farmers' cropping-plan decisions were structured in time through planning and adaptive phases. We first questioned farmers on the way they forsee their cropping-plan and then asked them to describe the sequence of decision concerning cropping-plan decisions made during the year before sowing. This section illustrates our methodological proposition with the example of analysing the sequence of decision farmers made through the transcription of their activity diagram (Figure 4.7). As an illustration, we describe the decision sequence for farmer Ce2 and PCh8 (Figure 4.7).

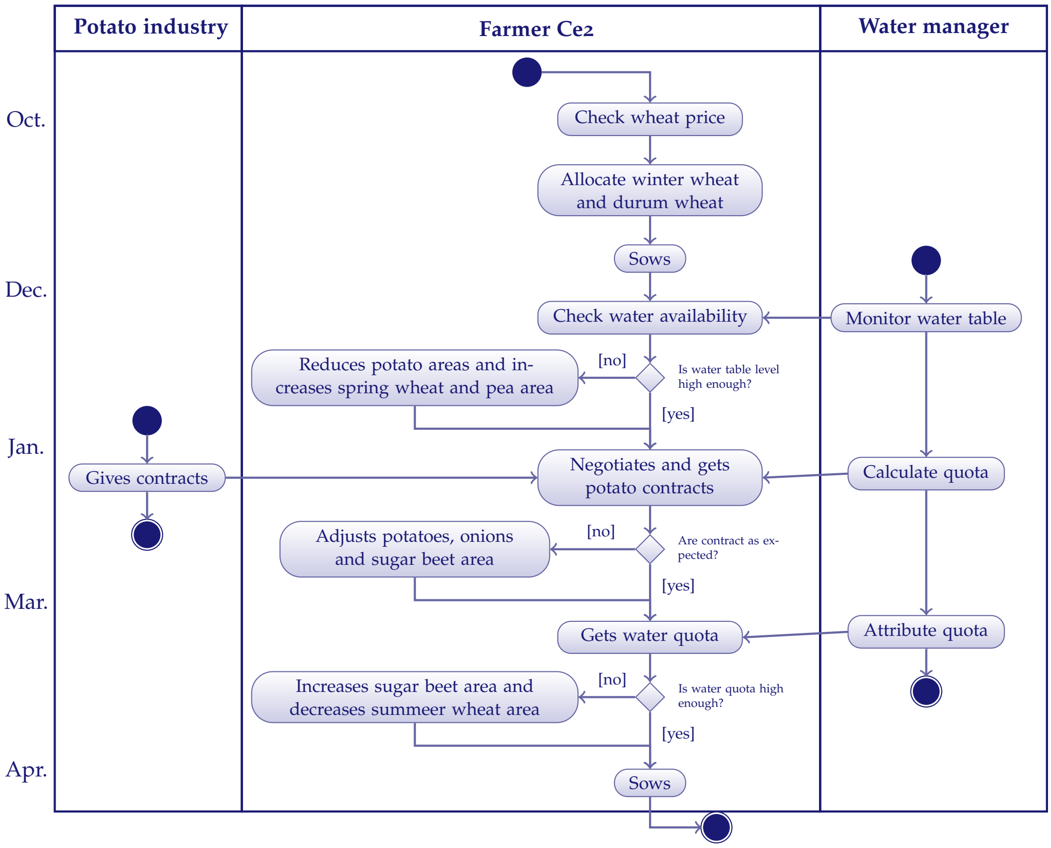
The activity diagram for Ce2 shows the three main factors (i.e. the price of crops, irrigation water availability and the negotiation of contracts) and their timing that encourage him to adapt his initial plan. For farmer PCh8 only crop price variation might drive cropping-plan changes. All these factors have some form of uncertainty, which justify their consideration for annual adaptations. Therefore, decisions taken at the strategic level (i.e. the choice of two crop rotations for farmer Ce2 and PCh8) establish a structure under which other decisions are made because of the changing context. In our modelling approach the dynamics of the decision-making process, identification of these factors has several consequences, it requires: 1) modelling beliefs that are related to these factors, 2) identifying the underlying goal of the decisions and the process for solving problems and 3) being able to simulate, even in a simple manner, external processes such as the price evolution, quota distribution.

Generalisation of activity diagrams revealed the different strategies and underlying concepts that farmers implemented to decide upon a cropping-plan. An important outcome of the decision-making dynamic analysis is identifying that all farmers have a clear plan of the sequence of decisions they must make. Plans differ from farm to farm and strongly depends on farmer strategies, socio-economic context and available information.

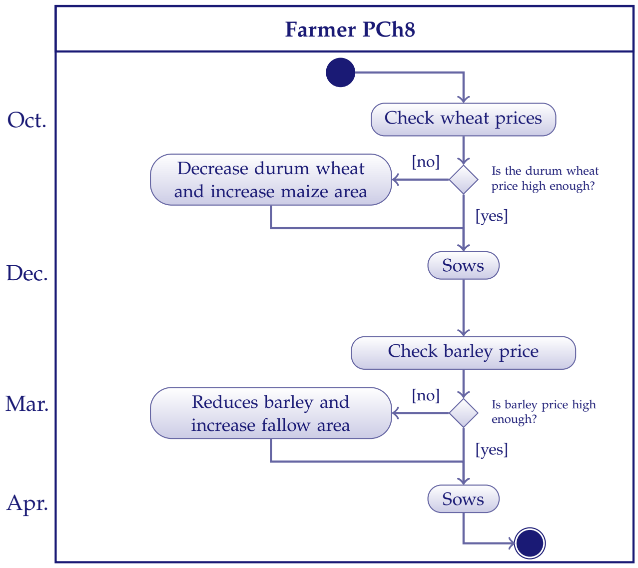
4.6 DISCUSSION

4.6.1 *Problem structuring and representation*

The decision-making literature is roughly divided into normative decision theory, which present models of ways in which decisions ought to be made and empirical decision theory, which describe ways people make decisions in real world settings (Jonassen, 2000). Well-structured decision problems with a single solution and a limited number of choices can be solved through some forms of normative



(a) Activity diagram, Ce2



(b) Activity diagram, PCh8

Figure 4.7: UML activity diagram that depict the planed sequence of activities and decision as described by Ce2 and PCh8. This shows the decisions and related events (prices, contract and information on water resource availability) that could disturb the initial cropping-plan. On left, the time scale is only indicative of the period when decisions are undertaken. [Rounded rectangles represent activities, diamonds represent decisions, black circles and encircled black circles represent initial and final work-flow state]

analysis. In most decision modelling approaches dealing with cropping-plan decisions, the exercise has mainly described mainly the problem of decision-making as a well-structured problem of crop-resource allocation to which to apply different optimisation algorithms (e.g. Sarker and Ray, 2009). Such normative modelling approaches are useful for exploring alternative solutions (Rossing et al., 1997; Dogliotti et al., 2005) but are of little use for supporting decision makers because of the decision problem formulation (Nevo et al., 1994; Cox, 1996; Ohlmer et al., 1998; Mackenzie et al., 2006). To reach beyond this traditional prescriptive approach on cropping-plan decisions that began with Heady (1948), we introduce an innovative approach to model the complexity of cropping-plan decision-making. Our approach combines the study of real-world decision-making with knowledge and software-engineering techniques. Because designing a decision model is primarily about problem structuring (Zannier et al., 2007), we use cognitive task analysis as an efficient transition path between real-world decision-making and the BDI framework. The use of the BDI model as a framework helps to structure the elicitation of knowledge and to formalise farmer reasoning. The BDI framework, in conjunction with the object-oriented paradigm also serves as architecture to develop consistent simulation models (Haddadi and Sundermeyer, 1996; Wooldridge, 2002). For example, Norling et al. (2001) has already proposed different way of implementing naturalistic decision-making model using the BDI framework. However the naturalistic decision-making framework does not provide direct methods for implementing planning activities in the naturalistic decision-making framework (Zachary et al., 1998).

4.6.2 *Decision-making process and uncertainty*

As for any decision-making process in complex and dynamic environments, cropping-plan decision-making involves a continuous sequence of interrelated decisions (Osman, 2010). The description of the decision-sequence is a starting point for understanding the way in which uncertainty influences decision-making (Hardaker et al., 1991). Analysis of the underlying drivers of decisions are also extremely important because they help identify and clarify ways in which farmers deal with uncertainty by new information at tactical and operational levels. This reveals the farmers' adaptive management practices that must be incorporated into models (Ascough II et al., 2008).

4.6.3 *Model genericity*

Although each farmer in our study had particular way of making decisions, we demonstrated that they used many common concepts to make decisions. Identifying and formalising these common concepts and their relationships through the description of structural knowledge is a great step forward in structuring the decision-making problem (Jonassen et al., 1993). However, use of knowledge-acquisition techniques to elicit farmers' representations is not straightforward and is time-consuming (Hoffman and Lintern, 2006). This indicates a significant limitation of our methodological proposition (i.e. a small number of case studies that can be analysed) (Eisenhardt, 1989). However, developing the ontology by combining both a bottom-up (from interviews) and a top-down (from experts and modellers) approach is a pragmatic way to develop consistent and reusable models based on shared concepts with farmers (Milton et al., 1999; Beck et al., 2010).

The use of inductive techniques to integrate concepts make possible to extend (new concepts) and/or update (new attributes) the current ontology with new case studies for other related decision-making problems. Intensive integration of case-specific features may lead to the description of atypical decision-making processes to overly complex decision models. In this respect, the sampling of case studies is an important step in the methodology; the criteria of diversity must be supported by existing literature. The intervention of external experts during the process of generalisation is also an important methodological element to prevent an overflow of too many case specific details.

4.6.4 *A Formal language for consistency and re-usability*

One objectives of our methodological development is to provide practical guidelines to develop decision models with methods and tools that analyse, formalise and model naturalistic decision-making problems. Like Becu et al. (2003), we argue that the use of the formal language UML is an efficient way to transcrib and abstract information for modelling purpose because of the similarity between knowledge objects and UML formalism (Table 4.3) (Milton et al., 1999). Other tools could have been used in place of UML at different steps in the methodology. For instance, the UML was not initially dedicated to ontology development. The Ontology Web Language (OWL) is one standard in ontology building (Lacy, 2005) and has powerful tools that accomplish such tasks (Beck et al., 2010). However, UML has a rapidly growing community with excellent support and has already been successfully tested for ontology building (Kogut et al., 2002).

In our methodology, the UML is used instead of cognitive maps traditionally used for knowledge representation (Mackenzie et al., 2006; Voinov and Bousquet, 2010) or as a replacement for decision trees in analysing the dynamics of decision-making (Hardaker et al., 1991). The use of UML as a unique formal language facilitates iterations and feedback between different methodological steps. It also ensures consistency and transparency during the process from knowledge transcription to decision-model implementation. The UML represents the decision-making problem in a standard and readily usable form for computer programming. For instance, the representation of concepts in UML class diagrams (e.g. the concept of *production techniques*) complies with the object-oriented paradigm (Papajorgji and Pardalos, 2006) and with database storage requirements. Therefore, it enables efficient programming and data storage while limiting distortions between the conceptual and computer models due to programming constraints. UML is also platform independent. At this stage, we did not use the possible code generation automation from UML diagrams.

The use of UML limits distortions between conceptual and the computer models due to programming constraints (Papajorgji and Pardalos, 2006). We also took advantage of the combination of the inductive approach and the use of a formal language to perform consistent conceptual validation as defined by Rykiel and Others (1996). Cross-validation was performed by agronomist/modeller experts by building agreement diagrams (Mosqueira-Rey and Moret-Bonillo, 2000) that compare classes of individual models of four farmers (from an independent sample) with classes of our conceptual models. This conceptual validation is only possible because we use a unique and transparent formal language during the model-design process.

4.7 CONCLUSION

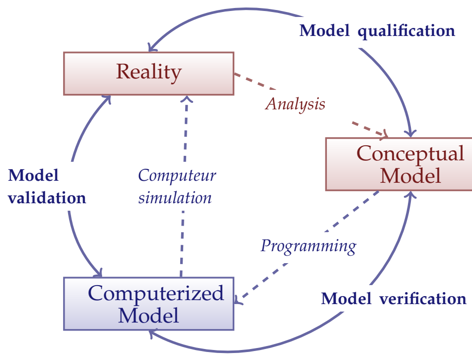
We proposed an integrated methodology that fills the gap between field observations and decision-model development. Our methodology draws upon a theoretical background of decision-making and consistently combined methods to respectively survey, analyse, model and implement such models. Based on this work, the simulation model CRASH is under development. In parallel, we are also working on completing this methodology with tools to perform conceptual validations.

5

CROPPING-PLAN DECISION-MAKING IN IRRIGATED CROP FARMS: A SPATIO-TEMPORAL ANALYSIS

Why this chapter?

This Chapter is intended to complete literature on cropping-plan decisions by analysing and modelling the interactions between the temporal and spatial dimensions of farmer cropping-plan decision-making. In **red**, phases of modelling and simulation that are concerned by this chapter.



(Adapted from Schlesinger, 1979 in Bellocchi et al., 2011)

Parts of this chapter were presented as:

Dury, J., Schallers, N., Akplogan, M., Aubry, C., Bergez, JE., Garcia, F., Joannon, A., Lacroix, B., Martin, P., Reynaud, A., Therond, O., 2009. Modelling crop allocation decision-making processes to simulate dynamics of agricultural land uses at farm and landscape level. In: Second Farming System Design. Monterey, CA.

Dury, J., Genest, Y., Garcia, F., Reynaud, A., Therond, O., Bergez, JE., 2010. The cropping plan decision-making in crop farms. In: AGRO2010. Montpellier, France.

5.1 INTRODUCTION

The need to increase food production driven by world population growth, pressing societal demand for more environmentally farming productions (McIntyre et al., 2008) and expected climate warming (Pachauri and Reisinger, 2007) are likely to heighten tensions between economic and environmental outputs in agricultural production systems. French irrigators are very concerned and affected by these significant ongoing changes (Amigues et al., 2006) particularly those concerning economy and irrigation water uses. They are under increasing pressure to maintain viability of their current irrigated crop production systems due to water quota reductions and irrigated crop margin squeezes consequently to market and regulation changes (OJEC, 2000).

The adoption by farmers of innovative cropping-plans is a promising way to explore for increasing resource use efficiency at the farm level (Amigues et al., 2006; Power et al., 2011). By cropping-plan, we mean the *acreages* occupied by all the different crops every year and their *spatial allocation* within the farmland (Dury et al., 2011). Cropping-plan decision-making is usually described as the choices of crops to be grown, determination of crop acreages, and their allocation to plots. The cropping-plan choice is one of the first step in the process of crop production occurring at the farm level. The other activities involved all along the crop production process, both managerial and operational, are related to this choice, and depends on its nature and quality (Nevo et al., 1994; Aubry et al., 1998a). As main land use decisions occurring at the farm level, these decisions are the core of the farm management strategies and have strong impacts on resource use efficiency.

Rodriguez et al. (2011) argued that identification of opportunities for adaptation should be performed at scales most relevant to decision-makers. At the farm level, explorative studies based on input-output optimisation have long been the main stream approaches to design alternative cropping-plans (e.g. Rossing et al., 1997; Dogliotti et al., 2004). But these approaches failed to design flexible crop production systems because they did not address the dynamic of farmer decision-making process (Ohlmer et al., 1998; Darnhofer et al., 2010). A deep understanding of cropping-plan decision-making process at the farm level is a start to model and design flexible and environmental-friendly cropping systems. A more complete understanding on the ways farmers make their cropping-plan decisions is also of primary interest to policy makers. Studying individual farmers' behaviour should be taken into account for efficient and effective policy assessment (Louhichi et al., 2010). Indeed, the collective dynamic generated by all individual farmers has consequences on processes occurring at the larger level than farm: economy (Chavas and Holt, 1990; Rounsevell et al., 2003), water resources (Bartolini et al., 2007), nutrient flows (Hengsdijk and van Ittersum, 2003), landscape (Thenail et al., 2009), erosion (Dogliotti et al., 2005; Joannon et al., 2006).

To date, research on farmer cropping-plan decision-making has been dominated by economic concerns and/or focused on a narrow set of decision determinants (Table 5.1). In these studies, cropping-plan choices were usually summarised as a single decision occurring once a year or once a rotation. A few studies have been made on the ways farmers make cropping-plan decisions (e.g. Aubry et al., 1998a), a few have addressed the dynamic of the decision-making processes (e.g. Dorward, 1999) and a few questioned the interactions between the spatial and temporal dimensions of the decision-making process. Despite apparent simplicity of this decision problem, cropping-plan decision-making depends on multiple factors interacting at the different spatial and temporal levels of the farm management (Nevo et al., 1994; Aubry et al., 1998a). Because cropping-plan decisions are uncertain and have considerable effects on farm productivity and profitability in short- and long-term horizons, cropping-plan decision-making clearly involves some risks (Chavas and Holt, 1990). To better support farmers in these complex decisions and efficiently allocate scarce resources at the farm level (e.g. irriation water, equipment, work), we studied the process of cropping-plan decision-making in irrigated arable farms.

The decision environment in agriculture is complex (Ohlmer et al., 1998). Taking decisions in complex and dynamic environments usually involves a continuous sequence of interrelated decisions (Brehmer, 1990; Osman, 2010). To achieve particular outcomes, farmers are required to make sequencial decisions that have to accommodate the multiple elements of their farming system, with some of them that change over time. The cropping-plan decision-making problem must therefore be analysed as a dynamic process (Brehmer, 1990) that is incorporated in a succession of other hierarchical and planned decisions along annual and long-term horizons (Aubry et al., 1998a; Ohlmer et al., 1998). Studying dynamic decision-making processes is a very complex task because it involves to take into account different individual farmers' behaviors in the way: (1) they understand their environment, (2) they process information to take decisions and (3) they sequence their decision in time. Orasanu and Connolly (1993) list eight factors which they claim characterise naturalistic settings. These factors are: 1) ill-structured problems, 2) uncertain dynamic environments, 3) shifting, ill-defined, or competing goals, 4) action/feedback loops, 5) time stress, 6) high stakes 7) multiple play-

Table 5.1: The most important determinants that were taken into account in cropping-plan studies at the farm scale. The last column are examples of studies. The authors are classified according to categories corresponding to the focus of these studies. It does not mean that the studies took into account all the mentionned determinants of the category and ignored others determinants from the others categories.

Categories	Sub categories	Determinants	Example of studies
Agronomy	Crop characteristics	Yields	Leroy and Jacquin 1991; Aubry et al. 1998a; Dogliotti et al. 2003; Bachinger and Zander 2007; Navarrete and Bail 2007; Power et al. 2011
	Rotation	Cycle period, length	
		Return time	
		Previous effect	
	Soil	Textures	
		Availaible water content	
		Maximum suitable area	
	Crop management techniques	All operations	
		Irrigation	
		Fertilisation	
Economy		Margin	El-Nazer and McCarl 1986; Abdulkadri and Ajibefun 1998; Itoh et al. 2003
		Price uncertainty	
Resources	Irrigation water	Amount	Leroy and Jacquin 1991; Annetts and Audsley 2002; Bartolini et al. 2007; Bachinger and Zander 2007; Power et al. 2011
		Flow rate	
	Equipment & labour	Machinery	
		Labour	
Farmland	Management unit	Field distance	Morlon and Trouche 2005b; Joannon et al. 2006
	Spatial	Crop location	
Climate		Temperature	Rodriguez et al. 2011
		Rainfall	

ers and 8) organisational goals and norms. Not all factors are present in every naturalistic setting, but each adds complexity to the problem (Norling et al., 2001). As regards to this framework the cropping-plan decision-making is concerned by all these factors expect in most cases multiple decision-makers. As opposed to input-output orientation, naturalistic decision-making approach does not attempt to explain which option is or will be implemented but rather to describe the cognitive process of the decision maker that lead to a particular choice (Lipshitz et al., 2001).

This paper is an empirical investigation of the question of how do farmer make their cropping-plan decision. The aim of this study is not to identify and quantify effects of the determinants on the cropping-plan selection, these have already been widely discussed in the literature (Table 5.1). We rather studied individual farmer decision-making process to understand the ways they used these determinants in their overall cropping plan strategy. We concurently focused on spatial and temporal dimensions of farmer cropping plan decision-making processes which as far as we know has not been treated in the literature.

The paper in organised as follow:
Section 5.2 explains the materials and methods we used to survey and analyse farmers' decision-making process. Section 5.3 presents the farm sample and analysis of farmer cropping-plan decision-making process. Then, we formalised findings into a spatio-temporal conceptual model to represent farmer cropping-plan decision-making process through generic concepts. Section 5.4 discusses relevance of the results as regards to the litterature and issues of implementing such decision-making-process as computer models.

5.2 MATERIALS AND METHODS

5.2.1 *Study cases and survey area*

The choice of surveyed farmers were diversity-oriented using available key-variables likely to affect cropping-plan choices: type of crops, farm size, water resources and soil types. To add contextual diversity, we carried out the field surveys in three regions in France, Midi-Pyrénées (MiPy), Poitou-Charentes (PCh) and Centre (Ce). We used theoretical sampling approach (Glaser and Strauss, 1967; Eisenhardt, 1989) to choose farmers among lists of irrigated arable farms provided by agricultural extension services and cooperatives.

5.2.2 *Data collection*

We made use of Cognitive Task Analysis (CTA) to study farmer decision-making process during the spring 2009; the survey concerned the period 2005-2009. We conducted CTA methods by mixing between work domain analysis and critical decision methods (Hollnagel, 2003; Hoffman and Lintern, 2006) to respectively elicit individual farmer knowledge representations and bring out decision sequences. We performed non-structured interviews with experts from local agricultural extension services (n=3) within the three surveyed areas to capture specificities of each regional context. Then, we conducted semi-structured farmer interviews (n=30). The farmer questionnaire was structured into three parts as presented in the following sub-sections.

5.2.2.1 *Farmer objectives and goals*

We questioned farmers about their productions in relation to their business objectives. We analysed ways objectives impact farmer cropping-plan design strategies and translate into actions. We associated farmers' objectives with decisions they employed to achieve them.

5.2.2.2 *Farmer constraints*

We characterised the on- and off-farm constraints that affect cropping-plan decisions by accessing to farmer knoweldge representations. We carrefully allowed free rein to evoke factors that could not be identified in advance by choosing open discussion over close-ended questions. We complemented questions with different media (e.g. farm map, warning bulletin for irrigation) to efficiently collect data and facilitate knowledge elicitation.

5.2.2.3 *Decision-making process analysis*

We characterised farmer strategies by studying the way sequences of decisions leading to individual cropping-plan choice were structured in time through strategic and tactical decision. Farmers were asked on the way they made decisions, what information they used and which activities undertaken when a decision is made. We determined annual and long-term sequences of decisions, and characterised planning strategies. We completed interviews with past scenarios on climate, prices and water regulations adapted to each regional context to highlith the range of possible decisions for adapting to various situations.

5.2.3 *Data analysis*

Farmer decisions are usually classified as operational, tactical and strategic decision-making, with an increasing time horizon of the decision (Le Gal et al., 2011). In this sutudy, we analysed strategic and tactical decisions that were related to croppping-plan choices.

5.2.3.1 *Strategic decisions*

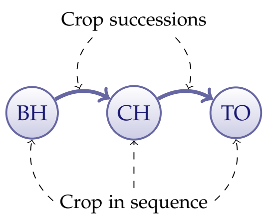
When decision-makers manage complex and dynamic systems, they use a set of concepts and heuristics to reduce the complexity of the world to a manageable level (Osman, 2010). Therefore to understand farmer's strategic decisions, we characterised their planning strategy through identification and formalization of the concepts they used to take their decisions at the strategic level.

In time: We defined a generic concept, the concept of *crop sequence pattern*, to describe the different concepts that farmers use to plan the succession of crops over time (Table 5.2). The concept of crop sequence pattern makes possible to describe in a single and formal representation, a directed graph (Figure 5.1), the different strategies that farmers used to plan succession of crops in time.

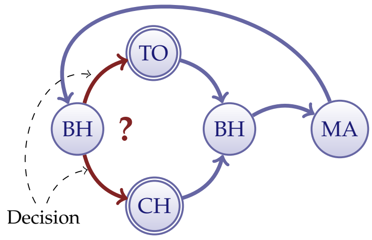
Table 5.2: Concept definitions that are included within the generic concept of *Crop sequence pattern* as usually used by farmers and agronomist to described the succession of crops on plot.

Concepts	Definitions
Crop sequence	The crop sequence is the order of appearance of crops on the same piece of land during a fixed period (Leteinturier et al., 2006).
Crop rotation	Crop rotation is defined as the practice of growing a sequence of plant species on the same land (Bullock, 1992). The crop rotation is characterised by a cycle-periods while the crop sequence is limited to the order of appearance of crops on the same piece of land during a fixed period (Leteinturier et al., 2006). The crop rotation is a specific crop sequence.
Crop succession	The crop succession is defined by the succession of two crop on the same peace of land. It is often characterised by the preceding and the succeeding effect.
Crop in sequence	A crop in sequence refer to a crop in its specific position within the crop sequence pattern. A crop in sequence is a therefore characterised by a position and its preceding and succeeding crops.

The formalisation of the crop sequence pattern as directed graph allowed to compare and quantify different farmer planning strategies on the temporal dimensions (e.g. Rodriguez et al., 2011). A directed graph refers to a collection of nodes and a collection of directed edges that connect pairs of nodes. Applied to the concept of crop sequence pattern, it refers to a collection of crop in sequence (nodes) and a collection of crop succession (edges) (Figure 5.1). We build upon the R package *graph* (R Development Core Team, 2011; Gentleman et al., 2011) dedicated algorithms to analyse crop sequence patterns planned by farmers. These algorithms are based on traditional algorithms used in the field of graph analysis (e.g. dijkstra, johnson algorithms). Therefore, we calculated different indicators on crop sequence patterns (i.e. length, cyclicity, flexibility, number of decisions, substitutable crops) in order to characterise strategies of the farmers that they used to plan the succession of crops over time.



(a) Simple sequence, length=3, decision=0



(b) Flexible crop rotation, length=4, decision=1

Figure 5.1: Example of crop sequence patterns and related concepts represented as directed graph. In the crop sequence pattern (b), the same crop BH is present twice, but refer to two different crops in sequence since they do not have the same preceding and succedding crops. In crop sequence pattern (b), the crops TO and CH are anticipated to be substitutable crops because of the decision options. In the crop sequence pattern (a) the crops TO and CH are not substitutable. [BH: *winter wheat*, CH: *rape seed*, TO: *sunflower*, MA: *maize*, ? : decision, ◎: substitutable crops].

In space: We characterised the way farmers tooke into consideration that decision factors may be differently constraining over space. Therefore, we described the spatial dimension of farmers cropping-plan decision-making through the description of different organizational levels, namely management units. These management units are decided by farmers to allocate resources, equipments and to organise works through the choices of the crops to be grown and their management techniques.

We collected spatially explicit data at the CAP islet and plot levels by the use of farmers' CAP declaration over the period 2005-2009. We mediated interviews by using maps and aerial photographies to localise soil types, management units, water access points and all other factors affecting cropping-plan choices. To study the spatial dimension of the cropping plan decision-making of farmers, we draw relationships between farmers' decisions and the different management units they handle when deciding their cropping-plan (Table 5.3).

Table 5.3: Definition of the different types of management units that we took into account in our analysis.

Concepts	Definitions
Irrigable area	Area within the farmland that are equiped with irrigation water access points.
Irrigation block	It is the area irrigated by a single set of equipments with given constraints of water amount and flow rate (Bergez et al., 2001).
Crop management block	A crop management block is a subset of plots managed in a coherent way (Aubry et al., 1998b). Crop management block are characterised by a cropping system (Sebillotte, 1990; van Ittersum and Rabbinge, 1997), i.e. one crop sequence pattern and the use of a coherent set of production techniques applied to these crops (e.g. fertilizer, irrigation water).
CAP Islet	A CAP islet is a set of contiguous plots belonging to the same farm and limited by readily-identifiable and permanent landscape and/or administrative elements, such as paths, roads, streams and other farms. The CAP islet unit are used by the Franch adminstration as basis for farmer CAP declarations. Boundary are fixed over long term periods
Plot	Continuous piece of land belonging the same farm that is homogeneous in terms of annual crop management. Boundaries can evolve over years.

5.2.4 *Tactical decisions*

Based on the critical decision methods (Hollnagel, 2003; Hoffman and Lintern, 2006), we elicited with farmers their decision sequence concerning cropping-plan that they take during the whole year before spring sowing. We formalised individual farmer decision sequences as standard flowchart in the form of UML activity diagrams. These diagrams provide simple means for capturing the decision-making process. Activity diagrams provides more efficient representation than simple task diagrams or decision trees. The description of decisions were always made in relation to information and uncertainty underlying problems to solve (Hardaker et al., 1991). We also differentiated planning decisions and adaptation of already made decisions. Adaptations were always linked with factual changes in the environment that could justify plan adaption by farmers.

5.3 RESULTS

5.3.1 *Farm characterisation*

5.3.1.1 *Farm type*

From the 30 surveyed farms, two were left because they were mixed farms and the cropping-plan decisions-making driven by animal feed productions. So far, we kept 28 arable farms in the analysis (MiPy=9, Pch=9 , and Ce=10) from the initial set of farmer interviews (n=30). The total number of plots concerned by the survey were 2637 for the period 2005-2009 covering a total area of about 4400 ha year^{-1}. The sample represents a great diversity of irrigated arable farm in the three regions as illustrated by the variation of their land areas ranging between 33 and 400 ha farm^{-1}, with an average of 161 ha farm^{-1} (sd 91) (Table 5.4).

Table 5.4: Values of some key-variables describing surveyed farms for the period 2005-2009 (standard deviation).

	Farm land		**Crops**		**Irrigation area**	
Region	**Area** (ha farm^{-1})	**Plot** (# farm^{-1})	**Number** (# farm^{-1})	**Diversity** (Simpson index^{a})	**Irrigable** (% farm^{-1})	**Irrigated** (% farm^{-1})
Ce	168 (50)	28 (13)	9.6 (3.3)	0.75 (0.09)	87 (16)	34 (26)
MiPy	125 (107)	27 (13)	4.8 (2.0)	0.56 (0.24)	79 (19)	64 (25)
PCh	191 (106)	36 (20)	5.6 (1.5)	0.71 (0.13)	57 (23)	37 (17)
All	161 (91)	31 (15)	6.7 (1.9)	0.70 (0.15)	74 (19)	45 (23)

[a] Simpson index: $D = 1 - \sum_i^s p_i^2$. The value of this index ranges between 0 and 1, the greater the value, the greater the crop diversity per farm. pi is the fraction area of the i^{th} crop.

5.3.1.2 *Crop productions*

All together, farmers grow 29 different crops with a majority of cereals on about 2/3 of their farming area (Figure 5.2). The main crops were maize (26% of the area), winter wheat (23%), rapeseed (11%), durum wheat (9%), sunflower(7%) and fallow (7%). Farmers grow on average 6.7 (sd 1.9) different crops per farm. Irrigated crops represented 34%, and 64% and 37% of the total area per farm for the regions Ce, PCh and MiPy respectively (Table 5.4). The crop diversity was higher in the region Ce (Table 5.4). This was explained by specific crops usually grown under contracts such as sugar beet, potato and open field vegetables (Figure 5.2). In this region, the irrigation was concentrated on these crops with high and secure returns as compared to the other two regions where irrigated areas were mainly sown with maize (Figure 5.2).

We compared observed farmer yields and acreages across regions for the most important crop species (Figure 5.2). The most important yield differences across region concerned the winter wheat. Yields and acreges were both higher in Ce as compared to the other regions. Concerning the other crops, we did not find trends where higher yield translate into higher crop acreages across regions. At the opposite, higher acreage of the durum wheat in MiPy was explained by a specific CAP subsidies despite lower yields than in other regions.

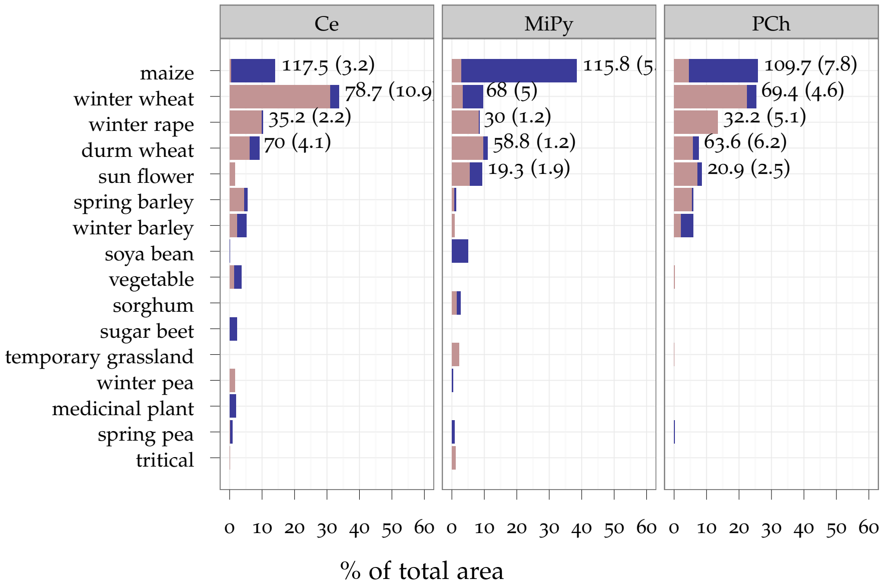


Figure 5.2: Average crop acreages in each region for the period 2005-2009. Only crops with an acreage higher than 1% are presented in the figure. The number are expected yields (standart deviation) as mentioned by famers while choosing the crop [■ : rain fed crops, ■ : irrigated crops] Crop name

5.3.1.3 *Farmers objectives and marketing opportunities*

All farmers reported incomes as main objectives for their farms (Table 5.5). However, less than 1% of the farmers mentioned profit maximization as sole criteria, 71% searched first for good and secure income rather than profit maximization at any risks. The desire of income security were indeed mentioned by 20 farmers (see Table 5.5), but not always associated with same actions: increasing crop diversity with crop rotation (10/20), searching for robust cropping-plans (5/20), securing crop sales (contract and cooperatives) (5/20) and/or decreasing input costs (4/20). The desire to increase and/or maximize income was mainly associated with the search of market opportunities and contracts (8/14). The second motivation for 42% of the farmers was the workload management, mostly recall as a simplifi-

Table 5.5: Main objectives of farmers (n=28) that drive cropping-plan decision-making.

Category	Desires (objectives)	Answers
Income	Secure - good	20
	Increase - Maximization	14
Workload	Decrease - minimization	10
	Spread in time	1
	Maintain	1
Farm status	Maintain - heritage	2
	Survival of the farm	1
	Pass farm on to the next generation	1
Technical aspect	Experimentation (varieties, pesticides)	2
	Simplification of the production system	2
	Technical crop (vegetable)	1
Environment	Increase biodiversity	1
	Input minimization	1

cation of their crop production systems (10/12). Again the actions associated with this objective were not the same for all farmers (e.g. introduction of no-tillage practices, decrease of irrigation, reducion of the crop number).

Regarding to economic partners of the farmers, cooperatives were the most important trading outlets (Figure 5.3), all farmers excepted 10% sold a portion of their production to them. 42% farmers dealt with traders or directly with food and seed companies. In most cases, volumes sold to traders and food industry did not exceed 50% of the total farm production. Crop productions grown under contracts were mainly sold to food and seed companies. Finally, few farmers (18%) sold their productions through forward contract markets. We noticed that in PCh, the number of market opportunities is less diverse than in others region (Figure 5.3).

5.3.2 *Sequence of problem solving*

We identified for a majority of farmers two distinct types of decisions in their decisions-making process: planning and adaptive (Figure 5.4). Planning decisions were about making cropping-plan choice (or partial choice) for the future, and adaptation decision about changes of the existing plan. Planning cropping-plan occured in both phases of the decision-making process (strategic and tactical) while adaption decision only occured in the tactical phase. These two types of decision (planning and adaptative) did not necessarily mobilise same decision determinants and vary from one farmer to another. Figure 5.4

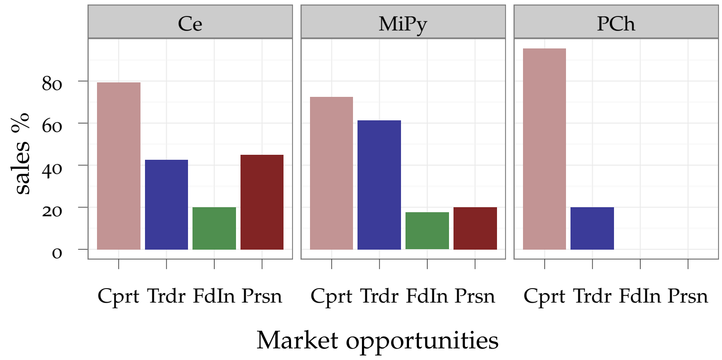


Figure 5.3: Economic opportunities of farmers in the three different regions. [Cprt: Cooperatives, TrDr: Freelance traders, FdIn: Food and seed companies, Prsn: Personal sales]

depicts the timing of the different farmer cropping-plan decisions at the strategic level (Figure 5.4) and tactical level (Figure 5.4). Whether the distinction between these two phases were evident, we acknowledge that there were strong relationships between the two.

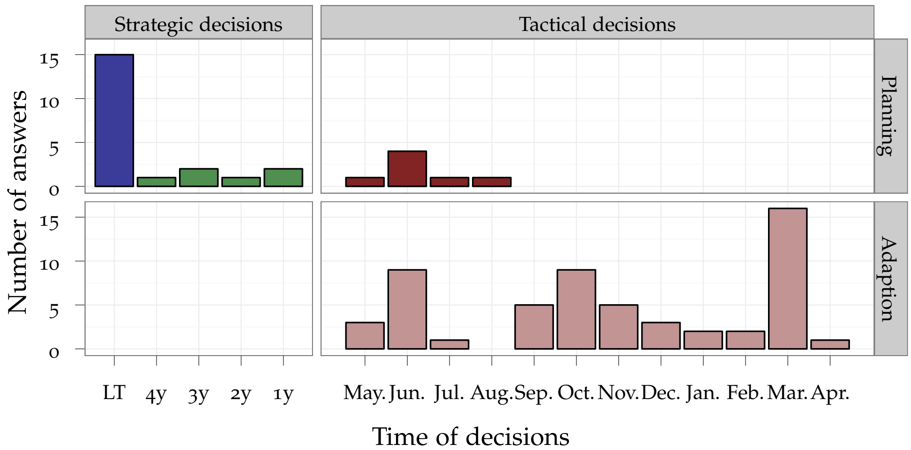


Figure 5.4: Timing of the cropping plan decision. Decisions are separated between pluri-annual and annual decisions and between planning and adaptative decisions [LT: long term planning, 4y...1y : number of years of anticipation for planning, number of month of anticipation for planning, adaptation decision timing]

5.3.2.1 *Planning decisions*

At the farm scale: 53% of farmers revealed to have stable cropping-plans over time and to not seek for changes (in Figure 5.4). They justified stability by using long crop rotations, long-established mono-cropping or simply the satisfaction of their current cropping-plan. Following a more flexible strategy, 14% of the farmers looked between one and four years forward when setting up their cropping-plans (

in Figure 5.4). 32% reported that they anticipate their cropping-plan only during the year before the winter sowing period (■ in Figure 5.4). These farmers usually do not had fixed plan for their cropping-plan and annually requestion the choice of crops to be grown (Figure 5.5 Annual).

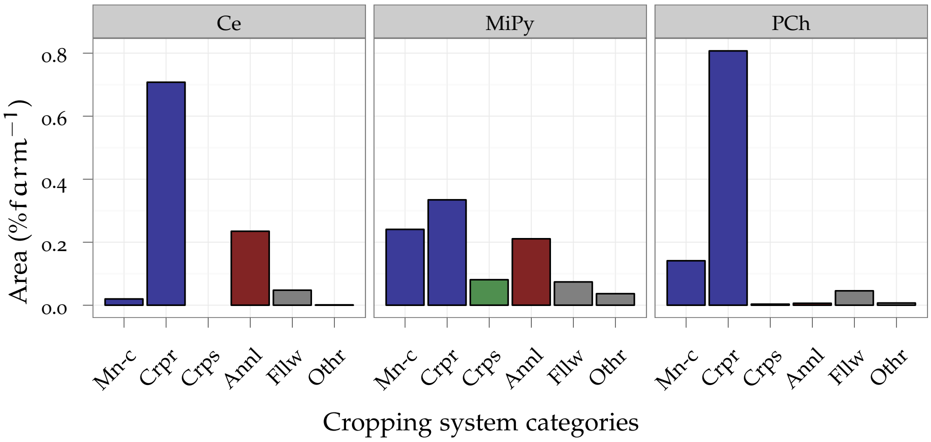


Figure 5.5: Crop sequence pattern characteristics that the farmers used to design thier cropping systems. [Mn-c: mono-cropping, Crpr: crop rotation, Crps: crop sequence, Annl: no planning, Fllw: fallow, Othr: Others, colors refer the timing of the decision: ■ long term planning, ■: >4 years planning, ■ : >1 year planning]

At the crop management block scale: Based on the number of crop sequences patterns that the farmers reported using, we calculated that they had on average 2.7 cropping systems per farm (Ce: 2.1, MiPy:2.5, PCh: 3.5). Therefore, we questioned them on the way they designed their cropping-plan while taking into account interactions between the different crop management blocks (i.e. interactions between the different cropping systems).

We characterised farmers planning strategy by describing the different crop sequence patterns that the farmers used to project into the future. The analysis revealed that most of the farmers (57%) used different types of crop sequence pattern (Figure 5.5) to design their different cropping systems within their farm. Only a few of the farmers (n= 2) did use one type of crop sequence pattern to design all their cropping systems (e.g. only crop rotation). This demonstrates that farmers did not use a single planning strategy for all their cropping systems to project into the future. We also identified that the mix of crop sequence pattern to design cropping systems were crucial to define the overall crop acreage balance within the farmland. This largely determine the framework of the cropping-plan. However, planning strategies, characterised by the mix of crop sequence patterns within each farm, were different between regions due to local contexts:

- *Centre:* In region Ce, 80% of the farmers set up crop rotations on both irrigable and rain fed area. Contrasting with other regions, the use of crop rotations on irrigated area was explained by the integration of specific irrigated crops such as open field vegetable (e.g. onion), potato, pea, sugar beet. These crops, even grown on small area (see *vegetable* in Figure 5.2) were of particular importance from the economic point of view because they were mostly grown under contracts (e.g. sugar beet) or intended to niche markets (e.g onion). All of these specific crops have a long return period (e.g. potato: 5 years, sugar beet: 6 years, pea:6 years) and compelled farmers to anticipated their cropping-plan long-time before. Long return period justified long rotations on irrigable area (4.1 year length on average). Despite using long rotations, the crop sequence pattern were kept very flexible on this management units by the integration of adaptations options (2.8 decisions on average into the crop sequence patterns). Long crop rotations explained 1) the few maize mono-cropping systems in Ce as shown in Figure 5.6 (the crop succession maize-maize did not exist), and 2) the higher crop succession diversity in the crop sequence pattern as compared to the other region (Figure 5.6). Rain fed areas were mainly devoted to winter wheat and durum wheat with 59% of the rain fed area. In these areas, the crop rotations were build around these two main crops having a return period of 2 years. Crop rotations in rain fed areas were not presented by farmer as flexible.

  To summarise strategies of farmers in the region Ce, rain fed cropping systems were based on winter wheat and routinely applied to provide secure income to farms. Irrigated cropping systems were in contrast more flexible. They were designed with adaptation options to fit market opportunities with high return crops. Acreage of irrigated maize were used as adjustment variables as regards to the irrigation water availability.

- *Midi Pyrénées:* In region MiPy, 75% of the farmers combined two crop sequence patterns for planning, mostly mono-cropping on irrigable areas and crop rotations on rain fed areas. Irrigable areas were mostly grown with maize (62% of the irrigated area). In this region, irrigated maize is easy and secure to grow because the amount of available water was not a limiting factor for the farmers. Wether maize mono-cropping was the main cropping systems, a few farmers kept some flexibility on irrigated area by timely introducing other irrigated crops such as winter wheat (10% of the irrigated area), soybean (9%) and sunflower (6%). The extra crops introduced on irrigated area were often

grown under contract for seed producers (Figure 5.3). On rain fed areas, the main crops were durum wheat (28% of the rain fed area), rapeseed (23%), sunflower (15%) and winter wheat (10%). These crops were usually grown in a 3 years length crop rotation. The crop rotations described by farmers on the rain fed areas did not have adaptation options. We also found differences between soil types on rain fed area, the sunflower is much less grown in heavy clay soils (i.e. boulbènes soil type).
To summarise strategies, farmers mostly based irrigated cropping systems on maize, and fixed crop rotation around durum wheat on rain fed area. The flexibility is given by introducing some crop diversity on irrigated areas, and by substituting between sunflower and winter rape on rain fed areas.

- *Poitou Charentes:* PCh is the region were the number of cropping system is the higher with 3.5 on average per farm. The high number of cropping systems was explained by a combination of factors:
  1. Spatial: the high number of plots (Table 5.4) and their spatial distribution. The mean distance between the homestead and the plots were 4.1 km in PCh as compared to Ce and MiPy with 2.1, 2.6 km respectively.
  2. Agronomic: contrasting soil types with very different agronomic features.
  3. Resource: limited and non secured irrigation water availability (Bry and Holflack, 2004). In our survey, 78% farmers reported to have a limiting and non secure access to irrigation water (60% and 38% for Ce and MiPy respectively).

  The large majority of farm (88%) set up at least one irrigated mono-cropping system of maize and one rain fed crop rotation, and 77% of the farmers had more than one crop rotation. The most important differences were between crop rotation designed on irrigable and rain fed areas were the number of planned adaptation options. The farmers did not mention any adaption options while planning there crop rotation on rain fed area contrasting with crop rotations on irrigable areas (2.8 decisions on average per crop rotation plan).
  To summarize strategies used by farmers in PCh, mono-crop of maize allowed maximizing the water use efficiency on the secure volume of water. To maximise the non secure volume of water, adjustments of the irrigation water uses were allowed by flexibility in the crop rotation on irrigable areas. The crop rotations set up on rain fed areas were fixed and specific to soil types.

The various crop sequence patterns as planned by farmers had consequences on the different temporal planned crop successions in time.

In general, there were greater diversity of planned crop successions on irrigable area, this being particularly true for region Ce. We noticed that diversity of crops at the farm scale in region Pch (Table 5.4) did not necessarily translate into the same crop succession diversity at the crop management block scale (Figure 5.6).

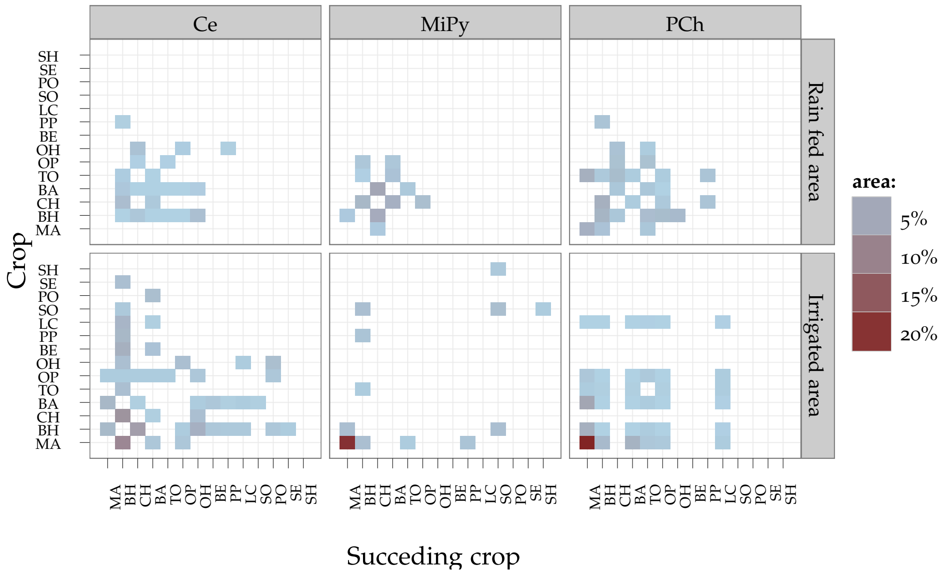


Figure 5.6: Adjacency matrix depicting crop successions that were part of planned crop sequence pattern of farmers. Crop succession are differentiated per region and access to water (irrigable vs. rain fed areas). Crops are in the y axis and succeeding crops on the x axis. Crops are sorted by their total acreages across the regions. The percentage of area is expressed per region. [MA: maize, BH: winter wheat, CH: winter rape, BA: durum wheat, TO: sun flower, OP: spring barley, OH: winter barley, BE: sugar beet, PP: spring pea, LC: vegetable, SO: soya bean, PO: medicinal plant, SE: rye, SH: sorghum]

5.3.2.2 *Adaptation decisions*

We inferred the sequence of decisions that farmers take during the year before sowing to adapt their initial plan. An important outcome of the cognitive task analysis we conducted was that all farmers had a clear plan of the sequence of problem solving they have to face during the year. But these plans were very different from farm to farm. Although the majority of farmers reported to seek for cropping-plan stability (■ in Figure 5.4), all except one mentioned at least one reason that encourage them to adapt their initial cropping-plan during the year (Adaptation in Figure 5.4). Some of the adaptation options were taken into account during the planning phase of the cropping systems by the use of flexible crop sequence pattern, some were taken into account only during the year before sowing.

Stated reasons (Figure 5.7) were always linked with uncertain factors related to market (contract 29%, crop price 29%), climate (water resource availability 20%, field accessibility for sowing 14%) and agronomy (seedling emergence, weed and pest issues 9%). For 71% of the farmers, changes from initial plan usually concerned only a small portion of the cropping area (■ in Figure 5.8), did not take place every years but most frequently concern crop with high profitability (e.g. contract, market opportunity).

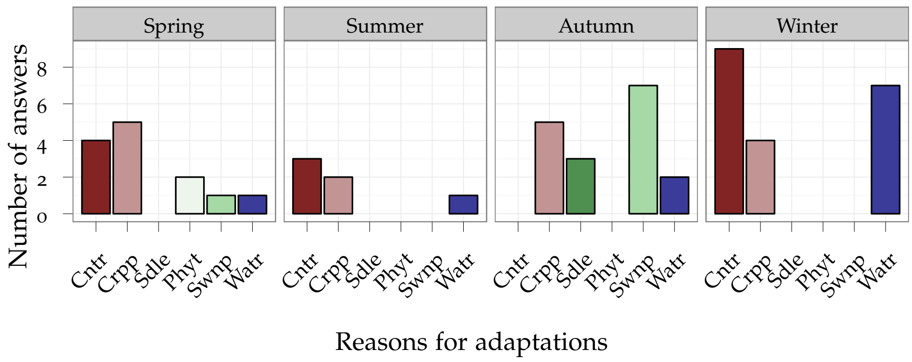


Figure 5.7: Reasons that motivate changes from planned cropping-plan during the year and timing at which those changes occur. Values indicate the number of time the factor was mentioned by farmers while describing their decision-making processes [■ Cntr: crop contracts; ■ Crpp: crop price; ■ Sdle: seed emergence issues; □ Phyt: field state, weed and pest issues; ■ Swnp: sowing possibility; ■ Watr: availability of water for the irrigation]

We analysed the planned crop successions in the crop sequence patterns that farmer used for planning their cropping-plan (Figure 5.6) and compared with what they did during period 2005-2009 (Figure 5.8). The first results were that all of planned crop successions in crop sequence patterns were found during the period 2005-2009. The differences between observed and planned area was for a majority of crops lower than 5% of planned area (see ■ in Figure 5.8). This means that farmers mostly respected their planning strategy. These small changes were mainly explained by rotations of crops between plots that were not strictly equal in terms of areas.

We also noticed that maize crop was concerned in all region with changes higher than 5% of the area. It illustrates that maize crop was used by farmers as buffer crop for adapting irrigated areas as regards to irrigation water availability. Results also showed that cropping-plan adaptations resulted into crop successions that were not planned by farmers (see ■ in Figure 5.8). These crop successions were not always compliant with agronomic rules as mentioned by the farmers themselves. Unplanned crop substitutions were justified by farmers with different reasons: potential outcomes (prices, contract opportunities), resource requirements (water) and crop functions into crop sequence patterns (weeding effects). Unplanned adaptations (e.g. reducing maize area, getting a contract on new crop) often resulted in the adjustment of the management units boundaries. These changes of the management units boundaries participated to the occurrences of unplanned crop succession as shown in Figure 5.8.

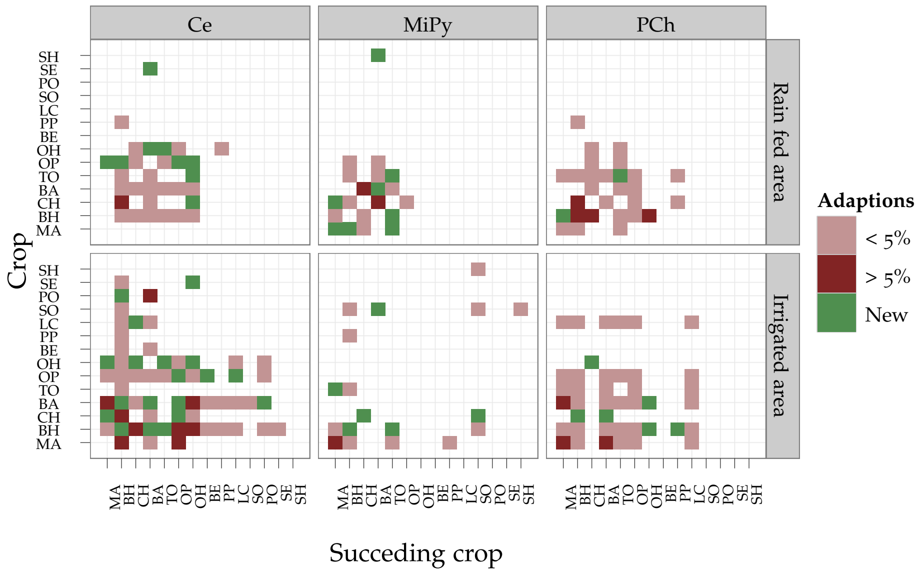


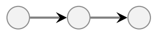
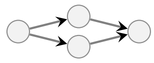
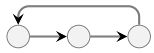
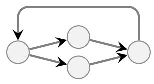
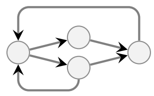
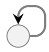
Figure 5.8: Adjacency matrix depicting planned vs. observed crop successions over the period 2005-2009. Crop successions are differentiated per region and irrigable vs. rain fed areas. Crops are in the y axis and succeeding crops on the x axis. Crop successions that were part of farmers' plan are presented in red. Observed crop successions that cover an area higher than ±5% from what was planed are in ■ and lower than ±5% are in ■. In ■, observed crop succession that were not part of farmer's crop sequence pattern plan [MA: maize, BH: winter wheat, CH: winter rape, BA: durum wheat, TO: sun flower, OP: spring barley, OH: winter barley, BE: sugar beet, PP: spring pea, LC: vegetable, SO: soya bean, PO: medicinal plant, SE: rye, SH: sorghum]

5.3.3 *Formalising spatial and temporal interactions of the cropping-plan decision-making*

5.3.3.1 *Planning phase*

The cropping-plan planning depends not only on objectives, resource availabilities and business opportunities of farmers but were highly dependent on strategies they used to design their cropping systems. Because of uncertainty not all cropping-plan can be decided once and for all at strategic level. Farmers anticipated variability of uncertain production factors by using a mix different crop sequence patterns when designing their cropping systems. We developed a crop sequence pattern classification to describe the diversity of strategies that farmer used to plan the succession of crops over time (Table 5.6). This classification is based on the formal representation of crop sequence pattern and take into account concepts that farmers used to plan succession of crops at the crop management block scale.

Table 5.6: Crop sequence pattern types.

Name		**Sequence features**			**Graph scheme**
Category	Name	Flexibility	Cyclic	Length	
Crop sequence	Simple sequence	Fixed	No	Fixed	
	Flexible sequence	Flexible	No	Fixed	
Crop rotation	Simple rotation	Fixed	Yes	>2	
	Flexible rotation	Flexible	Yes	>2	
	Very flexible rotation	Flexible	Yes	Variable	
Mono-crop	Mono-cropping	Fixed	Yes	1	
Adaptative	Adaptative cropping	Flexible	No	1	

At the strategic level, planning cropping-plan consists of designing different cropping systems based on different crop sequence pattern types in order to allocate crops and resources to land. We used the crop sequence pattern types to characterise farmers strategies to design their cropping systems that we summarised into three types:

- *Robust cropping system:* usually in the form of secure crop rotation (e.g. cropping system (1) in Figure 5.9) or long-establish mono-cropping system (e.g. cropping system (2) in Figure 5.9).
- *Flexible cropping system:* planning flexible crop sequence patterns where some substitutable crop are beforehand identified (e.g. cropping system (3) in Figure 5.9). Such strategies are complex to set up but allow to plan temporal agronomic interactions.
- *Adaptive cropping system:* delaying as far as possible the cropping-plan decision. Crop choices were made year after year (adaptative crop sequence pattern). Such cropping systems are suitable to fit to the changing context (market opportunities, resource) but make difficult to anticipate temporal interactions between crops in plots (e.g. return period, previous effect).

Cropping system design required to farmers to jointly delineate different management units and to plan successions of crops in the form of crop sequence patterns (Figure 5.9). Depending on farmland characteristics and on heterogeneity, farmers had more or less freedom in delineating boundaries of their management units. We classified the different levels at which shaping the management units can be differently constraining (Figure 5.9):

- *Biophysical constraints:* biophysical constraints mostly concern soil characteristics, spatial distribution and shapes of the different CAP islet units. These constraints are likely to evolve only in a very long-term perspective.
- *Structural constraints:* these constraints concern factors that farmers might want to adapt while considering long-term horizons. For instance, irrigation networks, points of access to water and irrigation pivots are significant investments. Their changes were not considered for the cropping-plan decisions in a short- and mid-term horizon.
- *Organizational constraints:* these constraints limit the number of options for farmers when allocating crops and resources. For instance, the choice of irrgated crops is limited by the spatial arrangement of the irrigation equipments and management units. At this level, farmers have rooms for manoeuvre to overcome these constraints by moving mobile irrigation equipments, grouping identical crops, and above by adapting boundaries of some management unit types (i.e. irrigation and crop management blocks, and plots).

We observed that planning the successions of crops over time were usually carried out around main crops that form the core of the crop sequence patterns. These main crops were chosen on the basis of economical concerns (margin and return security) and on their feasibility in farm (e.g. equipment, farmer's skills, suitable soil types). Acreages of the main crops were usually as large as possible, but limited by structural and biophysical constraints associated to the management units, by agronomic constraints (return period) and resource availabilities (water and work). Acreage of the main crops and their position into the crop sequence pattern were therefore limited by spatial constraints as illustrated in Figure 5.9. Choices of the other crops usually respected some crop succession rules and fulfilled various functions not always related to economic concerns (e.g. price, market opportunities). These crop functions were used to take advantage of the temporal interactions between crops into crop sequence patterns (e.g. agronomic concerns: succeeding and previous effects), but also to manage spatial interaction between cropping systems (e.g. spreading workload over time, flexibility in the management of water resource). Because some of these functions were associated with uncertain factors (e.g. contract, field states), some farmers introduced flexibility to delay decisions by planning different options in their crop sequence pattern in order to anticipate different situations (e.g. (3) in Figure 5.9).

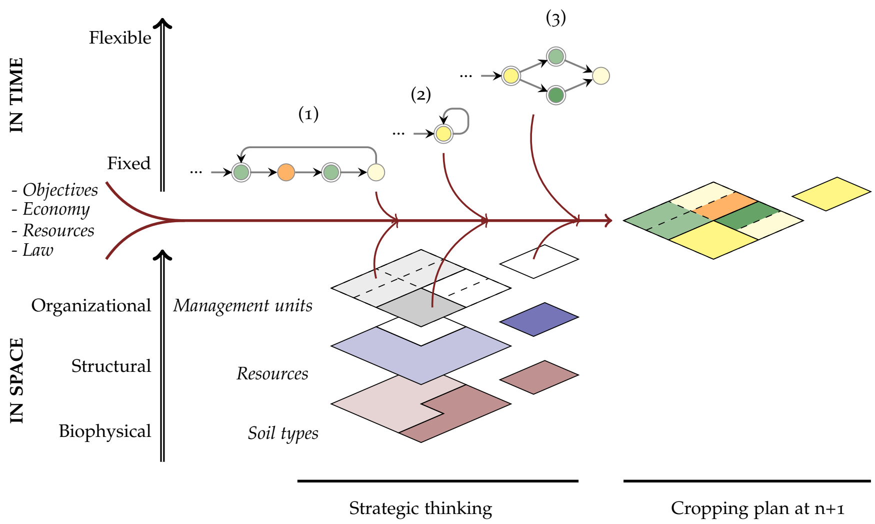


Figure 5.9: Schematic representation that shows interactions between spatial and temporal dimensions along the strategic cropping-plan decisions making processes represented by ⟶. At the strategic level, farmers build their cropping-plan by designing a set of cropping-systems that combine spatial and temporal allocation strategies. These strategies take into account their objectives, the socio-economic context, the resource availabilities and the features of their farms. Vertical arrows (⇑) are directed towards higher flexibility. In time, farmers can decide from fixed to adaptative crop sequence pattern for planning the succession of crops over years. In space, farmers have take into account different level of constraint from biophysical to organizational constraints. [simple rotation: (1), mono-cropping: (2) , Flexible sequence: (3), main crops: ◯, past land use: ... →]

5.3.3.2 *Adaptation phase*

We identified that adaptations of the initial cropping-plan can differently affect delimitation of the planned management units (Figure 5.10). We summarised the effects of the cropping-plan adaption decisions on the management units into three groups:

- *Crop substitution:* It refers to the exchange of a crop by another without affecting the management units boundaries. It can be planned by farmers into flexible crop sequence patterns (1 in Figure 5.10) or not case of unanticipated situations (2 in Figure 5.10).
- *Adjusting management unit boundaries:* We distinguished two types of adjustment: between plots within a cropping system (4 in Figure 5.10) and between plots within different cropping systems (5 in Figure 5.10). Adjustment of the management units bound-

aries are used to adapt acreages of the crops to resource availabilities (irrigation water) and/or crop price variations.

- *A combination of the two firsts:* Sometimes the introduction of new crops require to adjust the management unit boundaries (3 in Figure 5.10). This type of adaptation occurs with contract opportunities concerning specific crops with high return and that require small area (e.g. onions).

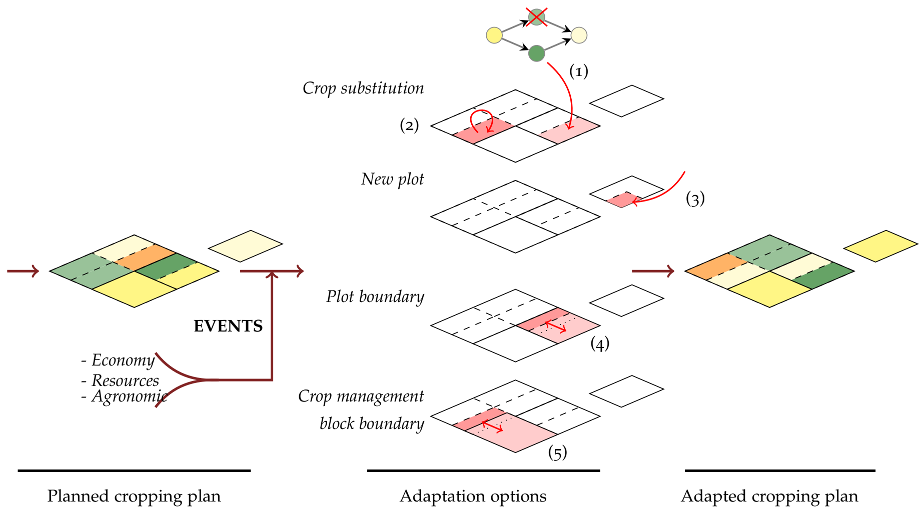


Figure 5.10: Schematic representation that shows the effect of cropping-plan adaptations (■) on the management unit boundaries. The adaptations are responses to external events (e.g. price change, water quota reduction, regulation change) and can have different consequences on the management units: 1) planned or 2) unplanned substitution of crops, 3) introduction of new plots, 4) increasing/decreasing plot sizes with in a crop management block and 5) increasing/decreasing crop management block sizes.

5.4 DISCUSSION

5.4.1 *The cropping-plan emerges from the design of the different cropping systems*

Planning is a forward-looking concept and is intimately linked with decision maker strategy. The decision maker desires a state of affair and arranges his resource strategically so that his chances of reaching his objectives are improved. The farmer objectives were sometimes competing and cropping-plan decision-making was necessarily a trade off between a set of heterogeneous objectives and constraints. As already argued by Nevo et al. (1994) and Aubry et al. (1998a), we showed in this study that representing cropping-plan selection as a single problem of resource allocation (e.g. Annetts and Audsley, 2002; Itoh et al., 2003) or as a problem crop rotation design (e.g. Dogliotti et al., 2004; Bachinger and Zander, 2007) is not sufficient to account for the problem solving that farmers are facing (Ohlmer et al., 1998).

To understand the cropping-plan decision-making process, we characterised the farmer strategies that drive their production choices. We demonstrated that the cropping-plan decision-making were intimately linked with the design of the different cropping systems and their spatial allocation within the farms. Aubry et al. (1998a); Navarrete and Bail (2007) already proposed this idea in a modelling approach where the different cropping systems emerged from the iterative allocation of crops hierarchically sorted while respecting a set of constraints regarding resources (e.g. soil, water, equipment) and crop sequencing rules (e.g. return time, preceding crop). However unlike Aubry et al. (1998a), we identified several strategies, between and within farm(s), to design the different cropping systems.

In the same way that crops fulfill different functions within crop sequence patterns (see: Bullock, 1992; Leteinturier et al., 2006; Castellazzi et al., 2008), the different cropping systems have purposely specific functions in the overall farmer strategy of cropping-plan choice. Functions associated to cropping systems were 1) the search of the best resource use (e.g. water, labour), 2) to take advantage of the farmland heterogeneity (e.g. soil type), but also 3) the search of stability and/or flexibility as regard to uncertain production factors (e.g. economic, water, agronomic).

5.4.2 *Planning and adaptive activities*

It is sometimes admitted that farmers who focus exclusively on crop rotations to design their cropping systems ensure the robustness of the cropping-plan over time but reduce their leeway for contextual adaptations (e.g. Kein Haneveld and Stegeman, 2005). At the other extreme, farmers focusing only on annual crop acreage allocation fit better to the changing context but does not consider inter-annual interactions between crops (e.g. Dogliotti et al., 2004). However, we found that only few farmers followed these two extreme strategies.

We confirmed our hypothesis that the cropping-plan decision-making does not occur once a year or once a rotation but is a continuous process. It consists in a permanent and dynamic update of the initial cropping-plan. This finding as several consequences:

– The timing of the strategic decision that we identified was more likely the time horizon over which the farmer make a plan rather than the time when the decision was taken. Thus, the strategic decisions are more plausibly a partial and continuous redesign of the existing cropping systems rather than design activities from scratch. This implies that the representation of cropping-plan decision-making processes must necessarily be done by considering the past cropping systems with their underlying design coherence. Cropping systems are not build *ex nihilo*.

– Whether some adaptation options were anticipated by farmers while considering uncertainty of some production factors, some adaptations did not refer to any plans as described by the farmers. This means that either, we did not captures the whole complexity of the decision-making processes of farmers or either that farmers take some decisions that exceed their planning strategies to fit at best unanticipated situation and/or market opportunity. Such unplanned behavior were very difficult to understand and therefore to describe in formal way.

5.4.3 *Uncertainty and cropping-plan decision-making process*

Uncertainty are important features of agricultural production and play an important role in almost every important agricultural decisions (Chavas and Holt, 1990; Hardaker et al., 2004). The analysis and understanding of the farmer decision-making process is intimately linked to the goal of understanding individual attitudes toward uncertainty (Dorward, 1999). The descriptions of the decision sequences were therefore a starting point to understand the way uncertainty impact on the cropping-plan decision-making. In this analysis, we confirmed that decision under uncertainty is not only a matter of taking into account the probabilities of occurrence of future events. But deciding in complex and dynamic environments also concerns strategies, information processing (Chavas, 2004) and adjustment responses (Dorward, 1999) to the so-called embedded risk (Hardaker et al., 1991).

5.4.4 *Modelling perspectives*

Modelling and simulating decision-making process of farmer is becoming a critical issue in the field of agricultural modelling (Le Gal et al., 2011; Bergez et al., 2010; Nuthall, 2010). This paper provides formal concepts to describe the farmers' cropping-plan decision strategies in their spatial and temporal dimensions at strategic and adaptive levels. The representation of the crop sequence pattern as graph has already been used into modelling approaches by Rodriguez et al. (2011) to study farming system flexibility. Same concept could be used in a decision modelling approach to represent farmers' knowledge and to structure decision factors in a comprehensive way. The development of decision support tools that are based on the modelling of farmers' cropping decision-making process could enable researchers to provide knowledge and tools as a way to enhance decision-making at specific stages of the decision process (Cox, 1996; Bacon et al., 2002; Sorensen et al., 2010).

5.5 CONCLUSIONS

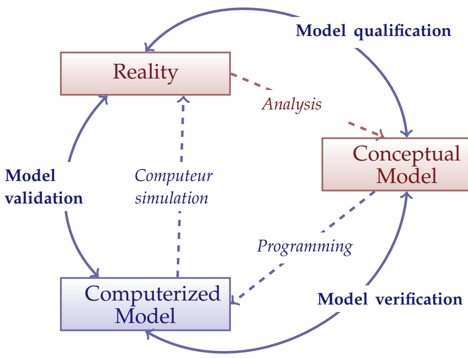
This study demonstrated that the cropping-plan does not emerge from a single decision but is a dynamic decision-making process, incorporated into a succession of other decisions. Whether the timing of decision-making leading to the cropping plan is very different from farm to farm, we showed that some common features that drive the spatio-temporal dynamic of the decision-making. We proposed formal representation of the main concepts to described the spatio-temporal interactions taken into account by farmers while designing their cropping-plan. All these formal concepts could be used for developing models addressing the question of cropping-plan choices at the farm level.

6

FARMER'S RISK ATTITUDE: RECONCILIATING STATED AND REVEALED PREFERENCE APPROACHES

Why this chapter?

This Chapter presents an analysis of farmers' attitude towards risk. We compared different stated and revealed methods to elicit and estimate individual farmer's risk aversion. In **red**, phases of modelling and simulation that are concerned by this chapter.



(Adapted from Schlesinger, 1979 in Bellocchi et al., 2011)

This chapter is under review as:
Reynaud A., S. Couture, Dury, J., Bergez, JE. 2011. Farmer's Risk Attitude: Reconciliating Stated and Revealed Preference Approaches? American Journal of Economic, Submitted.

Parts of this chapter were presented as:
Couture S., A. Reynaud, J. Dury, JE. Bergez, 2010. Farmer's risk attitude: Reconciliating stated and revealed preference approaches? In Fourth World Congress of Environmental and Resource Economists. Montreal, Canada, p. 34.

Reynaud A., S. Couture, J. Dury, JE. Bergez, 2010. Farmer's risk attitude: Reconciliating stated and revealed preference approaches? In Risk Elicitation and Stated Preference Methods for Climate Change Research. Trento, Italy, p. 25.

6.1 INTRODUCTION

Risk and uncertainty are important features of agricultural production, and play a fundamental role in almost every important agricultural decisions. Since differences in farmers' willingness to take risks can induce differentiated agricultural decisions, understanding individual attitudes toward risk is intimately linked to the goal of analyzing and understanding economic behaviors of farmers.

As a result, there exists a large literature in agricultural economics aiming at identifying farmer's risk preferences. Two different approaches have been followed: "stated preference methods" and "revealed preference methods". In stated preference approaches, risk attitudes are elicited through use of hypothetical questions regarding choices of risky lotteries, see the seminal papers by Binswanger (1980) or Binswanger and Binswanger (1981). In revealed preference methods, risk attitude of farmers is imputed based on the divergence between observed farmer's decisions (input use, output choices) and optimal decisions under risk, see Antle (1987) or Chavas and Holt (1990). In fact, the two risk attitude elicitation approaches strongly differ in terms of underlying assumptions and in the way they have been empirically implemented (sample size for instance). The central issue we empirically investigate in this article is then to evaluate the consistency of risk preferences elicited by revealed and stated preferences approaches on the same sample of individuals.

There are in fact two main reasons that may explain why risk attitudes elicited through the two elicitation methods might not coincide. First, the literature in psychology has demonstrated that risk attitude is not a stable personality trait, see Weber et al. (2002), and that risk preferences are in fact highly domain-dependent. Blais and Weber (2006) provide some evidence showing that it is possible to identify specific risk preferences for seven different domains (e.g., social, recreational, health, safety, gambling, ethical, and investments). If revealed and stated preference methods do not measure risk attitude on the same domain, this may constitute a first reason of discrepancies. The second reason is related to the distinction made by Binswanger and Siller (1983) and Eswaran and Kotwal (1990) between *"pure risk aversion"* and *"market risk aversion"*. Those authors suggest that there are two types of risk aversion: pure risk aversion which defines the utility function curvature and market risk aversion which is the revealed risk preference that may be influenced by other constraints. The risk aversion elicited from a stated preference approach

---

MacCrimmon and Wehrung (1990) have showed that executive managers have different risk attitudes when making decisions involving personal versus company money or when evaluating financial versus recreational risks.

should be pure risk aversion, and the revealed preference approach provides market risk aversion. Since pure risk and market risk aversion have different foundations, nothing guarantees a priori that they may coincide.

Consistency of risk preference measures across elicitation methods is not a new issue. As mentioned by Liu (2008), there exists for instance a long standing debate regarding the external validity of experimental approaches. However, it is surprising to notice that, although there exists a number of farmer's risk preference assessments using either a revealed preference approach or a stated preference one, only a few works have directly compared the two methods on the same sample of individuals. To our best knowledge, Lin et al. (1974) is the unique study that aims at comparing the results of direct risk preference elicitation with observed economic behavior represented by expected profit maximization models. The authors conclude that although the expected utility model gives more accurate predictions of behavior than the expected profit maximization model, "none of the models predicted actual behavior well, with a strong tendency for all models to predict more risky behavior than was in fact observed." A check of consistency across risk preference elicitation methods is interesting since risk aversion elicited through lottery tasks are more and more often used to understand real decisions of farmers. For instance, Engle-Warnick et al. (2006) have included risk aversion elicited through a stated preference approach to explain observed crop diversification of farmers. They report however that the predictive power of risk aversion is low.

In this paper, we propose (a) to review and to critically assess the state of knowledge on risk preference elicitation methods and empirical results on agricultural producers and (b) to compare risk attitude elicited on the same sample of French farmer using stated and revealed preferences approaches. In order to elicit risk preferences, we first use an experimental approach based on two lottery tasks (the Holt and Laury (2002) procedure and a variation of the Eckel and Grossman (2008) procedure). Second, we develop a simple farm-level land allocation model under climatic risk and we econometrically assess farmer's risk preferences. The comparison of the two different approaches reveals that risk attitudes vary within subjects across elicitation methods. However, our results indicate that risk attitudes measured through stated and revealed preference approaches are more consistent than what has been reported in the existing literature.

Antle (1987) provides a comparison of econometrically estimated risk attitudes to experimental results obtained by Binswanger (1980) for a similar group of farmers. However, the comparison is only conducted at an aggregated level.

The remaining of the paper is organized as follows. In Section 6.2, we survey the empirical literature on farmers' risk aversion. In Section 6.3, we describe the data used for eliciting farmer risk aversion on French farmers. Section 6.4 and 6.5 present our estimation of farmers risk preferences respectively using stated and revealed preference approaches. In Section 6.6, we analyze the consistency of risk attitude measures across the stated and the revealed preference approaches.

6.2 A survey of empirical studies on farmer's risk aversion

Both direct and indirect elicitation approaches have been used to measure farmer's risk attitudes. In this section, we review the main empirical works having used these two approaches.

6.2.1 *Revealed preference approaches*

Some researches have attempted to estimate farmer's risk attitudes using observed decisions of farmers (input use, land use, contract choice), see Table 6.1. In revealed preference approaches, risk aversion is then obtained from the divergence between actual farmer's decisions and optimal decisions under risk neutrality (Moschini and Hennessy, 2001). Three main econometric methodologies for estimating farmer's risk preferences have been proposed: reduced-form, structural and non-structural approaches, see Saha et al. (1994) or Antle (1989).

The reduced-form approach specifies an exogenously given risk preferences structure which induces a set of restrictions on changes in optimal inputs or outputs due to variations in parameters such as wealth. Reduced-form approaches allows to test restrictions of certain risk preference structures. All the reduced-form studies have found that risk preferences are characterized by Decreasing Absolute Risk Aversion (DARA). The nature of relative risk aversion is more ambiguous. Constant Relative Risk Aversion (CRRA) hypothesis is not rejected by Pope and Just (1991) but is rejected by Chavas and Holt (1990). Increasing Relative Risk Aversion (IRRA) is accepted by Saha et al. (1994) whereas Lins et al. (1981) report various types of relative risk aversion.

The structural-form approach attempts to directly estimate the degree of risk aversion and the structure of risk preferences (i.e. changes in absolute or relative risk aversion associated with changes in wealth).

The interested reader may refer to Lins et al. (1981), Chavas and Holt (1990), Pope and Just (1991) or Saha et al. (1994). Notice however that the method in Saha et al. (1994) can also be considered as a structural approach since it provides a measure of risk attitudes but also and estimate of the risk preferences of farmers.

Table 6.1: Risk preferences of farmers: Results from revealed preference studies

Study	Country	Production	Sample size	Approach[a]	Measures of risk aversion[b] ARA	RRA	Structure of risk preferences[c]
Wiens (1976)	China	Arable crops	–	SA	[0.0085,0.091]	–	Not evaluated
Brinck and McCarl (1978)	US	Arable crops	38	SA	[0,0.25]	–	Not evaluated
Lins et al. (1981)	US	Crop and livestock	3,637	RA	–	–	DARA, varying RRA
Buccola (1982)	US	Tomatoe	1	SA	[0.0012,0.00196]	–	Not tested
Antle (1987)	India	Rice	282	SA	3.272	1.963	DRA
Antle (1989)	India	Arable crops	350	NSA	PRA[-0.10,1.40]	–	DRA
Chavas and Holt (1990)	US	Arable crops	–	RA	–	–	DARA
Pope and Just (1991)	US	Potato	32	RA	–	–	CRRA
Love and Buccola (1991)	US	Arable crops	264	SA	[0.016,0.538]	–	Not evaluated
Saha et al. (1994)	US	Wheat	15	RA/SA	[0.0045,0.0083]	[3.759,4.075]	DARA, IRRA
Chavas and Holt (1996)	US	Arable crops	–	SA	[3.523,15.922]	[1.414,6.813]	DARA, DRA
Saha (1997)	US	Arable crops	15	SA	[0.5308,0.8966]	–	DARA, varying RRA
Bar-Shira et al. (1997)	Israel	Veg.	101	SA	0.0000044	0.615	DARA, IRRA
Coyle (1999)	Canada	Crop and livestock	–	SA	–	–	CARA rejected
Lansink (1999)	Netherlands	Crops and Rootcrops	46	SA	[0.09,0.014]	[0.20,0.31]	Not evaluated
Lence (2000)	US	All sectors	61	SA	–	[1.061,1.211]	Not evaluated
Bontems and Thomas (2000)	US	Corn	140	SA	–	3.717	Not evaluated
Torkamani and Haji-Rahimi (2003)	Azarbaijan	Wheat and peas	20	SA	[-0.0293,0.0077]	–	DARA, DRA
Kumbhakar (2002a)	Norway	Salmon	28	SA	–	RRP[0.116,0.293]	Not evaluated
Kumbhakar (2002b)	Norway	Salmon	216	SA	0.106	0.051	DARA
Kumbhakar and Tveteras (2003)	Norway	Salmon	28	SA	[0.308,0.441]	RRP[0.115,0.315]	DRA
Isik and Khanna (2003)	US	Corn	198	SA	1.479	–	DARA, IRRA
Gardebroek (2006)	Netherlands	Arable crops	227	NSA	2.432,3.064	–	Not evaluated
Sckokai and Moro (2006)	Italy	Arable crops	6,858	SA	–	[0.049,5.531]	Not evaluated
Zheng et al. (2008)	US	Hog	599	SA	0.00014	–	Not evaluated
Groom et al. (2008)	Cyprus	Cereals and Veg.	283	NSA	0.0726,0.3401	–	DRA
Serra et al. (2008)	Spain	Arable crops	3754	NSA	–	–	DARA
Koundouri et al. (2009)	Finland	Wheat and barley	443	NSA	[-0.900,0.246]	RRP[-0.02,0.45]	DARA
Sckokai and Moro (2009)	Italy	All sectors	15777	SA	–	0.097	Not evaluated
Kumbhakar and Tsionas (2010)	Philippines	Rice	43	SA	–	RRP[0.02,0.14]	Not evaluated

[a]: Reduced-form Approach (RA), Structural-form Approach (SA), Non-structural Approach (NSA).

[b]: ARA and RRA for respectively Absolute and Relative Risk Aversion coefficients; PRA is Partial Risk Aversion coefficients; RRP is Relative Risk Premium.

[c]: CARA, IARA and DARA for respectively constant, increasing and decreasing ARA.

DRA for downside risk aversion.

It usually consists first in estimating the probability distribution of output given inputs and then in inferring each farmer's risk attitude from deviations between his choice of inputs and the profit-maximizing input choice. For example, when the estimated marginal cost exceeds the marginal profit of pesticides, Antle (1987) interprets the excessive application of pesticides as a risk premium paid by risk-averse farmers. Structural approaches include the works by Wiens (1976), Brinck and McCarl (1978), Buccola (1982), Saha et al. (1994), Antle (1987), Love and Buccola (1991) or Torkamani and Haji-Rahimi (2003).

Some works identify risk preferences separately from production technology whereas others consider a joint estimation of preferences and technology with a specified utility function or a more flexible utility function. All studies based on the structural approach report a low level of farmer's risk aversion. When flexible utility functions are used, no consensus on the structure of risk preferences seems to emerge.

The non-structural form approach proposes to measure risk preferences using changes in the moments of the profit distribution. Similarly to the structural approach, this approach is based on an expected utility framework but it is non-structural in the sense that no explicit optimal decision rules are derived. The moments of the distribution of random profits are related to optimal changes in expected utility. Arrow-Pratt coefficients of risk aversion can be derived by assuming that changes in expected utility are randomly distributed in the population of farmers and specifying parameters for this distribution. All the results of the non-structural approach works confirm that farmers are risk averse.

In Table 6.1, we have surveyed the main studies having used revealed preference approaches for estimating farmer's risk attitudes. In general, those studies find that farmers are risk averse, but generally with a low risk aversion. The CARA structure of risk preferences is generally rejected, and evidence concerning the other possible structures be mixed. Some studies such as Antle (1987) or Groom et al. (2008) have found downside risk aversion. Notice that a vast majority of studies deal with developed countries.

(See Wiens, 1976; Brinck and McCarl, 1978; Buccola, 1982)

(See Love and Buccola, 1991; Coyle, 1999; Lence, 2000)

(See Saha et al., 1994; Chavas and Holt, 1996; Bar-Shira et al., 1997; Kumbhakar, 2002a,b; Torkamani and Haji-Rahimi, 2003; Kumbhakar and Tveteras, 2003; Isik and Khanna, 2003)

(See Antle, 1989; Gardebroek, 2006).

Downside risk aversion means that when there is a choice between two output distributions with the same mean and variance, the output distribution which is less skewed to the left is preferred (Kumbhakar and Tveteras, 2003). The intuition behind

6.2.2 *Stated preference approaches*

Alternatively, risk attitudes can be inferred using a stated preference approach. A stated preference approach usually involves hypothetical questions regarding risky decisions with probabilities and payoffs objectively defined. One advantage stated preference approach is that risk preferences and perceived risks are not confounded. According to Harrison and Rutström (2008), five elicitation procedures have been used to ascertain individual risk attitudes using experimental settings, see Table 6.2. Among the five methods, two have been extensively used: a multiple price list experiment proposed by Holt and Laury (2002) and an ordered lottery selection initially developed in Binswanger (1980) for Indian farmers.

In Table 6.2 we have surveyed the empirical studies having elicitated farmer's risk aversion using stated preference approaches. First, it is interesting to notice that the reported studies differ significantly in terms of method, sample size (from 5 individuals to a few hundred) and type of payoffs (hypothetical versus real). Second, they however focus mainly on developing countries. Third, they demonstrate that farmers tend to exhibit relatively high levels of risk aversion, whatever the payoff type or the method used. Last, risk aversion does not seem to systematically monotonically vary with wealth.

6.2.3 *Discussion*

The main conclusion to be drawn from the previous analysis is that empirical results on risk preferences of farmers appear to be approach-dependent. Farmers appear to be more risk averse with a stated preference approach than with a revealed one. The CARA structure of risk preferences is generally rejected with revealed preference approaches whereas no similar result emerges with stated preference approaches.

There are several reason that may explain differences obtained with stated and revealed preference approaches. First, Binswanger and Siller (1983) suggest that there are in fact two types of risk aversion namely, *pure risk aversion* and *it market risk aversion*. Pure risk aver-

---

this is that farmers are willing to pay a premium in order to avoid particularly bad outcomes.

Several studies have compared different experimental designs in order to test the consistency of elicited risk preferences but no consensus has yet clearly emerged. Slovic (1969), Hershey et al. (1982), Hershey and Schoemaker (1985), Harrison and Rutström (2008), Engle-Warnick et al. (2006), Andersen et al. (2006), Dave et al. (2008), Anderson and Mellor (2009), van den Berg et al. (2009) have found discrepancies between experimental methods whereas Holt and Laury (2002) or (Harrison and Rutström, 2008) obtain no significant divergence.

Table 6.2: Risk preferences of farmers: results from stated preference studies

Study	Location	Sample size	Method[a]	Payoffs[b]	Measures of risk aversion[c]	Structure of risk preferences[d]
Officer and Halter (1968)	Australia	5	OD	H	IRA=-0.076-0.605	n.a.
Dillon and Scandizzo (1978)	Brazil	130	OD	H	ARA= -3.46 - 0.40	IRRA
Bond and Wonder (1980)	Australia	201	OD	H	RP=0.02 - 0.09	No significant effect
Binswanger (1980)	India	240	OLS	R,H	CRRA = 0.71	IPRA
Belaid and Miller (1987)	Algeria	78	OLS	R	PRA: 1.12 - 2.60	No significant IPRA
Grisley and Kellog (1987)	Thailand	39	OLS	R,H	PRA= 0 - 8.3458	CPRA or IPRA
Nielsen (2001)	Madagascar	70	OLS	R,H	PRA: 0.315; 0.321	n.a.
Henrich and McElreath (2002)	China, Tanzania	257	OLS	R	Risk-preferring	No effect
Binici et al. (2003)	Turkey	50	OLS	H	ARA= -0.0185 - 0.5062	n.a.
Barr (2003)	Zimbabwe	678	OLS	R	Risk-preferring	n.a.
Knight et al. (2003)	Ethiopia	342	OD	H	RA	n.a.
Pennings and Wansink (2004)	Netherland	128	OD	H	ARA= -0.462	n.a.
Wik et al. (2004)	Zambia	110	OLS	R		DARA, IPRA
Liu (2008)	China	320	MPL	R	RRA=0.48	DRRA
Engle-Warnick et al. (2008)	Peru	160	OLS	R	NT=2.074	DARA
Galarza (2009)	Peru	378	MPL	R	RRA = 0.52	EU[f] (35 %), CPT[e] (65 %)
Yesuf and Bluffstone (2009)	Ethiopia	262	OLS	R	PRA: 4.204	DARA, IPRA
Tanaka et al. (2010)	Vietnam	184	MPL	R	ARA = 0.60; 0.67	IARA
Harrison et al. (2010)	Ethiopia, India, Uganda	531	OLS	R	RRA= 0.536	n.a.
(Akay et al., 2011)	Ethiopia	92	MPL	R	RRA=0.73	CRRA

[a] Harrison and Rutström's classification of elicitation procedures: Multiple Price List (MPL), Random Lottery Pairs (RLP), Ordered Lottery Selection (OLS), Becker-DeGroot-Marschak (BDM), Trade-Off (TO), Other Design (OD).

[b] (R) for real and (H) for hypothetical payoffs.

[c] IRA: The Index of Risk Aversion used by the authors is the slope of an E-V indifference curve; RP: Risk Premium; RRA: Relative Risk Aversion; PRA: Partial Risk Aversion; ARA: Absolute Risk Aversion; NT: Number of times subjects chose safe gamble.

[d]: n.a.: not analyzed; IRRA: Increasing Relative Risk Aversion; IPRA: Increasing Partial Risk Aversion; CPRA: Constant Partial Risk Aversion; DRRA: Decreasing Relative Risk Aversion; DARA: Decreasing Absolute Risk Aversion; IARA Increasing Absolute Risk Aversion.

[e]: Unavailable works but previously cited in other works.

[f] EU = Expected Utility; CPT = Cumulative Prospect Theory.

sion defines the utility function curvature whereas market risk aversion is the revealed risk preference which may be influenced by other constraints. The risk aversion elicited from experimental approaches should be pure risk aversion. The risk preferences elicited through revealed approaches correspond to market risk aversion. There are a priori no reasons why pure and market risk aversion should coincide.

Another explanation could be related to the fact that individual often exhibit domain-specific risk preferences. A suggested by Deck et al. (2008), the observed instability of risk preferences could be related to the fact that risk attitudes may vary depending on the considered domain. If revealed and stated preference approaches allow to elicit risk preferences for two distinct domains (for instance the professional and financial domains), then the measures of risk aversion should not necessarily coincide.

A third explanation could be related to some bias associated to each approach. As already mentioned, the main limit of the revealed preference approaches is to confound risk behavior with other behavior determinants such as resource constraints and risk perceptions, see Eswaran and Kotwal (1990) or Lybbert and Just (2007). Moreover, Lence (2009) has recently shown that identifying the structure of risk aversion using agricultural production data relies on sources of information often too weak to allow for a reliable econometric estimation. Stated preference approaches are not exempt from bias and framing effects. The most well documented bias is the hypothetical bias which has been shown to be a relevant issue in many situations (Harrison, 2006).

A last explanation for differences in the risk aversion obtained with stated and revealed preference approaches could be a sample selection bias. Hence, as mentioned previously, almost all studies having used a revealed preference approach deal with developed countries whereas stated preferences approaches have been implemented mainly in developing ones. The lower risk aversion obtained in revealed preference approaches could be due to the fact that farmers

All elements of decision-making are supposed to be controlled by imposing decisions under risk based on lotteries that limits the effects of external factors.

Estimation of risk preferences by revealed preference approaches comes from the difference between observed and predicted behaviors. This difference is entirely attributed to risk aversion whereas it could be also justified by many factors other than risk aversion.

MacCrimmon and Wehrung (1990) have showed that executive managers have different risk attitudes when making decisions involving personal versus company money or when evaluating financial versus recreational risks. The literature in psychology has demonstrated that risk-taking is in fact highly domain-specific, see Weber et al. (2002).

In experiments using farmers, Binswanger (1980) and Nielsen (2001) have found no significant difference between risk aversion elicited from experiments involving real and hypothetical payoffs whereas Grisley and Kellog (1987) has reported significant differences.

in developed countries have access to a lot of risk management tools (precautionary saving, long-term production contract, crop insurance) which are not often available in developing countries.

Since it is difficult to show if differences in risk preference evaluations obtained by the two approaches should be attributed to some differences in sample characteristics or in methodology issue, we implement in what follows both approaches on the same pool of subjects.

6.3 DATA

In this section, we present the data we have used for measuring farmer's risk preferences using a stated or a revealed preference approach.

The farmer sample is based on a farmer's survey we have conducted from May to June 2009 in three French regions, namely Midi-Pyrénées, Poitou-Charentes and Centre. The surveyed farmers have been randomly selected within three broader pre-selected lists of farmers provided by local extension services and cooperatives. The pre-selected lists include farms covering a large diversity of situations (location, soil and climate, cropping system, farm size) within each of the three regions. To insure a minimum level of farmer's homogeneity, the final sample has however been restricted to only cash crop producers using irrigation. Hence, mixed and animal farms have therefore been avoided from our sample.

30 farmers have finally been surveyed using face-to-face interviews. Among these 30 farmers, 10 are located in the Midi-Pyrénées region, 10 in the Poitou-Charentes region and 10 in Centre region. We have used semi-structured farmer's interviews and non-structured interviews with key informants from local extension services (n=3). The interview questionnaire was divided into four complementary parts: 1) farmer's objectives for farm productions (past, current and future), 2) characterization of the on and off-farm constraints that affect cropping plan decisions, 3) Characterization of the how farmers make decisions, what information they use and what are the operations to be done when an option is selected, and 4) risk aversion elicitation through stated preference approaches.

In the three first parts of the questionnaire, we have collected various technical information about farmers. In particular farmers have reported their land allocation across crops for year 2006, 2007 and

The sample size might appear low but previous studies using stated preference methods report sample size varying from 5 farmers to a few hundreds. Moreover, the average duration of each interview was 3 hours, which has limited the number of interviews that could be conducted within two months.

Table 6.3: Descriptive statistics on farmer characteristics per region

	Total sample		Centre		Midi-Pyrénées		Poitou-Charentes	
	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
Land use								
Total land (ha)	164.33	90.85	168.64	50.54	130.85	113.01	189.30	104.56
Irrigated land (ha)	105.25	62.79	143.86	53.34	89.30	80.36	76.54	30.31
share of irrigated maize	0.24	0.20	0.14	0.09	0.37	0.27	0.23	0.15
share of pluvial maize	0.03	0.06	0.01	0.02	0.04	0.10	0.04	0.04
share of hard wheat	0.09	0.12	0.12	0.15	0.07	0.11	0.07	0.10
share of soft wheat	0.21	0.17	0.32	0.14	0.10	0.15	0.21	0.13
share of rape	0.09	0.09	0.11	0.09	0.05	0.08	0.10	0.09
share of barley	0.08	0.08	0.10	0.07	0.01	0.02	0.12	0.08
share of soybean	0.02	0.05	0.00	0.00	0.05	0.08	0.00	0.00
share of sunflower	0.07	0.10	0.01	0.04	0.13	0.13	0.09	0.09
share of fallow	0.08	0.06	0.06	0.03	0.08	0.03	0.09	0.10
share of other crop	0.09	0.12	0.14	0.09	0.10	0.18	0.04	0.08
Economic characteristics								
Gross income (10^3 €)[a]	153.27	82.06	165.61	35.45	115.86	90.37	176.96	103.69
Decoupled payment (10^3 €)	24.12	13.28	23.67	6.56	21.14	18.53	27.27	14.28
Full time workers	1.55	0.84	1.48	0.65	1.44	1.04	1.75	0.88
Other characteristics								
Age (in years)	47.48	7.79	47.40	6.33	46.00	10.48	49.25	6.48
Number of children	1.50	1.00	1.40	1.07	1.11	1.17	2.00	0.50
High education[b]	21.43%	0.41	20.00%	0.42	22.22%	0.44	22.22%	0.44

[a]: marketed value of all crop products in 2008

[b]: percentage of farmers having completed high school degree

2008 and different technical characteristics including the share of irrigated land for each crop. Table 6.3 provides some descriptive statistics on our farmer sample. Our sample is made of relatively large farms, since the average area of land used for crop production is above 160 ha compared to 110 ha on average in 2005 for French cash crop farms. It varies significantly across regions, from 130.85 ha in the Midi-Pyrénées to 189.30 ha in the Poitou-Charentes. Cropping systems are also quite different across regions. Irrigated maize represents a substantial part of the crop area in Midi-Pyrénées (more than 37%), whereas the dominant crop is wheat in Centre and in Poitou-Charente (42% and 28% respectively). Differences in gross income are related to differences in farm sizes: the gross profit per ha of land used for crop production are not statistically different from one region to another (from 885 € per ha for Midi-Pyrénées to 932 € per ha for Centre). Means for age, number of children and percentage of farmers having completed high school degree are not statistically different from one region to another.

6.4 RISK PREFERENCE ELICITATION THROUGH A STATED PREFERENCE APPROACH

In this section, we present the methodology used for measuring farmer's risk preferences using a stated preference approach. Then we discuss the results obtained on our sample of French farmers.

6.4.1 *Experimental design*

The experimental design is the last part of the 3-hour survey aiming at understanding farmer's land use and crop choices. For each subject, the experimental part which lasted around half an hour, is made of two experimental lottery choices. This experimental framework corresponds to an *artefactual field experiment* according to the Harrison and List (2004) terminology.

A comprehensive introduction of the methods and goals, and scoreless questions were necessary prior to the four tests to insure a good comprehension. In order to ensure incentive compatibility, subjects are usually informed that after the experiment a random device would determine how much they would be paid according to their decisions. Since, we have not been allowed to pay the subjects, we had to rely on another mechanism. In order to ensure a minimal level of incentives, farmers where explained that after the experiment they would receive a personal risk assessment of their behavior that can be useful to them in their professional of personal life. This personal risk assessment may be viewed as a non-monetary fixed payment. Since the experiment is based on a voluntary participation of all subjects, we believe that farmers interest is high enough to insure that their answers reflect effectively their real preferences. Moreover, Holt and Laury (2002) or Harrison (2006) have found that there are no significant differences in terms of observed decisions between lottery choices using hypothetical or real payoffs.

In the expected utility framework, differences in risk attitude are modeled by utility functions that differ in shape, with different degrees of concavity to explain risk aversion. Controlled laboratory experiments can then be used to study risk attitudes within this context. We consider two different tasks that have been extensively used in the experimental literature for eliciting risk preference. The first one

Farmers were also asked to pass a personality test and have provided a a self-assessment of their own risk preferences.

is derived from Holt and Laury (2002) who have developed a series of binary comparisons in which payoffs are the same for each comparison but probability of receiving the higher payoff varies across comparisons. We also adapt the task initially proposed in Eckel and Grossman (2002).

6.4.1.1 *Adaptation of the Holt and Laury (HL) experiment*

The first lottery task is an adaptation of the well known "multiple price list" proposed by Holt and Laury (2002) for the elicitation of risk attitudes. In the HL task, subjects are shown different binary lotteries and must select either option A (the "safe" lottery) or option B for each one (the "risky" lottery). The payoffs for option A are fixed at \$2.00 and \$1.60 while the payoffs for option B are fixed at \$3.85 and \$0.10. As noted by Holt and Laury, the payoffs for the safe lottery (Option A) are less variable than those for the risky lottery (Option B). In each successive row, the likelihood of receiving the larger payoff increases. In the final row there is no uncertainty and monotonicity alone is sufficient to lead a person to select option B. By assuming constant relative risk aversion, the subject risk aversion is then directly related to the line at which he switches from preferring option A to preferring option B going down the table.

Table 6.4: Adaptation of Holt and Laury task

		Option A		Option B		Implied Range	CRRA
Prob. 1	Prob. 2	Payoff 1	Payoff 2	Payoff 1	Payoff 2	of CRRA	code[a]
1/10	9/10	20.0	16.0	38.5	1.0	$r \leqslant -0.95$	RL3
2/10	8/10	20.0	16.0	38.5	1.0	$r \leqslant -0.95$	RL3
3/10	7/10	20.0	16.0	38.5	1.0	$-0.95 < r \leqslant -0.49$	RL2
4/10	6/10	20.0	16.0	38.5	1.0	$-0.49 < r \leqslant -0.15$	RL1
5/10	5/10	20.0	16.0	38.5	1.0	$-0.15 < r \leqslant 0.15$	RN
6/10	4/10	20.0	16.0	38.5	1.0	$0.15 < r \leqslant 0.41$	RA1
7/10	3/10	20.0	16.0	38.5	1.0	$0.41 < r \leqslant 0.68$	RA2
8/10	2/10	20.0	16.0	38.5	1.0	$0.68 < r \leqslant 0.97$	RA3
9/10	1/10	20.0	16.0	38.5	1.0	$0.97 < r \leqslant 1.37$	RA4
10/10	0/10	20.0	16.0	38.5	1.0	$1.37 \leqslant r$	RA5

All payoffs measured in euros

[a]: RL, RN and RA respectively for risk lover, neutral and averse.

We have chosen to use the framework provided by Holt and Laury (2002) except that the payoffs have been converted in euros and modified in order to represent a larger amount of money. In fact, all payoffs for options A and B have been converted in euros and multiplied by 10 compared to the original task. As a result, the implied range for the CRRA parameter are not modified. The payoffs we have considered are presented in Table 6.4. Column 7 in Table 6.4 provides the implied CRRA consistent with a subject first selecting option B on that decision. For example, a risk neutral person would select option A in the first four rows of Table 1 and option B in the last 6 rows. The last column gives the CRRA code that will be used in the remaining of the paper. *Risk lover* preferences correspond to a CRRA parameter smaller than -0.15 whereas a subject will be *risk averse* if the CRRA parameter is greater than 0.15.

Holt and Laury (2002) have examined stake size effects by scaling these payoffs by factors up to 90 times the original values. Their general result is that the elicited risk aversion increases with the size of the stakes. We also test the presence of stake size effects. As a result, subjects have been asked to complete the same lottery task except that all payoffs have been multiplied by a factor 20. This second task will be called the HL lottery with high payoffs, the first one being called the HL lottery with low payoffs.

6.4.1.2 *Adaptation of the Eckel and Grossman (EG) experiment*

The second lottery task played by subjects is an adaptation of recent task proposed by Eckel and Grossman (2002, 2008) for the elicitation of individual risk attitudes. Eckel and Grossman (2002, 2008) have proposed a simple experiment allowing to measure risk attitude. Their experiment consists in asking subjects to choose from among six possible gambles the one they prefer. All the gambles involve a 50/50 chance of a low or high payoff. The range of gambles includes a safe alternative involving a sure payoff with zero variance. The gambles increase in both expected return and risk (standard deviation of the expected payoff) moving from Gamble 1 to 5. More risk-averse subjects would choose lower-risk, lower-return gambles.

For making possible the comparison with the adapted HL lotteries, we have modified both the payoffs proposed originally Eckel and Grossman (2002,2008) and the number of gambles the subjects had to choose among. The payoffs have been chosen first to get the implied ranges of CRRA identical to the adapted HL lotteries and second, to have expected payoffs similar to the adapted HL lotteries. Table 6.5 presents the adapted Eckel and Grosman lottery that will be compared to the HL one with low payoffs. Table 6.5 also includes CRRA parameters implied by each possible choice under the assumption of constant relative risk aversion (CRRA). In what follows, this task will be referred as the EG task with low payoffs. To examined a payoff size effect, subjects have been asked to complete the same task but with all payoffs multiplied by a factor 20. This second task will be called the EG task with high payoffs.

This type of lottery is designed to keep the task as simple as possible. Hence, expected payoffs are easy to calculate since they are linear in risk, measured as the standard deviation of payoffs.

Table 6.5: Adaptation of the Eckel and Grossman lottery

Choice 50/50 gamble	Payoff 1	Payoff 2	Implied range of CRRA	CRRA code
Gamble 1	40	40	r>1.37	RA5
Gamble 2	32	51	0.97<r⩽ 1.37	RA4
Gamble 3	24	64	0.68<r⩽ 0.97	RA3
Gamble 4	16	78	0.41<r⩽ 0.68	RA2
Gamble 5	12	86	0.15<r⩽ 0.41	RA1
Gamble 6	8	91.5	-0.15<r⩽0.15	RN
Gamble 7	6	92.9	-0.49<r⩽ -0.15	RL1
Gamble 8	4	93.4	-0.95<r⩽ -0.49	RL2
Gamble 9	1	93.5	r⩽-0.95	RL3

All payoffs measured in euros

6.4.2 *Experimental results*

In Table 6.6, we report the distribution of farmers across risk classes using the HL and then EG adapted experiments.

Table 6.6: Proportion of subjects by risk class using lottery tasks

CRRA class	RA5	RA4	RA3	RA2	RA1	RN	RL1	RL2	RL3
CRRA range	>1.37	0.97;1.37	0.68;0.97	0.41;0.68	0.15;0.41	-0.15;0.15	-0.49;-0.15	-0.95;-0.49	<-0.95
Adapted Holt and Laury experiment									
-low payoffs	0.04	0.11	0.07	0.18	0.14	0.21	0.04	0.07	0.14
-high payoffs	0.07	0.11	0.14	0.18	0.11	0.21	0.04	0.07	0.07
Adapted Eckel and Grossman experiment									
-low payoffs	0.29	0.07	0.21	0.07	0.11	0.04	0.00	0.00	0.21
-high payoffs	0.29	0.36	0.07	0.07	0.11	0.04	0.00	0.00	0.07

In the HL experiment, 54% of subjects appear to be risk-averse for low payoffs. 21% of the subjects are risk-neutral and 25% are risk-lover. In case of a high payoff, the subjects appear slightly more risk averse (60% of the subjects are risk-averse). However, based on a *Kornbrot* test, the distribution of subjects across risk classes with low and high payoffs are not statistically different. This result means that risk aversion measured using the HL experiment is not modified by the level of the payoff. This result is in line with Holt and Laury (2002) who find that individual behavior is largely unaffected when

The *Kornbrot* test is based on the Wilcoxon matched-pairs signed-ranks test which can be used if data are distributed non-normally. It allows testing the equality of distributions for matched pairs of observations where the data are ordinal.

hypothetical payoffs are scaled up. Using the midpoint of each CRRA class , the mean CRRA coefficient is equal to 0.14 and 0.36 respectively for a low and a high payoff. Using the Holt and Laury (2002) terminology, subjects appear to be on average risk-neutral for a low payoff and slightly risk-averse for a high one.

The distribution of risk preference appears to be much more dissymmetric using the EG task than using the HL one. For low payoffs, 75% of subjects are classified as risk-averse. The percentage reaches 89% for high payoffs. Moreover, based on a *Kornbrot* test we find that the distribution of subjects across risk classes with low and high payoffs are statistically different (p<0.01). Using the midpoint of each CRRA class, the mean CRRA coefficient is equal to 0.62 and 1.02 respectively for a low and a high payoff. Using the Holt and Laury (2002) terminology, subjects appear to be on average risk averse for low payoffs and highly risk-averse for high ones.

6.4.3 *Discussion*

First, we do find a payoff effect affecting risk preference estimates. For a given task (HL or EG), the mean CRRA coefficient is significantly higher in the high payoff case. Secondly, we do find a task effect. Farmers appear to be on average significantly more risk averse in the EG task. Third, our CRRA coefficient estimates for French farmers are consistent with the existing literature dealing with risk preferences of farmers. For instance, in his classic study on Indian farmers, Binswanger (1980) find moderate to high CRRA parameters especially for high-stakes gambles (above 0.32). More recently, Liu (2008) reports an average CRRA coefficient for Chinese farmers equal to 0.71. Our estimates are also in line with risk preferences elicited on a wider population. Working on a representative sample of the Danish population, Andersen et al. (2006) find for instance that the mean CRRA coefficient in the field sample is 0.63 (with a 95% confidence interval between -0.49 and 1.87), while the mean coefficient is 0.79 in the laboratory sample (with a 95% confidence interval between -0.02 and 1.85).

For the RA5 and the RL3 classes, we use 2 and -2 as class midpoints.

One may attribute this result to the fact that the EG experiment includes a gamble without any risk whereas all binary lotteries in the HL task are risky. However, compared to Eckel and Grossman (2008), we still find a higher proportion for extreme classes (high risk aversion or high risk seeking attitudes).

6.5 RISK PREFERENCE ELICITATION THROUGH A REVEALED PREFERENCE APPROACH

In this section we elicit farmer's risk preference using a revealed preference approach. As mentioned previously, we will impute individual risk aversion from the divergence between observed production decisions made by farmers and optimal decisions under risk neutrality. Since we wish to compare risk preferences elicited through revealed and stated preference approaches, we will make in both cases the same parametric assumption for the type of utility function of farmers (CRRA utility).

6.5.1 *Method*

Risk preferences are revealed using a structural model of land use choice under uncertainty. A farmer located in a given region must allocated the land area L across K possible crops indexed by $k = 1, \dots, K$. We denote by l_k the land allocated to crop k. The farmer faces uncertainty with respect to crop yields (production risk). There are S equiprobable states of the nature which are indexed by $s = 1, \dots, S$. We denote the yield for crop k if state of the nature s is realized by $\tilde{y}_k(s)$. Since the 2003 reform of Common Agricultural Policy, one part of the direct payments received by French farmers is decoupled from production. We denote by DP the decoupled payment received by a farmer and by sub_k the coupled direct payment associated with crop k. Finally, the total cost of production is given by the function $C(l_1, \dots, l_k, \dots, l_K)$. The total profit of the farmer writes:

$$\tilde{\Pi}(s) = DP + \sum_{k=1}^{K} l_k \cdot \left(p_k \cdot \tilde{y}_k(s) + sub_k\right) - C(l_1, \dots, l_k, \dots, l_K) \quad (6.1)$$

where p_k is the unit price for crop k.

The utility function of farmer is denoted by $U(\cdot)$ with $U' > 0$ and $U'' < 0$. The optimization problem of the farmer under climate and price uncertainty $\mathcal{P}$ writes:

$$\max_{l_1, \cdots, l_k, \cdots, l_K} EU(\tilde{\Pi}(s)) \quad (6.2)$$

$$\text{s.t.} \quad \begin{cases} l_k \geqslant 0 \ \forall k \\ \sum_k l_k \leqslant L \\ \tilde{\Pi}(s) = DP + \sum_{k=1}^{K} l_k \cdot \left(p_k \cdot \tilde{y}_k(s) + sub_k\right) - C(l) \end{cases}$$

According to (Lence, 2009), identifying the structure of risk aversion using production data relies on sources of information too weak to allow for reliable econometric estimation.

where l denotes the vector $l_1, \ldots, l_k, \ldots, l_K$ and EU in the objective function corresponds to the expected utility. Solving the optimization problem $\mathcal{P}$ gives the optimal land use choices l_k^* that maximize the expected utility of the farmer. If we assume that farmer risk preferences may be represented by CRRA preference, then the utility function writes:

$$U(\Pi) = \frac{\Pi^{1-\rho}}{1-\rho} \tag{6.3}$$

where ρ represents the CRRA parameter of the farmer. Then we can parametrize the solution of $\mathcal{P}$ by ρ. We denote by $l_k^*(\rho)$ the optimal land allocated to crop k as a function of farmer risk aversion.

Assume that we observe the land share of the farmer l_k^o for a given year. Then the elicited CRRA coefficient is the one that minimizes the distance between land shares predicted by the structural model and the ones observed. Considering the sum of squared errors (SSE) as the distance metric, the revealed CRRA denoted by ρ^* is given by:

$$\rho^* = \operatorname{Arg}\min_{\rho} \sum_{k=1}^{K} \left(l_k^*(\rho) - l_k^o \right)^2 \tag{6.4}$$

As a result, the structural model of land allocation under uncertainty and the observation of land allocations allow us to elicit the level of risk aversion for each farmer of our sample.

6.5.2 *Empirical implementation*

Crops produced by farmers in our sample have been aggregated into height categories ($K = 8$): namely, irrigated maize, pluvial maize, hard wheat, soft wheat, sunflower, rape, barley, other. The category *other* corresponds to the other cereals produced by farmers.
Farmers face uncertainty concerning the yield for each crop. We have collected data for years 1997 to 2009 for the 8 crop categories in the three French regions where farmers are located. Each year is viewed as a realization of the state of the nature. Hence, there are 12 possible states of the nature ($S = 12$) characterized by a yield realization for each crop produced.

Crop yield for a given year and a given farmer corresponds to the average yield in the French department where the farmer is located. This information has been provided by the statistical services of the French Ministry of Agriculture (Agreste). Table 6.7 provides some descriptive statistics on yields. As expected, irrigated maize has the highest yield (10.25 tons par ha on average) but also a low coefficient of variation (0.15). Irrigation appears to be a way to secure high crop productivity levels but, as it will be discussed later, irrigated maize

Table 6.7: Descriptive statistics on crop yields (1997-2009)

	Yield (10^3 kg/ha)				
	mean	st. dev.	cv[a]	min	max
Irrigated maize	10.25	1.49	0.15	6.46	13.63
Pluvial maize	5.71	1.58	0.28	2.37	9.02
Hard wheat	5.26	1.03	0.20	2.80	7.71
Soft wheat	5.96	1.07	0.18	3.70	8.90
Rape	2.94	0.44	0.15	1.90	4.20
Barley	5.35	1.06	0.20	3.25	8.55
Sunflower	2.30	0.31	0.14	1.40	3.20
Other[b]	3.28	1.05	0.32	1.40	6.00

Source: Agreste.

[a] Coefficient of variation.

[b] *Other* corresponds to other cereals produced by farmers.

has also the highest cost of production per ha. Pluvial maize appears to be a very risky crop since its pluvial maize yield has the second highest coefficient of variation (after the other category). For pluvial maize, the average yield varies from 2.37 to 9.02 tons per ha over the period 1997-2009. Both average yields and coefficients of variation for yields are low for rape and sunflower. Large land areas should allocated to those crops in the case of risk averse farmers.

Crop prices are the same for all farmers. They correspond to the annual mean price directly provided by the Statistical services of the French Ministry of Agriculture (Agreste). In 2008, highest unit crop prices are found for rape, sunflower and soybean (319.08, 290.61 and 285.11 € per ton respectively). Coupled and decoupled CAP payments are computed for each farmer based on his own crop productions reported in the survey.

Lastly, to solve the program $\mathcal{P}$ for each farmer, we need to specify the cost function $C(l)$. To estimate the cost function, we have used the French RICA/FADN database for year 2004 by selecting only cash-crop oriented farmers. The cost function is approximated by a simple quadratic form. The estimation procedure and the estimated parameters of the cost function are provided in Appendix C. Most of the estimated coefficients are significant and make sense. The predictive power of the estimated cost function is good with a R^2 greater than 0.8.

6.5.3 *Results from the revealed preference approach*

For each farmer, the program $\mathcal{P}$ has been solved for 160 possible values of the CRRA coefficient equally distributed on the interval

$[-4, 4]$ using the Gams software. The elicited CRRA coefficient is then the one that minimizes the sum of squared errors between the optimal land predicted by the model and the observed land uses reported by farmers for year 2006 to 2008. A simple grid search algorithm is used to identified the CRRA coefficient for each farmer.

Table 6.8: Farmer risk attitude based on the revealed preference approach

CRRA class	RA5	RA4	RA3	RA2	RA1	RN	RL1	RL2	RL3
CRRA range	>1.37	0.97;1.37	0.68;0.97	0.41;0.68	0.15;0.41	-0.15;0.15	-0.49;-0.15	-0.95;-0.49	<-0.95
	0.31	0.21	0.04	0.11	0.04	0.07	0.11	0.00	0.11

In Table 6.8 we report the distribution of the CRRA parameters using the CRRA classes defined in the stated preference approaches. For 22% of the sample, the CRRA coefficient is negative which means that those farmers ar risk lover. 7% of the farmers appear to be risk neutral and the remaining 71% are risk averse.

The average CRRA coefficient is 0.76. Using the Holt and Laury (2002) terminology, the French farmers appear to be on average very risk-averse.

6.6 ARE RISK ATTITUDE MEASURES CONSISTENT ACROSS ELICITATION TECHNIQUES?

In this section, we analyze the consistency of risk attitude measures across the stated and the revealed preference approaches. We propose to analyze the consistency of risk preference by comparing the average CRRA estimates, the distributions of the CRRA coefficients and by evaluating the correlations across CRRA. We also check is the determinants of farmer's risk aversion are similar across measurement methods.

6.6.1 *Comparison of mean risk preferences*

A first way to compare elicited and revealed risk preferences is to consider the average CRRA coefficients. In Table 6.9, we report the results of the T-tests used for comparing the mean CRRA coefficients.

To allow for a comparison with risk aversion elicited through HL and EG tasks, for revealed risk aversion falling in the RA5 and the RL3 classes, we use 2 and -2 as class midpoints. Without these changes for the extreme risk aversion classes, the average CRRA coefficient is 0.95.

Table 6.9: Mean-comparison tests on average risk preferences (revealed versus stated approaches)

	H&L		E&G	
	Low payoffs	High payoffs	Low payoffs	High payoffs
T-test	2.25**	1.72*	0.55	-1.01
Pr(|T| > |t|)	(0.03)	(0.09)	(0.59)	(0.32)

Null hypothesis: average CRRA coefficients are significantly different
***,**,* for significant at 10,5,1% respectively.

We do not reject the null hypothesis of significantly different CRRA average coefficients when considering the HL task (at 5 and 10% in the case of low and high payoffs respectively) and the revealed ones. On contrary, the CRRA coefficients elicited through the revealed approach and through the EG task appear to be not significantly different. The size of the payoff in the stated approach does not seem to have an impact on the results of the tests.

The comparison across mean risk preferences elicited through revealed and stated preference approaches seems to depend upon the type of lottery task used in the stated preference approach. Thus, the consistency conclusion significantly differs when considering the HL or the EG tasks.

6.6.2 *Comparison of risk preference distributions*

Another way to compare elicited and revealed risk preferences is to consider the distribution of risk preferences. Table 6.10 report the result of the Kornbrot tests between stated and revealed CRRA coefficients.

Table 6.10: Kornbrot test on CRRA coefficients (revealed versus stated preference approaches)

	H&L		E&G	
	Low payoffs	High payoffs	Low payoffs	High payoffs
Z-test	-0.68	0.81	-2.53*	-2.21**
Prob > |z|	(0.50)	(0.42)	(0.01)	(0.03)

Null hypothesis: both distributions are the same
***,**,* for significant at 10,5,1% respectively.

We do reject the null hypothesis of the same distribution of CRRA coefficients in the HL tasks and in the revealed approach. However, when considering the EG task, we cannot reject the null hypothesis of the same distribution.

Here again, the risk preference consistency conclusion across elicitation approach significantly differs when considering the HL or the EG tasks.

6.6.3 *Correlations across risk preferences*

In Table 6.11, we report the Spearman's rank correlation coefficients between the CRRA classes obtained using the two types of lotteries (HL and EG) on one hand, and the revealed preference approach on the other hand. We also present the correlations across CRRA coefficients.

Table 6.11: Spearman's rank correlation coefficients (Stated versus revealed preference approaches)

	H&L		E&G	
	Low payoffs	High payoffs	Low payoffs	High payoffs
Correlations[a]	0.05	0.31**	0.30**	0.27*
Spearman[b]	0.06	0.29**	0.36***	0.17

[a] Correlation across CRRA coefficients.
[b] Spearman's rank correlation coefficients across CRRA classes.
***,**,* for significant at 10,15 and 20% respectively.

Interestingly, the risk attitudes obtained though the revealed and the stated preference approaches are all positively correlated. The correlation is significant at 10% only in the case of the EG task with low payoffs. The positive correlations could be interpreted as a property of consistency across methods used for measuring risk preference.

6.6.4 *Analyzing the determinants of risk attitudes*

As demonstrated by Deck et al. Deck et al. (2008), individual differences may help explain the apparent within subject inconsistency between different behavioral measures of risks. This is the assumption we test here by assessing if some observed characteristics of the respondent (personality or socioeconomic characteristics) have a significant impact on the observed risk behavior in some elicitation techniques and not in others. If risk preferences are found to be driven by the same determinants in the different elicitation methods, this may be interpreted as property of consistency across methods.

Table 6.12: Interval regression for CRRA classes

Variable	Revealed	EG		HL	
	Approach	Low payoffs	High payoffs	Low payoffs	High payoffs
Single	0.77	-0.14	-0.55	-1.17	-1.60***
	(0.74)	(0.50)	(0.43)	(0.96)	(0.53)
Young	-0.57	0.34	0.59**	0.64	0.53*
	(0.45)	(0.29)	(0.25)	(0.58)	(0.33)
Educ+	-0.36	0.07	-0.54	-0.20	0.14
	(0.64)	(0.42)	(0.36)	(0.79)	(0.44)
Income	-0.02**	-0.02***	-0.01**	-0.03**	-0.02**
	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)
Decoupled	0.19***	0.08**	0.04	0.18**	0.09**
	(0.07)	(0.04)	(0.03)	(0.08)	(0.04)
Region_{MP}	0.77	-0.83**	-0.54*	-0.50	-0.52
	(0.53)	(0.35)	(0.30)	(0.66)	(0.37)
Region_{PC}	1.09**	0.37	0.35	1.31**	0.21
	(0.48)	(0.30)	(0.25)	(0.61)	(0.33)
Intercept	-0.81	0.98**	0.90***	1.05	1.25***
	(0.62)	(0.42)	(0.33)	(0.78)	(0.39)
Cragg-Uhler R^2	0.48	0.47	0.52	0.45	0.53

Single: dummy variable equal to 1 if the household head is single.
Young: dummy variable equal to 1 if the household head is less than 45 years old.
Educ+: dummy if education level beyond secondary school.
Income: farm level production value of the previous year (in 10^3 euros).
Decoupled: farm CAP decoupled aid of the previous year (in 10^3 euros).
Region_{MP}, Region_{PC}: regional dummy variables for Midi-Pyrénées and Poitou-Charente.
***,**,* for significant at 1,5 and 10% respectively.

In Table 6.12, we report the results of the interval regressions for the CRRA classes obtained with the HL and the EG lotteries and with the revealed preference approach. By using interval regressions, we specify the dependent variable as a range defined by the subject's lower and upper bounds of the risk preference parameter. As a result it allows to account for cases where the data are right or left-censored (e.g., the range is bounded by infinity). As potential determinants, we include farmer's marital status (Single), an indication of farmer's age (Young), farmer's level of education (Education+), farmer's income (Income) and the amount of decoupled payment received by the farmer (Decoupled). To control for possible local

Notice that all equations have also been estimated by Zellner's seemingly unrelated regression. The qualitative results do not significantly differ from the one presented in Table 6.12.

conditions affecting risk preference, we have also introduced some dummy regional variables (Region_{MP} and Region_{PC}).

Globally, the predictive power of the models is correct with a pseudo R^2 around 0.5 for all regressions. As it will be discussed, the signs of estimated coefficient make globally sense. More important, the signs and the magnitudes of estimated coefficients are consistent across regressions models. This could be interpreted as a consistency properties of risk preferences elicited through the different methods.

The Income variable is significant in all regressions with a negative sign. Impact of income on risk preference is stable across regression since the estimated coefficient varies from -0.03 to -0.02. Thus, as it would have been expected, farmers with higher gross income appear to be less risk averse than other farmers. This result is consistent with the findings reported by Abdulkadri et al. (2003) for Kansas farmers.

We can notice some regional variations in terms of risk preferences. In particular, farmers located in the Poitou-Charente region seem to be more risk averse than those located in the two other regions. This result could be related to the fact that the Poitou-Charente region is characterized by a strong gap between water availability and water demands. Thus, farmers located in that region have experienced a lot of administrative irrigation interdictions during the last years, which may have modified their risk preferences.

Socio-demographic variables appear to have a limited impact on risk preferences. The farmer's age is only significant in the stated preference approach with high payoffs. Young farmers appear to be more risk averse. Being single has a significant impact on risk preferences only in the HL model with high payoffs. In that case and, as expected, single farmers tend to be more risk lover.

Finally, notice that we cannot test for a gender effect (women are known to adopt less risky behavior than men) since our sample is exclusively made of men.

6.6.5 *Discussion*

Consistency of risk preferences elicited through the revealed and the stated preference methods varies significantly across lottery tasks used in the stated preference approach. When using the EG task, preferences appear to be quite consistent in terms of average risk aversion, distribution of risk aversion, correlations across CRRA coefficients and determinant of risk preferences. On contrary, with the

HL task, the consistency is much more questionable.

As suggested by Deck et al. (2008), one possible explanation could be that risk attitudes may vary depending on the context (health of financial domains for instance). The two lottery tasks may not measure the same type of risk preferences. Hence, Reynaud et al. (2010) have shown that risk preferences elicited though the EG task are strongly correlated with risk preferences corresponding to the finance domain whereas the correlation is significantly lower when using the HL task. Another explanation could be the fact that the HL task is cognitively more difficult than the EG one. Dave et al. (2007) who have also elicited individual risk preferences using the HL and the EG mechanisms have found that the two tasks yield to different risk preference estimates. In particular, subjects exhibit a greater risk aversion in the HL task than in the EG one. However, they report that excluding subjects with lower math ability leads to similar estimates of predictive accuracy across the two experimental elicitation methods.

Compared to the existing empirical literature on risk preference of farmers, we however find a higher level of consistency in risk preferences across methods. Having implemented the two elicitation methods on the same sample of farmers may be an explanation of this result.

6.7 CONCLUSION

Stated and revealed preference approaches have been extensively used in the last decades to assess the level and the shape of risk preferences of farmers. Despite the divergent results obtained, it is surprising to notice that no direct comparison of those methods on the same sample of farmers has been conducted. In this article, we have tried to fill this gap by using different methods to measure risk attitudes on a sample of French farmers. In order to elicit risk preferences, we first have used an experimental approach based on two lottery tasks (the Holt and Laury (2002) procedure and a variation of the Eckel and Grossman (2008) procedure). Second, the revealed approach is based on a standard farm-level land allocation model under climatic uncertainty from which farmer's risk preferences can be assessed. The comparison of the two approaches reveals that the consistency of risk preferences varies according to the type of lottery used in the stated preference approach. When using the EG task, preferences appear to be quite consistent in terms of average risk aversion,

The HL task involves ten decisions between gambles and allows categorization of decision makers into 10 risk categories, while the EG task is simpler, involving a single choice among 6 gambles, but only allows categorization of decision makers into 5 risk categories.

distribution of risk aversion, correlations across CRRA coefficients and determinant of risk preferences. This result contradicts Bardsley and Harris (1987) who reports that estimates of risk attitudes based on experiments are artificial and may offer poor guidance regarding behavior in real economic environments. However, with the HL task, the consistency with revealed preferences appears to be much more questionable. The main conclusion is then that the type of lottery matters a lot and should be carefully made if risk preferences elicited through experiments are expected to be used to predict real decisions of farmers. This result has important implications since risk aversion elicited through lottery tasks are more and more often used to understand real decisions of farmers. Among others, Engle-Warnick et al. (2006) use for instance the risk aversion elicited through a stated preference approach to explain observed crop diversification of farmers.

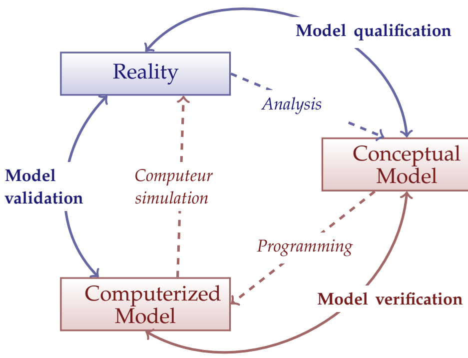
Some extensions of our framework could be developed in particular to address if instability of risk preferences is related to the risk tasks we have chosen or to our elicitation procedure. First, different risk tasks involving different cognitive difficulties could be considered in order to more carefully address the question of the impact of cognitive difficulties of tasks on elicited risk preferences, Anderson and Mellor (2009). Second relaxing our assumption of expected utility behaviors in order to derive risk preferences could be relevant since, for instance, Harrison et al. (2010) have shown that rural households in Ethiopia, India and Uganda are more likely to follow prospect theory than expected utility theory.

7

CRASH: A MODELLING FRAMEWORK TO SIMULATE FARMER'S CROPPING-PLAN DECISIONS

Why this chapter?

This Chapter presents the modelling framework CRASH and the series of experiments that we conducted for model verification. Model verification focused on the innovative and most critical modules of the CRASH framework. In **red**, phases of modelling and simulation that are concerned by this chapter.



(Adapted from Schlesinger, 1979 in Bellocchi et al., 2011)

Parts of this chapter were presented as:
Akplogan, M., Dury, J., de Givry, S., Quesnel, G., Joannon, A., Reynaud, A., Bergez, JE., Garcia, F., 2011. A Weighted CSP approach for solving spatio-temporal farm planning problems. In: Soft'11, 11th Workshop on Preferences and Soft Constraints. pp. 1–15.

7.1 INTRODUCTION

The call for more effective integration of environmental sciences and decision-making is very omnipresent in the field of environmental (Parker et al., 2008; Liu et al., 2007; Liu, 2008) and farming system modelling (Keating and McCown, 2001; McCown, 2002; Matthews et al., 2007). One approach that is receiving growing attention is the development of coupled human and natural systems (Liu et al., 2007; An, 2011) also known as agent-based modelling (Matthews et al., 2007). These approaches are first based on the explicit representation of the feedbacks between individual agents and natural systems (e.g Individual Based Modelling), and the social interactions between agents when multiple agents are taken into account (e.g. multi-agent based modelling). Deliberative agent-based models are very useful to facilitate decision-makers supports (e.g. Power et al., 2011) by linking science and actions through well structured conceptual and implemented modelling frameworks. Combining simulation models with deliberative processes provides powerful approach for addressing environmental and agricultural issues across space, time, and organisational units (Liu et al., 2007; Matthews et al., 2007). This allows to model in a mechanistic and spatially explicit way the influences of decision-makers on their environment, also taking into account adaptation behaviors and the different levels of decision-making.

In agricultural systems, decision-making is best studied at the farm scale at which interactions between natural and human controlled processes are the most salient (Rodriguez et al., 2011). A key argument for this is that farmers manage a complex system (i.e. the farm) with a limited amounts of resources to allocate, tend to satisfy competing objectives with particular risk preference (Power et al., 2011), and operate in highly uncertain environments. Modelling cropping-plan decisions has already been treate by researchers using many different approaches (Dury et al., 2011). At the farm level, crop production planning is traditionally based upon cropping pattern selection using different optimisation algorithms. These studies particularly focused on maximising income by selecting cropping pattern under resource constraints (e.g. McCarl et al., 1977; Leroy and Jacquin, 1991; Annetts and Audsley, 2002; Sarker and Ray, 2009) or by selecting crop rotations while respecting agronomic constraints (e.g. Dogliotti et al., 2004; Bachinger and Zander, 2007). Most of the existing approaches were normative and prescriptive, were not spatially explicit, and did not address the dynamics of mechanisms involved in the processes of farmer's decision-making (Aubry et al., 1998b). Because decision indicators such as water availability, prices, contracts and weather are changing day after day, and are hardly predictable, a successful decision-making process is dynamic to proceed with the most up to date information (Nuthall, 2010). As far as we know, a few of the tools addressing the issues of cropping pattern selection have been based on the realistic modelling and simulation of management strategies of individual farmers (e.g Power et al., 2011).

The cropping-plan decision-making combines long-term planning activities with managerial and operational activities to timely control the crop production process (Nevo et al., 1994; Dury et al., 2011). Modelling a decision-making process to support such farmers' decisions requires therefore to consider the planning of crop allocation over a finite horizon, and to explicitly consider the sequence of problem-solving imposed by the changing context (e.g. weather, price) (Cox, 1996; Bacon et al., 2002). A cropping-plan decision is therefore the result of a dynamic decision-making process in which farmers pursue multiple objectives and face many constraints included in different spatial and temporal dynamics. This entails developing and integrating on a farm scale basis a coherent and complementary set of tools addressing the different facets of this complex issue.

This paper presents the modelling framework CRASH (Crop Rotation and Allocator Simulator using Heuristics) which integrates a set of tools to plan, simulate and analyse the dynamic of cropping-plan decision-making process in uncertain environment (weather and price) at the farm scale. Our modelling framework is developed enhancing traditional knowledge base system and respects most of the desirable features of any classical *problem specific* environmental decision support systems as described by Rizzoli and Young (1997). Our approach to develop the CRASH model emphasised on (1) the explicit representation of the decision making process in their temporal and spatial dimensions, and (2) the representation of the domain knowledge through generic concepts that are close to ones used by decision-makers.

The paper is organized as following:
Section 7.2 presents the different software components that constitute the modelling framework CRASH in order to clarify the role of each and to introduce the functionalities of CRASH. This section justifies using a mutli modelling simulation platform to develop such integrated simulation framework. In section 7.3, we give details on the main simulator of the CRASH framework that is used to simulate the cropping-plan decision-making process of individual farmers. In Section 7.4, we conducted a series of simulation experiments to perform a model verification on the most critical part of the CRASH framework. And last, we discuss on advantages and limits of our approach to develop decision support systems.

7.2.1 *VLE: a multi-modelling simulation platform*

CRASH (Crop Rotation and Allocator Simulator using Heuristics) modelling framework is a set of integrated software components (Figure 7.1) providing different utilities to plan, simulate and analyse cropping-plan decision-making at the farm scale. The CRASH modelling framework takes full advantage offered by the VLE multi-modelling simulation platform (Quesnel et al., 2009) that has been choosen within the RECORD project (Bergez et al., 2009). VLE is a complete software environment dedicated to events driven modelling and simulation approaches. It implements the DEVS formalism (Zeigler et al., 2000) and provides formal simulation algorithms that allow to deal with simultaneous and instantaneous events affecting heterogeneous models. The formalism relies on atomic models characterised by as a set of input and output ports and a set of state transition functions. Every atomic model can be coupled with others in order to build the overall hierarchical model structure. VLE provides a set of C++ libraries and companion programs (e.g. simulators, graphical interface) integrated to facilitate the development and use of coupled DEVS simulation models.

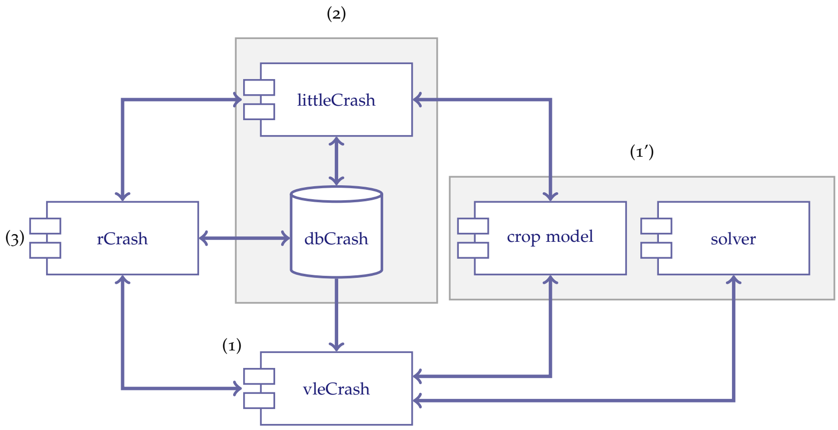


Figure 7.1: Main software components of the CRASH modelling framework: (1) the main simulator: *vleCrash* with (1′) its coupled external programs, (2) inputs management systems, and (3) analysis and plotting utilities.

7.2.2 *CRASH framework components*

To acquire, represent and structure input knowledge involved in the description of the cropping-plan decision problem, we developed an object-relational spatial database called *dbCrash* (Figure 7.1). The database stores the farmer's expert knowledge, his decision profile, and the structure of his farm including a spatially explicit description of the farmland. The farmer decision profile is the set of threshold values, decision rules and objectives that drive the cropping-plan decision-making process. The *dbCrash* component is implemented with the database management system postgresql. The spatial features are accounted for using the wkb format (Herring, 2006) provided by postgis, an extension of postgresql for geographic objects. The input data are either manually filled, derived from GIS files or generate by simulations (Figure 7.1).

The main software component of the CRASH modelling framework is a spatially explicit farm scale agent-based simulator called vleCrash (Figure 7.1). vleCrash is a set of coupled DEVS atomic models integrating external solver algorithms and encapsulated models. vleCrash is indeed coupled with a weighted constraint satisfaction solver called Toulbar2 (Bouveret et al., 2005; Lee and Leung, 2010) and with a generic crop model, namely "*Simulateur mulTIdisciplinaire pour les Cultures Standard* (STICS) (Brisson et al., 2003). vleCrash is connected to the database which provides input data needed for planning and simulating cropping-plan decisions.

littleCrash is a plot scale agent-based simulator used to simulate and analyse crop production as regards to the soil and climate conditions and to the specific production techniques described in the form of decision rules (Figure 7.1). *littleCrash* is used to generate input data concerning farmer's expert knowledge about crop production variabilities related to crop management, weather, soil types and market conditions. *littleCrash* shares the same libraries that *vleCrash*.

In order to separate simulation and data analysis during the process, we developed a standalone component dedicated to perform the analysis and plotting of the simulation inputs/outputs. The component is a collection of R functions (R Development Core Team, 2011) gathered in a R package called *rCrash* (Figure 7.1). *rCrash* is based on RVLE (Quesnel et al., 2009), another R packages used to call VLEs Application Programming Interface (API) from R software. Therefore *rCrash* is also used to parametrize and run the two simulators.

7.3 VLECRASH: THE MAIN SIMULATOR

In recent developments, farm systems have been represented as three interacting subsystems: the manager, operating and biophysical systems (Martin-Clouaire and Rellier, 2009). We choose a similar structure with the three main atomic models that we call agent system, operating system and biophysical system (Figure 7.2). The three atomic models, agent, operational and biophysical systems, are subsystems in the sense that they have their own processes, have inputs, outputs and an agenda of events (Martin-Clouaire and Rellier, 2009). The agent system sends orders to the operating system that interacts with the biophysical system through operational processes that simulate the execution of actions. The agent system receives informations from the operating and biophysical systems. In *vleCrash*, the agent system represents the ways farmers select a cropping-plan and implement the corresponding technical interventions. The operating system translates decisions taken within the agent system into actions that impact on the biophysical system by modifying particular states or flows. The biophysical system, also known as crop model in plant production, is usually described by mathematical equations representing reactions occurring within plants and their interactions with its environment (Wallach et al., 2006). In *vleCrash*, the crop models are distributed along spatial units to represent the farmland. The distribution of the crop models is carried out by the model manager (Figure 7.2).

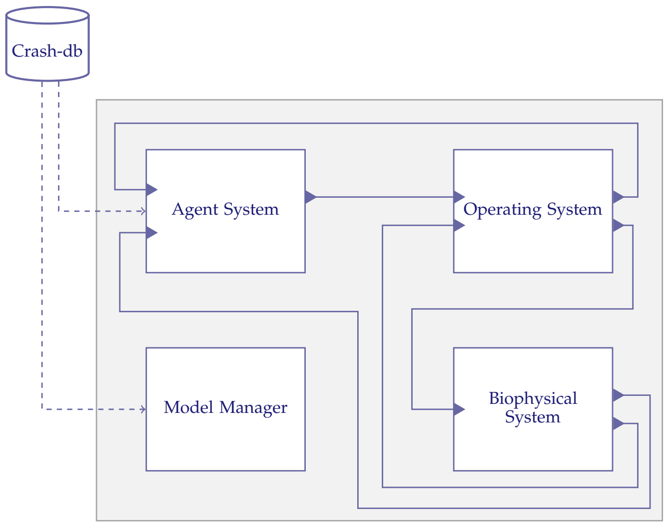


Figure 7.2: The four main atomic models of the *vleCrash* simulator, i.e. agent, operational and biophysical systems, and the model manager with their connections to the database.

7.3.1 *Agent system*

The design of the conceptual model of the agent system is based upon a methodology that integrates field observations with a theoretical framework of the decision maker's behaviour (Dury et al., 2010). Using techniques from the cognitive sciences and knowledge engineering, we modelled farmers' representation of their own agricultural systems and used them as basis for designing the decision models relying on the theory of the procedural rationality (Simon, 1976). In our approach, the cropping-plan decision-making is described as a combination of design activities (Simon, 1973) and dynamic decision-making (Busemeyer et al., 2001) for achieving a control over a dynamic system in order to produce a desired outputs, rather than as an unique resolution of choice dilemma. The agent as a computer system situated in a dynamic and uncertain environment, is capable of autonomous action in this environment in order to meet its objectives (Wooldridge, 2002).

The BDI framework is one of the most popular architectures for developing agents in complex and dynamic environments (Bratman, 1987). The BDI approach was developed according to the theoretical conception of procedural rationality through the particular model of *practical reasoning* (Wooldridge, 2002). The BDI framework provides goal-directed behaviour, whereby an agent's actions are motivated by a hierarchy of goals rather than being purely reactive. The BDI approach is characterised by an explicit representations of the agent knowledge through its Beliefs, Desires and Intentions (Figure 7.3) (Rao and Georgeff, 1991). The beliefs correspond to information the agent has about the world. Desires represent state of affairs that the agent would wish to be brought about. Intentions represent desires that the agent has committed to achieve. The reasoner represents the deliberative process of the agent.

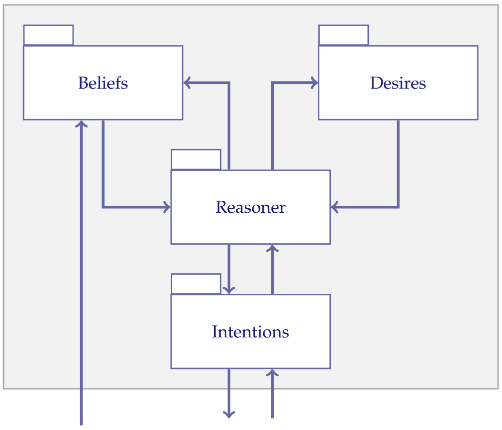


Figure 7.3: Main packages and their relationships constituting the agent system. The structure of the agent system is based on the traditional BDI architecture

7.3.1.1 *Beliefs*

Beliefs express the managers' current state of knowledge about the production system (past, current and trends) and about itself. Beliefs are information immediately available for reasoning to solve particular decision-making problems. In *vleCrash*, the belief of the agent, is represented as a set of classes following the object-oriented paradigm.

We choose object-oriented approach mostly due to the ability of this paradigm to create adequate knowledge abstractions (Hillyer et al., 2003; Papajorgji and Pardalos, 2006). The belief component of the CRASH model is organized into two main parts to represent different aspects of the agent knowledge: structural and procedural knowledge.

Structural knowledge: Structural knowledge is knowledge of how concepts within the domain are interrelated (Jonassen et al., 1993). In CRASH, the structural knowledge was formalised as UML class diagrams through an ontological analysis of the concepts that farmers used to decide their cropping-plan. Structural knowledge has two dimensions (Jonassen et al., 1993), the content and the structure. In Crash, we distinguished two sorts of content:

- The system knowledge as the belief on concepts and related state variables of the simulated systems. The system knowledge is based on observations of the external subsystems and also deduced from other beliefs. The systems knowledge is dynamically updated during the simulation period.
- The expert knowledge is the knowledge that is not simulated by the systems. The expert knowledge is static, i.e. provided by the database (Figure 7.2) at model initialisation.

Procedural knowledge: The procedural knowledge corresponds to the *plan library* of the Georgeff's Procedural Reasoning System (Georgeff and Ingrand, 1989) which can be seen as a subset of the agents beliefs (Haddadi and Sundermeyer, 1996). The plan library provides declarative representations of activities for responding to changes in goals (mean-end reasoning) or in beliefs (situated behavior). The body of procedural knowledge is a set of sub-plans represented by partial graphs of activities. The procedural knowledge is provided by the database (Figure 7.2) at model initialisation.

7.3.1.2 *Desire*

Desires are the objectives or situations that decision-maker would like to achieve, this represent the motivation of the agent. In our approach, the decision-maker has goal of satisficing instead of optimising (Zannier et al., 2007). In CRASH, the farmer objectives are specified as input of the model through the different variables that define the decision profile (e.g. economy, production choices). In the BDI approach, goal are also generated during simulation. For instance, when crops and crop management options are chosen during the simulation, they are also considered as objectives to satisfy.

7.3.1.3 *Reasoner*

Sequence of problem solving: The component reasoner executes a sequence of problem solving that represents the deliberative process of the agent. This sequence of problem solving combines long term planning (2- in Figure 7.4) with tactical decisions (3- in Figure 7.4) to timely adapt cropping-plan and crop management options to the ever changing environment. At the strategic level, the reasoner embeds constraint reasoning algorithms coupled with utility function to choose crops, define their acreage and allocate them to land units on a predefined time horizon. These decisions concern the design of the different cropping systems of the farms. At this stage, the planning of the cropping-plan is made concurrent with choices of crop production techniques. The output of the strategic decisions is a dynamic graph of activities (or partial plan of actions). The graph represents the whole set of tactical and operational activities structured in time and space that the farmer planned to execute. The graph is build based on the structural and procedural knowledge and is timely updated when this knowledge changes.

Identification of candidate cropping-plan: This step aims to identify all potential candidate cropping-plans over a finite time horizon $\mathcal{H}$. The objective is to select only relevant cropping-plans as regard to structural constraints of the farm and farmer decision profiles:

- In space, the farm is organised in many different organisational levels called management units. The management units are decided by the farmer to organise his work and allocate resources (e.g. water, work).
  - The crop management block is the first management unit type that we took into account at the strategic level. The crop management block (b in Figure 7.5) are subset of plots managed in a coherent way. Crop management block are characterized by one cropping system Sebillotte (1990); van Ittersum and Rabbinge (1997): one crop sequence pattern (e.g. crop rotation) and the use of a coherent set of production techniques applied to these crops (e.g. fertilizer, irrigation water). Delimitation of the crop management blocks are not reshaped every years. They are mostly defined by the structural properties of the farm (e.g. access to irrigation water), and biophysical properties (e.g. soil type).
  - At a lower level, the plots (p_j in Figure 7.5) is concerned by the allocation of one crop every year and by the annual management of crops. Plot delimitations can be adapted over time to enforce the spatial balanced of crops acreages.

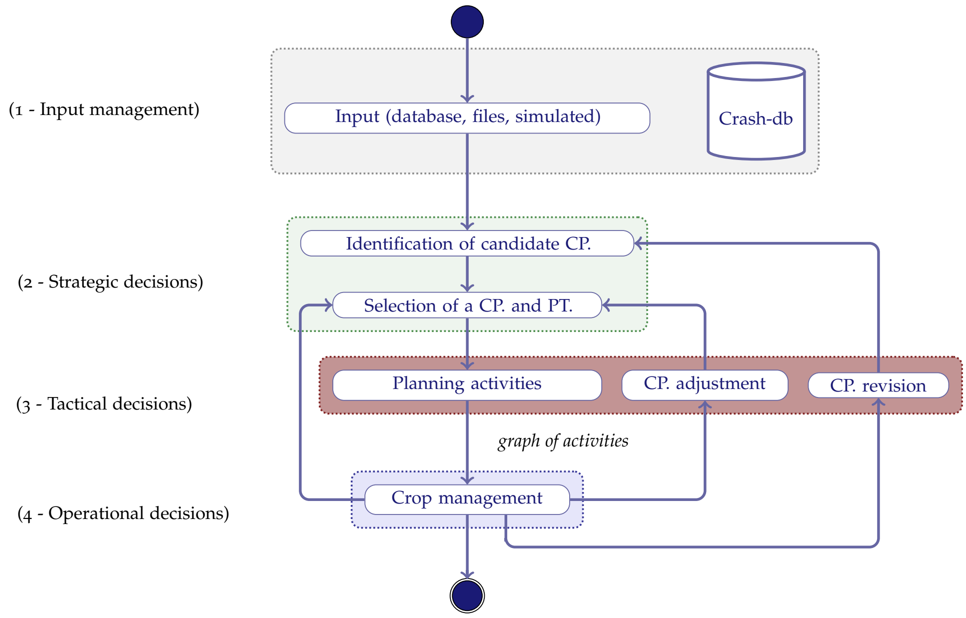


Figure 7.4: Activity diagram that depicts the main steps of the sequence of problem solving that implements the cropping-plan-decision-making process in *vleCrash* . 1 - Input of the *vleCrash* model from the database *dbCrash*. Part of the inputs are provided by pre-simulation using *littleCrash*. 2 - two steps processing the strategic decisions. The first step is the identification of all candidate cropping-plans over a finite time horizon. Candidates cropping-plan must respect a set of constraints and decision thresholds (agronomic, resource). The second step is the selection of the best cropping-plan based on economic and risk aversion considerations. 3 - The tactical decisions concern crop operations and cropping-plan adaptation activities: adjustment decisions trigger cropping adaptions and revision decisions reset the entire cropping-plan. 4 - The box "crop management" represents the execution in the intention component of the crop operations as described in the graph of activities. These crop operations affect the operational system [CP: cropping-plan; PT: production techniques].

  – The irrigation block unit describse water and irrigation equipment availabilities to land that determine water amount and flow rate that can be applied.

We took into account the biophysical properties of the land by defining soil units. These soil units are used by the farmers as factors to allocate or not the crops, and to adjust crop management techniques. The main soil properties that we took into account were the soil texture, the water holding capacity and drainage.

– In time, some crop successions on the same land unit are not allowed or not advisable without facing decrease in soil fertility, or increase in diseases or weed infestations. Farmers deal these temporal factors by designing crop sequence patterns that respect a set of agronomic rules usually summarized by two indicators: the minimum return time (rt) and the preceding effect (kp) (Leteinturier et al., 2006). rt is defined as the minimum number of year before growing the same crop on a same plot. The return time was also used to take into account the history of the land by constraining future choices. We introduced the concept of crop rotation as option because it is widely used by farmers as decision indicator while designing their crop allocation plan. This mean that the proposed crop sequence pattern could be repeated over time without breaking the constraint rt. kp is an aggregated indicator representing the effect of the previous crop on the next one on the soil structure, diseases, pests, weeds and nitrogen (Leteinturier et al., 2006). Based on kp, some crop successions can be ignored for their effects or recommended for their beneficial effects for production purposes.

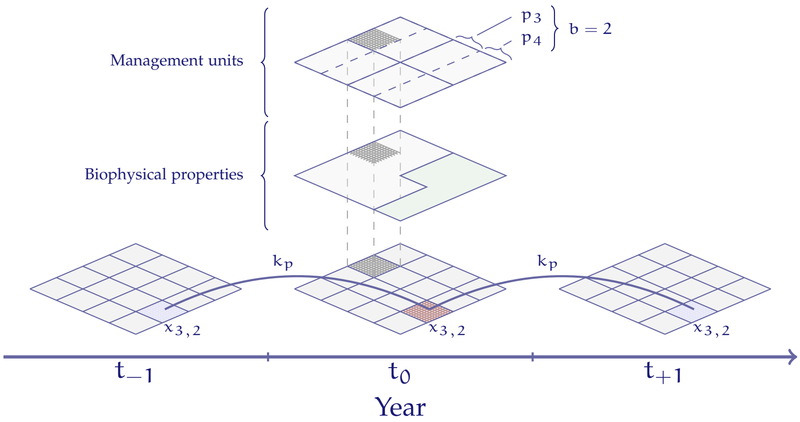


Figure 7.5: Schematic representation of the spatial and temporal aspects of the decision-making problem (t_i: year, b: crop management block, p_j: plot, $x_{b,i}$: land unit, k_p: preceding effect). As illustration, to allocate crop on the land unit $x_{3,2}$, the farmer has to jointly take into account temporal constraints (past allocation t_{-1} and future allocation t_{+1}), but also spatial constraints (biophysical properties, organisation in management units and resource availabilities).

Identification of candidate cropping-plans was treated as a spatio-temporal crop allocation problem whose relevance was assessed by a global cost function. For computational reason, we introduced at the low level (Figure 7.5) the concept of land unit x. A land unit is defined as a piece of indivisible and homogeneous peace of land whose history and biophysical properties are identical. Thus any management units are a combination of land units. The goal of the crop allocation problem is then to find an assignment of crops to all the land units x over a fixed horizon $\mathcal{H}$ of time and the total cost is minimized (Figure 7.5). An assignment of crops must satisfied a set constraints. The choices and the definitions of the constraints that we formalized and implemented in the Weighted Constraint Satisfactory Problem (WCSP) framework are presented in the Table 7.1 and the WCSP formalism are presented in the Appendix D.

Selection of a cropping-plan and production techniques This step aims to select the cropping-plan scenario and corresponding production techniques that fit at best to farmer economical objectives while considering risk preference. Selection is based on farmers' expert knowledge about joitn crop and production techniques expected outputs (yields, water use, return). The expected production levels are simulated with *littleCrash*. The cropping-plan selection is carried out among all the candidates which are indexed by $c = 1, \ldots, C$. Then the reasoner builds a graph of activities using the selected cropping-plan. The graph is build by aggregating partial plans of action from the agent procedural knowledge. Result of this process is a plan of actions which can be performed in terms of sequence of crop operations. The plan is structured in time over the horizon $\mathcal{H}$, and in space over all plot units $p_{i,j}$. It is written as activity plan as defined in the VLE decision plugin (Quesnel et al., 2009). This plan should lead to satisfice the goal states as defined in the farmer decision profile.

Calculation to select among all cropping-plan scenario candidates are as following:

- *Cropping-plan scenario profit:* Crops are indexed by $k = 1, \ldots, K$. We denote by $l_i k$ the land unit i allocated to crop k. The farmer faces uncertainty with respect to crop price (market risk), crop yields and irrigation water use (production risk). There are s equi-probable states of the nature which are indexed by $s = 1, \ldots, S$. We denote the price for crop k if state of the nature s is realized by $\tilde{p}_k(s)$. We denote the yield and irrigation water use for crop k and production activities a if state of the nature s is realized by $\tilde{y}_{ka}(s)$ and $\tilde{e}_{ka}(s)$ respectively. We denote by ψ_{ka} the fix production cost and w the unitary cost of irrigation water. We took into account the direct payments received by farmers in France is decoupled from production. We denote by DP the total decoupled payment received by a farmer and by sub_k the coupled direct payment associated with crop k. The total profit of the farmer for a year is therefore written as following:

$$\tilde{\Pi}(s) = DP + \sum_{i=1}^{I} l_{ik} \cdot \left(\tilde{p}_{ka}(s) \cdot \tilde{y}_{ka}(s) + sub_k - \psi_{ka} - w \cdot \tilde{e}_{ka}(s)\right) \tag{7.1}$$

Table 7.1: Main spatio-temporal constraints used to identify candidate cropping-plan. The column *scale* relates management units and constraints. All spatial constraints are grouped in the upper part of the table, and all temporal constraints are grouped in the below part.

Category	**Name**	**Scale**	**Description**	**code**
Management Unit	Growing area	All	Define the compatibility of a crop for a given management or biophysical units . Reasons that justify the impossibility to grow a crop within specific area can be of very different natures (e.g. soil type, equipment)	h-SCC
	Farm topology	Islet	The land units where the same crops are assigned must be spatially grouped. By this, we mean that is preferable to group as most as possible the same crop on a same Islet. Every isolated land unit is penalised by a cost	s-TOP
	Crop acreages	All	Solutions must respect a pre-defined range of acreage of crops every year. Any deviation is penalised by a cost	s-SBC
	land unit equality	Plot	All the land units within a plot must have the same crop every year. These land units are decided by the farmer to be managed in the same manner	h-EQU
Resources	Resources capacity	All	A fixed amounts of resources are available for a given area of the farm (e.g irrigation water at irrigation block scale, labour at farm scale). The potential quantities of resource use in relation the crop assignement should not exceed the limits.	h-RSC
Agronomic	Crop return period	All	The minimum returned time of crops rt must be always enforced on all land units within the given management units	h-TSC
	Crop rotation	Management block	The crop sequence after the history must be endlessly repeated by enforcing return period of crops within the given management units	h-CCS
	History	All	Each land unit has defined history values that constraint choices for the future as regards to the other temporal constraints	h-HST
	Crop sequence quality	Management block	Each pair of previous and next crops is associated to a cost k_p that defines its preceeding effect	s-CSQ
Management unit	Same crops assigned	Management block	Over the time, the same subset of crops must be assigned to every land units of the same crop management block	h-SCA
	Crop acreages in sequence	All	A defined acreage of some crops on each land unit over years. Any deviation is penalised by a cost. This ensure the presence of a crop in the sequence within the given management unit	s-TBC

We then calculate the mean expected profit and the variance of a cropping-plan scenario c over the time horizon $\mathcal{H}$. The mean profit writes:

$$\mathcal{E}(\tilde{\Pi}(s)) = \frac{1}{\mathcal{H}} \cdot \sum_{t=1}^{\mathcal{H}} \tilde{\Pi}_t(s) \tag{7.2}$$

The variance writes:

$$\mathcal{V}(\tilde{\Pi}(s)) = \sum_{t=1}^{\mathcal{H}} \left(\tilde{\Pi}_t(s) - \mathcal{E}(\tilde{\Pi}(s))\right)^2 \tag{7.3}$$

- *Cropping-plan scenario selection:* Selection of the cropping-plan scenario is performed by maximising the expected utility function. We introduced risk aversion of the decision-maker at this stage using the Constant Relative Risk Aversion (CRRA) coefficient (Reynaud et al., 2010) denoted by θ. The optimization problem of the farmer under climate and price uncertainty $\mathcal{P}$ writes:

$$\max_{c_1,\cdots,c_z,\cdots,c_Z} \mathcal{EU}\big(\mathcal{E}(\tilde{\Pi}(s)) - \theta \cdot \mathcal{V}(\tilde{\Pi}(s))\big) \tag{7.4}$$

where $\mathcal{EU}$ in the objective function corresponds to the expected utility.

7.3.1.4 *Intention:*

The intention component contains all tactical and operational activities structured as a plan of actions that the decision-maker is committed to execute to achieve one or more goals (Rao and Georgeff, 1991). Using the extension library of the VLE modelling platform (Quesnel et al., 2009), the actions are formalized as a set activities respecting activation and sequencing rules. During simulation, the agent system maintains up to date the beliefs of the agent when new information are coming from the operating and biophysical systems (Figure 7.2). Based on these new information, a set of predicates are dynamically updated. Gathered into rules, this predicates triggers activities that are committed to be executed. This prevents complicated reasoning at every time step: since once an agent has planed activities, it will continue to do it until the plan is updated or changed. The activities concern crop management operations but also cropping-plan adaptation decisions.

Adaptation decisions Simulation of the cropping-plan decision-making dynamic refers to the sequence of decisions that affect the cropping-plan choices and are taken in response to the dynamic changes of the system states of the farmer's environment. This requires describing sub-plans of actions that define cropping-plan adaptation activities, their pre-conditions to be executed, and to develop the system knowledge in accordance to the information that are required for such decisions. These sub-plans of actions are part the decision profile of the agent and are described in the procedural knowledge. In our approach, we defined two types of cropping-plan adaptation decisions (3 in Figure 7.4):

- *Adjustment decisions* : These decisions are rules based reasoning. They are anticipated decisions and are intended to adjust the cropping-plan to changing current context (e.g. crop price, water quota). This requires to describe dynamics of the events that drive such decisions. For instance, the adjustment of the cropping-plan according to the annual water quota requires to simulate occurrence of the water quota at a given date.
- *Revision decisions* : These decisions are executed when the strategic decisions are challenged as a whole. This lead to the partial (e.g. one cropping system) or the total reappraisal of the strategic decisions. It reloads the process of cropping-plan decision making at strategic level. These decisions require to define situations from which farmers consider that the current cropping-plan is not any more relevant to fit objectives.

Crop management operations Simulation of the crop management refers to all decisions that concerns cultivation of crops at the plot scale. These decisions trigger events in the operational system and affect the biophysical system. In CRASH, we simulated sowing, fertilisation, irrigation and harvest operations. We did not simulate pests and diseases technical interventions. The crop management operations are activities defined by a set of diiferent rules. The decisions rules concerned the period to perform crop operations, the sequencing rules (chronological order of crop operations) and the activation rules (predicates based on dynamic indicators) (Aubry et al., 1998b).

7.3.2 *Operating system*

The *Operating system* is represented by discrete and finite state automaton. Discrete Systems are dynamic systems that evolve in discrete steps in reaction to internal or external events. States and events are natural medium to described the reactive behavior of the agent system by affecting states of the biophysical processes. The operating system is implemented using the state chart plugin of the VLE modelling platform.

7.3.3 *Biophysical system*

The biophysical system is a spatially explicit farmland model. The farmland model is represented by a distribution of crop models into homogeneous simulation units within the farmland. The biophysical system was implemented as a set of atomic models. Each atomic model was an encapsulated crop model STICS (Brisson et al., 2003) with its own set of parameters (soil type, crop parameter in relation to the cropping-plan). We used the extension *difference equation* of the VLE software to encapsulated the STICS crop model.

The simulation units are irregular spatial units (i.e. not grid) defined by the biophysical heterogeneity of the farmland (e.g. soil characteristics, past management) but also by its organisation into management units (e.g. plots, irrigation blocks, crop management blocks). These land units constitute the simulation units but also the units from which the WCSP solver assigns crops over time. We had to develop an algorithm to delineate the farmland into simulation units equal in area because of the use the WCSP solver. This algorithm uses as input a set of spatial layers as described in the database *dbCrash* (i.e. the management and biophysical units and the work orientation into plots) to split the farmland into homogeneous spatial land units. The sampling algorithm is directly implemented in the database using the postgis features.

The agent system had knowledge about the spatial constraints as presented in the Table 7.1 through the implementation of classes in his belief describing all the management and biophysical units of the farmland.

At initialization, the model manager (see Figure 7.2) has the responsibility to configure spatial features of the *vlecrash* model. The model managers is a model of type *executive* in the VLE platform and has ability to manipulate the structure of the model itself. Therefore, based on the spatial descriptions of the land unit layer stored in the database, the model manager creates as many atomic crop simulators as there are land units in the farmland and connects them together (Figure 7.6).

7.4 MODEL VERIFICATION

We conducted a series of tests on the CRASH modelling framework to perform a model verification. Our main objective was to translate critical points of the conceptual model into an implementation under the VLE platform. Therefore, tests focused on innovative and most critical parts of the CRASH framework. The following results must be

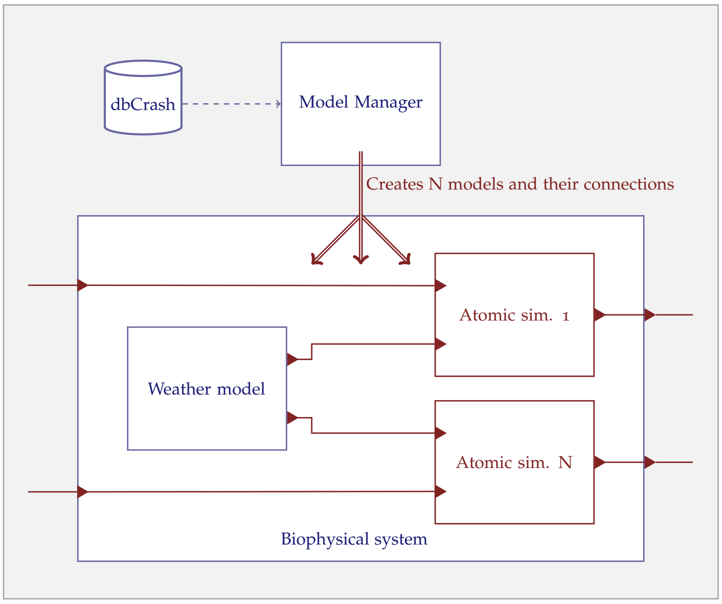


Figure 7.6: The model manager reads the spatial land units layer in the database (*dbCrash*), dynamically creates the corresponding number of atomic crop simulators, and build the connection between them and the other models, i.e. the weather model, the operating and agent system models (not in the Figure) [Atomic sim.: atomic crop simulator]

seen as model verification rather than case study results. Because the tests were independant of each others, they are presented in separate sections. Figures of this sections illustrate the potentiallity of *rCrash* for plotting model outputs including maps.

7.4.1 *Experiment 1: testing the WCSP approach*

We conducted an experimentation on the WCSP implementation used to sovle the first step of the strategic decisions (Figure 7.4). The objectives were to test the capabilites of CRASH to find solution taking into account interaction between spatial and temporal constraints. For this test, we did not implement all constraints, we mostly focused on agronomic constraints

7.4.1.1 *Material and methods*

Virtual farm We performed the experimentations by using four instances of a virtual farm presented in Figure 7.7. Each instance corresponds to a new sampling of the farmland into 15, 30, 60, 120 land units. For the instance with 15 land units, sampling was done such as plots (see Figure 7.7) were bound up with that of land units. These land units were gradually refined by splitting them into 2, 4 and 8 smaller ones, to respectively build the instances with 30, 60 and 120 land units. This sampling was a gradual ramp-up from a simple case up to a more representative case of a real farm.

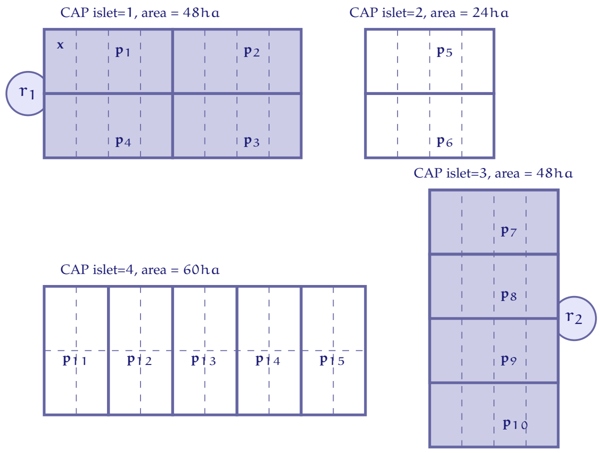


Figure 7.7: The virtual farm with the 4 crop management blocks, 15 plots split into 60 land units. The crop management blocks in ☐ have their own irrigation equipment (r1, r2).

Farm features and farmers' decision profile The virtual farm had four cropping systems (Table 7.2) corresponding to the four crop management block presented in Figure 7.7. The farm had two soil types: Soil 1 for the CAP islet 1 and 3, soil 2 for CAP islet 2 and 4.

Table 7.2: Cropping-plan history of the five previous years on the four crop management blocks [MA: Maize, BH: Winter wheat, CH: Rape seed, OP: Spring barley]

Cropping systems	Plots	t1	t2	t3	t4	t5
1 – irrigated	p_1	MA	MA	BH	OP	MA
	p_2	OP	MA	MA	BH	OP
	p_3	BH	OP	MA	MA	BH
	p_4	MA	BH	OP	MA	MA
2 – rainfed	p_5	BH	OP	BH	CH	BH
	p_6	OP	BH	CH	BH	OP
3 – irrigated	$p_{7:10}$	MA	MA	MA	MA	MA
4 – rainfed	p_{11}	BH	CH	BH	OP	BH
	p_{12}	CH	BH	OP	BH	CH
	p_{13}	BH	OP	BH	CH	BH
	p_{14}	OP	BH	CH	BH	OP
	p_{15}	BH	CH	BH	OP	BH

We implemented the following set of constraints:

- *Agronomic constraints:* We introduced agronomic constraints at the land unit level by using the minim return time of crops (rt) (h-TSC in Table 7.1) and the aggregated crop succession indicators

(k_p) (s-CSQ in Table 7.1) with values presented in Table 7.3. The minimum return time constraints had to be consistent with history land allocation (h-HST in Table 7.1). We purposely did not used the same rt for future allocation that the ones used in the past. For instance the succession maize-maize was existing in history (Cropping system 3 Table7.2) but was not allowed for new solutions because we choose $rt = 2$ to avoid monocropping.

- *Resource constraints:* Based on resource availability, the maize crop was not allowed to be grown on rainfed areas (h-SCC in Table 7.1). We defined a cost function to represent farm scale preferences and constraints (resource availabilities) such that the annual global acreage of maize and winter wheat over all blocks should be respectively within the range of 40–72 ha and 70–100 ha (s-SBC in Table 7.1).
- *Cropping system:* We defined constraints at the crop management block level in order to ensure that the same subset of crops will be assigned to every land units within each crop management block over years (h-SCA in Table 7.1).
- *Biophysical constraint:* We introduced biophysical constraints (h-SCC in Table 7.1) by preventing assignements of *rape seed* to land units whose soil type 1.
- *Topology:* We implemented a cost function (s-TOP in Table 7.1) to penalised by a cost isolated crop allocations.

Table 7.3: Agronomic constraint values that were used for testing the WCSP module on the virtual case study [rt: crop return time, kp: previous crop effect indicator (Leteinturier et al., 2006), MA: Maize, BH: Winter wheat, CH: Rape seed, OP: Spring barley].

			Previous crop effect (kp)			
Crops	rt	**Irrigation**	**BH**	**OP**	**MA**	**CH**
BH	2	-	4	1	1	0
OP	3	-	2	3	1	0
MA	2	Yes	0	0	3	0
CH	3	-	0	0	0	4

7.4.1.2 *Experiment results*

We searched for solutions on a four year horizon ($\mathcal{H}$). Results showed that with small and reasonable number of land units, relevant solutions can be found in acceptable computational time as presented in Table 7.4.

Table 7.4: Number of optimal solutions and computational time for the four experiments

Experiments	Time	number of solutions
#	*second*	#
15	21	2
30	323	12
60	2413	136
120	-	-

The WCSP succefully generated solutions that were respecting all constraints as defined in the experiments. As illustration, Figure 7.8 depicts solutions for the crop management block 1 as generated in the experiments with 60 land units. The Figure 7.8 shows that the 136 solutions at the farm scale translate into only two different crop sequences on the crop management block 1. This difference of number of solution between the farm scale and crop management block scale is explained by the combination (partial) of solutions between the four crop management blocks.

7.4.1.3 *Experiment discussion*

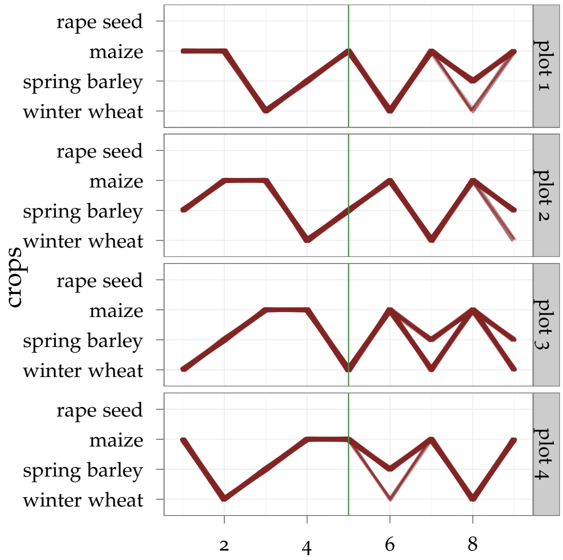
We did not solve the problem for the experiment with 120 land units. Dealing with large farm and many land units could be possible but will depends on the level of constraints. In these experiments with defined the minimal set of constraints that describe the strategic level of the cropping-plan decision-making. More expert knowledge should be included to better take into account resource management (water availabilities), crop preference (growing area) and crop succession characteristics (e.g. nitrogen, weed effect). These new constraints could be based on the already developped and tested WCSP formalisms as presented in Table 7.1.

7.4.2 *Experiment 2: spatial management of farmlands*

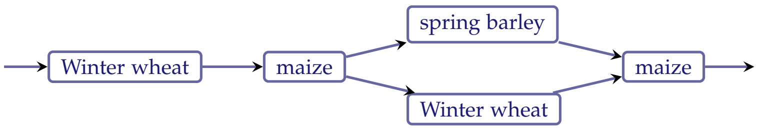
One requirement given by the WCSP solver was the use of land units equal in area. This required to split space into homogeneous and equal land units using the spatial layers that describe farmland characteristics.

7.4.2.1 *Material and methods*

We performed a series experiment to test the algorithm in its efficiency to sample space using a real farm spatial data set. The case study farm was located in the region Midi-Pyrénées and covered 281



(a) Solutions for the management block 1.



(b) Crop sequence pattern

Figure 7.8: a) Generated sequences of crops for all plots of the management block 1. Year 1-5 are the past allocation and the generated solutions are after the green line. b) Over all solutions, two crop sequences emerge that we summarised in one crop sequence pattern.

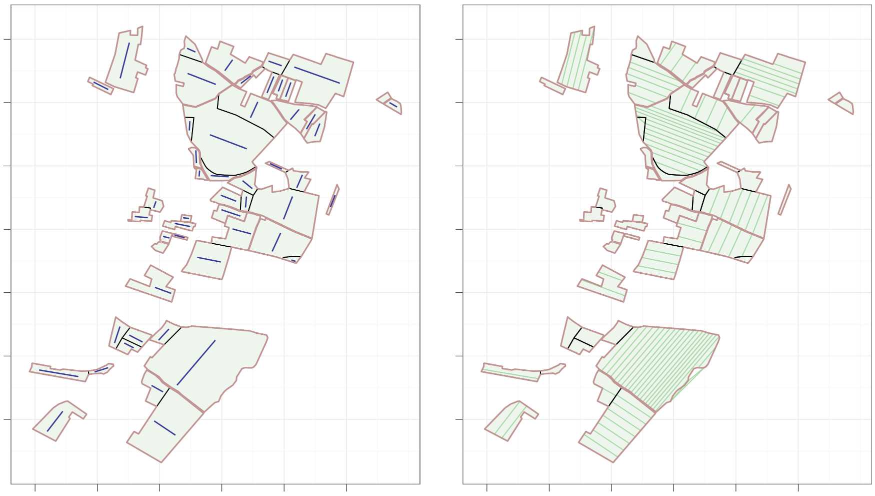
ha. The number plots of the spatial layer used as input were 62 and had an area of 4.5 ha (sd 6.6) on average (Figure 7.9a). The tests consisted in sampling the farmland into land units equal to a target surface area specified as parameter of the algorithm. We used the following target area: 0.5, 1, 1.5 and 2 ha.

7.4.2.2 *Experiment results*

Table 7.5 shows that the algorithm capability to sample the farmland into homogeneous land units with areas near to the targeted ones (Table 7.5). The standard deviation increased with increasing land unit areas. This was explained by existing small plots into the input spatial layer (Figure 7.10): 39% of the initial plots were already smaller than 1.5 ha before splitting.

7.4.2.3 *Experiment discussion*

Results show that compromise has to be found between the precision (i.e narrow distribution) and the number of generated land units:



(a) Input (b) Output

Figure 7.9: Part of the farmland that have been used to test the sampling algorithm. a) Sampling the farmland into homogeneous land units requires spatial descriptions of the management units (at least the existing plots), and optionally the working direction. b) Land units as generated by the algorithm (2 ha) developed for CRASH to sample the farmland.

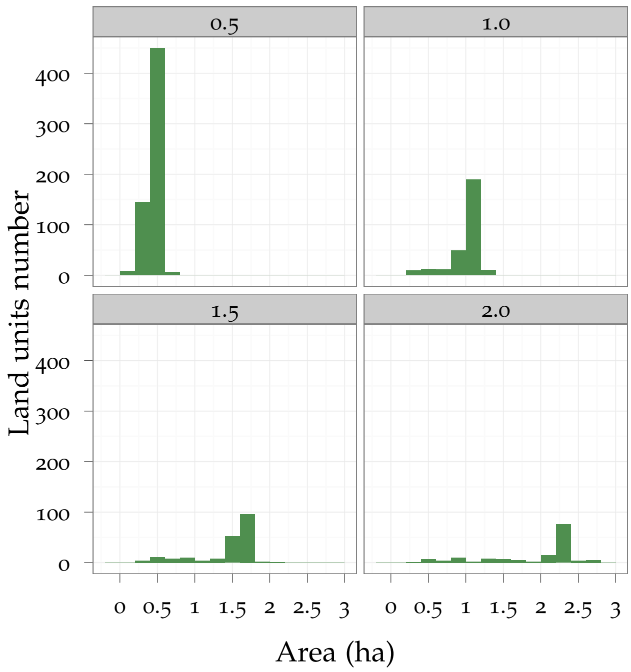


Figure 7.10: Distribution of the land unit areas generated by sampling the farmland MiPy 1 using 0.5, 1, 1.5 and 2 ha as targeted areas.

Table 7.5: Spatial sampling of the farmland of MiPy 1 using the plots and work orientation layers, and targeted area ranging from 0.5 to 2.5 ha. The initial plots numbers were 62 with 4.5 ha (sd 6.6) on average.

Targeted area *ha*	**Mean area** *ha (sd)*	**Land units** #
0.5	0.46 (0.09)	609
1.0	1.05 (0.20)	280
1.5	1.44 (0.38)	196
2.0	1.93 (0.62)	146

smaller are the land unit areas, narrower will be the distribution of land unit areas (Table 7.5). However, computational requirements for running the WCSP solver exponentially increase with the number land units.

7.4.3 *Experiment 3: Coupling models and simulations*

The CRASH framework is based on simulating farmers decisions at the strategic levels but also crop growth and related crop management decisions. We conducted this experiment to test:

1. The feasibility to couple the STICS crop model with an agent model in order to deal with dynamic crop management processes.
2. The capability of the reasoner to build a graph of activities using sub-plan stored into the database and to simulate it using the *decision plugin* of the VLE platform.
3. The capabilities of CRASH coupled with STICS to produce realistic outputs using light calibration methods. The crop model parameterisation was based on the generic crop files parameters provided with STICS and expert knowledge (Mahmood et al., ????). We purposely choose a very light calibration method to approach situations in which the CRASH framework could be used in the future.

7.4.3.1 *Material and methods*

We performed the tests on two farms located in Midi Pyrénées and Poitou Charentes (MiPy 1 and PCh 1 respectively) (Table 7.6). We questioned farmers on their crop management techniques for their main crops (Table 7.6) and related decision rules they used to adapt their crop operations to changing conditions. We formalised these crop management techniques as set of activities and decision rules to store them in the database.

Table 7.6: Farm areas and main cultivated crops in the period 2007-2009

Farm	Area *ha*	Irrigated area *ha*	Main crops
MiPy 1	281	134	Maize*, Winter wheat, Rape seed
PCh 1	97	25	Winter wheat, Durum wheat, Rape seed*∗, Sunflower*∗

* Permanently irrigated crops

* Occasionally irrigated crops

We compare observed vs. simulated yields for the period 2007-2009. Then, we performed simulations over a long climatic series (1988-2009) for the two farms to explore the magnitude of variations of simulated crop yields and irrigation water uses. We compared the variabilities of simulated crops yields for the period 1988-2009 and the range of expected yields and water uses that farmers considered for planning their cropping-plan.

7.4.3.2 *Experiment results*

Simulated vs. observed crop management Figure 7.11 depicts simulation and observed grain yield estimates for the period 2007-2009. Results of the Wilcoxon matched pairs signed ranks test (>0.05) do not give any reason to conclude that the overall medians differs between simulated and observed yield estimates. However, the overall root mean square error is high (1.19 ton ha^{-1}) as regards to precisions required in the overall cropping-plan decision-making. This is especially true particularly for the maize crop (1.53 ton ha^{-1}) and winter wheat (1.35 ton ha^{-1}) and rape seed (1.20 ton ha^{-1}) (Figure 7.11).

Simulated yields and irrigation water uses variabilities Results show that in general farmers considered narrow ranges of yields when planning their cropping-plan in comparison to the overall range of simulated crop yields over the period 1988-2009 (e.g. with winter wheat, durum wheat and sunflower in farm PCh 1 in Figure 7.12). This narrow range of yields correspond to a narrow range of relative frequency. As illustration, 19% of the simulated yields were between the range of expected yields for winter wheat that is considered by farmer PCh 1 for planning (Figure 7.12). This contrast a lot with with the 81% for simulated pea yields that were included in the range of expected yields as used by the same farmer (Figure 7.12). Results concerning irrigation water were quite satisfactory as regards to what farmers expected to use when planning their cropping-plan. As illutration, Figure 7.13 shows the cumulative relative frequency of simulated irrigation water use following irrigation practices of farmer MiPy 1. Farmers expectation cover 30% of the range of simulated irrigation

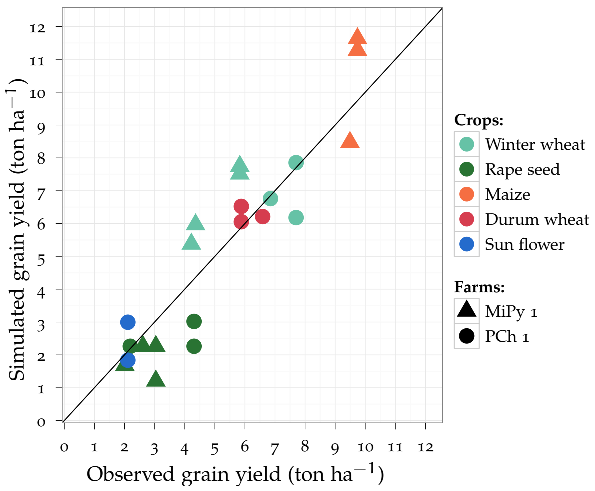


Figure 7.11: Simulated and observed grain yield estimates (ton ha^{-1}) for 22 observations in two farms (MiPy 1 and PCh 1) between 2007 and 2009. Root mean square error (ton ha^{-1}): winter wheat 1.35, rape seed 1.20, maize 1.53, durum wheat 0.44, sunflower 0.65.

water use and his expectation were rather on the above part of the curve.

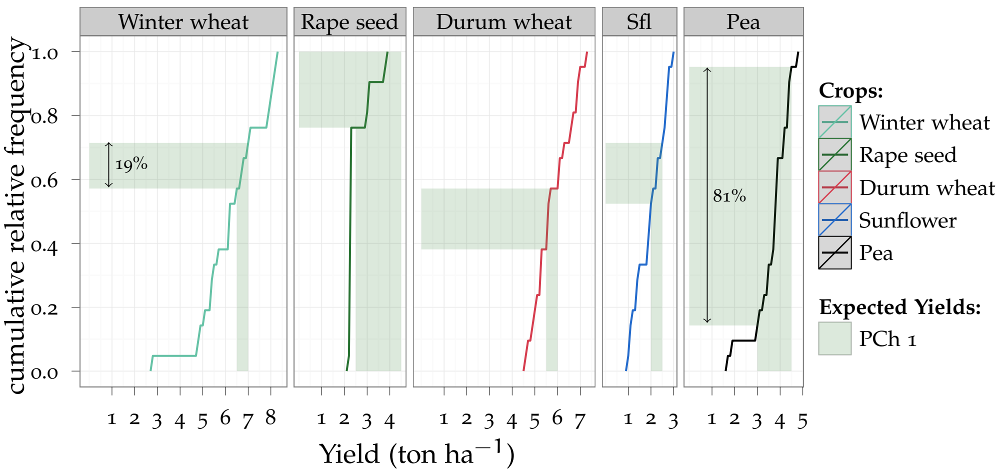


Figure 7.12: Cumulative distribution function for simulated crop yields (ton ha^{-1}) with the main cultivated crops of farmer PCh 1 for the period 1988-2009. In green, range of expected yields as mentioned by the farmer when planning his cropping-plan.

7.4.3.3 *Experiment discussion*

The first results look satisfactory as regards to the light parameterisation approach we used. Indeed, the model provides outputs around the observed medians but with high RMSE. These results call several questions on the ability of CRASH to simulate realistic crop

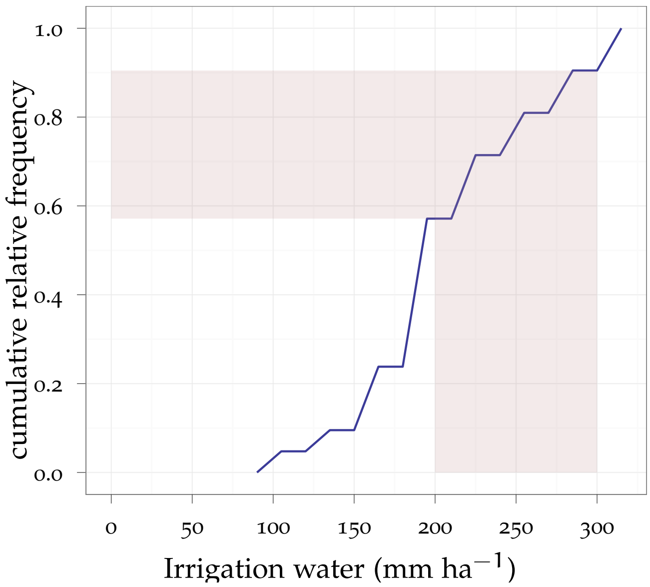


Figure 7.13: Cumulative distribution function for irrigation water consumption with maize in the farm MiPy 1. [MiPy: Midi Pyrénées].

yield variabilities at the farm scale for decision-making purposes. At this stage it is difficult to provide more explanations to these apparent inconsistencies: causes of discrepancies could be explained by the crop model capabilities, the quality of the parameterisation, or a insufficient representation of the farmer practices, and most probably a combination of all these factors. After model verification, a model validation is required to conclude on these aspects.

7.5 GENERAL DISCUSSION

In this paper, we presented the modelling framework CRASH with the aim to propose new directions to address the cropping-plan selection while taking farmers' decision determinants and strategies into account. The CRASH approach focuses on simulating and analysing the process of cropping-plan decision making rather than finding the best or optimum cropping-plan as regard to a set of constraints and objectives. In this sense, the CRASH is seen as a complementary approach, and not to be opposed to the more traditional ones being mostly based on single optimization procedures (e.g. McCarl et al., 1977; Leroy and Jacquin, 1991; Annetts and Audsley, 2002; Dogliotti et al., 2003; Bachinger and Zander, 2007). Our proposal also differs from others that did not have their root in operational research (e.g. Stone et al., 1992; Nevo et al., 1994; Aubry et al., 1998b) by explicitly taking into account the dynamics of decision-making process of farmers as well as an explicit representation of space through the biophysical and management units.

7.5.1 *Crash as potential decision support systems*

Our model clearly fits in the category of *Problem specific environmental decision support systems* as defined by Rizzoli and Young (1997). It was indeed tailored to relatively narrow domain of application, i.e. supporting farmers in their cropping-plan decision in irrigated farms, but are applicable to a wide range of different locations.

As potential decision support system, CRASH has the ability to be used for diagnosis, planning and management. The diagnosis could be carried out by simulating at farm scale existing cropping-plan with the current crop management techniques to assess the relevance and robustness of already made choices over different climatic and price scenario. Planning could be performed by running the the CRASH module that deal with strategic decisions. In addition to the determinion of an optimal combination of crops as regard to a set decision determinants, it also produces an optimal assignment of the crops to the plots of the farms. And then, exploring the effects of different decision strategies could be useful for the decision makers to question their management strategies while selecting the crops to grow in their farms.

7.5.2 *Model modularity*

The CRASH framework offers the opportunity to address the different facet of the cropping-plan decision problem (diagnosis, planning, management) as a whole or separately because the design and integration of the different components were based on a modular approach.

The modularity of the CRASH framework is first guaranteed by separating the data (input/output) and the simulation models. This was achieved by interfacing a single database describing the domain with different models, all being accessible by a single tool to perform simulations, analysis and plotting.

The second level of modularity concerns the development of the two simulators themselves using the VLE platform that is based upon the DEVS operational formalism. The specification of all the subsystems into atomic model characterised by as a set of input and output ports make easy the development and/or the re-use of other atomic models in replacement/addition to the existing one (Quesnel et al., 2009). In the VLE platform, the coupling of atomic models does not require any programming.

The third level of modularity concerns the knowledge base within the agent systems which can be extended. This is made possible by the use of the object oriented paradigm for representing the knowledge of the agents. Numerous object-oriented models have been reported in agricultural simulations (e.g. Shaffer et al., 2000; Papajorgji and Pardalos, 2006; Adam et al., 2010). All reported support for model conceptualization, program design, and reuse of the models as advantages of object-oriented approaches for model development. However, at this level the modularity requires programming skill.

7.5.3 *The crop model choices*

Taking advantage of the modularity offered by the VLE multi-modelling platform, the choice of the crop model could be requestioned to fit particular situations and eventually exchanged without compromising the whole CRASH framework. Therefore, we can say that the modelling framework CRASH is not strongly dependant on the initial choice of the STICS crop model.

The use of such complete models comes indeed with unnecessary development complexity (see in Appendix E) and with some significant difficulties and limitations in the overall uses of the CRASH framework. One strong limitation of using such models are the proper calibration for site specific conditions such as real farms. Wether calibration methods are now well documented (e.g. Wallach et al., 2001; Guillaume et al., 2011), these methods usually require a large amount of data with detailed measurements (.e.g Guillaume et al., 2011). Some possible approaches to overcome these well known limitations (e.g. Brun et al., 2001) could be: (1) the use of *summary crop models* as proposed by Tittonell et al. (2010) for African conditions, (2) the design of custom crop models following the approach of Donatelli et al. (2006a) and Adam et al. (2010).

7.5.4 *Future works*

Currently, CRASH is a prototype system that is designed to illustrate new approach of dealing with the planning and adaptations of the cropping-plan decision problem. As such it currently contains only a set of representative parameters which influence crop planning. To make it more complete for practical uses, some additional parameters should be included. For instance, the preceding effect is currently represented by a single aggregated parameter, i.e. k_p (Leteinturier et al., 2006). It would be more realistic to use a set of parameters to described the different dimension of previous crop effect on the next one by (e.g. soil structure, diseases, pests, weeds, nitrogen). Further the knowledge base should be expanded to include additional crops with different sets of crop management techniques. The work of adding new crop management techniques described as decision rules entail to extend to number of predicates that are taken into account within the agent system.

As future work, we will also investigate how the WCSP formalisms that describe the cropping-plan allocation problem could be improved. First introducing the cumulative constraints can be useful to improve the resource management using the WCSP approach. Another interesting work direction is to take inspiration from works done by Métivier et al. (2009) to investigate how the return time and preceding effects of crops could be mixed using regular-cost constraints.

7.6 CONCLUSIONS

In this paper, a farm model has been presented that can be used to simulate and analyse individual cropping-plan decision making of farmers. The originality of the CRASH approaches rely on (i) the design and integration of different components that are based on a realistic representation of the cropping-plan decision-making processes given the advances in modelling decisions, (2) the use of an advanced multi modeling simulation platform allowing for a powerful integration of different models that are based on different language and/or different formalisms, and (3) the use of dynamic simulation models on both the biophysical and the management processes.

The process of the models implementation fit to modern software engineering requirements. This was achieved by designing the models in a modular way allowing for switching on/off the modules and the possibility to integrate new modules, and by separating simulation models, data storages and tools to analyse inputs/outputs.

Part III

GENERAL DISCUSSION AND PERSPECTIVES

8 GENERAL DISCUSSION

The general objectives of this thesis were 1) to investigate cropping-plan decision-making process of farmers in irrigated arable farms, and 2) to propose an innovative modelling and simulation approach allowing for exploring and simulating cropping-plan decision-making at the farm scale. In addition to the many approaches based on optimization procedures, the objective of our approach was to propose new directions to address crop allocation planning while taking farmers' decision-making process into account. Our approach is intended to be complementary to the other approaches found in the literature that mostly have their roots in the field of operational research and agricultural economics (see Chapter 3).

In this thesis, I therefore did not address the issue of cropping-plan selection in irrigated arable farms through the single perspective of optimising water use and economic return but rather analysed and modelled the processes of decision-making. I took for granted the many studies that have already described the many determinants that affect farmer cropping-plan decision (see Chapter 3). To build upon this knowledge, I thought that it was more relevant to study how and when these determinants are taken into account by farmers in their decision-making process. To my knowledge, no research has specifically addressed the cropping-plan decision problem by modelling processes of decision-making of farmers explicitly taking into account temporal and spatial dimension of the problem. Only a few approaches addressing the issues of cropping pattern selection have been based on realistic modelling and simulation of management strategies of individual farmers (e.g. Aubry et al., 1998a; Navarrete and Bail, 2007).

To achieve these general objectives, I went through the five specific objectives as presented in Section 2.3. In addition to the review on cropping-plan and crop rotation models, the contribution of this thesis to the modelling of the cropping-plan decision-making can be summarized as follow:

– An integrated and generic methodology was developed to fill the gap between field surveys and decision-model implementation. The methodology is drawn upon a theoretical background of the decision-making, and consistently combined tools to respectively survey, analyse, model and implement coupled agent and biophysical models. This case based methodology enable to model in a formal and generic way decision-maker knowledge that are involved in the decision-making process under study. I argued that decision-making modelling must integrate the modelling of decision-makers' knowledge representation and problem structuring.

– The spatial and temporal dynamics of the farmer cropping-plan decision-making process were described through formal concepts. These concepts were defined and gathered into an ontology making them re-usable by others for future research. The modelling of concepts underlying the many determinants of the decision was useful for summarizing existing information but also for identifying when possible new knowledge involved in the process of cropping-plan decision-making. Describing the decision-making dynamic give insights to answer the question of how do farmers, at individual level, cope with uncertainty while deciding their cropping-plan. We demonstrated that cropping-plan does not emerge from a single decision but is a dynamic decision-making process, incorporated into a succession of other hierarchical and planned decisions along annual and long term horizons.
– A comparison of different stated and revealed methods to elicit and estimate individual farmer's risk aversion. This study shown that the consistency across methods is not straightforward despite evidences across methods to differentiate attitudes between farmers to cope with risk. The type of lottery should be carefully evaluated if risk preferences are elicited through experiments are expected to be used to predict real decisions of farmers.
– A simulation-based modelling framework, namely CRASH, to simulate and analyse cropping-plan decision of farmers in irrigated farms. CRASH is a set of integrated tools providing utilities to explore different farmers' management strategies to select their cropping-plan. The model takes into account the management of risk and uncertainty by farmers. The novelty of the approach proposed in this thesis rely on the coupling of dynamic models on both decision and biophysical processes to deal with the cropping-plan decision problem. CRASH was implemented within the VLE multi modelling simulation platform.

8.2 MODELLING THE DECISION-MAKING PROCESS

8.2.1 *The process of decision-making*

An important objective of this research was to understand the management strategies and decision rules which govern farmer decision-making to better assess consequences of such decisions on the environment. Farmer decisions are usually classified as operational, tactical and strategic with an increasing time horizon of the decision (Le Gal et al., 2011). However, scientists do not hold a consensus on the way to model farmer decision-making and its importance when analysing results of decision models. Progress has been made in recent years on decision-making representation, but fully integrated human and biophysical models for decision support and evaluation remains an ambitious undertaking (Parker et al., 2008). For instance, Berger (2001) argued that the predictive capacity of agent models will mainly be limited by their assumptions with regard to decision-making rather than by biophysical-model performances.

There is evidence for limitations of comparing different modelling approaches because of the many opposite/overlapping theoretical frameworks used in the different scientific fields that address dynamic decision-making problems (see Klein, 1993; Parker et al., 2008; Osman, 2010; An, 2011). Klein (1993) have pointed out key differences between decision-making as studied using traditional decision theory and as it occurs in real-world situations. The resulting naturalistic decision theory gives strong insights in analysing decision-making and underlying knowledge of the agents. But this had not yet resulted in practical solutions for developing agent-model based on the concept of situation awareness (Osman, 2010). Zannier et al. (2007) already demonstrated that in practice modellers are mixing different theoretical frameworks to design their models, even if they are presented as opposite by their authors. CRASH is not an exception to these practices. As suggest by Norling et al. (2001) and Zannier et al. (2007), we made use of aspects of naturalistic decision making and aspects of rational decision-making concurrently. We used rationalist and naturalistic paradigm as mirror of each other to re-question analysis of farmer decision-making. Because, it is difficult to study the decision process just from a rational point of view, the cropping-plan decision-making analysis (Chapter 4) were performed in a perspective close to the naturalistic setting. Indeed, we did not seek to prioritize or weigh between decision determinants (rationalist perspective), but rather focused on formalising decision-making process and decision-maker knowledge that are involved in cropping-plan decision-making. However, the CRASH model design (Chapter 7) is more in the line of the rationalist paradigm. Rational decision-making is indeed characterized by the choice of options among a generated set of options, with a goal of selecting the optimal option. At the strategic level, CRASH generates a set of solutions (candidate cropping plan scenario) from which a selection is performed. This solution is then simulated with a set of adjustment rules allowing adaptation to changing context. Beyond theoretical debates concerning decision-making representation, the primary objective of decision-making analysis is problem structuring. This is especially true for ill-structured problems (Jonassen, 1997) such as cropping plan decision-making problem. The shift between decision-making paradigms reflects the progress in decision problem structuring that took place during the CRASH modelling process.

Despite difficulties encountered in representing decision-making process in simulation models, the tasks are not vain. Understanding decision-making process provides paths to interact with decision-maker by facilitating the development of Decision Support System (DSS) (Cox, 1996; Carberry et al., 2002) and allows comprehensive support decision-making with regard to integrating participatory approaches (Ohlmer et al., 1998; Neef and Neubert, 2010). For modellers, formal description of decision-making process also gives insight to improve resolution and process to be considered in biophysical-models with regard to practical uses (e.g. the lack of biotic component in most crop models (Bergez et al., 2010)).

8.2.2 *Modelling the farmers' knowledge: an ontological analysis*

The coupling of module representing more finely decision-making can not be disconnected from the analysis of these processes in real setting (Parker et al., 2008; An, 2011). Therefore, farmer knowledge are a crucial component in the generation of scientific knowledge (Neef and Neubert, 2010) and particularly in decision-making process analysis (Klein, 1993). Methods of accessing and formalising local knowledge are part of the research methodological approach (Hoffman and Lintern, 2006) and may include various forms of individual and group interviews, participatory rapid appraisal tools, and participant observation. However, farmers' knowledge is often tacit and therefore eliciting, describing and formalising knowledge is difficult (Becu et al., 2003; Hoffman and Lintern, 2006). Farmer knowledge should be as critically examined as scientific knowledge that goes through a rigorous formalisation process by modellers.

"An ontology is a formal specification of concepts and their relationships within a particular domain" (Beck et al., 2010). Ontological analysis clarifies structures of knowledge of a specific domain and forms the heart of any system of knowledge representation (Chandrasekaran et al., 2002). In agro-ecological domain and agricultural system modelling, efforts have been done in developing ontology to provide shared knowledge formalisation (e.g. Athanasiadis et al., 2009; Martin-Clouaire and Rellier, 2009; Beck et al., 2010). Beyond similarities of the domain of interest, these ontologies were developed with specific purposes and therefore respond to different uses. For instance Martin-Clouaire and Rellier (2009) proposed a detailed ontology (i.e. DIscrete Event Simulation Environment (DIESE)) focusing on the conceptualisation of the technical production activities at the farm level and related farmer management strategies. This ontology facilitates developing simulation models representing farmer management practices (e.g. Martin et al., 2008) and could have been suitable for the project CRASH. In the Seamless project, ontology was mainly used as tool to address

the complexity of agricultural data management in order to facilitate model integration at the different scale of interest.(Athanasiadis et al., 2009).

The ontological analysis conducted in this thesis is not only dedicated to facilitate work of modellers but focused more on designing knowledge patterns for interfacing between modellers and stakeholders. I argued that a detailed understanding and a formal representation of relationship between expert decisions and their knowledge in a specific domain must be addressed as starting point to develop any decision-model or decision support systems. Therefore key concepts of cropping-system management commonly used by expert in their day to day work (i.e. farmers, advisor and agronomists) were examined. Starting point was the explicit and tacit knowledge used by them rather than concepts used by agricultural system modellers. The ontological analysis captures this expert knowledge into formal and machine manipulable model of the domain independent of any programming solutions (Kogut et al., 2002). This enable to bring closer ontological works in the field of agricultural system modelling and concepts used by expert in their daily decision-making. In this sens, this ontological analysis is complementary to the DIESE ontologies (Martin-Clouaire and Rellier, 2009) that focuses more on the abstraction of decision-making process in agricultural systems rather than the knowledge require for the decisions.

8.2.3 *Is CRASH a pure BDI agent?*

As particular type of bounded rational agent model (Wooldridge, 2002), BDI framework was used as basic architecture to structure the decision-making analysis and facilitate CRASH implementation. By separating agent knowledge (Beliefs), objectives (Desires), actions (Intentions) and deliberative functions (Reasoner), it allowed to use specific methods to analyse and model each part of the decision problems. However, CRASH is not a pure BDI agent implementations as described by Rao and Georgeff (1991, 1995).

CRASH was designed by simplifying some assumptions and some of the expressive power of the initial theoretical framework. For instance, CRASH does not explicitly use a logical model through which pure BDI agents reason. But the CRASH model shares several common features with BDI models such as the architecture, reactive and goal-directed behavior and a procedural representation of knowledge. It also provides mechanisms for separating the activity of selecting/building plans of activities (from the procedural knowledge) from executing currently committed plans (intention). In our approach, we took advantage of apsects of the hierchical planning approach by first planning crops to be grown, and then corresponding crop management techniques (see Chapter 7). This two stages hierchical approach produces multi-annual crop-operation plan that is spatially explicit. Similar to BDI agent, CRASH agent dynamically collects information during simulation of the plan. This gives to the CRASH agent real-time reactive behavior to changes of the environment. We took advantage of the decision plugin features provided by the VLE platform to model this mechanisms. CRASH also shares some limitations that have been acknowledged to BDI agents. The CRASH agents:

– Lacks specific mechanisms to learn from past behavior.
– Does not have an explicit representation of goals.

8.3 ARE CROP MODELS THE BOTTLENECK FOR SIMULATING FARMERS' DECISIONS AT THE FARM SCALE?

One -among other- important hypothesis upon which the development of agent models are justified in modelling farming systems is the importance of the interaction between humans and their biophysical environment (Parker et al., 2008; Le Gal et al., 2009; Martin-Clouaire and Rellier, 2009).

In agricultural systems, the biophysical systems are often represented by crop models from which we distinguish two main types:

1. The *empirical models* are direct descriptions of observed data generally expressed as regression equations. They are usually crop specific and are used to estimate final yields.
2. The *mechanistic models* consist of a set of mathematical equations describing the different processes of the soil-plant system in interaction with climate and technical operations. These models fit better for cropping system design purpose since they have the ability to mimic underlying behaviour of the system in terms of lower-level variables (Wallach et al., 2006). They also provide dynamic system state indicators those may be used to trigger actions. These models can be crop specific, e.g. Oryza2000 (Bouman, 2001), or generic, e.g. APSIM (Keating et al., 2003), CROPSYST (Stockle et al., 2003), APES (Donatelli et al., 2010), STICS (Brisson et al., 2003).

In the case of CRASH, the crop model requirement concerns the good prediction of few final variables (e.g. yields, water use, succession effect) to simulate cropping-plan decisions, and much more intermediate ones to simulate crop management decisions (e.g. soil bearing capacity, crop water/nitrogen needs, crop phenlological and physiological stage). An empirical crop model combined with some crop succession indicators (e.g. Leteinturier et al., 2006) could have been a good solution to only consider cropping plan decision-making because they have a better prediction power. But in the CRASH approach, we choose to use the second type of crop-model (i.e. STICS) in order to dynamically simulate crop growth and water use in relation to their management on every simulation unit. We choose it for its ability to simulate a large number of different crops under various conditions and for its ability to simulate agronomic variables as well as environmental variables. However, the preliminary tests of the CRASH framework (see Chapter 7) have shown some issues in using of such mechanistic crop model in real farm setting conditions. This highlights some critical gaps of the current design of mechanistic crop models for practical uses that have to be addressed in future research works. The main limits that we faced are of three types:

- *Model uncertainty and calibration:* Crop simulation models are by their nature a simplification of reality that inevitably lead to discrepancies between simulated and observed data. Their designs are a compromise between the loss of accuracy introduced by process aggregation and loss in precision through the error accumulation related to the estimation of a large number of parameters into very detailed process-based models (O'Neill and Rust, 1979; Brooks and Tobias, 1996). Further, outputs of the model should be reliable enough when used in a perspective of decision support (Tittonell et al., 2010) or in a perspective to be coupled with agent model (Bergez et al., 2010). In the context of simulating real farm performances, traditional calibration methods are not suitable because of the large amount of data that is required (e.g. Guillaume et al., 2011) and/or the large number of parameters to be considered (e.g. Wallach et al., 2001). Few improvement has been done to calibrate such complex models with restricted data availability (e.g. Langensiepen et al., 2008; Palosuo et al., 2011). The use of default value and/or light calibration methods leads to a high degree of uncertainty on outputs as recently demonstrated by Langensiepen et al. (2008) for CERES-wheat and Palosuo et al. (2011) for eight other crop growth simulation models, including STICS. They showed that models are good in predicting average output values but failed to produce reliable outputs in situation outside the average climatic conditions.
- *Model processes:* An important drawback with crop models such as STICS is the lack of component that simulate the biotic processes such as pests and weeds (Bergez et al., 2010). These factors were identified as important drivers of the cropping-plan adaptation decisions of farmers (see Chapter 5). The coupling of STICS with biotic models is an ongoing work within the MicMac project (Vericel, 2010).
- *Model coupling:* According to Brooks and Tobias (1996), two of the criteria to evaluate simulation models are their portability and their ability to be coupled with other models, e.g. an agent

model. As already discussed in the Chapter 7, coupling STICS to an agent model come with some limitations and implementation difficulties. The model was indeed not initially designed to be coupled with external models.

These crop model limits are not new and we did not discover them with CRASH. But still, it rises the question whether using STICS (or another mechanistic crop models) is a good option to be coupled with a agent model dealing with cropping-plan decisions? Choosing the best model for a specific use has never been an easy question (see: Brooks and Tobias, 1996) and changing from a model to another does not guarantee better results (see: Palosuo et al., 2011). Some authors, facing similar issues, have circumvented the problem by proposing different approaches than choosing between models. I retained two interesting paths to explore in order to make the CRASH framework more usable in practical perspectives:

- *Summary crop models:* Tittonell et al. (2010) proposed an approach where a model (FIELD) was designed based on simple summary functional relationships. These functions described only the main processes at a higher integration level than the processes under study. Some of functional relationships were summarized from more detailed crop models. This approach has been successfully applied in African condition to reduce the number of parameters and the need for model calibration.
- *Modular and flexible crop models:* On the basis of works conducted by Donatelli et al. (2006a), (Adam et al., 2010) proposed a methodology and tools within a modular crop modelling framework (CROSPAL), to design custom crop models for specific agronomist needs. A custom crop model can be build by incorporating crop growth functions available in a library of processes. The modularity of the framework is provided within a plug and play architecture implemented in the object-oriented paradigm. Soil process are not yet incorporated in the CROSPAL framework to enable the design of complete soil-plant models.

The two above mentioned approaches allows for designing custom crop models to satisfy specific objectives without reinventing the wheel at each problems. They fit to the Occam's razor philosophy stating that *"entities should not be multiplied beyond necessity"*. They also provide practical paths to design models targeting specific needs, and coupling agent with crop model require specific needs. The implementation of a modular crop models in the vein of Donatelli et al. (2006a); Adam et al. (2010) should be quite straightforward within the multi-modelling platform VLE (Chabrier et al., 2007; Quesnel et al., 2009). This require to program and make available a set of atomic models representing single crop or soil process in the form of difference equations. In addition to the modularity offered by VLE, this approach would allow a more direct coupling with decision-model since atomic model in the form of difference equations can easily be disturbed by external events.

Another approach could be to not use dynamic crop model. A simple approach could be the use of empirical crop models to estimate yield and water use in combination with simple dynamic models targeting the other processes affecting the cropping-plan decisions. These approach could be sufficient to feed the agent model and to analyze the decision-making process of farmers but will certainly be unsatisfactory to perform analysis on environmental variables. Such approach should be considered in combination with ex-ante assessment tools such as INDIGO (Bockstaller and Girardin, 1996; Bockstaller et al., 2009) or MASC (Sadok et al., 2009).

8.4 FROM PROTOTYPE MODEL TO OPERATIONAL TOOL

8.4.1 *State of progress in CRASH development*

At this stage of development, the CRASH framework should be considered as a *demonstration prototype* (■ in Figure 8.1) that is used to illustrate a new approach of dealing with planning and adaptations of cropping-plan decision problem.

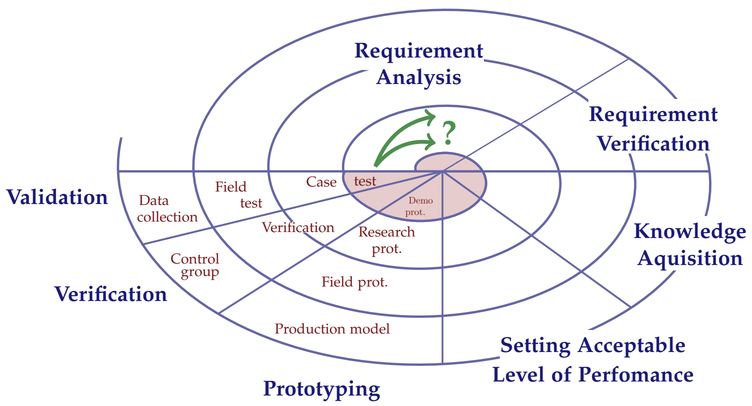


Figure 8.1: Spiral development methodology for intelligent systems (Lee and O'Keefe model in: Mosqueira-Rey and Moret-Bonillo, 2000). ■ : stages that have been currently achieved in the development of the system based-modelling CRASH. [Demo prot.: demonstration prototype, Research/field prot.: research/field prototype, ⟶: future development paths)

The development phase of the model did not reach its final stages yet (Figure 8.1), it just allowed to perform unitary tests on different components of the model. These tests (see Chapter 7) mainly focused on innovative and therefore most critical parts of the CRASH framework. Our main objective was to implement the innovative part of the conceptual model on the VLE platform to:

1. Test the relevance of the WCSP approach and its computational performances.
2. Test the management of explicit spatial units to parameterize the structure of the biophysical model based on a geographic information system.
3. Check the feasibility to plug and manage the STICS crop model with coupled agent model in order to deal with dynamic crop management process as well as dynamic crop-succession decisions.
4. Check the feasibility to build and simulate sub-plans of activities that are described in a database, i.e crop management techniques, using the *decision plugin* of the VLE platform.

As an objective of the UMT eau, CRASH should in the future be used as tool to help farmers' managerial support in their cropping-plan decisions and facilitate the analysis of farmers' practice evolutions. However, considering the spiral development of Lee and O'Keefe (in: Mosqueira-Rey and Moret-Bonillo, 2000), the work should again go across several development iterations before reaching the level that is required for an operational tool. As stated by Cox (1996), there is need of an analytical phase between the design and development of the process model and the development of an operational decision support systems. This phase, represented as as ⟶ in Figure 8.1, can help to identify possible features to change in the way the systems is designed and the implication of alternative courses of development (Cox, 1996). Future developments of the CRASH framework will partly depend on answers of the following two questions:

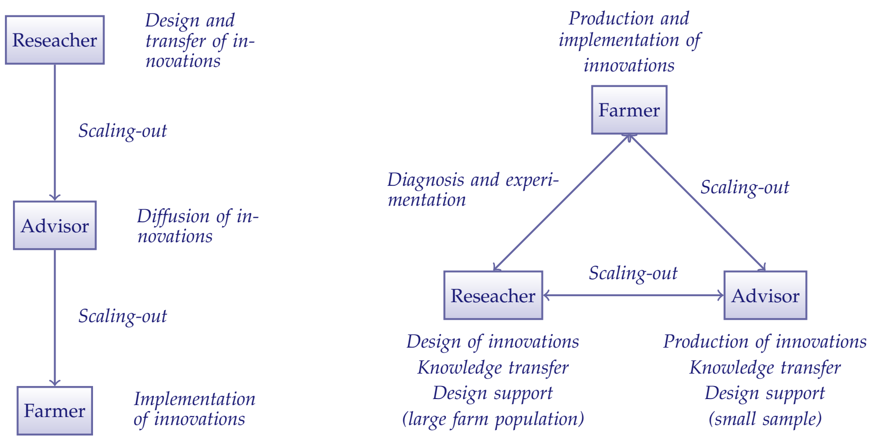
1. In which innovation process paradigms (Figure 8.2) is the CRASH framework intended to be used?
2. Is the CRASH framework intended to be used for cropping-plan *design* or cropping-plan *design support* (Figure 8.3)or both?

8.4.2 *How to support farmers in their cropping-plan choices?*

A joint reflection among partners of the UMT eau has already been carried out to clarify on objectives for future tool. Some of the answers already haves been mentioned (see Appendix A), but from the perspective of developing an operational tool based on CRASH answers have to be refined in order to continue the development of CRASH. I suggest some lines of thought:

8.4.2.1 *Innovation process*

Coming back to the rationale underlying this thesis (i.e. the support of farmers for planning and adapting their current cropping-plan in an ever changing context) raises the question on how the CRASH framework should be efficiently used to participate in the process of producing innovative cropping-plans. The CRASH framework was not designed to be used as prescriptive decision support system but rather to analyse by simulation the consequence of given farmer decision styles (i.e farmers' objectives and the set of decision rules and strategies). It is therefore not intended to provide turnkey solutions in a linear and top down innovation process (Figure 8.2a) as formerly accepted in the past (Leeuwis et al., 2004). To take full advantages of the CRASH framework, its uses should be thought within a more interactive innovation paradigm (Figure 8.2b) where CRASH could be used by agricultural extension services as well as researchers (e.g. McCown, 2002; Carberry et al., 2002). As shown by Vanloqueren and Baret (2009) comparing the adoptions of technical innovation and agro-ecological innovation, the adoptions of innovation are much more difficult when it does not translate into techniques. Because cropping-plan decision support is not about techniques, and because there is no general rule for answering question of the best cropping-plan, CRASH should be used by researchers and extension specialists in collaboration with farmers. CRASH is indeed intended to address site-specific issues in order to adapt farmer practices (Le Gal et al., 2011).



(a) Linear and diffusionist paradigm of innovation process

(b) Interactive and participative paradigm of innovation process

Figure 8.2: Schematic representation of two innovation process paradigms including farmers, advisors and researchers. The concept of «innovation» includes both new technologies and new ways of organizing and managing production systems. In paradigm (b) researchers and advisors carry out similar tasks but at different scales, which requires an efficient scaling-out process (From Le Gal et al., 2011).

8.4.2.2 *cropping-plan design and design support using CRASH*

Considering the interactive and participative paradigm of innovation process (Figure 8.2b), the CRASH framework could be used to fulfill different types of objectives by researchers or extension service advisors. According to Malezieux et al. (2001), the goals of any agro-ecosystem models can be categorized into four groups: 1) models that represent knowledge, concepts and methods for scientists; 2) models as tools for communication; 3) models as tools to manage or run systems; 4) models as tools to assist debate. Currently, CRASH fit into the first category. But in a more operational perspective, the model could fulfill the goals two and four. The beneficial outcomes of the CRASH model-based approach should be oriented toward the design and/or design support of decision rules to better select cropping-plan in irrigated agricultural production systems (McCown, 2002) (Figure 8.3).

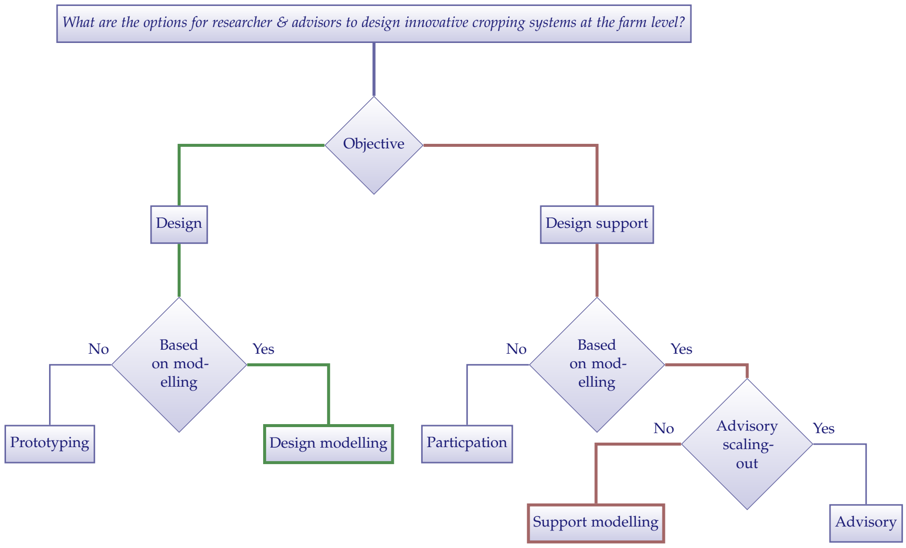


Figure 8.3: Adaptation of the distribution tree used by Le Gal et al. (2011) to differentiate how does research/advisory can address the design of innovative agricultural production systems at the farm level. [Rectangular box: category of approaches, diamond boxes: criteria, —— & —— : potential paths for using CRASH]

As demonstrated by Le Gal et al. (2011) in a literature review, models used in design and design support approaches are very similar, but target different audiences and purposes. The design enhance saliency through knowledge integration and design support enhance advisory towards farmers through modelling:

- *Design:* The design modelling applied to land use planning rely on ex-ante evaluation using models. The design of innovative cropping plan consists of evaluating compatibility of alternative solutions from a set of predefined constraints and objectives. The model-based design approach has long been based on sole input-output optimisation calculated from bio-technical models (e.g. Rossing et al., 1997; Dogliotti et al., 2005) following the principle of the best technical means (van Ittersum and Rabbinge, 1997). But more and more the design relies on models that describe interactions between biophysical and decision processes (Matthews et al., 2007; Le Gal et al., 2009; Martin-Clouaire and Rellier, 2009; Bergez et al., 2010; Sorensen et al., 2010). Such approaches are based on concurrent design of the system and its decision-rules used to manage it (Bergez et al., 2010). They are either combined with optimisation tools or with prototyping approach (Figure 8.3). The first has been successfully applied by Bergez et al. (2010) at the crop management techniques level and the last by Debaeke et al. (2009) at the cropping-system level. However, the use of sole optimization tools for such a complex decision-making problem is difficult due to the large number of decision variables, and prototypying hardly feasible at the farm level when dealing with cropping-plan design. Therefore the model-based design approach using CRASH should combine farmer agronomic expertise with the application of optimization tools on targetted variables (Figure 8.4). Expected outcomes from a design process using CRASH will be a cropping-plan scenario and corresponding decision-rules to apply rather than unique pre-packaged cropping-plan solutions.

- *Design support:* Design support aims to accompany farmers in the change of their production systems by exploring new management process through modelling. This approach gives critical role to farmers and advisory involvement through participative methods (e.g. Cros et al., 2004; Dogliotti et al., 2005). However, the involvement of stakeholders within participatory process is a difficult issue (Voinov and Bousquet, 2010) and require to carefully frame interactions between researcher, advisory, farmer and the model use in long term perspective (e.g. Dogliotti et al., 2005). Further, participatory approach does not automatically lead to the necessary commitment for problem solving (Sterk et al., 2006). Design support using decision-models have already been used to mediate dialogs between farmers and advisors to improve learning process and build a common background knowledge (e.g. Chatelin et al., 2005). The model should facilitate decision-making process formulation by farmers and understanding farmers' encountered bottlenecks to adapt their practices by the advisors.

Joint research-developement processes combined with particpatory approach with farmers (Figure 8.2b) will allow to question repeatedly the model in terms of performances and feature requirements. Using CRASH with farmers and advisors should influence the way researchers understand farmers' reality and identify knowledge gaps. Interactive research-developement may affect the way CRASH model was designed.

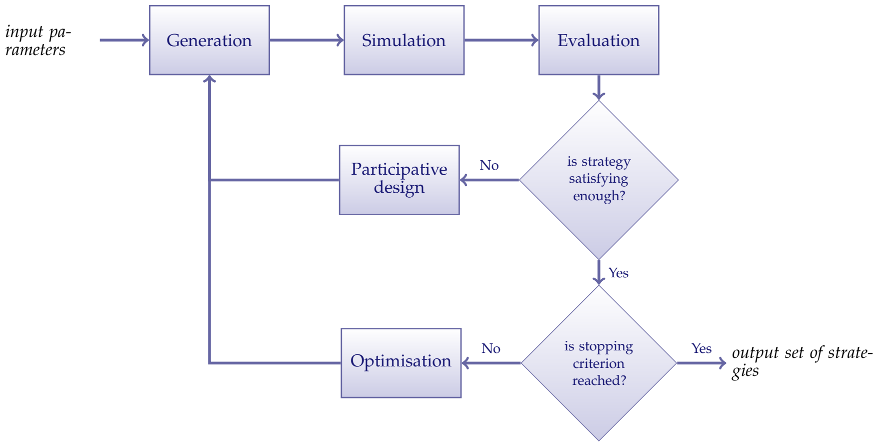


Figure 8.4: Steps to design cropping-plan strategies by coupling participatory design with optimization tools (adapted from: Bergez et al., 2010). Input parameters are complete representative case studies (i.e farm settings and farmer decision-making process). Then, the case studies are used as basis to assess the implication of new technologies, activities and/or important contextual changes on the system. The first loop involves participatory design with farmers or experts in order to explore and frame main lines of the alternative cropping-plan strategies. Then, the optimisation loop serves to improve the designed system through the optimisation of few targetted decision variables.

8.5 CONCLUSION

Through this thesis, I contributed to the long tradition of research on cropping-plan at the farm level by proposing an original modelling approach based on the analysis of farmer decision-making process. This research opens new perspectives for developing farm specific decision support systems that are based on simulating farmers' decision-making processes. Modelling and simulating the cropping-plan decision-making process should enable of designing with farmers cropping systems that reconciliate the adaptive capacities required for cropping-plan choices and the need to maintain cropping systems robustness at the farm level.

Abdulkadri, A. O., Ajibefun, I. A., 1998. Developing alternative farm plans for cropping system decision making. Agricultural Systems 56 (4), 431–442.

Abdulkadri, A. O., Langemeier, M. R., Featherstone, A. M., 2003. Estimating risk aversion coefficients for dryland wheat, irrigated corn and dairy producers in Kansas. Applied Economics 35, 825–834(10).

Adam, M., Ewert, F., Leffelaar, P., Corbeels, M., Van Keulen, H., Wery, J., 2010. CROSPAL, software that uses agronomic expert knowledge to assist modules selection for crop growth simulation. Environmental Modelling & Software 25 (8), 946–955.

Agreste, Mar. 2007. L'irrigation du maïs mise à mal par les sécheresses. Agreste Primeur, 4.

Agreste, 2008. Production céréalière française : elle repart à la hausse après trois années de baisse. Agreste Conjoncture, 4.

Akay, A., Martinsson, P., Medhin, H., Trautman, T., 2011. Attitudes toward uncertainty among the poor: an experiment in rural Ethiopia. Theory and Decision, Submitted.

Amigues, J., Debaecke, P., Itier, B., Lemaire, G., Seguin, B., Tardieu, F., Thomas, 2006. sécheresse et agriculture: Réduire la vulnérabilité de l'agriculture à un risque accru de manque d'eau. Tech. rep., INRA.

An, L., 2011. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling.

Andersen, J. C., Harrison, G. W., Lau, M. I., Rutström, E. E., 2006. Elicitation using multiple price list formats. Experimental Economics 9, 383–405.

Anderson, L. R., Mellor, J. M., 2009. Are risk preferences stable? Comparing an experimental measure with a validated survey-based measure. Journal of risk and uncertainty 39, 137–160.

Annetts, J., Audsley, E., 2002. Multiple objective linear programming for environmental farm planning. Journal of the Operational Research Society 53 (9), 933–943.

Antle, J. M., 1987. Econometric Estimation of Producers' Risk Attitudes. American Journal of Agricultural Economics 69 (3), 509–522.

Antle, J. M., 1989. Nonstructural Risk Attitude Estimation. American Journal of Agricultural Economics 71 (3), 774–784.

Ascough II, J., Maier, H., Ravalico, J., Strudley, M., 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological Modelling 219 (3-4), 383–399.

Askari, H., Cummings, J. T., Jun. 1977. Estimating Agricultural Supply Response with the Nerlove Model: A Survey. International Economic Review 18 (2), 257–292.

Assessment Millennium Ecosystem, 2005. Ecosystems and Human Well-being: Synthesis. Tech. rep., Island Press, Washington, DC.

Athanasiadis, I. N., Rizzoli, A. E., Janssen, S., Andersen, E., Villa, F., 2009. Ontology for seamless integration of agricultural data and models. In: Metadata and Semantic Research. pp. 282–293.

Attonaty, J.-M., Chatelin, M.-H., Garcia, F., Apr. 1999. Interactive simulation modeling in farm decision-making. Computers and Electronics in Agriculture 22 (2-3), 157–170.

Aubry, C., 2000. Une modélisation de la gestion de production dans l'exploitation agricole. Revue Française de gestion 129, 32–46.

Aubry, C., Biarnes, A., Maxime, F., Papy, F., 1998a. Modélisation de l'organisation technique de la production dans l'exploitation agricole: la constitution de systèmes de culture. Etudes & Recherches sur les Systèmes Agraires et le Développement 31, 25–43.

Aubry, C., Papy, F., Capillon, A., Jan. 1998b. Modelling decision-making processes for annual crop management. Agricultural Systems 56 (1), 45–65.

Audsley, E., 1993. Labour, machinery and cropping planning. In: Annevelink, E., Oving, R., Vos, H. (Eds.), Proceeding xxvc 10 STA-Congress. Wageningen, The Netherlands, pp. 83–88.

Bachinger, J., Zander, P., 2007. ROTOR, a tool for generating and evaluating crop rotations for organic farming systems. European Journal of Agronomy 26 (2), 130–143.

Bacon, P. J., Cain, J. D., Howard, D. C., 2002. Belief network models of land manager decisions and land use change. Journal of Environmental Management 65 (1), 1–23.

Baltas, N. C., Korka, O., 2002. Modelling farmers' land use decisions. Applied Economics Letters 9 (7), 453–457.

Bar-Shira, Z., Just, R. E., Zilberman, D., 1997. Estimation of farmers' risk attitude: an econometric approach. Agricultural Economics 17, 211–222.

Bardsley, P., Harris, M., 1987. An approach to the econometric estimation of attitudes to risk in agriculture. Australian Journal of Agricultural Economics 31, 112 – 126.

Barr, A., 2003. Risk Pooling, Commitment, and Information: An experimental test of two fundamental assumptions.

Bartolini, F., Bazzani, G., Gallerani, V., Raggi, M., Viaggi, D., 2007. The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: An analysis based on farm level multi-attribute linear programming models. Agricultural Systems 93 (1-3), 90–114.

Baudry, J., Thenail, C., Mar. 2004. Interaction between farming systems, riparian zones, and landscape patterns: a case study in western France. Landscape and Urban Planning 67 (1-4), 121–129.

Beck, H., Morgan, K., Jung, Y., Grunwald, S., Kwon, H.-y., Wu, J., 2010. Ontology-based simulation in agricultural systems modeling. Agricultural Systems 103 (7), 463–477.

Becu, N., Bousquet, F., Barreteau, O., Perez, P., Walker, A., 2003. A methodology for eliciting and modelling stakeholders' representations with Agent Based Modelling. In: Lecture notes in computer science. Springer, pp. 131–148.

Bel Haj Hassine, N., Simioni, M., 2000. Estimation of two-stage models of multicrop production: with an application to irrigated water allocation in Tunisian agriculture. Région et développement, 121–141.

Belaid, A., Miller, S. F., 1987. Measuring Farmers' Risk Attitudes: A Case Study of the Eastern High Plateau Region of Algeria. Western Journal of Agricultural Economics 12 (2), 198–206.

Beldiceanu, N., Katriel, I., Thiel, S., 2004. Filtering Algorithms for the Same Constraint. In: CPAIOR. pp. 65–79.

Bellocchi, G., Rivington, M., Donatelli, M., Matthews, K., 2011. Validation of biophysical models: issues and methodologies. Sustainable Agriculture Volume 2, 577–603.

Benoit, M., Le Ber, F., Mari, J. F., 2001. Recherche des successions de cultures et de leurs évolutions: analyse par HMM des données Ter-Uti en Lorraine. La statistique agricole 31, 23–30.

Berbel, J., Calatrava, J., Garrido, A., 2007. Water pricing and irrigation: a review of the European experience. In: Molle, F., Berkoff, J. (Eds.), Irrigation Water pricing Policy: The Gap Between Theory and Practice. CABI Publishing, Ch. 13, pp. 295–327.

Berger, T., Sep. 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agricultural Economics 25 (2-3), 245–260.

Bergez, J., Chabrier, P., Garcia, F., Gary, C., Makowski, D., Quesnel, G., Ramat, E., Raynal, H., Rousse, N., Wallach, D., 2009. RECORD: a new software platform to model and simulate cropping systems. In: Farming system design. Monterey CA, p. 2.

Bergez, J., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M., Justes, E., Loyce, C., Munier-Jolain, N., Sadok, W., 2010. Designing crop management systems by simulation. European Journal of Agronomy 32 (1), 3–9.

Bergez, J., Debaeke, P., Deumier, J. M., Lacroix, B., Leenhardt, D., Leroy, P., Wallach, D., 2001. MODERATO: an object-oriented decision tool for designing maize irrigation schedules. Ecological Modelling 137 (1), 43–60.

Bergez, J., Garcia, F., Martin-Clouaire, R., Nolot, J. M., Rellier, J. P., 2004. Anticipation in agricultural management. In: Proceedings of the European Workshop on Sequential Decisions under Uncertainty in Agriculture and Natural Resources (EWDA). D. Parsons, Silsoe, UK.

Bergez, J., Garcia, F., Wallach, D., 2006. Representing and optimizing management decisions. In: Daniel, W., Makowski, D., Jones, J. W. (Eds.), Working with Dynamic Crop Models. Elsevier Science Ltd, Ch. 6, pp. 177–207.

Binici, T., Koç, A. A., Zulauf, C. R., Bayaner, A., 2003. Risk Attitudes of Farmers in Terms of Risk Aversion: A Case Study of Lower Seyhan Plain Farmers in Adana Province, Turkey. Turkish Journal of Agriculture and Forestry 27, 305–312.

Binswanger, H. P., 1980. Attitudes toward Risk: Experimental Measurement in Rural India. American Journal of Agricultural Economics 62 (3), 395–407.

Binswanger, H. P., Binswanger, 1981. Attitudes toward risk: theoretical implications of an experiment in rural India. Economic Journal 91 (364), 867–890.

Binswanger, H. P., Siller, D., 1983. Risk Aversion and Credit Constraints in Farmers' Decision- Making: A Reinterpretation. Journal of Development Studies 20 (1), 5–22.

Blais, A.-R., Weber, E. U., 2006. A Domain-Specific Risk-Taking (DOSPERT) scale for adult populations. Judgment and Decision Making 1 (1), 33–47.

Bockstaller, C., Girardin, P., 1996. The crop sequence indicator: a tool to evaluate crop rotations in relation to the requirements of Integrated Arable Farming Systems. Aspects. Aspects Appl. Biol. 45, 405–408.

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M.-B., Gaillard, G., 2009. Comparison of methods to assess the sustainability of agricultural systems. A review. Agronomy for Sustainable Development 29 (1), 13.

Bond, G., Wonder, B., 1980. Risk attitudes amongst australian farmers. Australian Journal of Agricultural Economics 24 (1), 16–34.

Bontems, P., Thomas, A., 2000. Information value and risk premium in agricultural production: the case of split nitrogen application for corn. American Journal of Agricultural Economics, 59–70.

Booch, G., Jacobson, I., Rumbaugh, J., 2000. OMG Unified Modeling Language Specification.

Boote, K., Jones, J., Pickering, N., 1996. Potential uses and limitations of crop models. Agronomy journal 88 (5), 704–716.

Bouarfa, S., Brunel, L., Granier, J., Mailhol, J. C., Morardet, S., Ruelle, P., 2011. Évaluation en partenariat des stratégies d'irrigation en cas de restriction des prélèvements dans la nappe de Beauce (France). Cahiers Agricultures 20 (1-2), 124–129.

Bouman, B., 2001. ORYZA2000: modeling lowland rice. Vol. 1. International Rice Research.

Bouthier, A., Deumier, J. M., Lacroix, B., 2003. IRRINOV, a farmer-oriented scheduling method for maize, cereals and pea irrigation. In: Improved irrigation technologies and methods: Research, development and testing. Proceedings ICID International workshop. Montpellier, France, pp. 1–9.

Bouveret, S., Heras, F., de Givry, S., Larrosa, J., Sanchez, M., Schiex, T., 2005. Toolbar: a state-of-the-art platform for wcsp. Tech. rep.

Bratman, M., 1987. Intentions, Plans, and Practical Reason. Harvard University Press, Cambridge, MA, 200.

Brehmer, B., 1990. Strategies in Real-Time, Dynamic Decision Making. In: R. M. Hogarth (Ed.), Insights in decision making: a tribute to Hillel J. Einhorn. The University of Chicago Press, p. 262.

Brinck, L., McCarl, B., 1978. The Tradeoff between Expected Return and Risk among Cornbelt Farmers. American Journal of Agricultural Economics 60 (2), 259–263.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y. M., Cellier, P., Debaeke, P., Gaudilliere, J. P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., Jan. 2003. An overview of the crop model. European Journal of Agronomy 18 (3-4), 309–332.

Brisson, N., Launay, M., Mary, B., Beaudoin, N., 2009. Conceptual basis, formalisations and parameterization of the STICS crop model, quae Edition. Editions Quae.

Brooks, R., Tobias, A., Aug. 1996. Choosing the best model: Level of detail, complexity, and model performance. Mathematical and Computer Modelling 24 (4), 1–14.

Brun, R., Reichert, P., Künsch, H. R., 2001. Practical identifiability analysis of large environmental simulation models. Water Resources Research 37 (4), PP. 1015–1030.

Bry, C., Holflack, P., 2004. Le bassin versant de la Charente: une illustration des problèmes posés par la gestion quantitative de l'eau. Courier de l'environnement de l'INRA.

Buccola, S. T., 1982. Portfolio selection under exponential and quadratic utility. Western Journal of Agricultural Economics 7, 43–51.

Buick, R. D., Stone, N. D., Scheckler, R. K., Roach, J. W., 1992. CROPS: A whole-farm crop rotation planning system to implement sustainable agriculture. AI Applications 6 (3), 29–50.

Bullock, D. G., 1992. Crop Rotation. Critical Reviews in Plant Sciences 11 (4), 309–309.

Burel, F., Baudry, J., 2003. Landscape ecology: concepts, methods, and applications, science pu Edition. Science Publisher, Hampshire, USA.

Busemeyer, J. R., Neil J. Smelser, Paul B. Baltes, 2001. Dynamic Decision Making. Pergamon, Oxford, pp. 3903–3908.

Carberry, P. S., Hochman, Z., McCown, R. L., Dalgliesh, N. P., Foale, M. A., Poulton, P. L., Hargreaves, J. N. G., Hargreaves, D. M. G., Cawthray, S., Hillcoat, N., Robertson, M. J., 2002. The FARMSCAPE approach to decision support: farmers', advisers', researchers' monitoring, simulation, communication and performance evaluation. Agricultural Systems 74 (1), 141–177.

Castellazzi, M., Perry, J., Colbach, N., Monod, H., Adamczyk, K., Viaud, V., Conrad, K., 2007. New measures and tests of temporal and spatial pattern of crops in agricultural landscapes. Agriculture, Ecosystems & Environment 118 (1-4), 339–349.

Castellazzi, M., Wood, G., Burgess, P., Morris, J., Conrad, K., Perry, J., 2008. A systematic representation of crop rotations. Agricultural Systems 97 (1-2), 26–33.

Chabrier, P., Garcia, F., Martin-Clouaire, R., Quesnel, G., Raynal, H., 2007. Toward a simulation modeling platform for studying cropping systems management: the Record project. In: Proceeding of MODSIM07. pp. 10–13.

Chambers, R. G., Just, R. E., 1989. Estimating Multioutput Technologies. American Journal of Agricultural Economics 71 (4), 980–995.

Chandrasekaran, B., Josephson, J. R., Benjamins, V. R., 2002. What are ontologies, and why do we need them? Intelligent Systems and Their Applications, IEEE 14 (1), 20–26.

Chatelin, M. H., Aubry, C., Poussin, J. C., Meynard, J. M., Massé, J., Verjux, N., Gate, P., Le Bris, X., Jan. 2005. DéciBlé, a software package for wheat crop management simulation. Agricultural Systems 83 (1), 77–99.

Chavas, J. P., Holt, M., 1996. Economic Behavior Under Uncertainty: A Joint Analysis of Risk Preferences and Technology. The Review of Economics and Statistics 78 (2), 329–335.

Chavas, J. P., Holt, M. T., 1990. Acreage decisions under risk: The case of corn and soybeans. American Journal of Agricultural Economics 72 (3), 548–555.

Chavas, J.-P. P., Jun. 2004. Risk analysis in theory and practice. Elsevier.

Chipman, S. F., Schraagen, J. M., Shalin, V. L., 2000. Introduction to cognitive task analysis. In: Schraagen, J. M., Chipman, S. F. (Eds.), Cognitive task analysis. Routledge, pp. 3–23.

Clark, R. E., Feldon, D. F., van Merriënboer, J. J. G., Yates, K., Early, S., 2008. Cognitive Task Analysis. In: Spector, J., D., M. M., van Merriënboer, J. J. G., Driscoll, M. P. (Eds.), Handbook of research on educational communications and technology. Taylor & Francis, pp. 577–593.

Cognet, G., Lévi, Y., Germon, J., Legube, B., Block, J., des Abbayes, H., Houzelot, J., Gesillon, J., Blanc, G., Eymard, R., Amigues, J., Reynaud, A., Humbert, A., 2007. L'eau : Enjeux et perspectives de recherche. Tech. rep., Ministère délégué à l'enseignement supérieur et à la recherche.

Cooke, N. J., 1994. Varieties of knowledge elicitation techniques. International Journal of Human-Computer Studies 41 (6), 801–849.

Cox, P. G., 1996. Some issues in the design of agricultural decision support systems. Agricultural Systems 52 (2-3), 355–381.

Coyle, B. T., 1999. Risk Aversion and Yield Uncertainty in Duality Models of Production: A Mean-Variance Approach. American Journal of Agricultural Economics 81 (3), 553–567.

Cros, M. J., Duru, M., Garcia, F., Martin-Clouaire, R., Apr. 2004. Simulating management strategies: the rotational grazing example. Agricultural Systems 80 (1), 23–42.

Dalgaard, T., Hutchings, N. J., Porter, J. R., 2003. Agroecology, scaling and interdisciplinarity. Agriculture, Ecosystems and Environment 100 (1), 39–51.

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2008. Adaptive farming systems – A position paper. In: 8th European IFSA Symposium. Clermont-Ferrand (France), pp. 339–351.

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., Jan. 2010. Adaptiveness to enhance the sustainability of farming systems. A review. Agronomy for Sustainable Development 30 (3), 545–555.

Dave, C., Eckel, C., Johnson, C., Rojas, C., 2007. On the Heterogeneity, Stability, and Validity of Risk Preference Measures. Working Paper, University of Texas at Dallas.

Dave, C., Eckel, C., Johnson, C., Rojas, C., 2008. Eliciting Risk Preferences: When is Simple Better?

De Cara, S., Jacquet, F., Reynaud, A., Goulevant, G., Jeuffroy, M.-H., Montfort, F., Lucas, P., Aug. 2010. Economic Analysis of Summer Fallow Management to Reduce Take-All Disease and N Leaching in a Wheat Crop Rotation. Environmental Modeling & Assessment 16, 91–105.

de Juan, J. A., Tarjuelo, J. M., Valiente, M., García, P., Jun. 1996. Model for optimal cropping patterns within the farm based on crop water production functions and irrigation uniformity I: Development of a decision model. Agricultural Water Management 31 (1-2), 115–143.

De Wit, C. T., 1965. Photosynthesis of leaf canopies. Agricultural Research Report 663, 57–88.

de Wit, C. T., 1992. Resource use efficiency in agriculture. Agricultural Systems 40 (1-3), 125–151.

Debaeke, P., Aboudrare, A., Dec. 2004. Adaptation of crop management to water-limited environments. European Journal of Agronomy 21 (4), 433–446.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J. M., Faloya, V., Saulas, P., 2009. Iterative Design and Evaluation of Rule-Based Cropping Systems: Methodology and Case Studies–A Review. Sustainable Agriculture, 707–724.

Deck, C., Lee, J., Reyes, J., Rosen, C., 2008. Measuring Risk Attitudes Controlling for Personality Traits. Working paper, University of Arkansas.

Detlefsen, N. K., Jensen, A. L., 2007. Modelling optimal crop sequences using network flows. Agricultural Systems 94 (2), 566–572.

DeVoil, P., Rossing, W., Hammer, G., Sep. 2006. Exploring profit - Sustainability trade-offs in cropping systems using evolutionary algorithms. Environmental Modelling & Software 21 (9), 1368–1374.

Dillon, J. L., Scandizzo, P. L., 1978. Risk Attitudes of Subsistence Farmers in Northeast Brazil: A Sampling Approach. American Journal of Agricultural Economics 60 (3), 425.

Dogliotti, S., Ittersum, M. V., Rossing, W., 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agricultural Systems 86 (1), 29–51.

Dogliotti, S., Rossing, W. A. H., van Ittersum, M. K., 2003. ROTAT, a tool for systematically generating crop rotations. European Journal of Agronomy 19 (2), 239–250.

Dogliotti, S., Rossing, W. A. H., van Ittersum, M. K., 2004. Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay. Agricultural Systems 80 (3), 277–302.

Donatelli, M., Bellocchi, G., Carlini, L., 2006a. Sharing knowledge via software components: models on reference evapotranspiration. European Journal of Agronomy 24 (2), 186–192.

Donatelli, M., Russell, G., Rizzoli, A., M, A., Adam, M., Athanassiadis, A., Balderacchi, M., Bechini, L., Belhouchette, H., Bellocchi, G., Bergez, J., Botta, M., Braudeau, E., Bregaglio, S., Carlini, l., Casellas, E., Celette, F., Ceotto, E., Charron-Moirez, M., Confalonieri, R., Corbeels, M., Criscuolo, L., Cruz, P., A;, D. G., Ditto, D., Dupraz, C., Duru, M., Fiorani, D., Gentile, A., Ewert, F., Gary, C., Habyarimana, E., Jouany, C., Kansou, K., Knapen, R., Filippi, G., Leffelaar, P., Manici, L., Martin, G., Martin, P., Meuter, E., al, e., 2010. A component-based framework for simulating agricultural production and externalities. In: Environmental and agricultural modelling : integrated approaches for policy impact assessment / Brouwer Floor M. (ed.), van Ittersum Martin (ed.). Springer [Pays-Bas], Dordrecht, pp. 63–108.

Donatelli, M., Van Evert, F., Di Guardo, A., Adam, M., Kansou, K., 2006b. A component to simulate agricultural management. In: iEMSs Third Biannual Meeting, Summit on Environmental Modelling and Software. International Environmental Modelling and Software Society, Burlington, USA.

Doré, T., Sebillotte, M., Meynard, J. M., Jun. 1997. A diagnostic method for assessing regional variations in crop yield. Agricultural Systems 54 (2), 169–188.

Dorst, K., 2003. The problem of design problems. Expertise in Design, 135–147.

Dorward, A., Oct. 1999. Modelling embedded risk in peasant agriculture: methodological insights from northern Malawi. Agricultural Economics 21 (2), 191–203.

Dumanski, J., Pettapiece, W. W., McGregor, R. J., 1998. Relevance of scale dependent approaches for integrating biophysical and socioeconomic information and development of agroecological indicators. Nutrient cycling in agroecosystems 50 (1), 13–22.

Duru, M., Hubert, B., 2003. Management of grazing systems: from decision and biophysical models to principles for action. Agronomie 23 (8), 15 pages.

Dury, J., Garcia, F., Reynaud, A., Therond, O., Bergez, J.-E. J., 2010. Modelling the Complexity of the Cropping Plan Decision-making. In: and Software, E. M. (Ed.), International Environmental Modelling and Software Society. iEMSs, Ottawa, Canada, p. 8.

Dury, J., Schallers, N., Garcia, F., Reynaud, A., Bergez, J.-E., 2011. Models to support cropping plan and crop rotation decisions: a review. Agronomy for Sustainable Development.

Eckel, C., Grossman, P., 2002. Sex Differences and Statistical Stereotyping in Attitudes Toward Financial Risk. Evolution and Human Behavior 23 (4), 281–295.

Eckel, C. C., Grossman, P. J., 2008. Forecasting risk attitudes: An experimental study using actual and forecast gamble choices. Journal of Economic Behavior & Organization 68 (1), 1–7.

Edwards-Jones, G., 2006. Modelling Farmer Decision-Making: Concepts, Progress and Challenges. Animal Science 82 (06), 783–790.

Eisenhardt, K. M., 1989. Building theories from case study research. Academy of Management Review 14 (4), 532–550.

El-Nazer, T., McCarl, B. A., 1986. The Choice of Crop Rotation: A Modelling Approach and Case Study. American Journal of Agricultural Economics 68 (1), 127–136.

Engle-Warnick, J., Escobal, J., Laszlo, S., 2006. The effect of an additional alternative on measured risk preferences in a laboratory experiment in Peru.

Engle-Warnick, J., Escobal, J., Laszlo, S., 2008. Ambiguity Aversion and Portfolio Choice in Small-Scale Peruvian Farming.

Eswaran, M., Kotwal, A., 1990. Implications of Credit Constraints for Risk Behaviour in Less Developed Economies. Oxford Economic Papers 42 (2), 473–482.

European Parliament Council, 2006. Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

Foltz, J., Lee, J., Martin, M., Preckel, P., 1995. Multiattribute assesment of alternative cropping systems. American Journal of Agricultural Economics 77 (2), 408–420.

Galarza, F. B., 2009. Choices Under Risk in Rural Peru.

Garcia, F., Guerrin, F., Martin-Clouaire, R., Rellier, J. P., 2005. The Human Side of Agricultural Production Management: the Missing Focus in Simulation Approaches. In: Zerger, A., Argent, R. (Eds.), Proceedings of the MODSIM Conference the MODSIM. Melbourn, Australia, pp. 12–15.

Gardebroek, C., 2006. Comparing risk attitudes of organic and non-organic farmers with a Bayesian random coefficient model. European Review of Agricultural Economics 33 (4), 485–510.

Gentleman, R., Whalen, E., Huber, W., Falcon, S., 2011. graph: A package to handle graph data structures.

Georgeff, M. P., Ingrand, F. F., 1989. Decision-making in an embedded reasoning system. In: Proceedings of the Eleventh International Joint Conference on Artificial Intelligence. Detroit, Michigan, pp. 972–978.

Giampietro, M., 2004. Multi-scale integrated analysis of agroecosystems, technology Edition. CRC Press.

Glaser, B., Strauss, A., 1967. The discovery of grounded theory: Strategies for qualitative research, fourth pap Edition. Aldine.

Glen, J., 1987. Mathematical-models in farm-planning: A survey. Opreational Research 35 (5), 641–666.

Gras, R., 1990. Système de culture, définitions et concepts clés. In: Lacombe, L., Picard, D. (Eds.), Les sytèmes de culture, un point s Edition. INRA, Paris, France, pp. 7–14.

Griffon, M., 1999. The doubly green revolution: models and realities. Cahiers agricultures 8, 259–268.

Grisley, W., Kellog, E., 1987. Risk-taking preferences of farmers in northern Thailand: measurements and implications. Agricultural Economics 1, 127–142.

Groom, B., Koundouri, P., Nauges, C., Thomas, A., 2008. The story of the moment: risk averse cypriot farmers respond to drought management. Applied Economics 40 (3), 315–326.

Guillaume, S., Bergez, J., Wallach, D., Justes, E., 2011. Methodological comparison of calibration procedures for durum wheat parameters in the STICS model. European journal of agronomy 35 (3), 115–126.

Gupta, A. P., Harboe, R., Tabucanon, M. T., 2000. Fuzzy multiple-criteria decision making for crop area planning in Narmada river basin. Agricultural Systems 63 (1), 1–18.

Haddadi, A., Sundermeyer, K., 1996. Beliefs-Desire-Intention Agent Architectures. In: O'Hare, G. M. P., Jennings, N. (Eds.), Foundations of distributed artificial intelligence. Wiley-IEEE, pp. 169–185.

Hardaker, J. B., Huirne, R., Anderson, J., 2004. Coping with Risk in Agriculture, 2nd Edition. CABI Publishing, Wallingford.

Hardaker, J. B., Pandey, S., Patten, L. H., 1991. Farm Planning under Uncertainty: A Review of Alternative Programming Models. Review of Marketing and Agricultural Economics 59 (1), 9–22.

Harrison, G. W., 2006. Hypothetical bias over uncertain outcomes. Using experimental methods in environmental and resource economics. J.A. List (Ed.).

Harrison, G. W., Humphrey, S. J., Verschoor, A., 2010. Choice under Uncertainty: Evidence from Ethiopia, India and Uganda. Economic Journal 120 (543), 80–104.

Harrison, G. W., List, J. A., 2004. Field Experiments. Journal of Economic Literature 42 (4), 1009–1055.

Harrison, G. W., Rutström, E. E., 2008. Risk aversion in the laboratory. Risk aversion in Experiments. J.C. Cox and G.W. Harrison (Ed.).

Hayashi, K., 2000. Multicriteria analysis for agricultural resource management: A critical survey and future perspectives. European Journal of Operational Research 122 (2), 486–500.

Hazell, P. B. R., Norton, R. D., 1986. Mathematical Programming for Economic Analysis in Agriculture. Macmillan.

Heady, E. O., 1948. The Economics of Rotations with Farm and Production Policy Applications. Journal of Farm Economics, 645–664.

Heady, E. O., 1954. Simplified presentation and logical aspects of linear programming technique. Journal of farm Economics 36 (5), 1035–1048.

Hengsdijk, H., van Ittersum, M. K., 2003. Dynamics in input and output coefficients for land use studies: a case study for nitrogen in crop rotations. Nutrient Cycling in Agroecosystems 66 (3), 209–220.

Henrich, J., McElreath, R., 2002. Are Peasants Risk-Averse Decision Makers? Current Anthropology 43 (1), 172–181.

Herring, J. R., 2006. OpenGIS® Implementation Specification for Geographic information-Simple feature access-Part 1: Common architecture. Open Geospatial Consortium.

Hershey, J. C., Kunreuther, H. C., Schoemaker, P. J. H., 1982. Sources of bias in assessment procedures for utility functions. Management Science 28 (8), 936–954.

Hershey, J. C., Schoemaker, P. J. H., 1985. Probability versus certainty equivalence methods in utility measurement: are they equivalent? Management Science 31 (10), 1213–1231.

Hijmans, R., van Ittersum, M., 1996. Aggregation of spatial units in linear programming models to explore land use options. Netherlands Journal of Agricultural Science 44 (2), 145–162.

Hillyer, C., Bolte, J., van Evert, F., Lamaker, A., 2003. The ModCom modular simulation system. European Journal of Agronomy 18 (3-4), 333–343.

Hoffman, R. R., Lintern, G., 2006. Eliciting and representing the knowledge of experts. In: Ericsson, K., Charness, N., Feltovich, P., Hoffman, R. (Eds.), Cambridge handbook of expertise and expert performance, cambridge Edition. Cambridge University Press, New York, Ch. 12, pp. 203–222.

Hollnagel, E., 2003. Handbook of Cognitive Task Design. Routledge.

Holt, C. A., Laury, S. K., 2002. Risk Aversion and Incentive Effects. The American Economic Review 92 (5), 1644–1655.

Holt, M. T., 1999. A Linear Approximate Acreage Allocation Model. Journal of Agricultural and Resource Economics 24 (2), 383–397.

Howitt, R. E., 1995. Positive Mathematical Programming. American Journal of Agricultural Economics 77 (2), 329–342.

Huang, W., Liang, T., Wu, I., 1974. Optimizing water utilization through multiple crops scheduling. In: Annual Meeting of the American Society of Agricultural Engineers. Vol. 18. Oklahoma, p. 26.

Irnich, S., Desaulniers, G., 2005. Column Generation. GERAD 25th Anniversary Series. Springer, Ch. 2, pp. 33–65.

Isik, M., Khanna, M., 2003. Stochastic technology, risk preferences, and adoption of site-specific technologies. American Journal of Agricultural Economics 85 (2), 305–317.

Itoh, T., Ishii, H., Nanseki, T., 2003. A model of crop planning under uncertainty in agricultural management. International Journal of Production Economics 81-82, 555–558.

Joannon, A., Bro, E., Thenail, C., Baudry, J., 2008. Crop patterns and habitat preferences of the grey partridge farmland bird. Agronomy for Sustainable Development 28 (3), 379–387.

Joannon, A., Souchère, V., Martin, P., Papy, F., 2006. Reducing runoff by managing crop location at the catchment level, considering agronomic constraints at farm level. Land Degradation & Development 17 (5), 467–478.

Jonassen, D. H., 1997. Instructional design models for well-structured and III-structured problem-solving learning outcomes. Educational Technology Research and Development 45 (1), 65–94.

Jonassen, D. H., 2000. Toward a design theory of problem solving. Educational Technology Research and Development 48 (4), 63–85.

Jonassen, D. H., Beissner, K., Yacci, M., 1993. Structural knowledge: techniques for representing, conveying, and acquiring structural knowledge. Routledge.

Just, R. E., Zilberman, D., Hochman, E., 1983. Estimation of Multicrop Production Functions. American Journal of Agricultural Economics 65 (4), 770–780.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., Smith, C. J., Jan. 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18 (3-4), 267–288.

Keating, B. A., McCown, R. L., 2001. Advances in farming systems analysis and intervention. Agricultural Systems 70 (2-3), 555–579.

Kein Haneveld, W. K., Stegeman, A. W., 2005. Crop succession requirements in agricultural production planning. European Journal of Operational Research 166 (2), 406–429.

Kennedy, J. O. S., 1986. Dynamic Programming: Applications to Agriculture and Natural Resources. Elsevier Science Pub. Co, New York.

Kipkorir, E. C., Sahli, A., Raes, D., 2002. MIOS: a decision tool for determination of optimal irrigated cropping pattern of a multicrop system under water scarcity constraints. Irrigation and Drainage 51 (2), 155–166.

Klein, G., Klinger, D., 1991. Naturalistic decision making. Human Systems IAC GATEWAY 6 (3), 16–19.

Klein, G. A., 1993. Decision making in action: models and methods. Ablex Pub.

Knight, J., Weir, S., Woldehanna, T., 2003. The Role of Education in Facilitating Risk-Taking and Innovation in Agriculture. The Journal of Economics Studies 39 (6), 1–22.

Kogut, P., Cranefield, S., Hart, L., Dutra, M., Baclawski, K., Kokar, M., Smith, J., 2002. UML for ontology development. Knowldge Engineering Review 17 (1), 61–64.

Koundouri, P., Laukkanen, M., Sami, M., Nauges, C., 2009. The effects of EU agricultural policy changes on farmers risk attitudes. European Review of Agricultural Economics 36 (1), 53.

Kumbhakar, S. C., 2002a. Risk Preference and Productivity Measurement Under Output Price Uncertainty. Empirical Economics 27, 461–472.

Kumbhakar, S. C., 2002b. Specification and estimation of production risk, risk preferences and technical efficiency. American Journal of Agricultural Economics 84 (1), 8–22.

Kumbhakar, S. C., Tsionas, E., 2010. Estimation of production risk and risk preference function: a nonparametric approach. Annals of Operations Research 176, 369– 378.

Kumbhakar, S. C., Tveteras, R., 2003. Risk Preferences, Production Risk and Firm Heterogeneity. Scandinavian Journal of Economics 105 (2), 275–293.

Lacy, L. W., 2005. OWL: representing information using the web ontology language. Trafford Publishing.

Lambin, E. F., Geist, H. J., Lepers, E., 2003. Dynamics of and "land cover" change in tropical regions "land use". Annual Review of Environment and Resources 28 (1), 205–241.

Lançon, J., Wery, J., Rapidel, B., Angokaye, M., Gérardeaux, E., Gaborel, C., Ballo, D., Fadegnon, B., 2007. An improved methodology for integrated crop management systems. Agronomy for Sustainable Development 27 (2), 10.

Langensiepen, M., Hanus, H., Schoop, P., Gräsle, W., Apr. 2008. Validating CERES-wheat under North-German environmental conditions. Agricultural Systems 97 (1-2), 34–47.

Lansink, A. O., 1999. Area allocation under price uncertainty on Dutch arable farms. Journal of Agricultural Economics 50 (1), 93–105.

Lazrak, E. G., Mari, J. F., Benoit, M., 2010. Landscape regularity modelling for environmental challenges in agriculture. Landscape Ecology 25 (2), 1–15.

Le Bail, M., Lecroart, B., Gauffreteau, A., Angevin, F., Messean, A., 2010. Effect of the structural variables of landscapes on the risks of spatial dissemination between GM and non-GM maize. European Journal of Agronomy 33 (1), 12–23.

Le Ber, F., Benoit, M., Schott, C., Mari, J.-F., Mignolet, C., 2006. Studying crop sequences with CarrotAge, a HMM-based data mining software. Ecological Modelling 191 (1), 170–185.

Le Gal, P.-Y., Dugué, P., Faure, G., Novak, S., Nov. 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. Agricultural Systems 104 (9), 714–728.

Le Gal, P.-Y., Merot, A., Moulin, C.-H., Navarrete, M., Wery, J., 2009. A modelling framework to support farmers in designing agricultural production systems. Environmental Modelling & Software 25 (2), 258–268.

Lee, J., Leung, K., 2010. A Stronger Consistency for Soft Global Constraints in Weighted Constraint Satisfaction. In: Proc. of AAAI-10. Atlanta, Georgia, USA, pp. 121–127.

Leenhardt, D., Angevin, F., Biarnes, A., Colbach, N., Mignolet, C., 2010. Describing and locating cropping systems on a regional scale. A review. Agronomy for Sustainable Development 30 (1), 131–138.

Leenhardt, D., Cernesson, F., Mari, J. F., Mesmin, D., 2005. Anticiper l'assolement pour mieux gérer les ressources en eau: comment valoriser les données d'occupation du sol? Ingénieries - E A T, 13–22.

Leeuwis, C., van den Ban, A. W., Netherlands), T. C. f. A., (Ede, R. C., May 2004. Communication for rural innovation: rethinking agricultural extension. John Wiley & Sons.

Lence, S. H., 2000. Using Consumption and Asset Return Data to Estimate Farmers' Time Preferences and Risk Attitudes. American Journal of Agricultural Economics 82 (4), 934–947.

Lence, S. H., 2009. Joint estimation of risk estimation of risk preferences and technology: flexible utility or futility? American Journal of Agricultural Economics 91 (3), 581–598.

Leroy, P., Jacquin, C., 1991. LORA: A decision support system for the choice of crops on the irrigable area of a farm. Bruges, p. 11.

Leteinturier, B., Herman, J., Longueville, F. D., Quintin, L., Oger, R., 2006. Adaptation of a crop sequence indicator based on a land parcel management system. Agriculture, Ecosystems & Environment 112 (4), 324–334.

Liang, W., Oct. 1998. Farming systems as an approach to agroecological engineering. Ecological Engineering 11 (1-4), 27–35.

Lin, W., Dean, G. W., Moore, C. V., 1974. An Empirical Test of Utility vs. Profit Maximization in Agricultural Production. American Journal of Agricultural Economics 56 (3), 497–508.

Lins, D. A., Gabriel, S. C., Sonka, S. T., 1981. An Analysis of the Risk Aversion of Farm Operators: An Asset Portfolio Approach. Western Journal of Agricultural Economics 6 (1), 15–29.

Lipshitz, R., Klein, G., Orasanu, J., Salas, E., 2001. Taking stock of naturalistic decision making. Journal of Behavioral Decision Making 14 (5), 331–352.

Liu, E., 2008. Time to Change What to Sow: Risk Preferences and Technology Adoption Decisions of Cotton Farmers in China. Working paper 526, Princeton University, Industrial Relations Sections.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., Taylor, W. W., 2007. Complexity of Coupled Human and Natural Systems. Science 317 (5844), 1513 –1516.

Lô-Pelzer, E., Bousset, L., Jeuffroy, M., Salam, M., Pinochet, X., Boillot, M., Aubertot, J., 2010. SIPPOM-WOSR: A Simulator for Integrated Pathogen POpulation Management of phoma stem canker on Winter OilSeed Rape: I. Description of the model. Field Crops Research 118 (1), 73–81.

Loubier, S., Poussin, J. C., Gleyses, G., Le Mat, O., Garin, P., 2011. Faut-il subventionner la création de réserves d'eau pour l'irrigation ? Cahiers agricultures 20, 157–164.

Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Lansink, A. O., Ittersum, M. V., Oct. 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agricultural Systems 103 (8), 585–597.

Love, H. A., Buccola, S. T., 1991. Joint Risk Preference-Technology Estimation with a Primal System. American Journal of Agricultural Economics 73 (3), 765–774.

Loyce, C., Wery, J., 2006. Les outils des agronomes pour l'évaluation et la conception de système de cultures. In: Doré, T., Bail, M. L., Martin, P., Ney, B., Roger-Estrade, J. (Eds.), L'agronomie aujourd'hui. Editions Quae, Ch. 3, pp. 77–100.

Lybbert, T. J., Just, D. R., 2007. Is risk aversion really correlated with wealth? How estimated probabilities introduce spurious correlation. American Journal of Agricultural Econmics 89 (4), 964–979.

MacCrimmon, K. R., Wehrung, D. A., 1990. Characteristics of Risk Taking Executives. Management Science 36, 422–435.

Mackenzie, A., Pidd, M., Rooksby, J., Sommerville, I., Warren, I., Westcombe, M., 2006. Wisdom, decision support and paradigms of decision making. European Journal of Operational Research 170 (1), 156–171.

Mahmood, F., Belhouchette, H., Therond, O., Nolot, J. M., Bergez, J., Wallach, D., Wery, J., ???? Data, Using expert knowledge data to validate crop models on local situation, Submitted.

Mainuddin, M., Das Gupta, A., Raj Onta, P., 1997. Optimal crop planning model for an existing groundwater irrigation project in Thailand. Agricultural Water Management 33 (1), 43–62.

Malezieux, E., Trebuil, G., Jaeger, M., 2001. Modeliser les agroecosystemes. In: Modélisation des agroécosystèmes et aide à la décision. CIRAD, Montpellier, pp. 17–33.

Marques, G. F., Lund, J. R., Howitt, R. E., Aug. 2005. Modeling irrigated agricultural production and water use decisions under water supply uncertainty. Water Resources Research 41, W08423.

Martin, G., Duru, M., Martin-Clouaire, R., Rellier, J. P., Theau, J. P., Therond, O., Hossard, L., 2008. Towards a simulation-based study of grassland and animal diversity management in livestock farming systems'. Proc. iEMSs2008, 783–791.

Martin, G., Martin-Clouaire, R., Rellier, J., Duru, M., 2011. A Conceptual Model of Grassland-Based Beef Systems. International Journal of Agricultural and Environmental Information Systems (IJAEIS) 2 (1), 20–39.

Martin-Clouaire, R., Rellier, J. P., 2000. Modeling needs in agricultural decision support systems. In: Proceedings of CIGR World Congress. Tsukuba, Japan.

Martin-Clouaire, R., Rellier, J.-P., 2009. Modelling and simulating work practices in agriculture. International Journal of Metadata, Semantics and Ontologies 4 (1/2), 42 – 53.

Matthews, K., Rivington, M., Blackstock, K., McCrum, G., Buchan, K., Miller, D., Mar. 2011. Raising the bar? - The challenges of evaluating the outcomes of environmental modelling and software. Environmental Modelling & Software 26 (3), 247–257.

Matthews, R., Stephens, W., 2002. Crop management. In: Matthews, R., Stephens W. (Eds.), Crop-soil Simulation Models: Applications in Developing Countries. CAB International, Wallingford, UK, Ch. 5, pp. 29–53.

Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G., Gotts, N. M., Aug. 2007. Agent-based land-use models: a review of applications. Landscape Ecology 22, 1447–1459.

Maxime, F., Mollet, J. M., Papy, F., 1995. Aide au raisonnement de l'assolement en grande culture. Cahiers Agricultures 4, 351–62.

McCarl, B. A., Candler, W. V., Doster, D. H., Robbins, P. R., 1977. Experiences with farmer oriented linear programming for crop planning. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 25 (1), 17–30.

McCown, R. L., 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agricultural Systems 74 (1), 179–220.

McIntyre, B., Herren, H., Wakhungu, J., Watson, R., 2008. Synthesis Report of the International Assessment of Agricultural Knowledge. Tech. rep., IAASTD.

MEDDTL, 2011. Web Eider.

Merot, A., Bergez, J., Capillon, A., Wery, J., Sep. 2008. Analysing farming practices to develop a numerical, operational model of farmers' decision-making processes: An irrigated hay cropping system in France. AGRICULTURAL SYSTEMS 98 (2), 108–118.

Meseguer, P., Rossi, F., Schiex, T., 2006. Soft Constraints Processing. In: Rossi, F., van Beek, P., Walsh, T. (Eds.), Handbook of Constraint Programming. Elsevier, Ch. 9.

Métivier, J.-P., Boizumault, P., Loudni, S., 2009. Solving Nurse Rostering Problems Using Soft Global Constraints. In: CP. pp. 73–87.

Meynard, J. M., Doré, T., Habib, R., 2001. L'évaluation et la conception de systèmes de culture pour une agriculture durable. Comptes rendus de l'Académie d'agriculture de France 87 (4), 223–236.

Mignolet, C., Schott, C., Benoit, M., 2007. Spatial dynamics of farming practices in the Seine basin: Methods for agronomic approaches on a regional scale. Science of the Total Environment, The 375 (1-3), 13–32.

Miller, T. E., Woods, D. D., 1997. Key issues for naturalistic decision making researchers in system design. Naturalistic Decision Making, Laurence Erlbaum Associates, Mahwah, NJ.

Milton, N., Shadbolt, N., Cottam, H., Harmmersley, M., 1999. Towards a knowledge technology for knowledge management. International Journal of Human-Computer Studies 51 (3), 615–641.

Montginoul, M., Erdlenbruch, K., 2009. Les réserves de substitution sont-elles une solution à la pénurie d'eau. Ingénieries (59-60), 131–136.

Morlon, P., Trouche, G., 2005a. La logistique dans les exploitations de« grande culture»: nouveaux enjeux. 1-L'organisation spatiale des chantiers, une question dépassée en grande culture. Cahiers Agricultures 14 (2), 233–239.

Morlon, P., Trouche, G., 2005b. Nouveaux enjeux de la logistique dans les exploitations de grande culture: II. L'organisation spatiale des assolements: Exemples et questions. Agricultures(Montrouge) 14 (3), 305–311.

Moschini, G., Hennessy, D. A., 2001. Uncertainty, risk aversion, and risk management for agricultural producers. Chapter 2 in Handbook of Agricultural Economics, Bruce L. Gardner and Gordon C. Rausser Editors.

Mosqueira-Rey, E., Moret-Bonillo, V., 2000. Validation of intelligent systems: a critical study and a tool. Expert Systems with Applications 18 (1), 1–16.

Mottet, A., Ladet, S., Coqué, N., Gibon, A., 2006. Agricultural land-use change and its drivers in mountain landscapes: A case study in the Pyrenees. Agriculture, Ecosystems and Environment 114 (2-4), 296–310.

Navarrete, M., Bail, M. L., 2007. SALADPLAN: a model of the decision-making process in lettuce and endive cropping. Agronomy for Sustainable Development 27 (3), 209–221.

Neef, A., Neubert, D., May 2010. Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making. Agriculture and Human Values 28, 179–194.

Nevo, A., Amir, I., 1991. CROPLOT–An expert system for determining the suitability of crops to plots. Agricultural Systems 37 (3), 225–241.

Nevo, A., Oad, R., Podmore, T. H., 1994. An integrated expert system for optimal crop planning. Agricultural Systems 45 (1), 73–92.

Newell, A., Simon, H., 1972. Human problem solving. Prentice-Hall, Inc.

Nielsen, U., 2001. Poverty and Attitudes towards Time and Risk - Experimental Evidence from Madagascar.

Norling, E., Sonenberg, L., Rönnquist, R., 2001. Enhancing Multi-Agent Based Simulation with Human-Like Decision Making Strategies. In: Moss, S., Davidsson, P. (Eds.), Multi-Agent-Based Simulation, lecture no Edition. Springer Berlin Heidelberg, pp. 349–357.

Nuthall, P., 2010. Farm business management: The human factor. CAB International.

Officer, R. R., Halter, A. N., 1968. Utility Analysis in a Practical Setting. American Journal of Agricultural Economics 50 (2), 257–277.

Ohlmer, B., Olson, K., Brehmer, B., 1998. Understanding farmers' decision making processes and improving managerial assistance. Agricultural Economics 18 (3), 273–290.

OJEC, 2000. Directive 2000/60/EC of the European Parliament and of the Council, establishing a framework for Community action in the field of water policy.

Olarinde, L., 2008. Analysing Optimum and Alternative Farm Plans for Risk Averse Grain Crop Farmers in Kaduna State, Northern, Nigeria. World Journal of Agricultural Sciences 4 (1), 28–35.

O'Neill, R., Rust, B., Jul. 1979. Aggregation error in ecological models. Ecological Modelling 7 (2), 91–105.

Orasanu, J., Connolly, T., 1993. The reinvention of decision making. In: Klein, G. A., Orasanu, J., Calderwood, R., Zsambok, C. E. (Eds.), Decision making in action: models and methods. Ablex Publishing.

Orazem, P. F., Miranowski, J. A., 1994. A Dynamic Model of Acreage Allocation with General and Crop-Specific Soil Capital. American Journal of Agricultural Economics 76 (3), 385–395.

Ortega Álvarez, J., Juan Valero, J., Tarjuelo Martín-Benito, J., López Mata, E., 2004. MOPECO: an economic optimization model for irrigation water management. Irrigation Science 23 (2), 61–75.

Osman, M., 2010. Controlling uncertainty: a review of human behavior in complex dynamic environments. Psychological bulletin 136 (1), 65.

Pachauri, R. K., Reisinger, A., 2007. Climate change 2007: synthesis report. IPCC, Geneva, Switzerland.

Palosuo, T., Kersebaum, K., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J., Patil, R., Ruget, F., Rumbaur, C., TAKAC, J., Others, 2011. Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. European journal of agronomy 35 (3), 103–114.

Papajorgji, P. J., Pardalos, P. M., 2006. Software engineering techniques applied to agricultural systems: An object-oriented and UML approach, applied op Edition. Springer.

Papy, F., 2001. Interdépendence des systèmes de culture dans l'exploitation. In: Malézieux, E., Trébuil, G., Jaeger, M. (Eds.), Modélisation des agroécosystèmes et aide à la décision, cirad, inr Edition. Repères. pp. 51–74.

Parker, D. C., Hessl, A., Davis, S. C., Mar. 2008. Complexity, land-use modeling, and the human dimension: Fundamental challenges for mapping unknown outcome spaces. Geoforum 39 (2), 789–804.

Pennings, J. M. E., Wansink, B., 2004. Channel Contract Behavior: The Role of Risk Attitudes, Risk Perceptions, And Channel Members' Market Structures. Journal of Business 77 (4), 697–723.

Pesant, G., 2004. A Regular Language Membership Constraint for Finite Sequences of Variables. In: CP. pp. 482–495.

Piech, B., Rehman, T., 1993. Application of multiple criteria decision making methods to farm planning: A case study. Agricultural Systems 41 (3), 305–319.

Playán, E., Mateos, L., Feb. 2006. Modernization and optimization of irrigation systems to increase water productivity. Agricultural Water Management 80 (1-3), 100–116.

Pocewicz, A., Nielsen-Pincus, M., Goldberg, C. S., Johnson, M. H., Morgan, P., Force, J. E., Waits, L. P., Vierling, L., 2008. Predicting land use change: comparison of models based on landowner surveys and historical land cover trends. Landscape Ecology 23 (2), 195–210.

Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M., Cortés, U., Sep. 2004. Designing and building real environmental decision support systems. Environmental Modelling & Software 19 (9), 857–873.

Pointereau, P., Bisault, L., Nov. 2006. La monoculture et ses dangers pour l'environnement. Solagro, 4.

Pope, J. P., Just, M. T., 1991. On Testing the Structure of Risk Preferences in Agricultural Supply Analysis. American Journal of Agricultural Economics 73 (3), 743–748.

Power, B., Rodriguez, D., DeVoil, P., Harris, G., Payero, J., Nov. 2011. A multi-field bio-economic model of irrigated grain-cotton farming systems. Field Crops Research 124 (2), 171–179.

Quesnel, G., Duboz, R., Ramat, E., 2009. The Virtual Laboratory Environment – An operational framework for multi-modelling, simulation and analysis of complex dynamical systems. Simulation Modelling Practice and Theory 17 (4), 641–653.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramat, E., Preux, P., Mar. 2003. "Virtual laboratory environment" (VLE): a software environment oriented agent and object for modeling and simulation of complex systems. Simulation Modelling Practice and Theory 11 (1), 45–55.

Rammel, C., van den Bergh, J. C., 2003. Evolutionary policies for sustainable development: adaptive flexibility and risk minimising. Ecological Economics 47 (2-3), 121–133.

Rao, A. S., Georgeff, M. P., 1991. Modeling Rational Agents within a BDI-Architecture. In: Allen, J., Fikes, R., Sandewall, E. (Eds.), Second International Conference on Principles of Knowledge Representation and Reasoning. Morgan and Kaufaumann, San Mateo, CA.

Rao, A. S., Georgeff, M. P., 1995. BDI agents: From theory to practice. pp. 312–319.

Régin, J.-C., 1996. Generalized arc consistency for global cardinality constraint. In: Proceedings of the thirteenth national conference on Artificial intelligence - Volume 1. AAAI'96. AAAI Press, pp. 209–215.

Rehman, T., Romero, C., 1993. The application of the MCDM paradigm to the management of agricultural systems: Some basic considerations. Agricultural Systems 41 (3), 239–255.

Reynaud, A., Couture, S., Dury, J., Bergez, J.-E., 2010. Farmer's Risk Attitude: Reconciliating Stated and Revealed Preference Approaches? In: Risk Elicitation and Stated Preference Methods for Climate Change Research. Trento (Italy), p. 25.

Rizzoli, A., Young, W., 1997. Delivering environmental decision support systems: Software tools and techniques. Environmental Modelling and Software 12 (23), 237–249.

Rodriguez, D., DeVoil, P., Power, B., Cox, H., Crimp, S., Meinke, H., Nov. 2011. The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. Field Crops Research 124 (2), 157–170.

Romera, A., Morris, S., Hodgson, J., Stirling, W., Woodward, S., Feb. 2004. A model for simulating rule-based management of cow-calf systems. Computers and Electronics in Agriculture 42 (2), 67–86.

Rossing, W. A. H., Meynard, J. M., van Ittersum, M. K., 1997. Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. European Journal of Agronomy 7 (1-3), 271–283.

Rotmans, J., 2009. Two decades of Integrated Assessment tools: A promising way forward. In: Integrated Assessment of Agriculture and Sustainable Development (AgSAP). Egmond aan Zee, The Netherlands, pp. 8–10.

Rounsevell, M. D. A., Annetts, J. E., Audsley, E., Mayr, T., Reginster, I., 2003. Modelling the spatial distribution of agricultural land use at the regional scale. Agriculture, Ecosystems & Environment 95 (2-3), 465–479.

Rykiel, E., Others, 1996. Testing ecological models: the meaning of validation. Ecological Modelling 90 (3), 229–244.

Sadok, W., Angevin, F., Bergez, J., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messéan, A., Doré, T., 2009. MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. Agronomy for Sustainable Development 29 (3), 447–461.

Saha, A., 1997. Risk preferences estimation in the nonlinear mean standard deviation approach. Economic Inquiry 35, 770–782.

Saha, A., Shumway, C. R., Talpaz, H., 1994. Joint Estimation of Risk Preference Structure and Technology Using Expo-Power Utility. American Journal of Agricultural Economics 76 (2), 173–184.

Sarker, R., Ray, T., 2009. An improved evolutionary algorithm for solving multi-objective crop planning models. Computers and Electronics in Agriculture 68 (2), 191–199.

Sarker, R. A., Quaddus, M. A., 2002. Modelling a nationwide crop planning problem using a multiple criteria decision making tool. Computers & Industrial Engineering 42 (2-4), 541–553.

Sarker, R. A., Talukdar, S., Haque, A. F. M. A., 1997. Determination of optimum crop mix for crop cultivation in Bangladesh. Applied Mathematical Modelling 21 (10), 621–632.

Schraagen, J. M., Chipman, S. F., Shalin, V. L., Shalin, V., 2000. Cognitive task analysis. Routledge.

Sckokai, P., Moro, D., 2006. Modeling the Reforms of the Common Agricultural Policy for Arable Crops under Uncertainty. American Journal of Agricultural Economics 88 (1), 43–56.

Sckokai, P., Moro, D., 2009. Modelling the impact of the CAP Single Farm Payment on farm investment and output. European Review of Agricultural Economics 36 (3), 395–423.

Sebillotte, M., 1978. Itinéraires techniques et évolution de la pensée agronomique. CR Acad. Agric. Fr 64 (111), 906–914.

Sebillotte, M., 1990. Système de culture, un concept opératoire pour les agronomes. In: Lacombe, L., Picard, D. (Eds.), Les sytèmes de culture, un point s Edition. INRA, pp. 165–190.

Sebillotte, M., Soler, L. G., 1988. Le concept de modèle général et la compréhension du comportement de l'agriculteur. CR Acad Fr Agriculture 74, 59–70.

Serra, T., Zilberman, D., Gil, J. M., 2008. Differential uncertainties and risk attitudes between conventional and organic producers: the case of Spanish arable crop farmers. Agricultural Economics 39 (2), 219–229.

Sethi, L. N., Panda, S. N., Nayak, M. K., 2006. Optimal crop planning and water resources allocation in a coastal groundwater basin, Orissa, India. Agricultural Water Management 83 (3), 209–220.

Shaffer, M. J., Bartling, P. N. S., Ascough, J. C., 2000. Object-oriented simulation of integrated whole farms: GPFARM framework. Computers and Electronics in Agriculture 28 (1), 29–49.

Shumway, C. R., Rulon D. Pope, Nash, E. K., 1984. Allocatable Fixed Inputs and Jointness in Agricultural Production: Implications for Economic Modeling. American Journal of Agricultural Economics 66 (1), 72–78.

Simon, H., 1947. Administrative Behavior: A Study of Decision-making Processes in Administrative Organization. The Free Press, New York.

Simon, H., 1973. The structure of ill structured problems. Artificial intelligence 4 (3-4), 181–201.

Simon, H. A., 1976. From Substantive to Procedural Rationality. Cambridge University Press, New York, pp. 129–148.

Slovic, J., 1969. Differential effects of real versus hypothetical payoffs on choices among gambles. Journal of Experimental Psychology 79, 434–437.

Smit, B., Burton, I., Klein, R. J. T., Street, R., 1999. The science of adaptation: a framework for assessment. Mitigation and Adaptation Strategies for Global Change 4 (3), 199–213.

Smit, B., Wandel, J., Aug. 2006. Adaptation, adaptive capacity and vulnerability. Global Environmental Change 16 (3), 282–292.

SOeS, 2011. Eider - Données régionales.

Sorensen, C., Pesonen, L., Fountas, S., Suomi, P., Bochtis, D., Bildsø e, P., Pedersen, S., Jul. 2010. A user-centric approach for information modelling in arable farming. Computers and Electronics in Agriculture 73 (1), 44–55.

Sterk, B., van Ittersum, M., Leeuwis, C., Rossing, W., van Keulen, H., van de Ven, G., Feb. 2006. Finding niches for whole-farm design models â€" contradictio in terminis? Agricultural Systems 87 (2), 211–228.

Sterk, B., van Ittersum, M., Leeuwis, C., Wijnands, F., May 2007. Prototyping and farm system modelling–Partners on the road towards more sustainable farm systems? European Journal of Agronomy 26 (4), 401–409.

Stoate, C., Boatman, N. D., Borralho, R. J., Carvalho, C. R., Snoo, G. R., Eden, P., 2001. Ecological impacts of arable intensification in Europe. Journal of Environmental Management 63 (4), 337–365.

Stockle, C. O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy 18 (3-4), 289–307.

Stone, N. D., Buick, R. D., Roach, J. W., Scheckler, R. K., Rupani, R., 1992. The planning problem in agriculture: Farm-level crop rotation planning as an example. AI Applications 6 (1), 59–75.

Sumpsi, J., Amador, F., Romero, C., 1996. On farmers' objectives: A multi-criteria approach. European Journal of Operational Research 96 (1), 64–71.

Tanaka, T., Camerer, C. F., Nguyen, Q., 2010. Risk and Time Preferences: Linking Experimental and Household Survey Data from Vietnam. American Economic Review 100 (1), 557–571.

Teyssier, F., 2006. Les consommations d'eau pour irrigation en Midi-Pyrénées. Tech. rep., Prefecture de la région Midi-Pyrénées.

Thenail, C., Baudry, J., 2004. Variation of farm spatial land use pattern according to the structure of the hedgerow network (bocage) landscape: a case study in northeast Brittany. Agriculture, Ecosystems & Environment 101 (1), 53–72.

Thenail, C., Joannon, A., Capitaine, M., Souchère, V., Mignolet, C., Schermann, N., Di Pietro, F., Pons, Y., Gaucherel, C., Viaud, V., Others, 2009. The contribution of crop-rotation organization in farms to crop-mosaic patterning at local landscape scales. Agriculture, Ecosystems and Environment 131 (3-4), 207–219.

Thomas, A., 2003. A dynamic model of on-farm integrated nitrogen management. European Review of Agricultural Economics 30 (4), 439–460.

Tittonell, P., Corbeels, M., van Wijk, M., Giller, K., Jan. 2010. FIELD-A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32 (1), 10–21.

Todd, P. M., Gigerenzer, G., 2001. Putting naturalistic decision making into the adaptive toolbox. Journal of Behavioral Decision Making 14 (5), 381–383.

Torkamani, J., Haji-Rahimi, M., 2003. Evaluation of Farmer's Risk Attitudes Using Alternative Utility Functional Forms. Journal of Agricultural Science and Technology 3, 243–248.

Tsai, Y. J., Jones, J. W., Mishoe, J. W., 1987. Optimizing multiple cropping systems: A systems approach. Transactions of the ASAE 30 (6), 1554–1561.

Tsakiris, G., Spiliotis, M., 2006. Cropping pattern planning under water supply from multiple sources. Irrigation and Drainage Systems 20 (1), 57–68.

van den Berg, M., Fort, R., Burger, K., 2009. Natural Hazards And Risk Aversion: Experimental Evidence From Latin America.

van der Ploeg, J., Laurent, C., Blondeau, F., Bonnafous, P., May 2009. Farm diversity, classification schemes and multifunctionality. Journal of Environmental Management 90 (Supplement 2), S124–S131.

van der Ploeg, J. D., der van Ploeg, J. D., 1994. Born from within: practice and perspectives of endogenous rural development. Uitgeverij Van Gorcum.

van Ittersum, M. K., Leffelaar, P. A., van Keulen, H., Kropff, M. J., Bastiaans, L., Goudriaan, J., Jan. 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18 (3-4), 201–234.

van Ittersum, M. K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52 (3), 197–208.

Vandermeer, J., van Noordwijk, M., Anderson, J., Ong, C., Perfecto, I., 1998. Global change and multi-species agroecosystems: Concepts and issues. Agriculture, Ecosystems & Environment 67 (1), 1–22.

Vanloqueren, G., Baret, P., 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Research Policy 38 (6), 971–983.

Vavra, P., Colman, D., 2003. The analysis of UK crop allocation at the farm level: implications for supply response analysis. Agricultural Systems 76 (2), 697–713.

Verburg, P. H., Veldkamp, A., 2001. The role of spatially explicit models in land-use change research: a case study for cropping patterns in China. Agriculture, Ecosystems and Environment 85 (1-3), 177–190.

Vereijken, P., 1997. A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. European Journal of Agronomy 7 (1-3), 235–250.

Vericel, G., Nov. 2010. MicMac-Design Project.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software 11 (25), 1268–1281.

Wallace, J. S., Dec. 2000. Increasing agricultural water use efficiency to meet future food production. Agriculture, Ecosystems & Environment 82 (1-3), 105–119.

Wallach, D., Goffinet, B., Bergez, J., Debaeke, P., Leenhardt, D., Aubertot, J., 2001. Parameter estimation for crop models: a new approach and application to a corn model. Agronomy journal 93 (4), 757–766.

Wallach, D., Makowski, D., Jones, J. W., 2006. Working with dynamic crop models: evaluation, analysis, parameterization, and applications. Elsevier Science Ltd.

Weber, E. U., Blais, A., Betz, N. E., 2002. A Domain-specific Risk-attitude Scale: Measuring Risk Perceptions and Risk Behaviors. Journal of Behavioral Decision Making 15, 263–290.

Wery, J., Langeveld, J., Jan. 2010. Introduction to the EJA special issue on "Cropping Systems Design: new methods for new challenges". European Journal of Agronomy 32 (1), 1–2.

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., David, C., 2009. Agroecology as a science, a movement and a practice. A review. Agronomy for Sustainable Development.

Wielinga, B., Sandberg, J., Schreiber, G., 1997. Methods and techniques for knowledge management: What has knowledge engineering to offer? Expert Systems with Applications 13 (1), 73–84.

Wiens, T. B., 1976. Peasant Risk Aversion and Allocative Behavior: A Quadratic Programming Experiment. American Journal of Agricultural Economics 58 (4), 629–635.

Wijnands, E., 1999. Crop rotation in organic farming: theory and practice. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. Danish Research Centre for Organic Farming, pp. 21–35.

Wik, M., Kebede, T. A., Bergland, O., Holden, S. T., 2004. On the measurement of risk aversion from experimental data. Applied Economics 36 (21), 2443–2451.

Wilson, G. A., May 1997. Factors Influencing Farmer Participation in the Environmentally Sensitive Areas Scheme. Journal of Environmental Management 50 (1), 67–93.

Winder, N., Jeffrey, P., Lemon, M., 1998. Simulation of crop choice dynamics: an application of nested Master-Equation models. Etudes et Recherches sur les Systemes Agraire et le Developpment 31, 175–189.

Wooldridge, M. J., 2002. An introduction to multiagent systems. J. Wiley.

Yesuf, M., Bluffstone, R. A., 2009. Poverty, Risk Aversion, and Path Dependence in Low-Income Countries: Experimental Evidence from Ethiopia. American Journal of Agricultural Economics 91 (4), 1022–1037.

Zachary, W., Ryder, J. M., Hicinbothom, J. H., 1998. Cognitive task analysis and modeling of decision making in complex environments. In: Cannon-Bowers, J., Salas, E. (Eds.), Making decisions under stress: Implications for individual and team training. American Psychological Association, pp. 315–344.

Zannier, C., Chiasson, M., Maurer, F., 2007. A model of design decision making based on empirical results of interviews with software designers. Information and Software Technology 49 (6), 637–653.

Zeigler, B. P., Praehofer, H., Kim, T. G., 2000. Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems. Academic Press.

Zheng, X., Vukina, T., Shin, C., 2008. The Role of Farmers' Risk aversion for Contract Choice in the US Hog Industry. Journal of Agricultural & Food Industrial Organization 6 (1).

Zsambok, C. E., Klein, G. A., 1997. Naturalistic decision making. Routledge.

Part IV

APPENDIX

A EXPRESSION, ANALYSIS AND FORMALIZATION OF CROPPING PLAN MODELLING TOOL REQUIREMENTS

A.1 RAPPEL DE LA DÉMARCHE GÉNÉRALE DE MODÉLISATION

La mise en œuvre du développement d'un outil de simulation des choix d'assolement dans le cadre de la thèse s'appuie sur une approche itérative partagée en trois temps forts: (i) *la définition des objets étudiés*, (ii) *la vue métier* et (iii) *la vue opérationnelle* (Figure A.1):

- *(i) La définition du ou des systèmes étudiés:* Cette étape a pour objectif de définir les objets étudié (assolement et choix d'assolement) et de clarifier les objectifs de modélisation en relation avec le problème étudié.
- *(ii) Vue métier:* La vue métier permet de décrire les entités manipulées par les acteurs dans le cadre de la description du système étudié. Elle permet d'améliorer la compréhension des systèmes étudiés par la clarification des objets, concepts et processus du domaine. La vue métier est composée d'un ensemble de schéma qui forment la modélisation conceptuelle du système étudié. La méthodologie employée pour la réalisation de cette étape est décrite dans le document qui à été présentée lors de la conférence IEMSS 2010 (Dury et al., 2010).
- *(iii) Vue opérationnelle:* La vue opérationnelle correspond à la phase de développement informatique à proprement parlé et nécessite une démarche de modélisation explicitant et encadrant toutes les étapes du projet, de la compréhension des besoins à la production du code de l'application. La démarche générale de modélisation choisie est inspirée de la méthode *Unified Process* (UP) basée sur le langage de modélisation UML. Cette méthode ce caractérise en 4 points principaux: (1) itérative et incrémentale, (2) pilotée par les cas d'utilisation, (3) centrée sur l'architecture et (4) centrée sur les risques.

Ce document s'intéresse précisément aux premières étapes de la vue opérationnelle, i.e. l'expression, l'analyse et la formalisation des besoins pour un outil informatique d'aide aux choix d'assolement aboutissant à la description des cas d'utilisation.

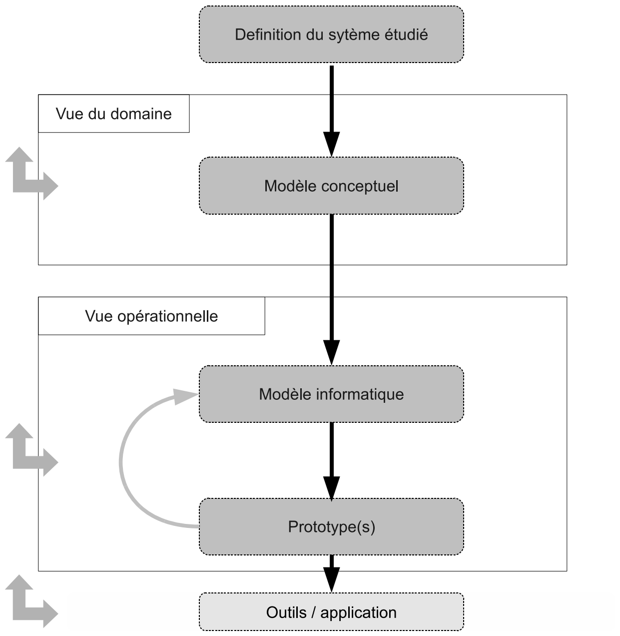


Figure A.1: Démarche générale de mise en œuvre pour le développement d'un outil informatique de simulation des choix d'assolement proposée dans le cadre de la thèse assolement.

A.2 MATÉRIELS ET MÉTHODES

A.2.1 *Identification des besoins et spécification des fonctionnalités*

A.2.1.1 *Identification des utilisateurs et des besoins*

L'identification des besoins nécessite la caractérisation et la formalisation des utilisations, des services attendus, et des contextes d'utilisation de cet outil pour les différents utilisateurs.

Expression des besoins: L'expression des besoins par les instituts techniques c'est fait en deux temps forts qui peuvent être vu comme deux itérations dans le processus de développement:

- Deux réunions préparatoires, sous la forme de brainstorming, ont permis aux ingénieurs de chaque institut technique, Arvalis-institut du végétale et le CETIOM, d'exprimer librement leurs visions de la notion d'assolement en exploitation de grandes cultures et de formuler les grands objectifs d'un outil de simulation des choix d'assolements.
- Une réunion de réflexion autour des attentes relativement à un outil d'aide au choix d'assolement. Cette réunions a été organisée suivant la méthode QQOQCCP (Tableau A.1) et à regroupé des ingénieurs et responsables scientifiques d'Arvalis-institut du végétale, du CETIOM et de la CACG. La méthode QQOQCCP permet la collecte exhaustive et rigoureuse de données précises

en adoptant une démarche d'analyse critique constructive basée sur le questionnement systématique.

Table A.1: Tableau de synthèse des principaux points de la méthodes QQOQCCP

Lettre	Question	Exemples
Q	De qui, Avec qui, Pour qui...	Responsable, acteur, sujet, cible...
Q	Quoi, Avec quoi...	Outil, objet, résultat, objectif...
O	Où	Lieu, service...
Q	Quand, tous les quand, à partir de quand, jusqu'à quand...	Dates, périodicité, durée...
C	Comment, par quel procédé...	Procédure, technique, action, moyens matériel...
C	Combien	Quantités, budget...
P	Pourquoi	Justification, raison d'être

Cas d utilisation: Suite à ces rencontres, les besoins ont été analysés et modélisés aux travers des diagrammes UML de cas d'utilisation. L'approche consiste à regarder l'outil à développer de l'extérieur, du point de vue de l'utilisateur et des fonctionnalités qu'il en attend. En aucun cas ces diagrammes ne permettent d'exprimer les solutions. Le but de la conceptualisation est de comprendre et structurer les besoins des utilisateurs. La description des besoins sous forme de diagrammes de cas d'utilisation permet d'identifier les utilisations, les acteurs principaux et secondaires, et de spécifier le contexte d'utilisation à travers la description des relations entre acteurs et utilisations. Les acteurs principaux sont les utilisateurs qui interagissent directement avec l'outils, en échangeant de l'information (en entrée et en sortie). Les acteurs secondaires, ou bénéficiaires, sont les personnes qui ne font que recevoir des informations à l'issue de la réalisation du cas d'utilisation ou qui sont sollicitées par le système. Dans ce document de synthèse, les cas d'utilisation généraux ont été synthétisés sous forme d'un tableau (Tableau A.2).

A.2.1.2 *Spécification des fonctionnalités*

L'ensemble du problème est décomposé en petites itérations définies à partir des cas d'utilisation. Les cas d'utilisation les plus importants sont traités en priorité. Le développement procède par des itérations qui conduisent à des livraisons incrémentales du système. La spécification des fonctionnalités passe par la spécification et l'affinement des cas d'utilisation. Cette étape permet de préciser de façon concrète les attentes des utilisateurs.

A.3 RÉSULTATS PRÉLIMINAIRES

A.3.1 *Objectifs et bénéficiaires de l'outil*

Deux objectifs auxquels l'outil devrait pouvoir s'adresser ont été identifiés lors du cycle de réunions: (1) la production d'informations à destination des pouvoirs publics et des responsables professionnels, et (2) le conseil destiné aux agriculteurs. Au regard de ces objectifs, les bénéficiaires de l'outils couvriraient alors un large public: les agriculteurs (individuels ou en groupe), les représentants des agriculteurs (responsables professionnels des syndicats), des pouvoirs publics (état, collectivités territoriales, établissements publics), les gestionnaires de la ressource en eau et les enseignants. Les résultats découlant de l'utilisation de l'outil feraient l'objet de communications orales et/ou écrites qui seraient spécifiques aux bénéficiaires visés.

A.3.2 *Domaine d'utilisation et utilisateurs de l'outil*

A.3.2.1 *Type d'exploitation*

L'outil doit s'intéresser à la totalité des exploitations agricoles de grandes cultures, irriguées ou non. L'étude de la sole irriguée est un objectif important et prioritaire. Cependant, il semble difficile de traiter séparément les soles irriguées et sèches. En effet, les deux soles partagent un certain nombre de ressources (e.g. main d'œuvre, équipements) et peuvent évoluer l'une en fonction de l'autre. De plus il y a une volonté d'avoir un outil relativement polyvalent pour étudier aussi les soles non-irriguées. L'outil doit alors pouvoir traiter conjointement les problématiques spécifiques des deux soles. Les ateliers hors grande culture ne seraient pas explicitement considérés mais plutôt intégrés comme contraintes au système étudié. L'échelle de travail la plus appropriée semble le parcellaire cultivé limité aux grandes cultures; les plus petites unités de gestion considérées étant les parcelles.

A.3.2.2 *Echelle d'utilisation*

L'échelle exploitation serait l'échelle de base pour l'analyse des choix d'assolement. Cependant, deux approches d'utilisation de l'outil correspondant à deux échelles de travail ont été évoquées:

- *(i) L'approche territoire.* Elle est la plus adaptée pour la gestion des ressources et l'accompagnement de la décision publique par les décideurs politiques et des responsables professionnels. Les ingénieurs des ICTA et les gestionnaire de la ressource (CACG) ont été identifiés comme utilisateurs privilégiés pour cette échelle de travail.

- *(ii) L'approche exploitation.* Elle est la plus pertinente pour l'accompagnement des agriculteurs dans leur choix de cultures, que se soit le conseil individuel ou collectif. Les conseillers de Chambres d'agriculture, éventuellement les organismes de stockage sont pré-sentis comme les utilisateurs de l'outil pour cette échelle de travail.

A.3.2.3 *Fonctions*

Trois grandes types de fonctions ont été identifiées lors du cycle de réunion que nous pouvons synthétiser en trois mots clefs: (i) *concevoir*, (ii) *évaluer* et (iii) *prévoir*.

- *(i) Concevoir.* L'outil devrait permettre de concevoir des assolements et stratégies d'assolement en exploitation de grande culture en relation avec les objectifs et contraintes des agriculteurs. L'outil devrait proposer des assolements optimaux ou sous-optimaux adaptés aux évolutions annuelles (e.g. prix, eau) et aux changements importants du contexte (e.g. évolution de la PAC, nouvelles opportunitées de marché). Mais l'objectif de l'outil devrait d'abord fournir une aide à la réflexion plutôt qu'un outil qui donne des solutions.
- *(ii) Evaluer.* L'outil devrait permettre d'évaluer des assolements existants ou sous forme de scénarios en multi-critères (économie, production, risque, niveau d'utilisation des ressources, impacts environnementaux...). L'évaluation doit pouvoir être conduite aussi bien à l'échelle de l'exploitation qu'à l'échelle d'un territoire.
- *(iv) Prévoir.* L'outil devrait permettre de conduire des analyses prospectives. Ces analyses prospectives pourraient permettre d'estimer les volumes de productions ou des consommations d'eau sur un territoire. Ces études prospectives seraient utilisées pour étudier les leviers d'interventions permettant d'atteindre des objectifs.

Table A.2: Tableau de synthèse des utilisations et utilisateurs pour les deux échelles d'utilisation

échelle	**Utilisation**	**Acteur principal**	**Acteur secondaire**
Exploitation	Evaluer un assolement	Chambre d'agriculture	Agriculteur individuel
	Concevoir les meilleurs assolements	Organisme économique	Collectif d'agriculteurs
	Concevoir des stratégies d'assolements		
Territoire	Evaluer un assolement	Ingénieur ICTA	Responsable de la prof. agricole
	Concevoir les meilleurs assolements	Gestionnaire de la ressource	Décideur politique
	Prévoir l'évolution des assolements		
	Etudier les leviers pour atteindre des objectifs d'assolements		

B ONTOLOGICAL ANALYSIS

We conducted an ontological analysis focusing on key concepts that structure cropping-plan decisions at the farm level. The ontological analysis was performed during the development process of two models: CRASH and a regional information system-based model. The ontological analysis was primarily based on transcription of information gathered under different forms from various experts involved in cropping systems management/research (Table B.1). Based on information transcription, ontological analysis was conducted through an iterative cycle of knowledge workshops with limited number of agronomist and modellers. All along the process, both definition of the concepts and their relationships were requestioned and refined.

Table B.1: Expert and information sources

Expert of the domain	**Source Information sources**
Farmers	interview
Advisers of agricultural services	interview, technical data sheet
Agronomists	personal communication, scientific paper
Agricultural system modellers	scientific literature, existing ontology

B.1 DESCRIPTION OF THE MAIN CONCEPTS:

To illustrate the ontological analysis, I present here some concepts that were defined and described during the developement of the CRASH modelling framework.

B.1.1 *Production techniques*

B.1.1.1 *Definition*

Production technique is a complete set of agronomic inputs to realise a particular production level in a certain physical environment (van Ittersum and Rabbinge, 1997). These agronomic inputs are provided to every plot through the combination of crop operations (Sebillotte, 1990). The type, the sequence and the implementation of the crop operations derived from decision rules.

B.1.1.2 *Description*

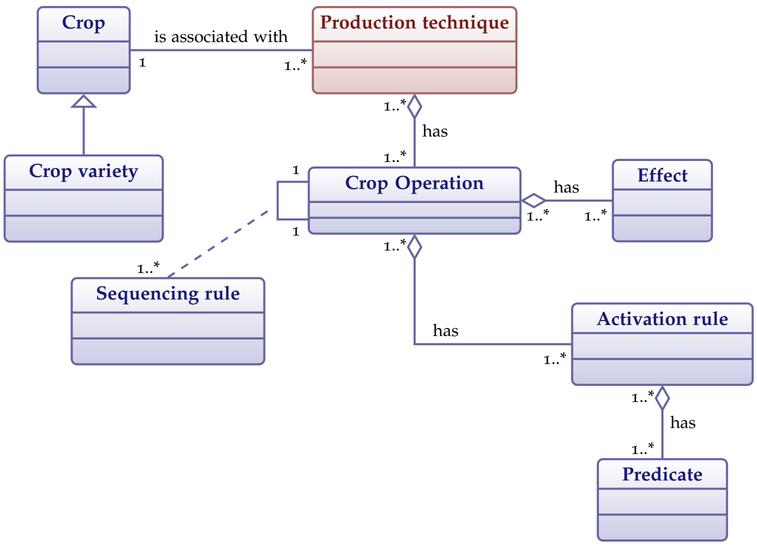


Figure B.1: UML class diagram: Production activity.

B.1.1.3 *Translation*

fr: Itinéraire technique (ITK).
Un itinéraire technique (ITK) est la combinaison logique et ordonnée des opérations culturales utilisées sur une parcelle (Sebillotte, 1978; van Ittersum and Rabbinge, 1997), qui permet, par le contrôle des états successifs de l'écosystème cultivé, d'atteindre un objectif de production donné, en quantité et en qualité. La combinaison des opérations culturales découle de la mise en œuvre de règles de décision ("décisions culturales") plus ou moins complexes.
L'itinéraire technique est la suite logique et ordonnée des techniques culturales appliquées à une espèce végétale cultivé, depuis le semis jusqu'a la recolte (Gras, 1990).

B.1.1.4 *Related concepts*

Production activity (van Ittersum and Rabbinge, 1997)

B.1.2 *Crop rotation*

B.1.2.1 *Definition*

Crop rotation is defined as the practice of growing a sequence of plant species on the same land (Bullock, 1992). The crop rotation is characterised by a cycle-periods while the crop sequence is limited to the order of appearance of crops on the same piece of land during a fixed period (Leteinturier et al., 2006).

B.1.2.2 *Description*

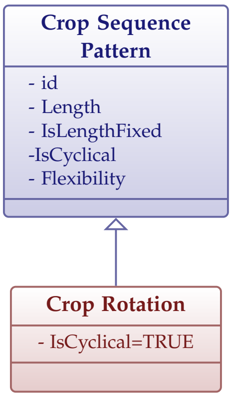
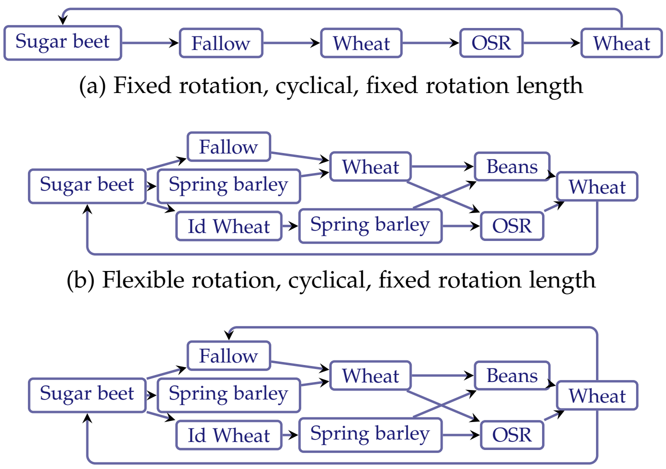


Figure B.2

A crop rotation is a particular crop sequence pattern because it is cyclical. Castellazzi et al. (2008) described four types of crop sequence pattern, we reproduce below three of the four examples corresponding to the definition of crop rotation:



(a) Fixed rotation, cyclical, fixed rotation length

(b) Flexible rotation, cyclical, fixed rotation length

(c) Flexible rotation, cyclical, variable rotation length

Figure B.3: Different crop rotation types

B.1.2.3 *Translation*

fr: La rotation est définie comme l'enchaînement de successions de cultures qui se reproduit dans le temps en cycles réguliers (Bullock, 1992). La rotation est caractérisée par un cycle alors que la séquence de cultures est limité à l'ordre d'apparition des cultures sur une même parcelle pendant une période déterminée (Leteinturier et al., 2006).

B.1.2.4 *Similar concepts*

crop sequence pattern, crop sequence

B.1.3 *Crop sequence*

B.1.3.1 *Definition*

A crop sequence is the order of appearance of crops on the same piece of land during a fixed period (Leteinturier et al., 2006). A crop sequence is a particular crop sequence pattern that is not cyclical.

B.1.3.2 *Description*

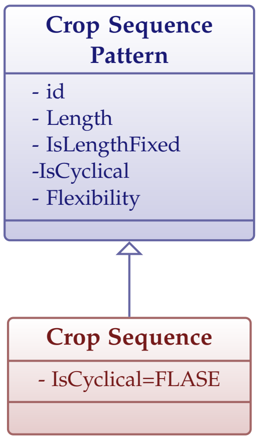
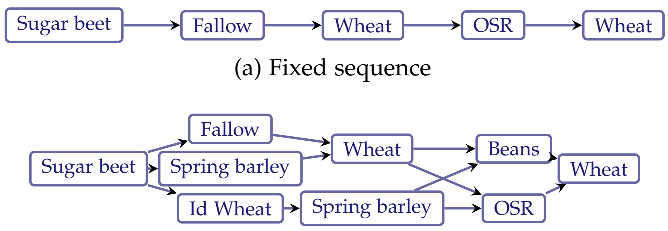


Figure B.4: UML Class diagramm: Crop Sequence Pattern

We present here tow types of crop sequence:



(a) Fixed sequence

(b) Flexible sequence

Figure B.5: Different crop sequence types

B.1.3.3 *Translation*

fr: Séquence de culture. La séquence de culture est l'ordre d'apparition des cultures sur une même parcelles pendant une période déterminée (Leteinturier et al., 2006).

B.1.3.4 *Similar concepts*

crop sequence pattern, crop rotation, crop succession

B.1.4 *Crop sequence pattern*

B.1.4.1 *Definition*

The crop sequence pattern is all the crops and crops successions that describe the order of appearance of crops on the same piece of land during a fixed period. A crop sequence pattern can be cyclical, i.e. crop rotation, or not cyclical, i.e.crop sequence.

B.1.4.2 *Description*

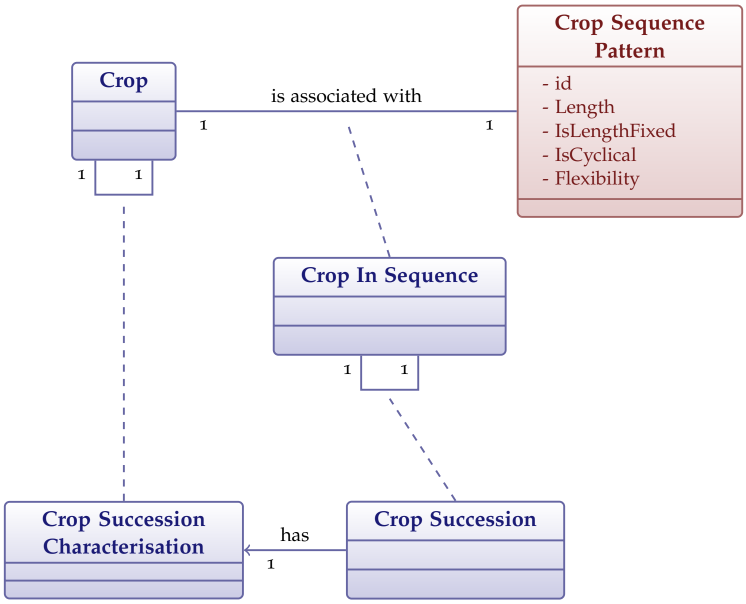


Figure B.6: UML Class diagramm: Crop Sequence

B.1.4.3 *Translation*

fr: Un schéma de sequence de culture est l'ensemble des cultures et des succession culturales qui decrive l'enchainement desc ultres sur une même parcelle. Un schéma de séquence de culture peut être cyclique, on parle alors de rotation, ou non, on parle alors de séquences de culture.

B.1.4.4 *Similar concepts*

crop rotation, crop succession, crop sequence

B.1.5 *Crop succession*

B.1.5.1 *Definition*

The crop succession is defined by the succession of two crop on the same peace of land. It is often characterised by the preceding and the succeeding effect.

B.1.5.2 *Description*

See. crop sequence pattern

B.1.5.3 *Translation*

fr: Une succession de culture est l'enchainement de deux cultures sur une même parcelle.

B.1.5.4 *Similar concepts*

crop sequence Pattern, crop sequence

C

APPENDIX: ESTIMATION OF THE FARMER COST FUNCTION

To estimate the cost function, we have used the French RICA/-FADN database for year 2004. This database is representative at the regional level. We have selected only cash-crop oriented farmers. Our final database is then made of 1782 observations of individual farmers.

The endogenous variable corresponds to the total operating cost (TOC) at the farm level. Total operating cost includes in particular all expenses related to pesticides, fertilizers, seeds, animal feeding, energy, etc. Crop productions have been aggregated into 10 categories: irrigated maize (im), pluvial maize (pm), hard wheat (hw), soft wheat (sw), rape (ra), barley (ba), soybean (so), sunflower (su) and other (ot).

Table C.1: Summary statistics for total operating cost and land use

Variable	Mean	Std. Dev.	Min.	Max.
TOC (in €)	55691.205	36061.133	3513.31	349708
l_{ot} (in ha)	28.781	30.325	0	221.19
l_{hw} (in ha)	5.191	17.934	0	203.77
l_{sw} (in ha)	43.825	36.944	0	311.51
l_{ra} (in ha)	14.327	20.638	0	165.29
l_{fa} (in ha)	8.327	9.877	0	118.24
l_{im} (in ha)	8.279	23.328	0	219.48
l_{pm} (in ha)	6.411	15.214	0	176.32
l_{ba} (in ha)	15.666	20.573	0	177.73
l_{so} (in ha)	0.647	3.705	0	66.099
l_{su} (in ha)	5.151	12.306	0	117.69

In Table C.1, we give some descriptive statistics for the total operating cost (TOC) and for the land area (in ha) allocated to each category of crop (l_k), with $k \in \{im, pm, hw, sw, ra, ba, so, su, ot\}$.

In Table C.2, we report the estimation of the cost function. We have considered a simple quadratic specification which provides a good fit to our data ($R^2 = 0.804$). Most of the linear and quadratic terms are significant. However, only a few cross terms are significant. Nevertheless, the estimated cost function appears to have good concavity properties since the linear terms are positive (except for fa) and the quadratic terms negative (except for ot). The estimated coefficients make sense. The highest linear term is found for irrigated maize which is know to be the most costly crop to produce. On contrary, the lowest linear term is found for sunflower, which is a very low input intensive crop.

Table C.2: Estimation of the cost function for French cash crop farmers (OLS)

Variable	Coefficient	(Std. Err.)	Variable	Coefficient	(Std. Err.)
l_{ot}	531.877***	(39.988)	$l_{hw} \cdot l_{sm}$	-8.04***	(2.956)
l_{hw}	554.149***	(69.997)	$l_{hw} \cdot l_{ba}$	6.417**	(3.075)
l_{sw}	473.628***	(37.115)	$l_{hw} \cdot l_{so}$	2.898	(6.679)
l_{ra}	309.119***	(72.608)	$l_{hw} \cdot l_{su}$	2.521*	(1.471)
l_{fa}	-370.991***	(124.528)	$l_{sw} \cdot l_{ra}$	1.416	(1.105)
l_{im}	612.500***	(49.748)	$l_{sw} \cdot l_{fa}$	0.923	(1.564)
l_{pm}	417.204***	(74.623)	$l_{sw} \cdot l_{im}$	-0.552	(0.700)
l_{ba}	390.964***	(58.453)	$l_{sw} \cdot l_{pm}$	-0.981	(1.086)
l_{so}	431.714	(349.869)	$l_{sw} \cdot l_{ba}$	-0.478	(0.866)
l_{su}	58.919	(96.920)	$l_{sw} \cdot l_{so}$	5.991	(10.249)
$l_{ot} \cdot l_{ot}$	0.654**	(0.275)	$l_{sw} \cdot l_{su}$	-0.918	(1.547)
$l_{hw} \cdot l_{hw}$	-0.146	(0.676)	$l_{ra} \cdot l_{fa}$	3.252	(2.273)
$l_{sw} \cdot l_{sw}$	-1.094***	(0.345)	$l_{ra} \cdot l_{im}$	0.483	(1.061)
$l_{ra} \cdot l_{ra}$	-0.201	(0.954)	$l_{ra} \cdot l_{pm}$	-0.319	(2.321)
$l_{fa} \cdot l_{fa}$	-1.451	(1.934)	$l_{ra} \cdot l_{ba}$	-0.034	(1.142)
$l_{im} \cdot l_{im}$	-0.705*	(0.375)	$l_{ra} \cdot l_{so}$	20.027	(20.422)
$l_{pm} \cdot l_{pm}$	-0.126	(0.653)	$l_{ra} \cdot l_{su}$	0.446	(1.952)
$l_{ba} \cdot l_{ba}$	-9.358	(7.305)	$l_{fa} \cdot l_{im}$	2.926	(1.821)
$l_{so} \cdot l_{so}$	-1.576**	(0.696)	$l_{fa} \cdot l_{pm}$	17.401***	(3.609)
$l_{su} \cdot l_{su}$	0.574	(1.478)	$l_{fa} \cdot l_{ba}$	0.229	(2.166)
$l_{ot} \cdot l_{hw}$	-2.685***	(0.908)	$l_{fa} \cdot l_{so}$	6.376	(19.033)
$l_{ot} \cdot l_{sw}$	2.134***	(0.524)	$l_{fa} \cdot l_{su}$	9.211**	(3.842)
$l_{ot} \cdot l_{ra}$	-7.613***	(0.723)	$l_{im} \cdot l_{pm}$	5.415	(4.483)
$l_{ot} \cdot l_{fa}$	-0.891	(1.630)	$l_{im} \cdot l_{ba}$	1.485	(2.026)
$l_{ot} \cdot l_{im}$	-1.618**	(0.723)	$l_{im} \cdot l_{so}$	-1.511	(6.177)
$l_{ot} \cdot l_{pm}$	1.409	(1.246)	$l_{im} \cdot l_{su}$	-4.516**	(1.997)
$l_{ot} \cdot l_{ba}$	1.110	(0.727)	$l_{pm} \cdot l_{ba}$	-0.609	(1.965)
$l_{ot} \cdot l_{so}$	-10.895**	(4.699)	$l_{pm} \cdot l_{so}$	4.395	(7.474)
$l_{ot} \cdot l_{su}$	-3.961***	(1.505)	$l_{pm} \cdot l_{su}$	5.683	(3.738)
$l_{hw} \cdot l_{sw}$	-0.406	(1.346)	$l_{ba} \cdot l_{so}$	-26.616	(25.712)
$l_{hw} \cdot l_{ra}$	0.386	(3.009)	$l_{ba} \cdot l_{su}$	3.328*	(2.000)
$l_{hw} \cdot l_{fa}$	-4.357	(2.780)	$l_{so} \cdot l_{su}$	-7.186	(11.499)
$l_{hw} \cdot l_{im}$	-0.776	(0.846)	Intercept	1789.633	(1339.775)
N	1782				
R^2	0.804				
$F_{(65,1716)}$	108.093				

***, **,*for respectively significant at 1%, 5% and 10%.

D

A WEIGHTED CSP APPROACH FOR SOLVING SPATIO-TEMPORAL PLANNING PROBLEM IN FARMING SYSTEMS

D.1 INTRODUCTION

The design of a cropping plan is one of the first step in the process of crop production and is an important decision that farmers have to take. By cropping plan, we mean the *acreages* occupied by all the different crops every year and their *spatial allocation* within a farming land. The cropping plan decision can be summarized as (1) the choice of crops to be grown, (2) the determination of all crops' acreages, and (3) their allocation to plots. Despite the apparent simplicity of the decision problem, the cropping plan decisions depend on multiple spatial and temporal factors interacting at different levels of the farm management. The cropping plan decision-making combines long term planning activities, with managerial and operational activities to timely control the crop production process. Modelling a decision-making process to support such farmers' decisions therefore requires to consider the planning of crop allocation over a finite horizon, and to explicitly consider the sequence of problem-solving imposed by the changing context (e.g. weather, price).

In this paper, we precisely focus on the activity of planning seen as a spatio-temporal crop allocation problem (CAP) whose relevance is assessed by a global objective function. In addition to many approaches based on optimization procedure, the objective of the work is to propose new directions to address crop allocation while taking farmers' decision factors into account. These factors are formalized as hard and preference constraints in the WCSP framework. The choice of constraints is based on a survey of farmers' processes taking into account annual working hours capacity restrictions (Dury et al., 2011). However, designing cropping plans with such an approach is still an open question due to many other decision factors that could be taken into account to solve the crop allocation problem. This preliminary work foreshadows the implementation of a spatially explicit decision-aid tool, namely CRASH (Crop Rotation and Allocation Simulator using Heuristics), developed for supporting farmers in their crop allocation strategies.

This appendix was presented as:
Akplogan, M., Dury, J., de Givry, S., Quesnel, G., Joannon, A., Reynaud, A., Bergez, JE., Garcia, F., 2011. A Weighted CSP approach for solving spatio-temporal farm planning problems. In: Soft'11, 11th Workshop on Preferences and Soft Constraints. pp. 1–15.

This paper is organized as follows. In section 2, we describe the crop allocation problem. It introduces some specific definitions and emphasize crop allocation problem. Section 3 describes existing approaches used to design cropping plans with a focus on their main limitations. In section 4, we introduce the constraint model compliant with the weighted CSP framework. In section 5, we illustrate our modelling approach by a virtual case study in order to highlight the interests of the proposed approach. And finally in section 6 we discuss and conclude the relevance and limits of using WCSP to solve the CAP.

D.2 CROP ALLOCATION PROBLEM (CAP)

D.2.1 *Global description of the problem*

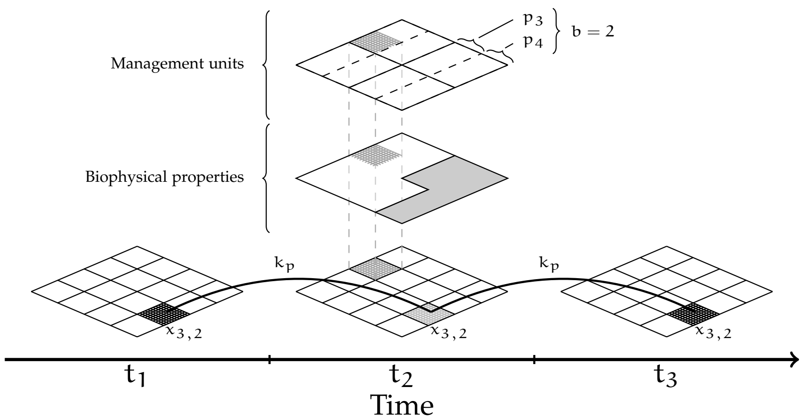


Figure D.1: Schematic representation of the spatial and temporal aspect of the decision-making problem (t_i: year, b: block, p_j: plot, $x_{b,i}$: landunit, k_p: preceding effect)

Let us consider a set of *landunits* defined as a piece of indivisible and homogeneous land whose historic and biophysical properties are identical. We define crop allocation as a spatio-temporal planning problem in which crops are assigned to landunits $x_{b,i}$ over a fixed horizon $\mathcal{H}$ of time (Fig. D.1). These landunits are spatial sampling of the farmland where $x_{b,i}$ denotes the landunit i of *block* b.

The planning problem depends on multiple spatial and temporal factors. In space, these factors are organized in many different organizational levels called *management units* (Fig.D.1). These management units are decided by the farmer to organize his work and allocate resources. In order to simplify our example, we only considered the two main management units: *plot* (p_j) and *block* b. The first concerns the annual management of crops. A plot is a combination of landunits. Their delimitations are adapted over years in order to enforce the spatial balanced of crop acreages. As shown by Fig.D.1 *blocks* are subset of plots managed in a coherent way. Blocks are characterized by one cropping system defined by the same collection of crops and by the use of a coherent set of production techniques applied to these crops (e.g. fertilizer, irrigation water). The delimitation of blocks are not reshaped in the CAP considered in this work. They are mostly defined by the structural properties of the farm such as the availability of resources (e.g. access to irrigation water) and by the biophysical properties (eg. soil type, accessibility, topography). These *biophysical properties* are also used to define if a crop could not be produced in good condition on certain soil types.

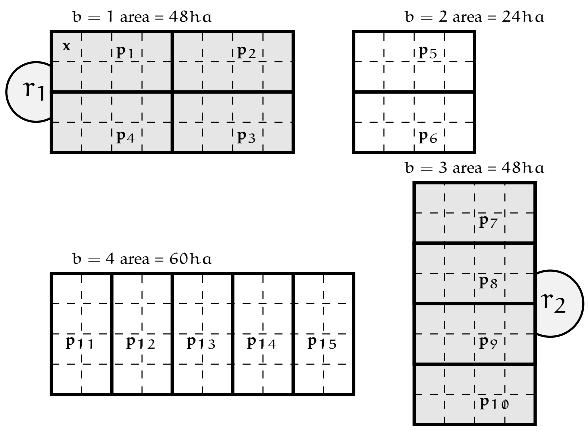
In time, the sequence of crops on the same landunit is not allowed or not advisable without facing decrease in soil fertility, or increase in diseases or weeds infestation. We deal with these temporal factors by summarizing the assessment of crop sequence quality in two indicators: the *minimum return time (*rt*)* and the *Preceding effect(*k_p*)*. The *minimum return time (*rt*)* is defined as the minimum number of years before growing the same crop on a same landunit. On the figure D.1, the minimum return time of the crop produced on $x_{3,2}$ (landunit 2 of block 3) at t_1 is equal to 2 years. More generally let t, t' be two different years ($t < t'$), $x_{b,i}$ a landunit and v a crop, $x^t_{b,i} = x^{t'}_{b,i} = v$ **if** $(t' - t) \geqslant rt(v)$.

The *preceding effect (*k_p*)* is an indicator representing the effect of the previous crop on the next one (Leteinturier et al., 2006). Based on k_p, some crop sequence can be ignored for their effects or recommended for their beneficial effects for production purposes. Further, some authors (Dogliotti et al., 2003) have argued that the reproducibility of a cropping system over time is only ensured when crop allocation choices are derived from finite crop sequence which can be repeated over the time. We therefore introduce the concept of repeatability while looking for such a crop sequence. This means that the proposed crop sequence could be repeated over time without breaking the constraint rt. We introduce this concept, known as a *"crop rotation"*, because it is widely used by farmers as decision indicator.

D.2.2 *Constraints description*

Solving the crop allocation problem (CAP) is to assign crops to landunits $x_{b,i}$ over a fixed horizon $\mathcal{H}$ of time. An assignment of crops must satisfy a set of constraints.

We retained as hard constraints the minimum *returned time* (rt), the *historic* of landunits and the *physical properties* (soil types, resource accessibility). Preference constraints are related to the *preceding effects* (k_p) and the spatio-temporal balance of crop acreages such that resources are efficiently used. Hard and preference constraints are defined either at:



Plots	t1	t2	t3	t4	t5
p_1	MA	MA	BH	OP	MA
p_2	OP	MA	MA	BH	OP
p_3	BH	OP	MA	MA	BH
p_4	MA	BH	OP	MA	MA
p_5	BH	OP	BH	CH	BH
p_6	OP	BH	CH	BH	OP
p_7	MA	MA	MA	MA	MA
p_8	MA	MA	MA	MA	MA
p_9	MA	MA	MA	MA	MA
p_{10}	MA	MA	MA	MA	MA
p_{11}	BH	CH	BH	OP	BH
p_{12}	CH	BH	OP	BH	CH
p_{13}	BH	OP	BH	CH	BH
p_{14}	OP	BH	CH	BH	OP
p_{15}	BH	CH	BH	OP	BH

Figure D.2: A virtual farm with 4 blocks, 15 plots (12ha for each plot) split into 120 landunits. The grey blocks have their own irrigation equipment (r_1, r_2). The table contains the historic values for each plot

- *plot level* to express for each plot (i) if they can be split/combined, (ii) if they must be fixed over the planning horizon in order to enforce the static aspect of the plot.
- *block level* to express for each landunit and crop the spatial compatibility of crop, the return time and the preceding effect.
- *farm level* to express preferences or the global use of resources.

Let us consider the crop allocation problem described in Fig. D.2. In this problem, we consider 4 blocks and 15 plots sampled into 120 landunits. The size of the farmland (180 ha) and its sampling into landunits correspond to a middle real-world CAP. Four crops are produced over the all blocks: *winter wheat* (BH), *spring barley* (OP), *maize* (MA) and *winter rape* (CH). Each block has a fixed area (see Fig. D.2). The blocks 1 and 3 have an access to irrigation equipments r_1 and r_2. The annual quota of irrigation water over the blocks is $6000m^3$ (respectively $4000m^3$) for r_1 (respectively r_2). Only the *maize* (MA) can be irrigated. There are two different types of soil: type 1 (block 1, 3) and type 2 (block 2, 4). The table on Fig. D.2 shows the sequence of crops produced by each plot during the five previous years.

D.2.2.1 *Spatio-temporal hard constraints*

1. **h-SCC** - *spatial compatibility of crops*: for instance, the crop CH cannot be assigned to landunits whose soil type is 1 (block 1,3). This biophysical property is not suitable for the crop growing.
2. **h-EQU** - *landunit equality*: landunits on the plots p_7 (respectively p_9) and p_8 (respectively p_{10}) must have the same crop every

	previous crops			
	BH	OP	MA	CH
BH	4	1	1	0
OP	2	3	1	0
MA	0	0	3	0
CH	0	0	0	4

Figure D.3: Table of preceding effect

year. Indeed, these landunits are decided by the farmer to be managed in the same manner.

3. **h-HST** - *landunit historic*: each landunit has defined historic values. The table in Fig. D.2 defines the historic of each plot.
4. **h-TSC** - *temporal sequence of crop*: for each couple of crops and landunits, the minimum returned time rt must always be enforced. For instance in the CAP above, $rt(BH) = 2$, $rt(OP) = 3$, $rt(MA) = 2$ and $rt(CH) = 3$.
5. **h-CCS** - *cyclicity of crop sequence*: for each landunit, the crop sequence after the historic must be endlessly repeated by enforcing temporal sequence of crops.
6. **h-RSC** - *resources capacity*: a fixed amount of resources are available. The quantities of resources accumulated on the landunits do not exceed some limits. For instance, in the CAP defined above, we have only one irrigated crop (*maize* - MA). Knowing that we need $165m^3$ of water by hectare, the annual production of MA on the blocks 1 cannot exceed $36, 36$ ha.
7. **h-SCA** - *same crops assigned*: over the time, the same subset of crops must be assigned to every landunit of the same block.

D.2.2.2 *Spatio-temporal preferences*

1. **s-TOP** - *Farm topology*: landunits where the same crops are assigned must be spatially grouped. By this we mean that it is preferable to group as most as possible the same crop on the same block. Thus, traveling time can be reduced as well as the time spend by the farmers on operational activities that control the crop production process. Therefore, every isolated landunit is penalized by a cost δ_1.
2. **s-SBC** - *Spatial balanced of crop acreages*: a defined acreage of some crops every year. For instance, in the CAP defined above, the acreage of MA should be within the range $[24, 48]$ ha on block 1 and $[12, 24]$ ha on block 3. Any deviation is penalized by a cost δ_2.

3. **s-TBC** - *temporal balanced of crop acreages*: a defined acreage of some crops on each landunit over years. In the CAP defined above, between $[12, 24]$ ha of crop CH should be produced on every landunit. Any deviation is penalized by a cost δ_3.
4. **s-CSQ** - *Crop sequence quality*: each pair of successive crops is associated to a cost k_p that defines its preceding effect. Fig. D.3 define all k_p values.

In practice, we suggest to define the costs k_p, δ_1, δ_2 and δ_3 such that $\sum k_p > \sum \delta_2 > \sum \delta_1 > \sum \delta_3$. By doing so, a realistic hierarchy can be introduced among the soft constraints. Indeed, first and foremost, the preceding effects k_p must be minimized because of their consequences on the next crops. The spatial balanced of crop acreages related to cost δ_2, implicitly defines the annual receipts of the farmer. It must be ensured as much as possible. Afterwards the working hours can be reduced by grouping the same crops together (δ_1). Lastly, the additional preferences related to the temporal balanced of crop acreages (δ_3) can be enforced.

D.3 RELATED WORK

Since Heady (1948), the cropping plan decision was represented in most modelling approaches as the search of the best land-crop combination (Kein Haneveld and Stegeman, 2005). Objectives to achieve a suitable cropping plan were often based on complete rationality paradigm using a single monetary criteria optimization, multi-attribute optimization (Annetts and Audsley, 2002) or assessment procedures (Bachinger and Zander, 2007). In these approaches, the cropping plan decision is mainly represented into models by one of the two concepts, i.e. the cropping acreage (McCarl et al., 1977; Itoh et al., 2003; Sarker and Ray, 2009) or crop rotation (El-Nazer and McCarl, 1986; Dogliotti et al., 2003). These two concepts are two sides of the cropping plan decision problem, i.e. the spatial and temporal aspects. The originality of our approach lies on the consideration of both dimensions, i.e. spatial and temporal while solving the CAP. In most of the modelling approaches, the cropping plan is not spatially represented and is summarized as simple crop acreage distributions across various land types. At the farm level, the heterogeneity of a farm territory is generally described using soil type as the sole criterion (Dury et al., 2011).

D.4 WEIGHTED CSP MODEL OF CROP ALLOCATION

D.4.1 *Weighted CSP Formalism*

According to the CAP definition, and assuming a purely CSP formalism cannot deal with preferences easily, we focus on the Weighted

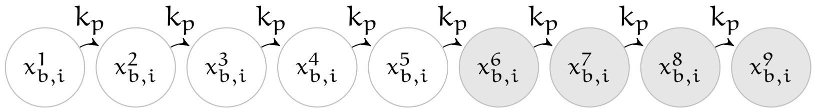


Figure D.4: A temporal sequence of variables over landunit i in block b

CSP (WCSP) formalism which is more appropriate for solving optimization problems. The WCSP formalism (Meseguer et al., 2006) extends the CSP formalism by associating cost functions (or preferences) to constraints. A WCSP is a triplet $\langle \mathcal{X}, \mathcal{D}, \mathcal{W} \rangle$ where:

– $\mathcal{X} = \{1, \cdots, n\}$ is a finite set of n variables.
– $\mathcal{D} = \{D_1, \cdots, D_n\}$ is a finite set of variables domain. Each variable $i \in \mathcal{X}$ has a finite domain $D_i \in \mathcal{D}$ of values.
– $\mathcal{W} = \{W_{S_1}, \cdots, W_{S_e}\}$ is a set of cost functions where $S_i \subset \mathcal{X}$ be a subset of variables (i.e., the scope). We denote $l(S_i)$ the set of tuples over S_i. Each cost function W_{S_i} is defined over a subset of variables S_i ($W_{S_i} : l(S_i) \to [0, m]$ where $m \in [1, \cdots, +\infty]$).

Solving a WCSP is to find a complete assignment $A \in l(\mathcal{X})$ that minimizes $\min_{(A \in l(\mathcal{X}))} \left[\sum_{W_{S_i} \in \mathcal{W}} W_{S_i}(A[S_i])\right]$, where $A[S_i]$ is the projection of a tuple on the set of variables S_i.

D.4.2 *Crop allocation problem definition*

The CAP is defined by a set of landunits and crops. The planning problem is defined over a finite horizon $\mathcal{H}$. We define the associated WCSP problem as follow.

$\mathcal{X}$ a set of variables $x^t_{b,i}$ that define the landunit i in block b ($i \in [1, \mathcal{N}_b]$, $b \in [1, \mathcal{B}]$ $\mathcal{B} = 4$ and $\mathcal{N}_1 = 32$ in the CAP described in Fig. D.2) at year t ($t \in [1, \mathcal{H}]$). Thus, each landunit is described by $\mathcal{H}$ variables that represent the landunit occupation at every time. We define $[1, h]$ and $[h+1, \mathcal{H}]$ respectively the historic and the future times. For instance, following Fig. D.2) and considering $\mathcal{H} = 9$ and $h = 5$, landunit i in block b will be represented by 9 variables where the first five variables (white nodes) are historic variables.

$\mathcal{D}$ the domains $D_{b,i}$ of variables $x^t_{b,i}$ is the set of possible crops over the landunit i in block b. Considering the problem in Fig. D.2, $\forall b \in [1, \mathcal{B}], \forall i \in [1, \mathcal{N}_b], \quad D_{b,i} = \{1, 2, 3, 4\} = \{BH, OP, MA, CH\}$

$\mathcal{W}$ the cost functions are divided into five different types of hard and soft constraints: (1) simple tabular cost functions (arity up to 5), (2) same global constraint, (3) regular global constraint, (4) gcc global cardinality constraint, (5) soft-gcc soft global cardinality constraint. These cost functions are precisely defined in the next sections.

D.4.3 *Simple cost functions*

The constraints h-SCC, h-EQU, h-HST, s-TOP and s-CSQ are defined by cost functions W_{S_i} over the scopes S_i. Given a complete assignment $a \in D_{\mathcal{X}}$, $l(S_i)$ denotes the set of tuples over S_i and $a[S_i]$ denotes the sub-assignment of a to the variables in S_i.

D.4.3.1 *h-SCC:*

$\forall t \in \mathcal{H}^+$, $\forall b \in \mathcal{B}$, $\forall i \in \mathcal{N}_b$, $\forall v \in D_{b,i}$, let $W_{S_1^{b,i,t}}$ be a set of unary cost functions associated to spatial compatibility of crops. $W_{S_1^{b,i,t}}$: $l(S_1^{b,i,t}) = l(x^t_{b,i}) \to \{0, \infty\}$

$$uW_{S_1^{b,i,t}} = \begin{cases} \infty & \textit{if } a[S_1^{b,i,t}] \textit{ cannot be assigned} \\ 0 & \textit{otherwise} \end{cases} \tag{D.1}$$

D.4.3.2 *h-EQU:*

$\forall t \in \mathcal{H}^+$, $\forall b \in \mathcal{B}$. For all couple of landunits $(i, j) \in \mathcal{N}_b \times \mathcal{N}_b$ that are decided by the farmer to be manage in the same manner, we define a set of binary cost functions $W_{S_2^{b,i,t}}$ that described the equality between the landunits. $W_{S_2^{b,i,t}} : l(S_2^{b,i,t}) = l(x^t_{b,i}, x^t_{b,j}) \to \{0, \infty\}$

$$W_{S_2^{b,i,t}} = \begin{cases} 0 & \textit{if } \forall (v_i, v_j) \in a[S_2^{b,i,t}], v_i = v_j \\ \infty & \textit{otherwise} \end{cases} \tag{D.2}$$

where v_i and v_j are the values assigned to the variables $x^t_{b,i}$ and $x^t_{b,j}$.

D.4.3.3 *h-HST:*

$\forall b \in \mathcal{B}$, $\forall i \in \mathcal{N}_b$, $\forall v_p \in D_{b,i}$, $\forall t \in \mathcal{H}^-$, let $W_{S_3^{b,i,t}}$ be a set of unary cost functions associated to the historic values of landunits. $W_{S_3^{b,i,t}} : l(S_3^{b,i,t}) = l(x^t_{b,i}) \to \{0, \infty\}$

$$W_{S_3^{b,i,t}} = \begin{cases} 0 & \textbf{if } a[S_3^{b,i,t}] = \textbf{historic}(x_{b,i}, t) \\ \infty & \textit{otherwise} \end{cases} \tag{D.3}$$

where **historic**$(x_{b,i}, t)$ returns the historic value of the landunit i in the block b at date t.

D.4.3.4 *s-TOP:*

$\forall t \in \mathcal{H}^+$, $\forall b \in \mathcal{B}$, $\forall (i, j) \in \mathcal{N}_b \times \mathcal{N}_b$, let $W_{S_4^{b,i,t}}$ be a set of binary cost functions associated to the farm land topology. $W_{S_4^{b,i,t}}$: $l(S_4^{b,i,t}) = l(x^t_{b,i}, x^t_{b,j}) \to \{0, \delta_1\}$. We define a neighbourhood function **neighbour**(j) which return the landunits $i \in \mathcal{N}_b$ spatially close to j.

$$W_{S_4^{b,i,t}} = \begin{cases} \delta_1 & \textit{if } \forall (v_i, v_j) \in a[S_4^{b,i,t}], (v_i \neq v_j) \bigwedge (i \in \textbf{neighbour}(j)) \\ 0 & \textbf{otherwise} \end{cases} \tag{D.4}$$

where v_i and v_j are the values assigned to the variables $x^t_{b,i}$ and $x^t_{b,j}$. For instance, the neighbourhood function associated to the problem in figure D.2 returns the von Neumann neighbourhood.

D.4.3.5 *s-CSQ:*

$\forall t \in \mathcal{H}$, $\forall b \in \mathcal{B}$, $\forall i \in \mathcal{N}_b$, $\forall v_i, v_i' \in D_{b,i} \times D_{b,i}$ let $W_{S_5^{b,i,t}}$ be a set of binary cost function associated to the preceeding effects k_p. We define a function $\mathsf{KP}(a[S_5^{b,i,t}])$ that return the preceeding effect k_p of doing the crop v_i' after v_i, with $a[S_5^{b,i,t}] = (v_i, v_i')$.

$$W_{S_5^{b,i,t}} = \mathbf{KP}(a[S_4^{b,i,t}]) \tag{D.5}$$

D.4.4 *Crop collection over a block using* same *constraints*

D.4.4.1 *h-SCA:*

Considering a block b, the subset of $(\mathcal{H} - h)$ future variables $x_{b,i}^t$ (with $t \in [h+1, \mathcal{H}]$) associated to each landunit i in b must be assigned to the same crop collection. Thus, $\forall (i,j) \in \mathcal{N}_b \times \mathcal{N}_b$ (with $i \neq j$), the set of values assigned to the temporal sequence of variables defining i is a permutation of those of j. By using the same constraint introduced in Beldiceanu et al. (2004) we define h-SCA. For each block b, we choose a leading landunit i. We then define a $2 * (\mathcal{H} - h)$-ary cost function W_S^{SCA} associated to each pair of sequence of variables that defines $x_{b,i}^t$ and $x_{b,j}^t$ ($i \neq j$). Thus, the scope S is $\{x_{b,i}^{h+1}, \cdots, x_{b,i}^{\mathcal{H}}, x_{b,j}^{h+1}, \cdots, x_{b,j}^{\mathcal{H}}\}$. Let $A[x_{b,i}^{h+1}, \cdots, x_{b,i}^{\mathcal{H}}]$ and $A[x_{b,j}^{h+1}, \cdots, x_{b,j}^{\mathcal{H}}]$ denote the two sub-assignments of the variables in S. The constraint W_S^{SCA} requires that $A[x_{b,i}^{h+1}, \cdots, x_{b,i}^{\mathcal{H}}]$ is a permutation of $A[x_{b,j}^{h+1}, \cdots, x_{b,j}^{\mathcal{H}}]$.

$$W_S^{SCA} = \mathsf{same}(\underbrace{x_{b,i}^{h+1}, \cdots, x_{b,i}^{\mathcal{H}}}_{i}, \underbrace{x_{b,j}^{h+1}, \cdots, x_{b,j}^{\mathcal{H}}}_{j}) \tag{D.6}$$

D.4.5 *Crop sequence using* regular *global constraints*

The constraints h-TSC and h-CCS are related to temporal crop sequences. We represent them by using the regular constraint (Pesant, 2004). $\forall t \in [1, \mathcal{H}]$, $\forall b \in \mathcal{B}$, $\forall i \in \mathcal{N}_b$, $\forall a \in D_{b,i}$, let $M_{b,i}^a$ be a non deterministic finite automaton (NFA), $\mathcal{L}(M_{b,i}^a)$ the language defined by $M_{b,i}^a$, and $S_{b,i}$ a temporal sequence of $\mathcal{H}$ variables that describes landunit i of block b over the horizon. Solving a $\mathsf{regular}(S_{b,i}, M_{b,i}^a)$ constraint is to find an assignment $A[S_{b,i}]$ such that $A[S_{b,i}] \in \mathcal{L}(M_{b,i}^a)$.

D.4.5.1 *h-TSC:*

Considering each landunit $x_{b,i}$, the crop sequence is enforced by defining for each crop $a \in D_{b,i}$ a language $\mathcal{L}(M_{b,i}^a)$ such that the same value a is assigned to ($x_{b,i}^t$ and $x_{b,i}^{t'}$) *iff* $x_{b,i}^{t'}$ enforces the minimum returned time $rt(a)$ i.e., $\forall t' \neq t, \quad t' \geqslant t + rt(a)$. We define

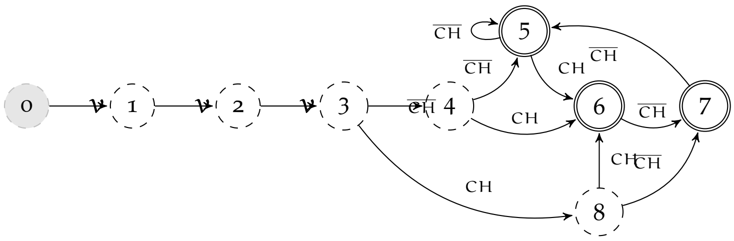


Figure D.5: Automaton for crop CH with $rt(CH) = 3$ and $h = 5$. ν denotes any value in $D_{b,i}$. The notation $\overline{CH}$ corresponds to $D_{b,i} \setminus \{CH\}$. The associated language accepts every pattern over the historic variables and only the patterns that enforce the minimum return time in the future variables (e.g., CH-OP-CH-OP-CH-BH-OP-CH-BH).

$\mathsf{regular}(S_{b,i}, M^{a}_{b,i})$ where $M^{a}_{b,i}$ is described as in Fig. D.5 for crop $a = CH$ the minimum return time of which is $rt(CH) = 3$ years. Here, the initial state is 0 while final states are $4, 5, 6$. Arcs are labelled with crop values.

As shown by the NFA in Fig. D.5, the historic variables are used to enforce the minimum return time over the future variables. We then define an $\mathcal{H}$-ary cost function $W^{TSC^{a}}_{S_{b,i}}$ associated to each pair of landunit i in block b and each crop a such that:

$$\forall b \in \mathcal{B}, \forall i \in \mathcal{N}_b, \forall a \in D_{b,i}, W^{TSC^{a}}_{S_{b,i}} = \mathsf{regular}(x^{1}_{b,i}, \cdots, x^{t}_{b,i}, \cdots, x^{\mathcal{H}}_{b,i}, M^{a}_{b,i}) \tag{D.7}$$

D.4.5.2 *h-CCS:*

Considering each landunit $x_{b,i}$, we combine h-TSC with a repeatability constraint also defined by a set of $\mathsf{regular}$ constraints. The constraint h-CCS ensures that any crop sequence assignment after the historic can be endlessly repeated without violating the minimum return time constraint h-TSC. Fig. D.6 describes a cyclic NFA for crop CH. The initial state is 0 while final states are $3, 6, 9, 12$. The scope of the cost function $W^{CCS^{a}}_{S_{b,i}}$ is restricted to future variables.

$$\forall b \in \mathcal{B}, \forall i \in \mathcal{N}_b, \forall a \in D_{b,i}, W^{CCS^{a}}_{S_{b,i}} = \mathsf{regular}(x^{h+1}_{b,i}, \cdots, x^{\mathcal{H}}_{b,i}, M^{a}_{b,i}) \tag{D.8}$$

D.4.6 *Resource capacity constraints using global cardinality constraints*

In CAP, each landunit consumes a fixed amount of resources according to some structural (crop type, the area of landunits, etc.) and numerical (the irrigation dose) requirements. For instance, the maize (MA) is an irrigated crop whereas winter wheat (BH) does

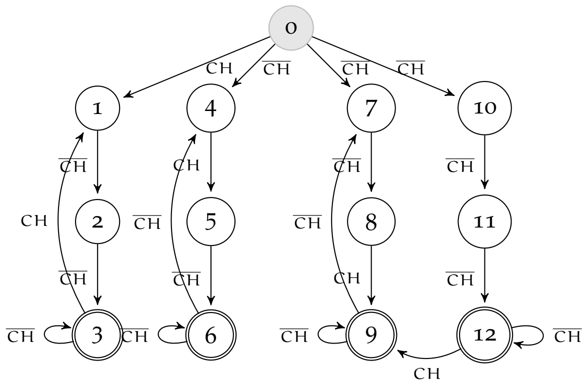


Figure D.6: Cyclic automaton for the crop CH with $rt(CH) = 3$ and $\mathcal{H} - h = 4$.

not need irrigation. A classical approach to deal with resources is to solve a shortest path problem with resource constraints (Irnich and Desaulniers, 2005). The problem is NP-hard if the path needed is elementary. Loosely, solving a resource allocation problem involves both sequencing and counting reasoning. We assume in the CAP that this problem can be reduced to a counting problem under hypothesis 1 and 2.

Hypothesis 1 *: Resources are supposed to be usable and systematically renewed every year without doing anything (e.g. annual quota of irrigation water).*

This hypothesis is closed to a real CAP because farmers usually have a fixed quota of irrigation water. That can be exactly the case for the working hours capacity in a year if work regulations is taken into account.

Hypothesis 2 *:* $\forall t \in [1, \mathcal{H}]$, $\forall (b, b') \in \mathcal{B} \times \mathcal{B}$ *a couple of blocks,* $\forall (i, j) \in \mathcal{N}_b \times \mathcal{N}'_b$ *a couple of landunits. The areas of landunits* i *and* j *of block* b *(respectively* b'*) can be considered equivalent according to the problem size.*

We make the assumption that the spatial sampling of the farm land into landunits is homogeneous. Under these hypothesis the annual resource allocation is seen as a counting problem at every time $t \in [h + 1, \mathcal{H}]$. Thus, given annual resources capacities for a CAP, we define for each time $t \in [h + 1, \mathcal{H}]$ an upper and lower bound to the number of variables $x^t_{i,b}$ that are assigned to a given crop according to both structural and numerical requirements.

D.4.6.1 *h-RSC*

: to enforce resource capacity constraints h-RSC, we use the global cardinality constraint gcc (Régin, 1996) over the assignments of crops to landunits.

$\forall t \in [h+1, \mathcal{H}]$, let $W^{RSC}_{S^t_b}$ be a $\mathcal{N}_b$-ary global constraint associated to resource capacities.

Given $S^t_b = (x^t_{b,1}, \cdots, x^t_{b,\mathcal{N}_b})$ the global cardinality constraint (gcc) specifies, for each value $a \in \bigcup D_{b,i}$, an upper bound $ub(a)$ and a lower bound $lb(a)$ to the number of variables $x^t_{b,i}$ that are assigned to a.

$$W^{RSC}_{S^t_b} = \mathsf{gcc}(S^t_b, lb, ub) \tag{D.9}$$

has a solution if there exists an assignment of S^t_b such that

$$\forall a \in \bigcup D_{b,i},\ lb(a) \leqslant |\{x^t_{b,i} \in S^t_b | x^t_{b,i} = a\}| \leqslant ub(a) \tag{D.10}$$

D.4.7 *Spatio-temporal balance of crops using soft-gcc*

Preferences related to the spatio-temporal balance of crops (s-SBC and s-TBC) are defined as soft global cardinality constraints (soft-gcc) that allow the violation of both lower and upper bounds of the associated hard constraint gcc.

$$\begin{aligned} \mathsf{soft\text{-}gcc}(S, lb, ub, z, \mu) &= \\ \{(A[S], a_z) | A[S] \in l(S), a_z \in D_z, \mu(A[S]) \leqslant a_z\} \end{aligned} \tag{D.11}$$

where lb and ub are respectively the lower and upper bounds, z a cost variable with finite domain D_z, μ the violation measure for the global constraint soft-gcc. In this work, we use the variable-based violation measure which is the minimum number of variables whose values must be changed in order to satisfy the associated gcc constraint. Thus $\mathsf{soft\text{-}gcc}(S, lb, ub, z, \mu)$ has a solution if $\exists\ A[S]$ such that $min(D_z) \leqslant \mu(A[S]) \leqslant max(D_z)$. Based on this definition the constraints s-SBC and s-TBC are formalized as follow.

D.4.7.1 *s-SBC*

: $\forall t \in [h+1, \mathcal{H}]$, $\forall b \in \mathcal{B}' \subseteq \mathcal{B}$. Let $W^{SBC}_{S^t_b}$ be a $|\mathcal{B}'|$-ary soft-gcc constraint associated to block b at time t. The scope $S^t_b = \{x^t_{b,i} | i \in [1 \cdots \mathcal{N}_b]\}$.

$$W^{SBC}_{S^t_b} = \mathsf{soft\text{-}gcc}(S^t_b, lb, ub, z, \mu) \tag{D.12}$$

D.4.7.2 *s-TBC*

: $\forall b \in \mathcal{B}' \subseteq \mathcal{B}$, $\forall i \in \mathcal{N}_b$. Let $W^{TBC}_{S_{b,i}}$ be a $(\mathcal{H}-h)$-ary soft-gcc constraint associated to each landunit i. The scope $S_{b,i} = \{x^{h+1}_{b,i}, \cdots, x^{\mathcal{H}}_{b,i}\}$. Excepted the scope, $W^{TBC}_{S_{b,i}}$ is exactly defined as the global soft cardinality constraint defined for s-SBC.

D.5.1 *CAP instances description*

We performed the experimentations by using four instances of the virtual farm presented in Fig. D.2. Each instance corresponds to a new sampling of landunits. The number of landunits is increased from 15 to 120 (15, 30, 60, 120). For the CAP instance with 15 landunits, $\mathcal{N}_1 = \mathcal{N}_3 = 4, \mathcal{N}_2 = 2$ and $\mathcal{N}_4 = 5$ where $\mathcal{N}_i$ denotes the number of landunits in the block i. In this problem, sampling is done such that the plots (see Fig. D.2) are also the landunits (12 ha per landunit). These landunits are gradually refined by splitting them into 2, 4 and 8 smaller ones, to respectively build the instances with 30, 60 and 120 landunits. These sampling are chosen to be representative of different farm sizes. The planning horizon is nine years. According to the minimum return time (*winter wheat* $rt(BH) = 2$, *spring barley* $rt(OP) = 3$, *maize* $rt(MA) = 2$ and *winter rape* $rt(CH) = 3$) the four last years are dedicated to the future while the five first are historic ones. We use the historic values presented in Fig. D.2.

We should emphasis that there is no constraints or preferences between blocks as described in Section D.2.2. Thus, we first focus on solving each block independently. The instances associated to the block 1 are B1-LU4, B1-LU8, B1-LU16, B1-LU32 respectively for 4, 8, 16, 32 landunits. For all these experimentations the costs associated to s-TOP, s-SBC and s-TBC are respectively $\delta_1 = 2$, $\delta_2 = 100$ and $\delta_3 = 10$. By doing so, we implicitly introduce a hierarchy among the soft constraints according to the criterion defined in the last paragraph of section D.2.2.2. To fine-tune the weight of preceding effects k_p in the global cost function, we introduced a factor $\delta_4 = 10$ such that k_p are set to $\delta_4 * KP$. By doing so, the crop sequences that minimize the preceding effects are desired to be satisfied as much as possible.

Secondly, we add a new preference over all blocks in our original model. We define a new cost function $W^{SBC}_{S^t}$, extending the previous $W^{SBC}_{S^t_b}$ described in section D.2.2 such that the annual global acreage of MA and BH over all blocks should be respectively within the range $[40, 72]$ ha and $[70, 100]$ ha. The CAP instances B1[1-4]-LU15(*), B[1-4]-LU30(*), B[1-4]-LU60(*) and B[1-4]-LU120(*) are associated to these new problems. The blocks are now interdependent and consequently the maximum arity of soft global cardinality constraints is equal to the total number of landunits. All of these instances are available in the cost function benchmark. For each instance, the number of constraints is approximately equal to $\frac{5}{2} \times \mathcal{N} \times \mathcal{H} \pm 30$, where $\mathcal{N}$ denotes the number of landunits and $\mathcal{H}$ the planning horizon.

http://www.costfunction.org/benchmark?task=browseAnonymous&idb=33

D.5.2 *Analysis of the results*

For solving the CAP, we use a Depth-First Branch and Bound (DFBB) algorithm implemented in the **Toulbar2** solver (version 0.9.1) using default options. Columns $|\mathcal{X}|$ and $|\mathcal{W}|$ of Tab. D.1 shows the number of variables and constraints for each instance.

The results presented in Tab. D.1 are performed on a 2.27GHz Intel(R) Xeon(R) processor. Total CPU times are in seconds. We measure total times to find and prove optimality (column Time(s) of One optimal (DFBB)) starting with a relatively good upper bound (column UB). The initial upper bound has an important impact on performance. We chose its value empirically. Based on optimal values, we also measure total times to find all the optimal solutions (column Time(s) of All optimal (DFBB)) by setting the initial upper bound to the optimum (column Opt.) plus one.

While focusing on independent blocks, the best solution is got in less than a minute excepte for B1-LU32. The optimum is found and proved for all the instances. The differences between CPU times to find one optimal and all the optimal solutions is mainly due to the quality of the initial upper bound. The results found while introducing interdependence between blocks are also acceptable compared to the problem size. Indeed, the scope of some gcc and soft-gcc constraints is equal to the number of landunits (120 variables in the worse case). This may explain why the instance B[1-4]-LU120(*) is not closed after 48 hours.

D.6 CONCLUSION

In this paper, we have modelled the crop allocation problem (CAP) using the Weighted CSP formalism. Contrary to existing approaches for solving such a problem, our proposition combines both the spatial and the temporal aspects of crop allocation. We explicitly described how the farmers' hard and soft constraints can be addressed as a global objective function optimization problem. The results have shown that on small and middle CAP, the *Toulbar2* solver can deliver relevant solutions in acceptable computational time. In the future, we will investigate the CUMULATIVE constraint for expressing more complex resource management and the COSTREGULAR constraint for mixing the return time and preceding effects, taking inspiration from the work done by Métivier et al. (2009).

---

http://mulcyber.toulouse.inra.fr/projects/toulbar2

Table D.1: An Optimal and all optimal solutions using DFBB

Instance of CAP	$\lvert\mathcal{X}\rvert$	UB	$\lvert\mathcal{W}\rvert$	Opt.	One optimal (DFBB)			All optimal DFBB			
					Time(s)	Nodes	BT	Time(s)	Nodes	BT	Nb.Sol
B1-LU4	36	1000	91	92	0.39	17	10	0.08	8	4	5
B1-LU8	72	2000	175	184	2.96	94	49	0.21	32	16	17
B1-LU16	144	4000	343	368	21.47	413	209	2.64	256	512	257
B1-LU32	288	6000	679	640	228	285	147	6.19	38	19	17
B2-LU2	18	1000	47	38	0.08	2	2	0.06	2	1	1
B2-LU4	36	2000	95	116	0.22	8	4	0.22	8	4	1
B2-LU8	72	4000	191	392	4.19	6	5	0.36	2	1	1
B2-LU16	144	6000	383	752	7.9	10	9	0.78	2	1	1
B3-LU4	36	1000	99	328	0.3	14	7	0.29	16	8	2
B3-LU8	72	2000	199	656	0.64	14	7	0.6	16	8	2
B3-LU16	144	4000	367	1312	1.51	18	9	1.37	16	8	2
B3-LU32	288	6000	703	2592	4.1	20	10	3.79	18	9	2
B4-LU5	45	1000	119	46	0.53	4	4	0.08	0	0	1
B4-LU10	90	2000	239	192	11.64	5	4	0.57	0	0	1
B4-LU20	180	4000	479	752	12.32	12	10	0.73	0	0	1
B4-LU40	360	6000	959	1504	39.33	23	19	1.97	2	1	1
B[1-4]-LU15(*)	135	2000	360	704	21.02	257	131	7.87	96	48	2
B[1-4]-LU30(*)	270	4000	712	1560	323.02	1029	521	155.9	498	249	12
B[1-4]-LU60(*)	540	4000	1384	3852	2412.97	1297	658	3697.23	2228	1114	136
B[1-4]-LU120(*)	1080	8000	2728	-	-	-	-	-	-	-	-

E

CROP GROWTH SIMULATION IN CRASH: THE CHOICE OF STICS

Modelling approaches for simulating agricultural decisions and crop production include models with detailed physical characterization of soil and plant interactions in the form of crop models.

We used STICS (Brisson et al., 2003) as crop model to dynamically simulate crop growth and water use on every land unit in response to farmers' technical interventions. We choose STICS for its ability to simulate a large number of different crops under different conditions that we meet in France (Brisson et al., 2009). Further, STICS simulates both agronomic variables (e.g. leaf area index, biomass, yield and input consumption) and environmental variables (e.g. soil profile water and contents, water drainage and nitrate leaching) which is of primary importance as regard to requirements for simulating crop operation activities. However, the choice of STICS and its coupling with external modules has some constraints and required to carry out some software engineering on different aspects:

1. STICS is written in a different language, i.e. fortran, than the one used by the VLE platform, i.e. C++. To overcome this, the STICS crop model was wrapped within a DEVS interface in the form of difference equation as defined in the VLE framework (Chabrier et al., 2007; Quesnel et al., 2009).
2. Wether STICS can simulate a sequence of succeeding crops (De Cara et al., 2010, e.g.), it has not been designed to be dynamically parameterised. The sequence of crops has indeed to be defined at model initialisation. To go beyond this limitation, we give to the crop rotation simulator the capability to stop and start the STICS crop model with a new sequence of crops, and this at any time step. Therefore, the crop rotation simulator can dynamically parametrize the STICS crop model when an event concerning the change of the sequence of crops come from the operating systems while maintaining the continuity of states of the soil variables (Figure E.1).
3. STICS was not designed to be plugged with external modules to be perturbed or observed during the simulation for managing technical operations. We build a set of connections between the crop rotation simulator and state variables of the STICS crop model in order to interfere with them, either as results of an activities (input of STICS) or to observe state variables (output of STICS).

Therefore, the crop model STICS was used as a kernel encapsulated in a DEVS atomic model (crop model in Figure E.1) that is linked with a crop rotation simulator. The crop rotation simulator allows for dynamic parameterisation of the crop model with crops and management options selected by the agent system through the operating system.

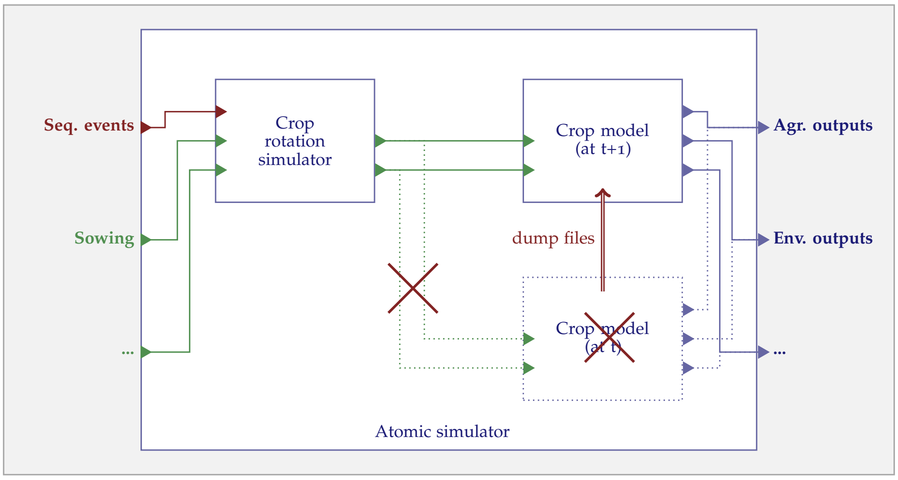


Figure E.1: Encapsulation and management of the STICS crop model by the crop rotation simulator on each land units of the farmland.

INDEX