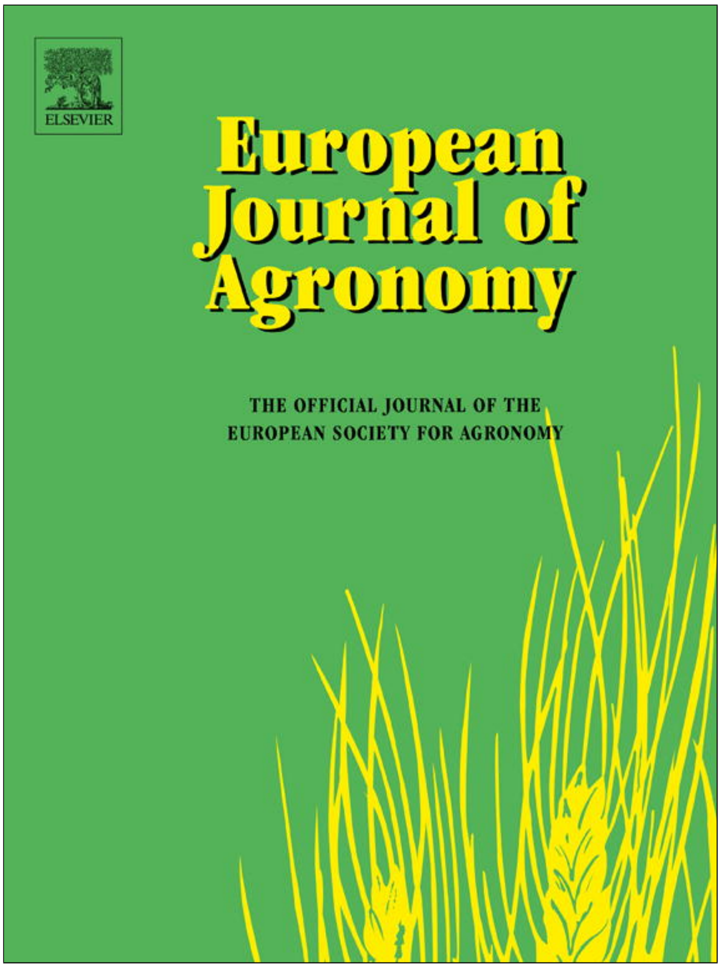
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Cropping-plan decision-making on irrigated crop farms: A spatio-temporal analysis

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ABSTRACT

This paper describes an analysis of farmer cropping-plan decision-making. We surveyed 30 farmers to study the dynamics of their cropping-plan decision-making on irrigated arable farms. Using methods from cognitive science, we analysed the ways farmers managed uncertainty through planning and reactive decisions. In this study we show that representing cropping-plan selection only as a resource-allocation or crop-rotation-design problem is not sufficient to account for farmers' decision-making processes. We show that cropping-plan decision-making does not occur once per year or per rotation, as is usually represented in models, but is a continuous process mixing design and adaptive activities. We describe the concepts that farmers use to plan cropping over time. We also highlight the importance of organising farmland into spatial crop-management blocks as a major determinant of cropping-plan strategies. We argue that deep understanding of these processes at the farm level is required before it is possible to model and design flexible and environmentally friendly cropping systems that fit with farmers' reality.

1. Introduction

The rising environmental concerns (Millennium Ecosystem Assessment, 2005) and 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 expected new regulations. All these elements question the vulnerability of the current farming systems and more over the need to strengthen their adaptive capacity to face an ever changing environment (Smit and Wandel, 2006; Darnhofer et al., 2010). Cropping systems in irrigated arable farms are particularly concerned by these changes (Bartolini et al., 2007). These farms are particularly concerned and affected by the significant on-going changes of economy, regulations and water scarcity (Amigues et al., 2006).

Adoption of innovative cropping plans by farmers' promises greater resource-use efficiency at the farm level (Amigues et al., 2006; Power et al., 2011). Cropping-plan decision-making is usually described as the choice of crops to be grown, determination of crop acreage, and their allocation to plots (Dury et al., 2011). The cropping-plan choice is one of the first steps in the process of crop production occurring at the farm level. Other activities involved throughout the entire crop-production process, both managerial and operational, are related to this choice and depend on its nature and quality (Nevo et al., 1994; Aubry et al., 1998a,b).

To date, research on farmers' cropping-plan decision-making has been dominated by economic concerns and/or has focused on a narrow set of decision determinants (Table 1). In these studies, cropping-plan choices were usually summarised as a single decision occurring once a year or once a rotation. These approaches failed to design flexible crop production systems because they did not address the dynamics nature of farmers' decision-making processes (Ohlmer et al., 1998; Darnhofer et al., 2010). Few studies have explored how farmers make cropping-plan decisions (e.g. Aubry et al., 1998a,b), addressed the dynamics of the decision-making processes (e.g. Dorward, 1999) or questioned the interactions between the spatial and temporal dimensions of the decision-making process. Despite the apparent simplicity of this decision problem, cropping-plan decision-making depends on multiple factors interacting at the different spatial and temporal scales of farm management (Nevo et al., 1994; Aubry et al., 1998a,b) and involves some risks (Chavas and Holt, 1990). A deeper understanding of

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Table 1
The most important determinants considered in cropping-plan studies at the farm scale, organised by category, and examples of studies that focused on these 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 Le Bail (2007); Power et al. (2011)
	Rotation	Cycle period, length Return time Previous effect	
	Soil	Textures Available water content Maximum suitable area	
	Crop management techniques	All operations Irrigation Fertilisation	
Economy		Margin Price uncertainty	El-Nazer and McCarl (1986); Abdulkadri and Ajibefun (1998); Itoh et al. (2003)
Resources	Irrigation water	Amount Flow rate	Leroy and Jacquin (1991); Annetts and Audsley (2002); Bartolini et al. (2007); Bachinger and Zander (2007); Power et al. (2011)
	Equipments and labour	Machinery Labour	
Farmland	Management unit	Field distance	Morlon and Trouche (2005); Joannon et al. (2006)
	Spatial	Crop location	
Climate		Temperature Rain fall	Rodriguez et al. (2011)

Note: the studies listed may not have included all determinants of a category or ignored determinants from other categories.

cropping-plan decision-making processes at the farm level is a starting point to model and design flexible, more environmentally friendly and profitable cropping systems.

To achieve particular outcomes, farmers are required to make sequential decisions that must accommodate the multiple elements of their farming system, some of which change over time. The cropping-plan decision-making problem must therefore be analysed as a dynamic process (Brehmer, 1990) that is incorporated into a succession of other hierarchical and planned decisions over annual and long-term horizons (Aubry et al., 1998a,b; Ohlmer et al., 1998).

This paper provides an empirical investigation of how farmers make cropping-plan decisions. The aim of this study was not to identify and quantify effects of determinants on cropping-plan development; they have already been widely discussed in the literature. Rather, we studied individual farmer's decision-making processes to understand how they used these determinants in their overall cropping-plan strategy. We concurrently focused on spatial and temporal dimensions of farmers' cropping-plan decision-making processes at farm scale, which as far as we know have not been considered in the literature.

The paper is organised as follows: Section 2 explains the materials and methods we used to survey and analyse farmers' decision-making processes. Section 3 presents the farm sample and analysis of farmers' cropping-plan decision-making processes. Then, we formalised findings into a spatio-temporal conceptual model to represent farmers' cropping-plan decision-making processes through generic concepts. Section 4 discusses the relevance of the results in regard to the literature and issues of implementing such decision-making-processes as computer models.

2. Materials and methods

2.1. Study cases and survey area

We used a theoretical sampling approach (Glaser and Strauss, 1967; Eisenhardt, 1989) to choose farmers from large lists of irrigated arable farms provided by agricultural extension services and cooperatives. We focused only on irrigated arable farms, but within this population, the choice of farmers surveyed was diversity-oriented. We selected individual farmers using quantitative and qualitative criteria that were likely to affect cropping plan choices. The criteria were chosen on the basis of literature review (Dury et al., 2011) and the availability of the information prior to the interviews. After locating the farm, we used the French "Land Parcel Identification Systems" (LPIS) to collect information about the types and area of crops that were grown by farmers in the past, and then we used maps to account for soil type and irrigation water resource (e.g. river and water table) diversities between farms. To add contextual diversity (climate, socio-economical context), we performed the selection in three regions of France, Midi-Pyrenees (MiPy), Poitou-Charentes (PCh) and Centre (Ce).

2.2. Data collection

We used the Cognitive Task Analysis approach (Hollnagel, 2003; Hoffman and Lintern, 2006; Dury et al., 2010) to study farmer decision-making processes during the spring of 2009. The survey concerned the period 2005–2009. We performed non-structured interviews with experts from local agricultural extension services ($n = 3$) within the three surveyed areas to capture characteristics of each regional context. Then, we conducted semi-structured farmer interviews ($n = 30$). The farmer questionnaire was structured into three parts:

(i) Farmers' objectives and goals: Through semi-structured questions, we asked farmers about their production choices in relation to their business objectives. To overcome the assertion that farmer make decisions in order to maximise profit within a constrained environment, we analysed how objectives impact farmer cropping-plan design strategies and translate into actions. We associated farmers' objectives with decisions they employed to achieve them. We classified objectives reported by farmers into categories.

(ii) Farmers' constraints: We characterised the on- and off-farm constraints that affect cropping-plan decisions by accessing farmer knowledge representations. In the field of knowledge engineering, accessing knowledge representation involves analysing the abstraction that farmer uses to accurately and effectively make decisions within his environment (see chapter 25 in Harmelen et al., 2008). We carefully allowed free rein to evoke factors that could not be identified in advance

Table 2
Definitions of concepts related to crop sequence pattern to describe crop succession on plots.

Concept	Definition
Crop sequence	The order of appearance of crops on the same piece of land during a given period (Leteinturier et al., 2006).
Crop rotation	A sequence of plant species grown on the same land (Bullock, 1992), characterised by cycle periods (Leteinturier et al., 2006); it is a specific crop sequence.
Crop succession	One crop following another on the same piece of land, often characterised by preceding and succeeding effects.
Crop in sequence	The specific position of a crop within a crop sequence, characterised by the crops preceding and succeeding it.

by choosing open discussion over close-ended questions. We complemented questions with various media (e.g. farm map, warning bulletin for irrigation from agricultural services) to efficiently collect data and facilitate knowledge elicitation.

(iii) Decision-making process analysis: We characterised farmer strategies by studying how sequences of decisions leading to an individual cropping-plan choice were structured in time through strategic and tactical decisions. Farmers were asked about the way they made decisions, the information they used and which activities they undertook when a decision was made. We determined annual and long-term sequences of decisions and characterised planning strategies. We supplemented interviews with past scenarios on climate, prices and water regulations adapted to each regional context to stimulate farmers to evocate the range of possible decisions for adapting to various situations.

2.3. *Data analysis*

Farmer decisions are usually classified as operational, tactical and strategic decision-making, with an increasing time horizon for the decision and decreasing availability of relevant information (Le Gal et al., 2011). We analysed strategic and tactical decisions that were related to cropping-plan choices.

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 farmers' strategic decisions, we characterised their planning strategy by identifying and formalising the concepts they used to make strategic decisions.

In time: We defined the concept of *crop sequence pattern*, to describe the concepts that farmers use to plan crop succession over time (Table 2). Formalisation of the *crop sequence pattern* as a directed graph (Fig. 1) allowed comparison and quantification of the temporal dimensions of different planning strategies (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. In our approach, nodes are *crops in sequence* (Table 2), the edges characterised the *crop succession* (see Table 2). We built the direct graphs using the R package *graph* (R Development Core Team, 2011; Gentleman et al., 2011). Using an algorithm dedicated to graph analysis, we calculated different indicators of *crop sequence patterns*:

- length: The length of a crop sequence pattern corresponds to the maximum length of the graph. It refers to the number of years ahead that farmers plan their cropping.
- cyclic: If a *crop sequence pattern* graph is closed, it is considered cyclical, which means that the number of years of advance planning is essentially undefined. When the graph was closed, we also calculated the rotation length (Castellazzi et al., 2008).
- flexibility: If a crop sequence pattern graph has multiple paths, it is considered flexible, which means that farmers keep some options open while planning their cropping plan. Multiple paths exist when nodes have at least two out-going edges (b, Fig. 1). These nodes refer to *sequence decisions* that farmers must solve to complete planning.
- *sequence decision* number: The number of nodes with at least two outer edges (b, Fig. 1).
- substitutable crops: For each *sequence decision*, the crops that are considered in the decision are called substitutable crops.

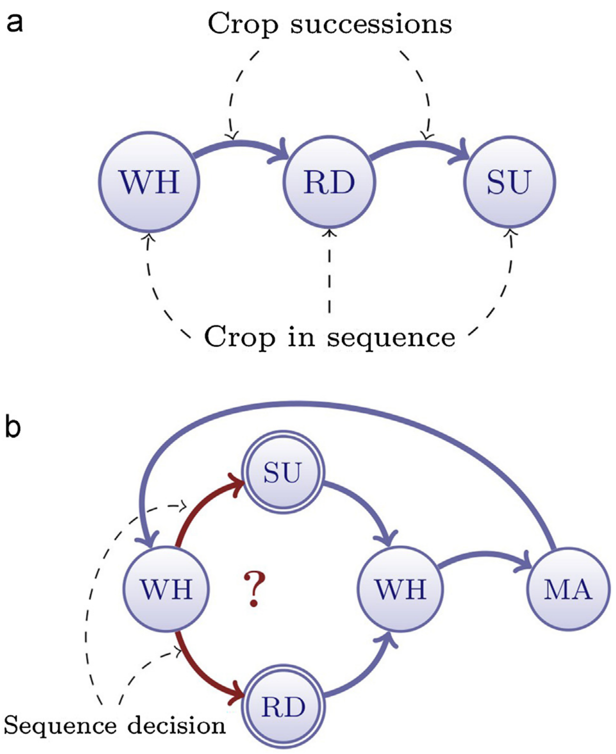


Fig. 1. Example of *crop sequence patterns* and related concepts represented as directed graphs and their indicator: (a) flexibility: false, length: 3 years, cyclical: false, sequence decision: 0; (b) flexibility: true, rotation length: 3 years, cyclical: true, sequence decision: 1. In *crop sequence pattern* (b), the crop WH is present twice, but refers to two different *crops in sequence* since they do not have the same preceding and succeeding crops. Also in *crop sequence pattern* (b), the crops SU and RS are planned as *substitutable crops* because of decision options. In *crop sequence pattern* (a) crops SU and RD are not substitutable. [WH: winter wheat, RD: rape seed, SU: sunflower, MA: maize, ?: sequence decision, ○ : substitutable crops].

2.3.1.1. *In space.*

We characterised the way farmers integrate space as a decision factor using the concept of management units. These management units are defined by farmers to allocate resources and equipment and to organise work through the choices of crops to be grown and their management techniques. Prior to the interview, we collected spatially explicit data at the Common Agricultural Policy (CAP) islet and plot levels from "Land Parcel Identification Systems" (LPIS) from 2005 to 2009. These materials were used to supplement and mediate interviews with maps and aerial photography to locate soil types, management units, water access points and other factors affecting cropping-plan choices. To study the spatial dimension of farmers' cropping-plan decision-making, we drew relations between farmers' decisions and the management units they considered when setting their cropping plan (Table 3).

Table 3
Definition of the management units in the study.

Concept	Definition
Irrigable area	Farmland area with access to irrigation.
Irrigation block	An area irrigated by a single set of equipment, with constraints on water amount and flow rate (Bergez et al., 2001).
Plot	A continuous piece of land belonging to the same farm with homogeneous annual crop management. Its boundaries can change over time.
Crop-management block	A set of plots defined by a cropping system (Sebillotte, 1990; van Ittersum and Rabbinge, 1997; Aubry et al., 1998b), i.e. one crop sequence pattern with consistent production techniques (e.g. fertilisation, irrigation).
CAP islet	The Land Parcel Identification System (LPIS) was designed as the main instrument for the implementation of the CAP first pillar, i.e. to identify and quantify the land eligible for direct payments. The CAP islet is the land unit reference used by farmer to declare land use. It can be defined as contiguous plots belonging to the same farm and bounded by easily identifiable and permanent landscape and/or administrative features, such as paths, roads, streams and other farms. Its boundaries are fixed over long periods.

Table 5
Main objectives of farmers ($n = 28$) that drive cropping-plan decision-making.

Category	Desires (objectives)	Responses
Income	Secure – good	20
	Increase – maximisation	14
Workload	Decrease – minimisation	10
	Spread over 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
	Crops requiring technicality (vegetable)	1
Environment	Increase biodiversity	1
	Input minimisation	1

2.3.2. Tactical decisions

Using the critical decision method (Hollnagel, 2003; Hoffman and Lintern, 2006), we elicited from farmers their decision sequences for cropping plans they make for the whole year before spring sowing. The critical decision method is used for eliciting expert knowledge and decision strategies. It is based on a retrospective interview that allows to build a comprehensive, detailed, and contextualised account of decisions. We formalised individual farmer decision sequences as a standard flowchart in the form of Unified Modelling Language (UML) activity diagrams. UML is a standardised object-oriented modelling language in the software-engineering field (Booch et al., 2000; Papajorgji and Pardalos, 2006). These diagrams provide a simple means to capture the decision-making process. Activity diagrams provide more efficient representation than simple task diagrams or decision trees. Descriptions of decisions were always made in relation to the information and uncertainty underlying the problems to solve (Hardaker et al., 1991). We also differentiated planning of new decisions from adaptation of decisions made previously. Farmers were always asked to justify reasons that motivated adaptation decisions in relation to factual change in the environment.

3. Results

3.1. Farm characterisation

From the 30 farms initially surveyed we retained 28 arable farms in the analysis (MiPy = 9, PCh = 9, and Ce = 10). The remaining two were withdrawn because they were mixed farms whose cropping-plan decision-making was driven mainly by animal-feed production. The sample represents a great diversity of irrigated arable farms in the three regions (Table 4).

Altogether, farmers grew 29 different crops, with cereals covering approximately 2/3 of their farming area. The main crops were maize (26% of the area), winter wheat (23%), rapeseed (11%), durum wheat (9%), sunflower (7%) and fallow (7%). Farmers grew a mean of 6.7 (standard deviation = 1.9) 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 4). Crop diversity was higher in the Ce region, where crops, such as sugar beets, potatoes and open-field vegetables are usually grown under contracts. In this region, irrigation was concentrated on these crops with high and secure returns, unlike the other two regions, where irrigated areas were sown mainly with maize.

All farmers reported income as the main objective for their farms (Table 5). Only one farmer mentioned profit maximisation as the sole criterion; 20 first sought adequate and secure income rather than profit maximisation at any cost. Twenty farmers mentioned the desire for income security, but it was associated with diverse actions: increasing crop diversity with crop rotation (10/20), searching for robust cropping plans (5/20), securing crop sales (contracts and cooperatives) (5/20) and/or decreasing input costs (4/20). The desire to increase and/or maximise income was associated mainly with the search of market opportunities and contracts (8/14). The second motivation for 42% of the farmers was workload management, mostly a simplification of their crop production systems (10/12).

3.2. Sequence of problem solving

Most farmers use two distinct types of decisions in their decision-making process: planning and adaptation. The former entails making a cropping-plan choice (or partial choice) for the future, while the latter entails changing an existing plan. Planning occurred in both strategic and tactical phases of the decision-making process, while adaptation occurred only in the tactical phase.

Table 4
Mean (and standard deviation) values of key variables describing farms surveyed in the Centre (Ce, $n = 10$), Midi-Pyrenees (MiPy, $n = 9$) and Poitou-Charentes (PCh, $n = 9$) regions for the period 2005–2009.

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

[a] Simpson index:, $D = 1 - \sum_i^s p_i^2$ where p_i is the proportional area of the ith crop. Its value ranges from 0 to 1, with higher values indicating greater crop diversity.

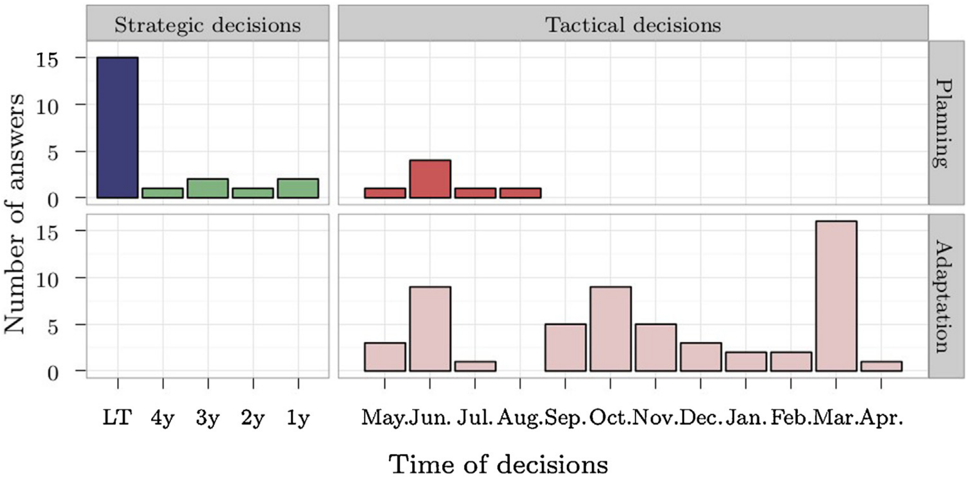


Fig. 2. Type and timing of cropping-plan decisions. Decisions are categorised as planning or adaptation, and the former are identified by the amount of time in advance they are made. [🟦 LT: long-term planning >4 years, 🟩 4–1 y: number of years of advance planning, 🟥 : number of planning decisions per month, ◻ : number of adaptation decisions per month].

3.2.1. *Planning decisions*

At the farm scale, 53% of farmers had stable cropping-plans over time and not seek changes (Fig. 2). They justified stability by using long crop rotations or long-established mono-cropping or simply by feeling satisfied with their current cropping plan. Twenty two percent of the farmers looked between 1 and 4 years forward when developing their cropping plans. Twenty five percent reported that they plan their cropping within the year of cropping. These farmers usually do not have a fixed plan for their cropping plan and annually reconsider the crops to be grown.

At the crop management block scale, based on the number of crop sequence patterns reported, farmers had a mean of 2.7 cropping systems per farm (Ce: 2.1, MiPy: 2.5, PCh: 3.5). Most farmers (57%) used several types of crop sequence patterns (Fig. 3) to design their cropping systems. Only a few farmers ($n = 2$) used one type of crop sequence pattern to design all their cropping systems (e.g. only crop rotation). The main differences between the three regions are as follows:

3.2.1.1. Centre. 80% of the farmers set up crop rotations on both irrigable and rain-fed areas. Rain-fed cropping systems were based on winter wheat (59% of rain-fed area) and were routinely applied to provide secure income. The use of crop rotation on an irrigated area was explained by the inclusion of specific irrigated crops, such as open-field vegetables (e.g. onion), potatoes, peas, and sugar beets. These crops, even when grown on small areas, were of particular economic importance because they were mostly grown under contracts (e.g. sugar beet) or intended for niche markets (e.g. onion). All of these crops have a long return period (e.g. potato: 5 years, sugar beet: 6 years, peas: 6 years) and compelled farmers to plan their cropping far ahead of time (4.1 years, on average), justifying long rotations on irrigable areas. Despite using long rotations, crop sequence patterns were kept flexible by integrating adaptation options (2.8 *sequence decisions*, on average, into the crop sequence patterns). Area of irrigated maize was used as a variable to adjust irrigation water availability.

3.2.1.2. Midi-Pyrenees. 75% of the farmers combined two crop sequence patterns when planning, mostly mono-cropping on irrigable areas and crop rotation on rain-fed areas. Irrigable areas were mostly planted with maize (62% of the irrigated area). A few farmers retained some flexibility for an irrigated area by introducing other irrigated crops such as winter wheat (10% of the irrigated area), soya bean (9%) and sunflower (6%). These crops were often grown under

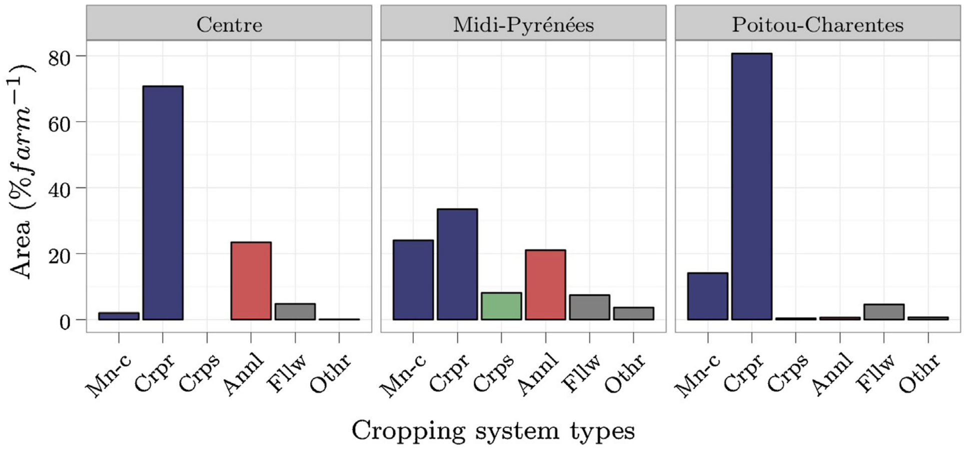


Fig. 3. Frequency of crop sequence patterns that farmers in the Centre (Ce, $n = 10$), Midi-Pyrenees (MiPy, $n = 9$) and Poitou-Charentes (PCh, $n = 9$) regions used to design their cropping systems. [Mn-c: mono-cropping, Crpr: crop rotation, Crps: crop sequence, Annl: no planning, Fllw: fallow, Othr: Others, colours refer to the advance timing of the decision, 🟦 : long-term planning, 🟩 : ≥4 and >1-year planning, 🟥 : ≤1-year planning]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

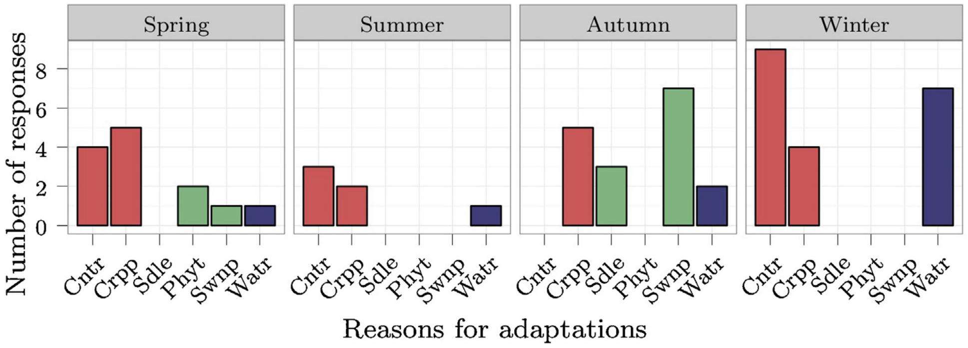


Fig. 4. Reasons that motivate changes from planned cropping plans during the year and the season during which those changes occur. Values indicate the number of times that farmers mentioned the factor when describing their decision-making processes [🟥 : economic context, Cntr: crop contracts, Crpp: crop price, 🟩 : agronomic reasons, Sdle: seed-emergence issues, Phyt: field state, weed and pest issues, Swnp: sowing ability, 🟦 : resources, Watr: availability of irrigation water].

contract for seed producers. 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-year-long crop rotation with no adaptation options.

3.2.1.3. Poitou-Charentes. This region had a higher number of cropping systems per farm (3.5, on average). This was due to a combination of spatial, agronomic and resource factors: (i) the relatively high number of plots compared to the other regions (Table 4) and their spatial distribution (mean distance between the homestead and plots was 4.1 km in PCh, compared to 2.1 and 2.6 km in Ce and MiPy, respectively); (ii) contrasting soil types with varied agronomic features; and (iii) limited and non-secure irrigation water availability. Seventy-eight percent of farmers reported having limited and non-secure access to irrigation water (60% and 38% for Ce and MiPy, respectively). Eighty-eight percent set up at least one irrigated mono-cropping system of maize and one rain-fed crop rotation, and 77% had more than one crop rotation. The maize mono-crop maximised water-use efficiency on the secure volume of water. The most important differences between crop rotations designed on irrigable and rain-fed areas were the number of planned adaptation options. Farmers mentioned no adaptation options while planning crop rotations on rain-fed areas but mentioned a mean of 2.8 adaptation decisions per crop-rotation plan on irrigable areas. These options were specific to soil types.

3.2.2. Adaptation decisions

An important outcome of the cognitive task analysis was that all farmers had a clear plan of the sequence of problem solving they face during the year. However, these plans differed from farm to farm. Although most farmers reported seeking cropping-plan stability, all but one mentioned at least one reason that leads them to adapt their initial cropping plan during the year. Some adaptation options were included during the planning phase of cropping systems by the use of flexible crop sequence patterns; some were included only during the year before sowing. Stated reasons (Fig. 4) were always linked to uncertain factors related to the market (contract 29%, crop price 29%), climate (water availability 20%, field accessibility for sowing 14%) or agronomy (seedling emergence, weed and pest issues 9%).

We analysed the crop successions planned in the crop sequence patterns that farmers used for their cropping plans and compared them with their actions during the 2005–2009 period (Fig. 5). For 71% of the farmers, changes from the initial plan, which did not

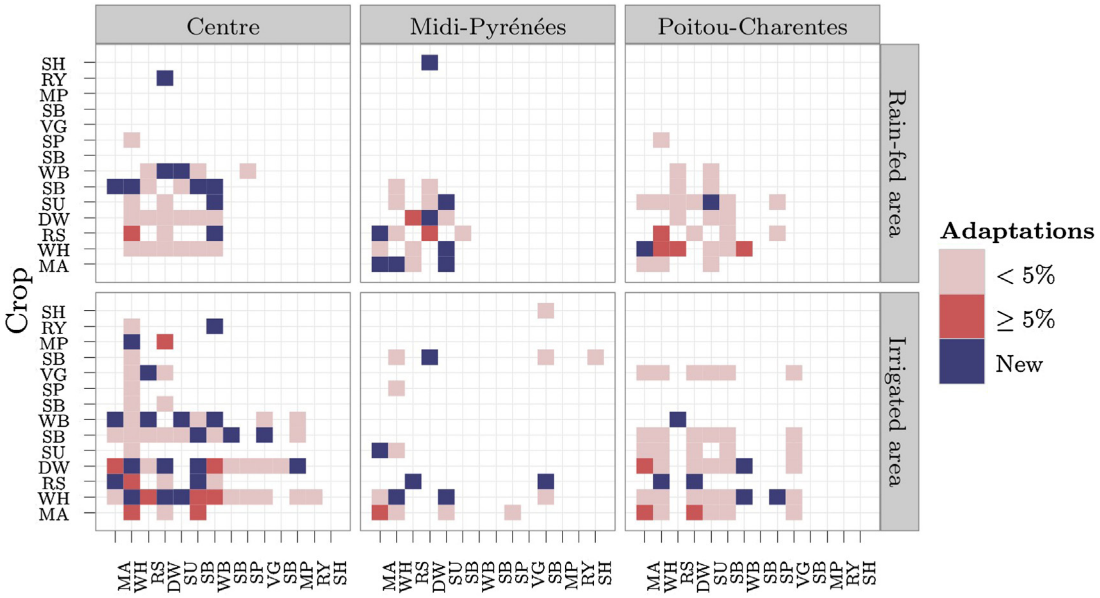
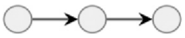
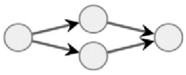
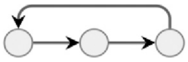
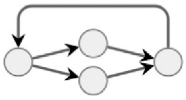
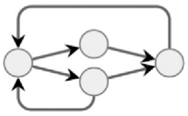


Fig. 5. Adjacency matrix depicting planned vs. observed crop successions over the period 2005–2009. Crop successions are differentiated by region (Ce: Centre, MiPy: Midi-Pyrenees, PCh: Poitou-Charentes) and irrigable vs. rain-fed areas. Crops are on the *y*-axis and succeeding crops on the *x*-axis. Observed planned crop successions are in shades of red, covering an area either >5% larger (🟥) or <5% larger (□) than that planned. Observed unplanned crop successions are in blue (🟦) [MA: maize, WH: winter wheat, RS: rape seed, DW: durum wheat, SU: sunflower, SB: spring barley, WB: winter barley, SB: sugar beet, SP: spring pea, VG: vegetables, SB: soya bean, MP: medicinal plant, RY: rye, SH: sorghum]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Table 6
Crop sequence pattern types, providing formal representation of all planning strategies of the surveyed farmers at the crop management block scale.

Category	Name	Characteristic			Graph scheme
		Flexibility	Cyclic	Length (years)	
Crop sequence	Simple sequence	Fixed	False	≥2	
	Flexible sequence	Flexible	False	≥2	
	Adaptive sequence	Flexible	False	1	
Crop rotation	Simple crop rotation	Fixed	True	≥2 =rotation length	
	Flexible crop rotation	Flexible	True	≥2 =rotation length	
	Very flexible crop rotation	Flexible	True	≥2 variable rotation length	
Mono-crop	Mono-crop	Fixed	True	1	

occur every year, usually concerned only a small portion of the cropping area and crops with high profitability (e.g. contract, market opportunity). All planned crop successions in the crop sequence patterns were found during the 2005–2009 period. Farmers usually respected their planning strategies, as the difference between observed and planned areas was less than 5% of the planned area for most crops. This small difference was explained mainly by the slightly different areas of plots involved in the same rotation.

In all regions, maize crops were involved in differences higher than 5% of the planned area because maize was used as a buffer crop for adapting irrigated areas to irrigation-water availability. Some cropping-plan adaptations resulted in unplanned crop successions, which farmers mentioned were not always compliant with agronomic rules. Indeed, farmers have to consider a much broader systems than cropping systems while making cropping-plans decisions. As a result, agronomic considerations are not always the most decisive factor of choice. Unplanned crop substitutions were justified by farmers for several reasons: potential outcomes (prices, contract opportunities), resource requirements (water) and crop functions in crop sequence patterns (weeding effects). Unplanned adaptations (e.g. reducing maize area, receiving a contract for a new crop) often resulted in the adjustment of management unit boundaries.

3.3. *Formalisation of spatial and temporal interactions of cropping-plan decision-making*

3.3.1. *Planning phase*

Because of uncertainties, cropping plans cannot be definitively decided at the strategic level. Farmers anticipated the variability of uncertain production factors by using a mix of crop sequence patterns when designing cropping systems. From the case study results, we classified crop sequence patterns to describe the diversity of strategies that farmers used to plan the succession of crops over time (Table 6). At this strategic level, developing a cropping plan consists of designing cropping systems from different crop sequence patterns to allocate crops and resources to the land. Cropping system design required farmers to simultaneously delineate management units and plan crop successions as crop sequence patterns (Fig. 6). Farmers' freedom to delineate boundaries of management units depended on farmland characteristics and heterogeneity. We propose three types of crop sequence patterns to describe farmers' strategies:

1. Robust cropping system: Usually in the form of secure crop rotation (e.g. (1) in Fig. 6) or a long-established mono-cropping system (e.g. (2) in Fig. 6).
2. Flexible cropping system: Planning flexible crop sequence patterns in which substitutable crops are identified beforehand (e.g. (3) in Fig. 6). These strategies are complex to develop but allow planning of temporal agronomic interactions.
3. Adaptive cropping system: Delaying cropping-plan decisions for as long as possible. Crop choices were made yearly. These cropping systems are suitable for changing contexts (e.g. market opportunities, resources) but make it difficult to anticipate temporal interactions between crops in plots (e.g. return period, previous effect).

Crop successions were usually planned around main crops that formed the core of the crop sequence patterns. These crops were chosen based on economic concerns (e.g. margin and return security) and on their feasibility on the farm (e.g. equipment, farmers' skills, suitable soil types). Surface areas of the main crops were usually as large as possible but were limited, as were their positions in the crop sequence pattern, by spatial constraints: structural and biophysical constraints of management units, agronomic constraints (return period) and resource availability (water and work). Choices of other crops usually conformed to crop-succession rules and often had agronomic functions, such as taking advantage of temporal interactions between crops in crop sequence patterns (e.g. succeeding and previous effects) or managing spatial interactions between cropping systems (e.g. spreading the workload over time, flexible water management). Because some of these functions were associated with uncertain factors (e.g. contracts, field states), some farmers introduced flexibility to delay decisions by planning several options in their crop sequence pattern to anticipate a variety of situations.

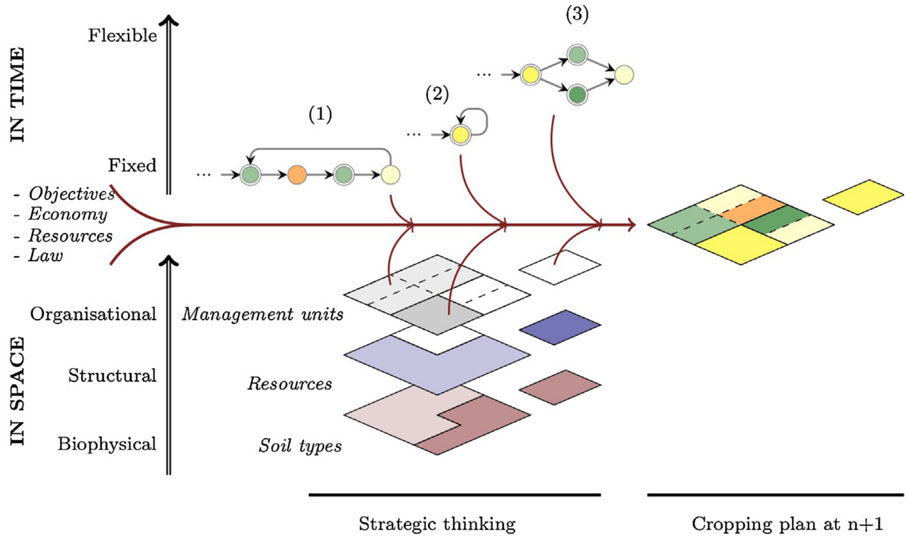


Fig. 6. Interactions (⟶) between spatial and temporal dimensions during the strategic cropping-plan decision-making process. Strategic cropping-plan decisions combine planning decisions by allocating *crop sequence patterns* at the *crop management block* level (IN TIME) with a multi-scale spatial organisation of the farmland into *management units* to account for different constraints (IN SPACE). This strategy considers farmers' objectives, the socio-economic context, resource availability and farm features. Vertical arrows (🡅) represent increasing flexibility. Over time, farmers can decide to switch from a fixed to an adaptive crop sequence pattern for planning crop successions. In space, farmers have to consider several scales of biophysical and organisational constraints. [(1) simple rotation; (2) mono-cropping; (3) flexible sequence; main crops: ○, previous crop:. . .→].

3.3.2. *Adaptation phase*

Adaptations to the initial cropping plan can affect delimitation of planned management units differently (Fig. 7). We categorised effects of cropping-plan adaptation decisions on management units into three groups:

1. Crop substitution: The replacement of one crop with another without affecting management unit boundaries, it can be planned into flexible crop sequence patterns ((1) in Fig. 7) or result from unanticipated situations ((2) in Fig. 7).
2. Adjusting management unit boundaries: Adjustment may occur between plots within the same cropping system ((4) in Fig. 7) or within different cropping systems ((5) in Fig. 7). Adjustment of management unit boundaries adapts crop area to resource availability (irrigation water) and/or crop-price variations.
3. A combination of the first two: Sometimes the introduction of new crops requires adjusting the management unit boundaries ((3) in Fig. 7). This type of adaptation occurs with contract opportunities for specific crops with a high return and which require a small area (e.g. onions).

4. Discussion

4.1. *The cropping plan emerges from cropping system design*

Planning is a forward-looking concept and is intimately linked with decision-maker strategies. The decision maker arranges resources strategically so that chances of reaching objectives are

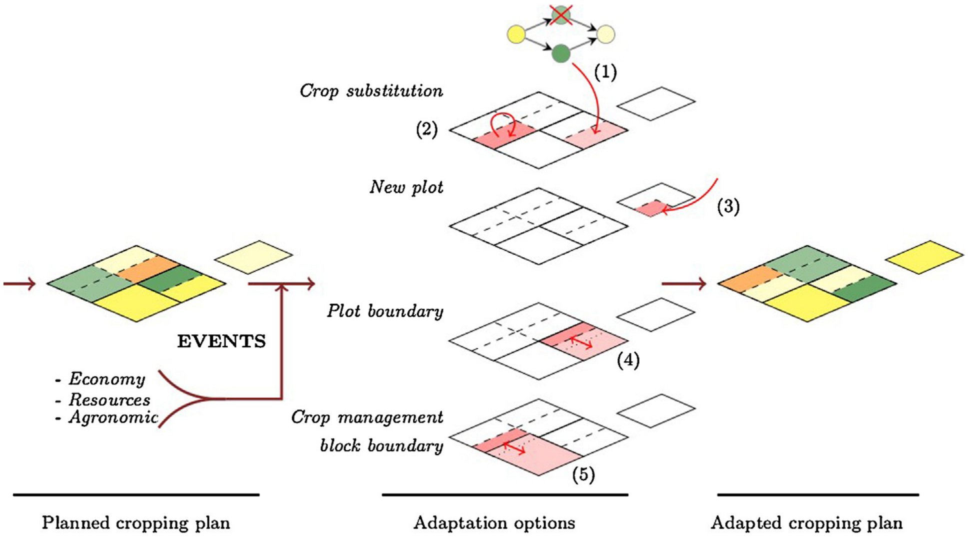


Fig. 7. Effects of cropping-plan adaptations (▨) on management unit boundaries [*plot* boundaries:, *crop management block* boundaries:]. The adaptations are responses to external events (e.g. changes in price, water quota, or regulations) and can have different consequences on management units: (1) planned or (2) unplanned substitution of crops for which boundaries do not change, (3) introduction of new plots, (4) changing plot sizes within a crop management block and (5) changing crop management block sizes.

improved. The farmers' objectives sometimes competed with one another, and cropping-plan decision-making was necessarily a trade-off between heterogeneous objectives and constraints. As already argued by Nevo et al. (1994) and Aubry et al. (1998a,b), we demonstrated that representing cropping-plan selection as only a problem of resource allocation (e.g. Annetts and Audsley, 2002; Itoh et al., 2003) or crop rotation design (e.g. Dogliotti et al., 2004; Bachinger and Zander, 2007) is not sufficient to account for the need for problem solving that farmers face (Ohlmer et al., 1998).

To understand the cropping-plan decision-making process, we described strategies that drove farmers' production choices. We demonstrated that cropping-plan decision-making was intimately linked to the design of cropping systems and their spatial allocation within farms. Aubry et al. (1998a,b) and Navarrete and Le Bail (2007) previously proposed this idea in a modelling approach, in which cropping systems emerged from the iterative allocation of crops hierarchically sorted according to a set of resource constraints (e.g. soil, water, equipment) and crop sequencing rules (e.g. return time, preceding crop). Unlike Aubry et al. (1998a,b), however, we identified several strategies between and within farms to design cropping systems.

In the same way that crops fulfil different functions within crop sequence patterns (Bullock, 1992; Leteinturier et al., 2006; Castellazzi et al., 2008), cropping systems have different functions in farmers' strategies. Functions associated with cropping systems included (1) optimising resource use (e.g. water, labour), (2) taking advantage of farmland heterogeneity (e.g. soil type), and (3) seeking stability and/or flexibility in uncertain production factors (e.g. economic, water, agronomic).

4.2. Planning and adaptive activities

It is acknowledged 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 to adapt to changing contexts (e.g. Kein Haneveld and Stegeman, 2005). At the other extreme, farmers that allocate crop area every year respond better to changing contexts but do not consider interannual interactions between crops (e.g. Dogliotti et al., 2004). However, few farmers in our study followed these two extreme strategies.

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

- The crop sequence and crop rotation length that we identified must be seen as the time horizon over which a farmer makes a plan rather than a time step at which strategic decisions were made. Thus, strategic decisions are more plausibly a partial and continuous redesign of existing cropping plan rather than a design of all activities from scratch. This implies that the representation of cropping-plan decision-making processes must consider past cropping systems, with their underlying design consistency. Cropping systems are not built *ex nihilo*.
- Although certain adaptation options were planned by farmers by considering uncertainty in production factors, some were unplanned. This indicates that either we did not completely capture the complexity of farmers' decision-making processes or farmers made some unplanned decisions to respond to unanticipated situations and/or market opportunities. Such unplanned behaviour was difficult to understand and therefore to describe in a formal manner.

4.3. Uncertainty and cropping-plan decision-making process

Uncertainties are significant features of agricultural production and play an key role in almost every important agricultural decision (Chavas and Holt, 1990; Hardaker et al., 2004). Analysis and understanding of the farmer decision-making process is intimately linked to the goal of understanding individual attitudes towards uncertainty (Dorward, 1999). Therefore, descriptions of decision sequences were a starting point to understand how uncertainty impacts cropping-plan decision-making. In this analysis, we confirmed that deciding under uncertainty is more than considering the probability of future events occurring. Making decisions in complex and dynamic environments also concerns strategies, information processing (Chavas, 2004) and adjustment responses (Dorward, 1999) to the "embedded" risk (Hardaker et al., 1991).

4.4. Modelling perspectives

Representing farmers' decision-making processes is becoming a critical issue in agricultural modelling (Le Gal et al., 2011; Bergez et al., 2010; Nuthall, 2010; Akplogan et al., 2011). This paper provides formal and generic concepts to describe spatial and temporal dimensions of farmers' cropping-plan decision strategies at strategic and adaptive levels. We find similar articulation between space and time in cropping plan decisions in other farming systems that irrigation crop farms as shown by Aubry et al. (1998a,b) in rain fed crop farms, and by Navarrete and Le Bail (2007) and Mawois et al. (2012) for gardeners.

Crop sequence patterns have been represented as graphs in previous modelling studies of farming system flexibility (Rodriguez et al., 2011). The same concept could be used in a decision modelling approach to represent farmers' knowledge and structure decision factors in a comprehensive way. Development of decision-support tools based on modelling how farmers make cropping-plan decisions could enable researchers to provide knowledge and tools to improve decision-making at specific stages of the decision process (Cox, 1996; Bacon et al., 2002; Sorensen et al., 2010).

5. Conclusions

This study demonstrated that a cropping plan does not emerge from a single decision but is a dynamic decision-making process, incorporated into a succession of other decisions. Although the timing of decision-making leading to the cropping plan differs from farm to farm, we demonstrated that several common features drive the spatio-temporal dynamics of decision-making. We developed a formal representation of the main concepts to describe spatio-temporal interactions that farmers consider when designing cropping plans. These formal concepts can be used to develop models that address cropping-plan choices at the farm level.

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