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Mining crop sequence patterns at a large regional scale: A case from mainland France

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Chapter I General introduction

1. General background

Agroecosystems are highly human-managed ecosystems that are designed to provide food, forage, fiber, bioenergy and pharmaceuticals. Traditionally, they have been considered primarily as sources of provisioning services, but more recently their contribution to various types of ecosystem services have been recognized. They are both providers and consumers of ecosystem services (Power, 2010). The challenge of agriculture in the 21st century requires an integrated and systemic approach that address sustainable use and management of natural resources through development and adoption of farming technology and management practices that will ensure food security and agricultural livelihoods (Fischer et al., 2002).

Agriculture is the dominant form of land management globally and it covers nearly 40% of the land surface of the Earth (FAO, 2013). It has been the greatest force of land transformation on this planet. Much of agricultural land has been created at the expense of natural forests, grasslands, and wetlands that provide valuable habitats for species and valuable services for humankind (Lambin and Geist, 2006). The expansion of cropland (approximate 12% increase in total areas) and "Green Revolution" after World War II (WWII) resulted in doubling the world grain harvests in the past four decades (Foley et al., 2005). Grain production, mainly from wheat, rice, and maize, has increased at a rate greater than human population in the past 35 years (Tilman, 1999). There has been a global trend toward specializing and intensifying farming systems for producing more food since the 1960s (Havet et al., 2014).

Despite the success of modern agriculture in increasing food production, agriculture has caused major global environmental impacts, e.g. degrading water and soil quality, declining in biodiversity, losing native habitats and habitat fragmentation for wildlife, and representing about one-quarter of global greenhouse gas emissions (Foley et al., 2005; Tilman et al., 2011; Nair, 2014). The main environmental impacts of agriculture come from the conversion of natural ecosystems to agriculture, from agricultural nutrients that pollute aquatic and terrestrial habitats and groundwater, and from pesticides, especially bioaccumulating or persistent organic agricultural pollutants (Tilman et al., 2002). Agricultural technologies and agricultural, environmental and rural development policies are increasingly designed to contribute to the sustainability of agricultural systems and to enhance contributions of agricultural systems to sustainable development at large (van Ittersum et al., 2008).

In most states of Europe, agriculture plays a small and declining role in employment and in gross domestic product (GDP) but it is the largest land user, accounting for 43% of the land area (Eurostat, 2010), and plays an important role in various environmental and land use issues (OECD, 2011). Van Zanten (2014) indicated that intensification and scale enlargement of agriculture which was initially driven by the widespread use of synthetic fertilizers, mechanization and production incentive of the European Common Agricultural Policy (CAP) have modified agricultural landscape across Europe after WWII. Agricultural intensification has been a feature of arable systems in both northern and southern Europe, while in the southern, abandonment of arable and livestock systems has been an additional threat to agroecosystems (Pinto-Correia, 1993; Stoate et al., 2001). The environmental impacts of agricultural intensification in Europe have been noticed during the past decade (Stoate et al., 2001; Robinson and Sutherland, 2002). The environmental consequences of agricultural abandonment have been also notable in both research community and society (MacDonald et al., 2000).

Agricultural policy is one of the most important and huge policy fields at European Community (Piorr, 2003). The CAP has an important role to play in achieving a balance of farming to maintain a sustainable environment against putting the environment at risk. Two major reforms of the CAP in the 1990s have taken increasingly into account the importance of the environmental dimension of farming (European Commission, 2003). Some specific measures within 1992 CAP reform to encourage environmentally friendly farming were enacted, for example, the agri-environmental regulation, the introduction of extensification premiums paid to beef producers claiming payments for low cattle stocking densities, and the introduction of a mandatory set-aside scheme. The 1999 CAP reform that was part of the Agenda 2000 package pursued these initiatives further via two pieces of legislation: “horizontal regulation” requires to taking account into the environmental aims in the implementation of first pillar measures and a now regulation on support for rural development as Pillar 2. Moreover, Member States were also required to set out codes of good farming practices (GFP) in their rural development plans (European Commission, 2003; European Communities, 1998). These environmental measures have experienced varying degrees of success in terms of their adoption by farmers, with inadequate funding, resistance to long-term obligations, and reluctance to abandon traditional practices being given as reasons for low adoption (Stoate et al., 2001). After the 1990s, globalization of commodity markets and successive CAP reforms drove a further intensification and scale enlargement, and land abandonment in less favored areas (van Zanten et al., 2014). The 2003 CAP reform introduced Single Payment Scheme and “cross-compliance” as a condition for receiving full payments. Decoupling of direct income payments was aimed at removing production incentives, which could have damaging environmental consequences (European Commission, 2003).An excellent summary on the ecological impacts of agricultural systems in the new policy context i.e. 2003 CAP reform and 2009 Health Check can be found in Stoate et al. (2009).

Furthermore, changes in the policy also had impacts on relative incentives to commodities and thus on land use allocation. In the early years of the establishment of the CAP, the CAP promoted production of major grains, livestock and milk through a system of market interventions. This had the effect of drawing land from other arable uses into the production of these commodities. CAP reforms in 1990s removed much of the market interventions promoting crops, replacing them with area payments for cereals, oilseeds and protein crops (COP). Because of group of commodities and higher oilseed payment per hectare, the overall effect of the policy was to draw land into production of supported grains and oilseeds from other arable uses until around the year 2000. In the following section, we will review the development of agriculture and agricultural land-use change in Europe (Western Europe only) in the context of common agricultural policy launched in 1962. Our special focus will be on the changes in the structure of agricultural holdings and in the proportion of areas under different crops of total arable land which are detected using historical agricultural statistics.

2. Agriculture in Europe

2.1 Overview of evolution of agriculture since 1960s

From 1960 to 1980, the utilized agricultural area (UAA) in the European Community (EC) decreased from 101.3 million hectares to 93 million hectares (European Community, 1981). The main feature of European agriculture over the 20 years has been the steady rise in production, with an annually by 1.9% on average in the six original Member States of the Community (Belgium, France, Germany, Italy, Luxembourg and the Netherlands). Use of inputs (e.g. purchases of feedingstuffs, fertilizers, pesticide, energy and service) has risen very significantly (increased by 60% in terms of volume over a 20-year period). For the farm structure, the number of farms was decreasing during the 20 years while the average area per farm has shown slight increase (rising from 10.1 in 1966 to 12.1 hectares UAA in 1983). Farms with 50 hectares or more possessed much more land than 20 years ago. For the final production, cereals represented 14% of European agricultural production in 1985 and the most common type of crops was cereals. Of the various cereals grown, wheat was the most common and provided 44% of the total tonnage of grain harvested. The importance of maize has increased slightly, accounting for 14% of the cereals' harvest in 1985. Although the rapid expansion of oilseed-growing during the period 1964-1985, oilseeds were still to be a marginal crop in Europe and represented only 1.5% of agricultural production in 1985 (European Community, 1987). As a result of the increase in agricultural production, by the 1970s, the EC was self-sufficient in key sectors (e.g. cereals) and in some sectors (e.g. dairy production, beef), was moving into surplus (European Community, 1980; European Commission, 1998). However, environmental damage caused by agriculture increased as well and is usually imputed to high intensity levels of modern agriculture (Stoate et al., 2001; Herzog et al., 2006).

Since 1990s agricultural land-use and arable land areas have followed a similar declining trend in the European Union (EU). As a result, at the end of the 2000s they were about 10% lower than in 1990 (OECD, 2011). In the EU-15, the proportion employed population in agriculture has continued to decline from 4.5% in 1999 to 4.0% in 2003. The number of farms decreased in all countries of EU-15 (except Greece and the United Kingdom between 1995 and 2007) while the average size of UAA per holding increased correspondingly (18.4 hectares in 1997). The share of farms with more than 100 hectares increased significantly in some countries between 1990 and 2007. In many EU-15 countries, around 40% of farms were between 20 and 100 hectares. The growth of the average standard gross margin (SGM) during the period 1975-97 for EU-9 was evident (increased from 6.8 European size units (ESU) to 21.6 ESU in 1997). On average, a third of farm holders in the EU-15 were over 65 years of age in 2007, and this proportion has been increasing since 1995 on average and in most countries. Cereal yields have increased until 1998 and have fluctuated since then a flatter trend. Milk yields have also increased in most member states and the growth has in general been more significant than that of cereals over the last 25 years (OECD, 2011). The growth in the volume of both crop and livestock production has slowed in the 2000s compared to the previous decade and has become negative in a number of them. This general movement is more pronounced after 2004 (OECD, 2011).

Moreover, for the type of tenure, in EU-6, two thirds of the UAA was given over to owner-occupied farms and one third to tenant farms in 1970. Between 1970 and 1997, there was a steady increase in tenant farming at the expense of owner-occupied farming. In 1997, the ratio of the UAA farmed by owner-occupied holdings fell to almost 47% and tenant farms became the most common type of agricultural holding (European communities, 2000a).

2.2 Monitoring agricultural land-use change in Europe using agricultural statistics

The decrease in the UAA in EU-6 (disregarding Germany unification) was accompanied between 1967 and 1997 by a reduction in permanent pasture and meadow (- 27%) and permanent crops (- 17%), whereas arable land increased (+ 4%). The expansion of arable land in EU-6 was particularly marked between 1987 and 1997. The area of arable land per holding more than doubled in EU-6 (rising from 6.7 hectares in 1967 to 17.0 hectares in 1997) (European communities, 2000a).

The percentage of arable land used for different crops has changed a lot during the period 1970-2000. The share of area under cereals in total arable land increased between 1966 and 1980 and peaked in 1980. There was then a steady contraction until 1993, promoted both by falling prices and the development of more profitable products such as oilseed and protein crops and the introduction of compulsory set-aside arrangements for major producers (European communities, 2000c). And then cereals have been making a comeback, rising to 53% of arable land in EU-12 (EU-9, Greece, Spain, Portugal) in 1997, compared with 48% in 1993. In total, the contraction in area under cereals was - 6% in EU-12 (disregarding Germany unification) between 1987 and 1997 (European communities, 2000a). This represents a reduction of 2.2 million hectares of area under cereals, the land being left fallow or converted to oilseed and protein crops. However, the 1992 EU CAP reform had a limited effect in some Member States like France, the Netherlands and Denmark where the area under cereals went up by 436,000 hectares. Although there was an overall decline of 7% in the area used for cereal production in EU-9 (EU-6, Denmark, Ireland, United Kingdom) between 1975 and 1997, areas under some cereals like wheat (+ 2.4 million hectares) and maize (+ 532,000 hectares) increased over this period. Common wheat production has shown a big rise since 1975 in France, Germany, the United Kingdom and Denmark. The greatest growth in terms of area under cultivation between 1975 and 1997 was maize (+ 29% in EU-12), with the area used for maize for silage doubling in size. The reduction in area used for barley and for secondary cereals i.e. rye and oats revealed in evidence between 1975 and 1995. In general, the percentage of arable land used for cereals has developed similarly since 1966 in EU-6, EU-9, EU-12, and EU-15 (European communities, 2000c).

Non-root fodder crops, accounting for 14.9 million hectares in 1997 in EU-15, occupied a fifth of the area of arable land. Between 1975 and 1997 in EU-9, the area under non-root fodder crops declined slightly (-6000,000 ha). This trend masked contrasting developments of an increase in annual fodder products (fodder maize) and a decline in perennial fodder products (leguminous plants) and temporary pasture. Between 1987 and 1997, the area under non-root fodder crops revealed an increase of 300,000 ha (+ 3%) in EU-12 (European communities, 2000b).

There was a sharp decline in area used for root crops (e.g. sugar beet, potatoes), owing to the need for considerable separate investment and expenses and the existence of quotas for sugar beet. The share of area used for root crops decreased from 9.4% in 1975 to 6.7% in 1987. The period 1987-1997 confirmed this trend, with a slight decline from 6.7% to 5.8% (European communities, 2000a).

In 1987, the share of fallow land in arable land was 1.2% (0.54 million ha) in EU-9 when no-set-aside arrangements had yet been put in place. Between 1987 and 1993, the area of fallow land increased more than eight-fold in EU-9 (10.2% in 1993) (European communities, 2000a). This increase was mainly due to fallow land subject to set-aside incentive schemes within 1992 CAP reform. Since 1993, the trend for set-aside area has been closely linked to the set-aside rate applied. The set-aside rate declined from 9.0% in 1995 to 4.7% in 1997. Between 1987 and 1997, the area of fallow without any subsides declined from 4.1 million ha to 3 million ha, whilst fallow land subject to set-aside incentive schemes increased from zero ha to 2.3 million ha over the same period.

Industrial crops in EU-9 include mainly oilseeds (the most important oilseed is rapeseed, followed by sunflower and soya beans) and partly textile crops (flax, hemp and cotton). They accounted only for 1.9% of areas of arable land in 1975. There was a sharp increase in area under industrial crops between 1975 and 1997 (accounted for 9% in 1997). The output of sunflower seed and soya bean production has been stabilized since 1987 whereas the output of rapeseed production has been growing (European Communities, 2002). From 1999 to 2003, areas under oilseeds strongly decreased by -16.7% for EU-15 (European Communities, 2005a).

In EU-9, the proportion of area under pulses increased from 0.8% in 1975 to 2.5% in 1987. It then has been almost stable during the period 1987-1997.

2.3 Main feature of agriculture in France after 1960s

France is the largest producer in the EU and produces approximately a quarter of EU cereals, oilseeds and cattle. It is a net exporter with a net market balance of 9 billion euros (Colson and Chatelier, 1997; Huyghe, 2005). The share of arable land in the total land area in mainland France was approximate 32.9% in 1992 and slightly increased to 33.7% in 2003 (approximate increase by 4.2 thousand km^2) (FAOSTAT, 2011). Many of the evolutions described above for Western Europe as a whole apply to France.

During over a century, from 1850 to 1970, the area for forage production (including permanent grassland and arable land under fodder crops) has increased to approximately 58% of the UAA. Since 1970s, the area under forage production has declined whereas the area under field crops has increased (Dussol et al., 2003). The proportion of arable land in the total UAA slightly increased almost the course of the period 1975-2003 (rising from 53.6% in 1975 to 61.9% in 2003) whereas the share of permanent pastures and meadows in the total UAA declined during the same period (fell from 41.4% in 1975 to 34.3% in 2003) (FAO, 2013). The pattern of the share of area used for cereals in total arable land in France show a similar trend to EU-6 until 1980s. Then it decreased from 52.3% in 1987 to 46.8% in 1993. And then cereals have been making a comeback, rising to 50.6% of arable land in 1997. There was then a steady contraction until 2003 (European

Communities, 2005a). The share of area equipped for irrigation in the total UAA increased from 5.4% in 1987 to 8.8% in 2000 (FAO, 2013).

Historically in mainland France, protein crops, as the term used in the EU are legumes, were primarily planted for producing forage and often integrated in the mixed cropping livestock systems due to their nitrogen-fixing capacity and protein-rich for livestock feed (Bues et al., 2013). Moreover, legumes were often included in cereal-dominated rotations that were known as the 'three-field rotation' system and the 'Norfolk four-course system' (Molnar, 2003). Since 1960s, the comparative advantage of using land to grow cereals, in particular, to grow wheat and maize instead of protein-rich grain legumes has increased. The consumption of grain legumes as human diets (e.g. lentil, chick peas and vetch) decreased from 7.3 kg per capita in 1920 to 1.4 kg per capita in 1985 (Cavaillès, 2009). The decrease in area of grain legumes has occurred after the 1992 CAP reform while planting area under peas peaked in the year 1993 (Cavaillès, 2009). Meanwhile, a sharp decline in area under legumes-based sown pasture (e.g. alfalfa, clover, and sainfoin) has occurred during the period 1960-1990 due to the replacement of leguminous pasture with silage maize and gramineous forage grass (Cavaillès, 2009). The increasing availability of N fertilizers and soya bean feed at low costs and need for high per area productivity favored these fertilized forage crops and ruminant diets based on maize and grasses supplemented by soya bean (mostly by importation). Pigs and poultry diets are cereal-based and approximately 30% of cereal (i.e. wheat, maize and barley) harvested was used to feed livestock in the agricultural year 1990-91. The inclusion of forage maize into subsidies under the past CAP further increased the competition between forage crops.

The average farm size increased from 17.6 ha in 1967 to 41.7 ha in 1997 and continued to increase to 45.3 ha in 2003. The share of farms with 50 hectare or more in total farms also increased (rising from 8% in 1975 to 31% in 1997 to 33% in 2003). The average SGM per holdings increased from 9.6 ESU in 1975 to 35.3 ESU in 1997 to 47.5 ESU in 2000. The ratio of agricultural holdings with 40 ESU and more was approximately 72% in 1997 whereas it was only 21% in 1975. The total volume of agricultural labor fell sharply between 1966 and 1997 (- 68%). The average labor input of agricultural holdings was evident 1.54 annual working units (AMUs) in 2000.

The average area of the arable land per holding was 37.7 ha in 1997 which increased by 229% in thirty years. There was also a pronounced concentration of holdings with arable land between 1987 and 1997 in France. The average area of arable land per holding increased by 71% in ten years, i.e. on average, 6 hectares more per holding (European communities, 2000b). According to the community surveys of 1999-2000 on the structure of agricultural holdings, 56% of total number of agricultural holdings cultivated cereals, oilseed or protein crops and 15% of total number of agricultural holdings specialized in the cultivation of cereals (other than rice), oilseed and protein crops (COP) in 1999 (European communities, 2003). 23% of agricultural holdings which specialized in the COP cultivation planted on average more than 100 ha of them. 59% of the area under COP was occupied by these large holdings.

3. Why do we focus on crop sequences?

The household, its resources, and the resource flows and interactions at this individual farm level are together referred to as a *farm system*. Individual farm systems are organized to produce food and to meet other household goals through the management of available resources-whether owned, rented or jointly managed - within the existing social, economic and institutional environment. A *farming system* is defined as a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate (FAO and World Bank, 2001). *Cropping system* that is subsystem of farming system was previously defined by Sebillotte (1974) as “the crops, their succession order and the crop management systems associated with each crop” (Leenhardt et al., 2010).

Farming practices are crucial activities in the management of spatial patterns and environmental processes occurring in agricultural landscape (Benoît, Davide et al., 2012). Crop rotation that is “the sequence of crops grown in succession on a particular field” (Sebillotte, 1974; Sebillotte, 1990; Wibberley, 1996) has been practiced since the beginning of agriculture and some formal rules of thumb are known to have been practices since medieval times (Hennessy, 2006). It has been practiced in Europe temperate agriculture since at least the 18^{th} century for the purpose of eliminating the need for a fallow period (Liebman and Dyck, 1993). Field rotation systems that are based on the ‘three-field rotation’ system and the ‘Norfolk four-course system’ have been widely implemented in Western Europe in order to improve weed and pest control and fertility and allow crops and livestock to be raised on the same farm (Molnar, 2003). With farm amalgamation, farm size has increased and farms have become more specialized in their cropping systems, adopting simpler rotations than in the past (Stoate et al., 2001).

In the research community, the agronomic, environmental and economic effects of crop rotations have been well documented (Krupinsky et al., 2006; Rabotyagov et al., 2010; Bell et al., 2012). In particular, an excellent summary on the evolution of crop rotations and their environmental impacts in the EU can be found in European Commission (2010). Integrating crop rotations in the place of single crop into modeling framework for assessing environmental and economic performance of agricultural production systems is increasingly concerned in the research community (Beaudoin et al., 2005; Heard et al., 2005; Gaiser et al., 2009; Rode et al., 2009; Salmon-Monviola et al., 2012; Ouyang et al., 2013). In the context of the establishment of new economic, agronomic and governmental policies, farmers will be paid for re-establishing and increasing ecosystem services on agricultural land (Tilman et al., 2002; Miller, 2008). The positive effects of crop rotations have once more come to the attention of researchers (Gaiser et al., 2009; Merrill et al., 2012; Le Féon et al., 2013; Syswerda and Robertson, 2014).

Numerous cropping system models were developed to generate optimal or feasible crop rotations for farming system design or the assessment of the performance of agricultural production systems at the farm level (Dogliotti et al., 2003; Detlefsen and Jensen, 2007; Aurbacher and Dabbert, 2011). To meet the lack of information on crop rotations at a regional scale (Leenhardt et al., 2010; Therond et al., 2011), several recent studies propose spatially explicit crop rotation models (Castellazzi et al., 2010; Sorel et al., 2010; Schönhart et al., 2011) which can generate crop rotations served as input data for agricultural assessment.

In addition, many emerging studies modeled agricultural land-use change in relation to the shifts in agricultural management practices in EU during the past two decades, for example, changes in agricultural intensity at the EU scale (Temme and Verburg, 2011), dynamics of farming systems in Portuguese High Nature Value Farmland (Ribeiro et al., 2014), agricultural abandonment in Italian Alpine area (Cocca et al., 2012), and co-evolution of landscape patterns and agricultural intensification in Dutch dairy farming (van Apeldoorn et al., 2013). Drivers of the changes were also investigated in these studies. However, crop rotations as vital and widespread implemented agricultural management practice, changes in crop rotations and their driving forces have been rarely studied. Merely several recent studies (Stern et al., 2012; Plourde et al., 2013; Long et al., 2014a, 2014b) target on identifying primary crop rotations and quantifying the changes in their planting areas in certain regions of the United States. Monitoring crop sequence patterns and their spatio-temporal dynamics at a regional scale contributes the assessment of economic and environmental performance of agricultural production systems and thus is important for the agri-environmental policy making and evaluation, and sustainable farming system designing.

In this thesis, we define 'crop sequences' as the order of appearance of crops during a fixed period. Crop sequences are strictly synonymous with crop successions. Crop sequences are the partial or total development of a cycle of rotation or even the basis of several cycles, while crop rotations are characterized by the cycle period, e.g. biannual, triennial, quadrennial, etc. (Leteinturier et al., 2006; Dury et al., 2013). Fig I-1 gives a graphic representation of these two concepts. Referring to Castellazzi et al. (2008) and Dury et al. (2013), we distinguished both rotation and sequence into two types: simple (fixed length) and flexible (variable length).

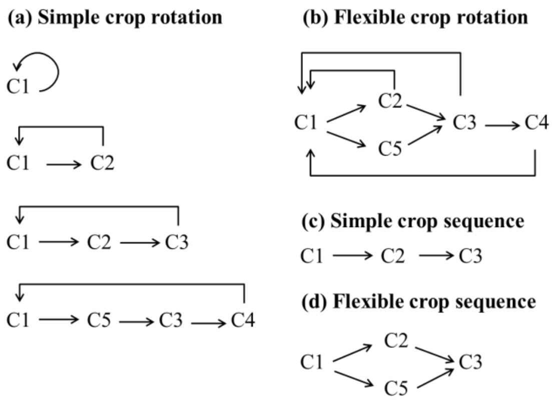

Fig. I-1. Graph scheme of the definitions of concepts 'crop rotation' and 'crop sequence'. C1 to C5: crop1, ⋯, crop 5. Only principal crops within one year were considered in the case of sole cropping systems. Monoculture of one crop is included in the category "simple crop rotation".

4. Objectives of the thesis

In the context of changing agricultural policy, shifts in economic and product demand, the development of agricultural production systems, and increasing concern on sustainability of agriculture and changes in agricultural land management practices-related land-use change, the main objective of this thesis was to mine crop sequence patterns (in both spatial and temporal aspects) and the relationships between crop sequence patterns and the biophysical and socio-technical-economic conditions in mainland France from historical census data (e.g. land-cover survey, agricultural censuses, population census). The study period of this thesis 1992-2003 which covers the period of implementation of 1992 EU CAP reform and Agenda 2000 in France allows us to explore the potential evolution of cropping systems in terms of crop sequence under agricultural policy change. Considering the pronounced decline in permanent pastures and meadows and the expansion of arable land during the same period and rarely linking grassland conversion to the following commodity production in the literature, we also focus on the crop sequence patterns after the grassland conversion. Hence, this thesis research consists of four sequential tasks as follows:

(i) Developing stationary model that represents the spatial distribution of crop sequences at the French national scale to understand the historical agricultural land-use pattern under rotational systems;

(ii) Investigating crop sequence patterns (CSP) following the grassland-to-cropland conversion in the period 1992-2010 to improve our understanding on agricultural land-use change;

(iii) Developing dynamic model to describe the temporal and spatial dynamics of CSP;

(iv) Exploring the dynamics of the relationships between the changes in CSP and the biophysical and socio-technical-economic conditions.

5. Outlines of the thesis

This thesis comprises six chapters, including the general introduction “Chapter I” (Fig. I-2). Each chapter addresses one of the research questions which were presented in Section 4.

In Chapter II a combination of hidden Markov models and an unsupervised clustering analysis was performed to describe the spatial distribution of crop sequences at the French mainland scale by processing sequentially observed (from 1992 to 2003) land-cover survey data. This study identified 21 homogenous zones in terms of 12-year averaged occurrences of 3-year crop sequences across French mainland. The 2549 3-year crop sequences were first identified as major crop sequences. Four cropping systems were further defined: vineyard-based cropping systems, maize monoculture and maize/wheat-based cropping systems, temporary pasture and maize-based cropping systems and wheat and barley-based cropping systems. The occurrence of major unfixed-length crop sequences within a spatial unit can be identified using the method proposed in this chapter. We took all of the ADs of one cluster that was identified previously as an example to demonstrate it. The results of the exploration of major non-fixed length crop sequences in the ADs of the other clusters can be found in the appendix III.

In chapter III we investigated the recent (1992-2010) transitions between grassland and cropland, encompassing a period of implementations of two EU CAP reforms at the French mainland scale using national time series land-cover survey datasets. We first assessed the grassland-to-cropland conversion and further explored the CSP that resulted after the conversion. We also compared the CSP after the grassland conversion identified in this study to the existing cropping patterns that were investigated in Chapter II.

In Chapter IV we investigated the dynamics of CSP between 1992 and 2003 in mainland France using time-series land-cover survey data. Inspired by ecology, we consider all of the crop sequences which occurred within the study area and period as a community of crop sequences. The occurrence rate of crop sequences is equal "abundance". We study the evolution of the crop sequences' community rather than studying the changes in the planting area of several specific or primary crop sequences. A Partial Triadic Analysis (PTA) was therefore performed for this purpose. The investigation was at two scales: (1) the national scale by analyzing both all of the 429 ADs and the assemblage of 90 representative agricultural districts; (2) the regional scale by separately analyzing three principal zones of temporary crop, particularly, cereals, oilseeds, and protein (COP) crops' cultivation. The 90 representative ADs and three major homogenous zones for COP crops' planting were identified in Chapter II.

In Chapter V STATICO method was applied to explore the temporal variation of the relationships between CSP and the socio-technical-economic and biophysical conditions during the period of 1992 EU CAP reform and Agenda 2000 implementation (1992-2003) using time series land-cover data and agricultural censuses data. This exploration was also at two scales like Chapter IV. We used high available data on biophysical and socio-technic-economic conditions like topography, model-based agro-climatic indicators and open-access information about French Agricultural censuses 1988 and 2000.

Finally, the major results of this thesis research were summarized in chapter VI. We concluded the strengths and limitations of data and proposed approaches in this thesis. We also discussed the potential application of the methods developed in this thesis and the contribution of our findings about the trends in crop sequence patterns in mainland France to the knowledge gap in changes in agricultural management practices-related land use dynamics.

In addition, in appendix I an analysis of variance-based study was done to investigate the changes in the probabilities of occurrence of 18 dominant 3-year crop sequences over time in northern of France. A temporal data mining tool CARROTAGE (Le Ber et al., 2006; Mari and Le Ber, 2006) based on second-order hidden Markov models was performed to identify the homogeneous periods in terms of the probabilities of occurrence of crop sequences. One-way ANOVA or Friedman test were applied to compare the mean values of the probabilities of occurrence of major 3-year crop sequences according to different sub- periods. Tukey HSD method or two-tailed Wilcoxon signed rank test were used for further multiple comparisons between two successive sub-periods. This analysis was a test of method for analyzing changes in crop sequences in the mid-stage of the thesis work. Because of the constraint in fixed-boundary of study area (homogenous area that was defined in Chapter II) and in number of target crop sequences (only for limit number of crop sequence), some interesting shifts in crop sequence patterns, i.e. changes of types of cropping systems of an AD (e.g. from temporary pasture and maize/wheat-based cropping systems to monoculture of maize-based cropping system, see Chapter IV) and the evolution of the entire cropping patterns could be hidden with using this approach, we abandoned this method. But using this method for analyzing changes in crop sequence patterns allows us understanding whether there are changes (in statistical sense) in occurrence of one crop sequence over the study period.

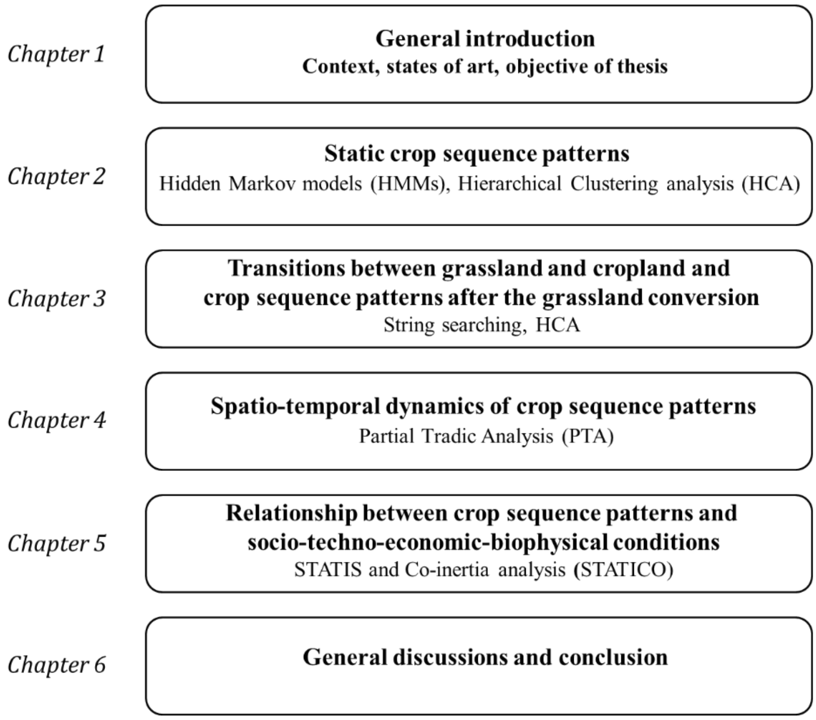

Fig. I-2. Schematic outline of the thesis.

Chapter II Modeling the spatial distribution of crop sequences at a large regional scale using land-cover survey data: A case from France

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Abstract

Assessing the environmental impacts of agricultural production systems requires spatially explicit information regarding cropping systems. Projecting changes in agricultural land use that are caused by changes in land management practices for analyzing the performance of land activity-related policies, such as agricultural policies, also requires this type of data for model inputs. Crop sequences, which are vital and widely adopted agricultural practices, are difficult to directly detect at a regional scale. This study presents innovative stochastic data mining that was aimed at describing the spatial distribution of crop sequences at a large regional scale. The data mining is performed by hidden Markov models and an unsupervised clustering analysis that processes sequentially observed (from 1992 to 2003) land-cover survey data on the French mainland named Teruti. The 2549 3-year crop sequences were first identified as major crop sequences across the entire territory, which included 406 (merged) agricultural districts, using hidden Markov models. The 406 (merged) agricultural districts were then grouped into 21 clusters according to the similarity of the probabilities of occurrences of major 3-year crop sequences using hierarchical clustering analysis. Four cropping systems were further identified: vineyard-based cropping systems, maize monoculture and maize/wheat-based cropping systems, temporary pasture and maize-based cropping systems and wheat and barley-based cropping systems. The modeling approach that is presented in this study provides a tool to extract large-scale cropping patterns from increasingly available time series data on land-cover and land-use. With this tool, users can (a) identify the homogeneous zones in terms of fixed-length crop sequences across a large territory, (b) understand the characteristics of cropping systems within a region in terms of typical crop sequences, and (c) identify the major crop sequences of a region according to the probabilities of occurrences.
Keywords: Crop sequences; Cropping patterns; Cropping systems; Hidden Markov models; Agricultural land-use; Teruti survey

1. Introduction

Currently, 43% of the area of Europe (Eurostat, 2010) and 36% of the total area of the world (FAOSTAT, 2011) are dominated by agricultural land use, including both cropland and grassland. The current challenge for agronomists, farmers and their allied partners is to satisfy humanity's need for food and fiber, as well as the accelerating demand for biomass, in an ecologically sustainable way through socially accepted production systems (Miller, 2008). Over the past decade, in the land change scientific community, the scientific interest regarding the investigation of land-cover modifications that are caused by changes in land management practices has increasingly been noticed by researchers. As noted by Lambin et al. (2000), changes in agricultural land-use management, e.g., changes in input levels, and their effect on profitability or the periodicity of complex land-use trajectories such as fallow cycles and rotation systems frequently drive land-cover modification. Incorporating the representation of agricultural land management practices and their changes into land system models will improve our understanding of the endogenous driving forces of land-cover modification. Several land system models have integrated the module for simulating farmer management practices and decision-making processes (Rounsevell et al., 2003). Agent-based models were specially developed and applied to represent human behavioral and decisional processes in the land system (Matthews et al., 2007). As one of the most significant forms of land-cover modification, agricultural land intensification has recently been studied using different land-use intensity indicators, such as livestock density and nitrogen input to UAA (utilized agricultural area), in relation to land management practices (Herzog et al., 2006). For instance, Temme and Verburg (2011) mapped and modeled agricultural land-use intensity in terms of nitrogen input at the European Union scale. A multi-scale modeling approach for exploring the spatial-temporal dynamics of European livestock distribution was proposed by Neumann et al. (2011). However, crop rotations, which are a vital agricultural land management practice, are rarely integrated into a land-use modeling framework at regional to global scales (Schönhart et al., 2011).

Crop rotations are defined as the practice of growing a sequence of crops on the same land (Wibberley, 1996). The term 'rotation' implies a cycle and is characterized by the identified starter crops and by the cycle period (e.g., biannual, triennial, and quadrennial) (Leteinturier et al., 2006). Because of the multiple benefits of crop rotations, such as increasing crop yields, decreasing the incidence of plant diseases and weeds, maintaining soil fertility, improving the soil structure, and preserving biodiversity, crop rotations are an old widespread practice. In the context of the establishment of new economic, agronomic and governmental policies, farmers will be paid for re-establishing and increasing ecosystem services on agricultural land (Miller, 2008). The positive effect of crop rotations has once more come to the attention of researchers (Merrill et al., 2012; Le Féon et al., 2013).

In the research community, which assesses the environmental impacts of agricultural systems, modeling frameworks are increasingly incorporating crop rotations instead of single crops for representing cropping patterns. These modeling approaches are related to nitrate leaching in intensive agriculture (Beaudoin et al., 2005), the impacts of agricultural management on the reduction of nitrogen content (Rode et al., 2009), the impact of farming on water resources (Graveline et al., 2012), etc. The manner of cropping system representation in terms of crop rotations in these studies was often simplified by expert knowledge, which was based on their own specific field observations or on interviews with farmers. A limited number of representative crop rotations were used for describing the cropping patterns in a spatial unit. For allocating these crop rotations within their study area, a crop rotation was usually stochastically assigned to a field, similar to the study by Rode et al. (2009). This simplified approach of representing cropping patterns is due to a lack of information concerning the allocation of crop rotations (Rode et al., 2009). Furthermore, a ‘crop generator’ was proposed for producing spatial and temporal crop distributions under certain conditions, such as soil types, agronomic rules or expert knowledge, and possibly calibrated with observed data (Dogliotti et al., 2003; Schöhart et al., 2011). A crop generator was included as an additional module in several hydrological models (Wechsung et al., 2000; Klöking et al., 2003). The limitation of agronomic rule-based crop generators is that these generators create theoretical crop rotations according to the agronomic suitability; however, actual crop rotation practices at the field level are primarily influenced by economic conditions, and biophysical conditions play only a secondary role (Klöking et al., 2003). Meanwhile, a study regarding uncertainty in the simulation of nitrate leaching at a large regional scale notes that the lack of information about agricultural land use management presents the greatest uncertainty and underlines its importance (Schmidt et al., 2008). All these reviewed modeling approaches represented cropping patterns from the field to regional mesoscale. For representing cropping patterns at a large regional scale or at a global scale, no modeling work has been proposed in the literature. In contrast to the existence of various models at a field scale for designing sustainable cropping systems, the lack of cropping system models at a regional or at a global scale results from the unavailability of spatially and temporally explicit information regarding crop rotations and their associated crop management system (Therond et al., 2011).

The aim of our study is to present an innovative stochastic data mining methodology for describing the spatial distribution of crop sequences at a large regional scale. The data mining is performed using hidden Markov models and an unsupervised clustering analysis that processes sequentially observed (from 1992 to 2003) land-cover data on the French mainland.

Our study can be considered an empirical analysis of historical cropping patterns at a large regional scale, which will contribute to the creation of scenarios of agricultural land-use changes that are caused by changes in land management practices to analyze the performance of land activity-related policies and land planning. This study also provides a tool to extract large-scale spatially explicit cropping pattern data from increasingly available time series data regarding land-cover and land-use, which will improve the accuracy of the assessment of environmental impacts of agricultural systems. In this study, we define ‘crop sequences’ as the order of appearance of crops during a fixed period. Crop sequences are strictly synonymous with crop successions. Crop sequences are the partial or total development of a cycle of rotation or even the basis of several cycles (Leteinturier et al., 2006). As noted by the field survey-based study, farmers have grown different crops over the years in their farm fields without necessarily designing strict rotations (Joannon et al., 2008). For the study of cropping patterns at a national scale, we have limited our investigation to major crop sequence-related cropping patterns.

We present our modeling approach as follows. First, we describe our study area and the available land-cover data sources. Next, we briefly introduce the temporal data-mining tool. We then apply our modeling approach, which uses this historical national land-cover survey data for clustering the French agricultural districts in terms of the similarity of occurrences of crop sequences. Finally, we further characterize the clusters of agricultural districts using both the typical regional crop sequences and the major crop sequences of a region.

2. Materials and methods

2.1. Study area

Our study area is the French mainland (the island of Corsica is not included) in Western Europe, which covers 552 thousand square kilometers. The percentage of the total land area in mainland France that was considered agricultural was 55.4% in 1992 and 54.2% in 2003 (FAOSTAT, 2011). The area of the main agricultural land use at the beginning and end of our study period is described in Table II-1. Because of the variation in environmental and socio-economic conditions across the entire territory, the French agricultural production systems reveal their regularity through the spatial distribution. Fig. II-1 describes the spatial distribution of farm typology, which is based on the community typology of agricultural holdings in France in 2000, which was performed by the French Ministry of Agriculture. This EU farm typology is based on economic criteria, such as economic size and type of farming. This typology provides a glimpse of the spatial distribution of farming systems across the French territory. The main cropping zones for cereal and oilseed production are in central, northern and southwestern France. The livestock zone is situated mainly in northwestern and in the Massif Central of France. The mixed cropping and livestock zone is located mainly in southwestern France.

Table II-1
The area of main agricultural land use in France in 1992 and 2003 (Agreste, 2004).

	Cereals (wheat, barley, oats, maize, rye and other cereals)	Sugar crops and oilseed crops (sugar beet, sunflower, rapeseed, textile crops and other oilseed crops)	Fallow	Pasture (temporary pasture, artificial pasture, permanent grassland and grass orchard
1992 (million hectares)	10.837	2.215	0.540	11.736
2003 (million hectares)	10.598	2.406	1.066	10.897

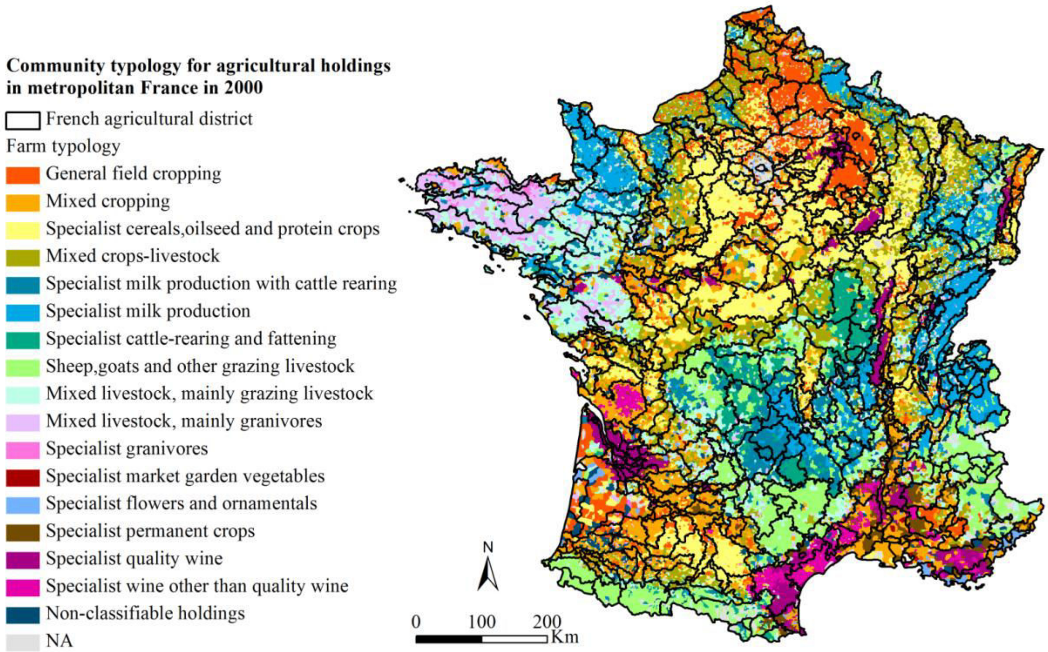


Fig. II-1. The economic criteria-based EU community typology for agricultural holdings in France in the year 2000. Data supported by the French Ministry of Agriculture.

2.2. Data source

The sequential land-cover data that were used in this study were derived from Teruti databases. Teruti is a two-level sampling survey of land-cover, which was conducted by the French Ministry of Agriculture (Ledoux and Thomas, 1992). Fig. II-2 illustrates the sampling method that was performed in this survey. At the first sampling level, the entire territory was segmented into 4700 grids, with an area of 12 × 12 km per grid (Fig. II-2a). In most regions, four aerial photos among eight at the positions numbered in 1, 2, 3, 4 (Fig. II-2b) were taken within each grid. In total, 15,579 aerial photos were taken every June during the survey period. One aerial photo covers approximately 3.24 square kilometers. At the second sampling level, 36 evenly spaced sampling points (approximately 300 m apart) were systematically distributed within the area of one aerial photo (Fig. II-2c). The land-covers of the entire territory were recorded in a matrix, in which the sampling points are in a row and the annual records of land-cover are in a column. A corpus of 555,382 sampling points that were labeled with their land-cover during the period from 1992 to 2003 was used in this study. This corpus has detailed information regarding 81 types of land-cover, including 41 types of crops. Moreover, the Teruti survey provides constant sampling points, which ensures the representativeness at different spatial scales that are based on the occurrences and richness of crops.

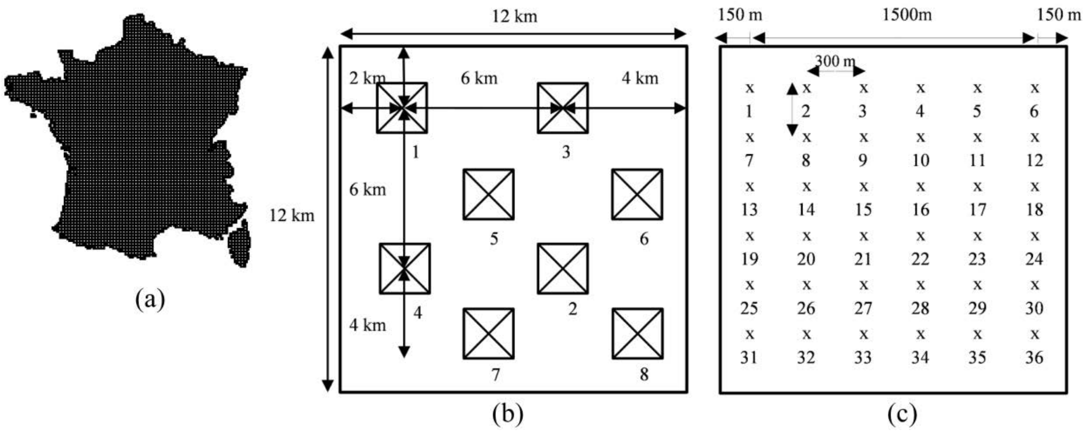


Fig. II-2. Graphical illustration of the two-level sampling method of the Teruti land-cover survey between 1992 and 2003. (a) The entire territory is segmented into 4700 grids. (b) The position of aerial photos taken in each grid. (c) The distribution of 36 sampling points within an aerial photo. One Teruti sampling point covers roughly 100 ha.

We chose the French agricultural district as the spatial unit in this study. This zoning was established by the French Ministry of Agriculture in 1946 primarily according to homogeneous agricultural activities and partly according to similar environmental conditions, such as the soil profile and climate (Richard-Schott, 2009). The study by Mignolet et al. (2007), which was based on interviews with the regional chambers of agriculture, indicates that after more than 50 years of development of the socio-technical system, the principal agricultural activities within an agricultural district have remained homogeneous in the Seine Basin. Thus, the level of aggregation of Teruti sampling points was defined with respect to the zoning of the agricultural district. All of the 430 agricultural districts in the French mainland territory were incorporated into this study. Because of the small quantity of sampling points (less than 100 points per district) in 21 agricultural districts, we merged these districts into one of their neighborhood districts according to the similarity of the main land-cover categories. Finally, 406 spatial units, which included 384 individual agricultural districts and 22 merged agricultural districts, were studied.

2.3. Overview of methods

Our strategy of modeling the spatial distribution of crop sequences is to classify the agricultural districts according to the similarity of the occurrences of crop sequences and, further, to map the clustering result. The modeling work was performed in three steps. First, temporal data mining software was applied to estimate the probabilities of the occurrences of crop sequences within each spatial unit. Second, we grouped the spatial units in terms of similar crop sequences by performing a classic non-supervised clustering technique. Finally, we mapped the clustering result using the program ArcMap 10. In this section, we first briefly introduce CARROTAGE, which is our temporal data-mining tool that was used to extract the land-use successions (LUSs) in each (merged) agricultural district. Then, we describe the procedure for identifying major crop sequences within 406 spatial units using this tool. Finally, the non-supervised classification of agricultural districts and the cartography of the clustering result will be presented. Here, we use the entire French mainland as a spatial unit example to demonstrate the procedure of identifying crop sequences using CARROTAGE. In our analysis, the identification of major crop sequences within a (merged) agricultural district was individually performed in an identical manner for all 406 (merged) agricultural districts.

2.3.1. Description of the temporal data-mining tool

CARROTAGE (Le Ber et al., 2006; Mari and Le Ber, 2006), which is free software, was used to extract the crop sequences from the Teruti survey databases.

In contrast to several published modeling frameworks of crop sequences that use first-order Markov chains (Aurbacher and Dabbert, 2011; Castellazzi et al., 2008; Salmon-Monviola et al., 2012), CARROTAGE implements second-order hidden Markov models (HMM2). The hidden Markov models (HMM) represent the variability that is inherent to land-cover by using land-cover distributions that are organized in a Markov chain rather than represent distinct Markov chains of land-cover. In a HMM2, the Markov chain is a second-order Markov chain that governs the sequence of land-cover distributions. This design allows more precise modeling of time events because the land-cover distribution at year t depends on the crop that is grown in year t - 1 and in t -2. Experiment results in speech recognition indicate that HMM2 provides better duration modeling than HMM1 (Mari and Le Ber, 2006). The main feature of HMM of any order is the existence of a learning algorithm (the Baum-Welch algorithm) that can tune the HMM parameters using a corpus of land-cover sequences (the training corpus).

2.3.2. Identification of major land-cover categories within a spatial unit

The first step in data mining is to find an adequate way to encode the data. We performed a temporal segmentation of the huge matrix of land-cover that includes the period 1992-2003 to reduce the number of columns and to represent each subperiod by the distribution of land-cover occurring in this subperiod. Following Le Ber et al. (2006), we specified 12 states left-right HMM2 with one-year land-cover as the observation symbol. Because our study period covers 12 years, the initial number of states that were defined for the first specified HMM2 was therefore 12. This HMM2 was trained using the entire matrix and provided 12 land-cover distributions. Among these 12 distributions, many of the distributions were similar. By systematically reducing the number of states, left-right HMM2 segmented the study period into five subperiods in terms of homogeneous land-cover distributions (more detail of the temporal segmentation see Mari et al., 2011). Thus, crops, such as bean, oats, fiber crops, and rye, that were not principal crops with extensive growing areas during the entire period but were dominant in the territory in several subperiods, could be incorporated in the study. This procedure of identifying main land-cover using temporal segmentation is useful for defining crops that will be incorporated into our investigation of crop sequence patterns, which considers crop diversity.

We defined major land-cover types as those types that represented at least 1% frequency among the total number of land-cover records in the dataset. Additionally, all major land-cover types that were identified in all of the five states were then retained as main land-cover categories of a spatial unit for the next analysis of

LUSs. Table II-2 outlines the main land-cover types that were identified in these five states. Because the goal of this study was to investigate crop sequence patterns, we kept crops (except for artificial pasture and temporary pasture) in individual categories and grouped several other land-cover types in one category according to their similar characteristics in land systems (for more details see Table II-3). Finally, 12 major land-cover categories (Table II-3) were defined and were further used for studying LUSs.

Table II-2
Result of 5 states left-right HMM2: the main land-cover types of French mainland and their percentage of total frequency at five temporal states between 1992 and 2003. This table shows the evolution of several land-covers such as the expansion of forest, the increase in areas of rapeseed cultivation, the decrease in areas of pea cultivation, etc.

State 1		State 2		State 3		State 4		State 5	
F	28	F	29	F	29	F	30	F	30
G	16	G	16	G	15	G	15	G	15
W	9	W	9	W	10	W	10	W	9
OS	8	OS	8	OS	7	OS	7	OS	7
M	6	M	6	M	6	M	6	M	6
Pt	4	An	4	An	4	An	5	An	5
An	4	Pt	4	Pt	4	Pt	4	Pt	3
B	3	Fa	3	B	3	B	3	B	3
H	2	B	2	H	2	R	2	Fa	2
Fa	2	H	2	R	2	H	2	R	2
V	2	S	2	Wa	2	Wa	2	H	2
St	2	V	2	V	2	V	2	Ab	2
S	2	Wa	2	S	2	Ab	2	Wa	2
Wa	2	St	2	St	2	Fa	2	V	2
P	1	R	1	Ab	1	St	1	St	1
Ab	1	Ab	1	Pm	1	S	1	Pm	1
Pm	1	Pm	1	Fa	1	Pm	1	S	1
R	1	P	1	P	1	P	1		
Pa	1	Sb	1	Sb	1				
Sb	1								

Main land-cover types of French mainland:
Artificial surfaces with construction (Ab), artificial surfaces without construction (An), barley (B), forest (F), fallow (Fa), grassland (G), herbaceous vegetation area (H), maize (M), heathland, moors and hedgerow (OS), pea (P), artificial pasture (Pa), alpine meadows (Pm), temporary pasture (Pt), rapeseed (R), sunflower (S), sugar beet (Sb), rocky areas (St), vineyards (V), wheat (W) and water bodies (Wa).

2.3.3. Extraction of all LUSs that involved the major land-cover categories

CARROTAGE allows users to specify HMM2, which can process either single land-cover sequences or sequences that are composed of overlapping fixed length land-cover subsequences. For example, the 12 year land-cover sequence: *rapeseed-wheat-barley-rapeseed-wheat-barley*… can be parameterized into a sequence of 11 overlapping 2-year land-cover subsequences: *rapeseed-wheat*, *wheat-barley*, *barley-rapeseed*… or even by 10 3-year land-cover subsequences: *rapeseed-wheat-barley*, *wheat-barley-rapeseed*, *barley- rapeseed-wheat*… The longer the length of the subsequence (say *n*) is, the more different *n-uplets* we obtain. This situation leads to under-training issues when the Baum-Welch algorithm estimates the distributions. In contrast, the greater n is, the more interesting it is for agronomists to determine long crop sequences. To choose a suitable observation symbol, we referred to the previous studies of Le Ber et al. (2006) and Mignolet et al. (2007) in the Seine Basin, where the main field crop cultivation zone in France is located, and to the national statistics on farming systems that were published by the French Ministry of Agriculture (Agreste, 2010a). The former study confirms that crop sequences within the Seine Basin are frequently organized in three or four years. The national agricultural statistics indicate that the crop sequences that are implemented on French territory generally consist of three times wheat and/or barley and once or twice special regional crops. Considering all the above factors, we chose a 3-year land-cover subsequence as the elementary observation symbol in this study.

Table II-3
Major land-cover categories of French mainland and their composition between 1992 and 2003.

Land-cover category	Composition
Perennial areas	Forest, artificial surface with and without construction (including vegetable gardens)
Natural grassland	Natural pasture (not under a rotation system), alpine meadows, grass orchard and herbaceous vegetation area
Sown pasture	Artificial pasture (predominantly cultivated on alfalfa and clover) and temporary pasture
Wheat	Soft wheat and durum wheat
Barley	Barley and six rowed barley
Maize	Maize
Sugar beet	Sugar beet
Rapeseed	Rapeseed
Peas	Peas
Sunflower	Sunflower
Fallow	Fallow
Other semi-natural areas and inland water	Rocky areas, water bodies, heathland, moors and hedgerow

Referring to the work of Lazrak et al. (2010), we applied a search pattern (Table II-4) for extracting all 3-year LUSs that involved a given major land-cover category. Because field rotation systems that are based on the 'three-field rotation' system and the 'Norfolk four-course system' are widely implemented in Western Europe (Molnar, 2003), we further introduced a field-adopted agronomic rule: starter crop to define the search pattern. The starter crops are often the precedent crop of wheat (mainly) or barley. The field residues of these crops play an important role in soil organic matter and P and K fertilizer restoration. The specialization of starter crops in different agricultural districts composes the base of the diversification of cropping patterns, whereas wheat and barley are ubiquitous. Table II-4a shows the search pattern that we used for extracting the LUSs that involved these five main starter crops in France: maize, rapeseed, peas, sunflower and sugar beet. For the other land-cover categories, the search pattern that is shown in Table II-4b was performed. The introduction of the search patterns in the form of 'starter crop-wheat' can be considered a use of HMM2 in a supervised way. In comparison to using one major crop that is involved in the search pattern (Lazrak et al., 2010), the search pattern 'starter crop-wheat' avoids the repetitions of the same 3-year LUSs in different Dirac states (states within HMM2 whose distribution are zero except on a given land-cover category). Using the search pattern maintains the non-agronomical sustainable crop sequences that are implemented in practice, such as the successive cultivation of maize or wheat in a separate state, called a 'container state' (state associated with all the other less frequent land-cover categories). Thus, this method provides a better result.

A one-column ergodic HMM2 (all transitions between states are possible) was used to perform this extraction of 3-year land-use successions. The number of Dirac states of the model depended on the major land-cover categories that were previously identified plus a container state (Le Ber et al., 2006).

Table II-4
Search pattern for extracting all 3-year LUS involving one given major land-cover category.

	1st year	2nd year	3rd year
a	?	X	wheat
	X	wheat	?
	wheat	?	X
b	X	?	?
	?	X	?
	?	?	X

2.3.4. Filtration of major crop sequences from all 3-year LUSs

The goal of this task was to filter out the major 3-year LUSs that included 3-year successive crops (referring to crop sequences in our study) in the output of a one-column ergodic HMM2 that was obtained previously.
We first filtered the 3-year LUSs in each Dirac state in the CARROTAGE output files of a spatial unit using double criteria: at least a 1% probability of occurrence and the occurrence of the given land-cover categories in the 3-year LUS. For the container state, all of the LUSs that had at least a 1% probability of occurrences were kept for the next step. Because the aim of our study was to investigate the major crop sequence-related cropping patterns at a national scale, many 3-year LUSs were removed using the threshold of a 1% probability of occurrence. Next, the 406 individual records of main LUSs of a (merged) agricultural district were used to build an inventory table, in which the 3437 LUSs were in a column and the 406 agricultural districts were in a row. In this inventory table, we further removed 888 land-use successions, which included non-crops in 3-year successions. The remaining 2549 3-year land-use successions, which strictly included three successive years of crops, called 'crop sequences' in this study, were retained to cluster 406 (merged) agricultural districts.
Finally, to facilitate the interpretation of the characteristics of crop sequence patterns by understanding the context of the agricultural land use, we reclaimed 11 land-use successions that were relevant to the perennial land categories from the 888 removed land-use successions. These 11 land-use successions were 3-year successions of forest, natural pasture, grass orchard, Alpine meadows, herbaceous vegetation area, rocky areas, water bodies, other semi-natural areas, vegetable gardens and artificial areas with and without construction. Thus, the probabilities of occurrences of 2549 3-year crop sequences and 11 perennial land-covers were retained as the parameter vector of the 406 (merged) agricultural districts.

2.3.5. Clustering and mapping agricultural districts in terms of homogenous crop sequences

To cluster the 406 (merged) agricultural districts, we chose the principal component methods before using Ward's agglomerative hierarchical clustering method (AHC) according to the Euclidean distance (Husson et al., 2010) using the R software (R Core Team, 2012) 'FactoMineR' package (Lê et al., 2008). Performing PCA on the raw data is an efficient technique for avoiding high correlations between variables. In our case, taking a typical 3-year "wheat-barley-rapeseed" crop rotation as an example, the occurrences of its three forms, "rapeseed-wheat-barley", "wheat-barley-rapeseed" and "barley-rapeseed-wheat", should be strongly correlated. Thus, performing PCA can be considered a preprocessing of the crop sequence data. This preprocessing can improve the robustness of the clustering analysis (Josse and Husson, 2012). The PCA was performed without the use of standardized variables because the 3-year crop sequences were measured on scales without widely differing ranges and because the units of measurement are identical.

In addition, in PCA, 2549 crop sequences were used as active variables, and 11 perennial land-covers were used as supplementary variables. The AHC was performed on the first principal components, which accounted for 80% total inertia. To choose the suitable number of clusters in AHC, we first defined the least possible and the most possible numbers of clusters according to the evident drop in the bar graph of the distance values, which were drawn using the package "Cluster" within R. Next, we determined the suitable number of clusters within the range of the least and most possible numbers of clusters using the R software's (R Core Team, 2012) "clValid" package (Brock et al., 2011). All six measures that were relevant to 'internal' and 'stability' measures that were implemented in 'clValid' package were used to validate the number of clusters. This number of clusters was then used as argument in the function 'HCPC' of "FactoMineR" for performing AHC. The advantage of using the FactoMineR package is that this package integrates a function of the description of clusters by all initial continuous variables both active and supplementary. This measure is named v-test (Lebart et al., 1995), which can be considered a "standardized" deviation between the mean of those individuals with category q and the general average (Husson et al., 2010). To understand the characteristics of clusters, the probabilities of occurrences of major 3-year crop sequences were estimated by performing a one-column ergodic HMM2 on the corpus of Teruti land-cover data on the agricultural districts that belong to one cluster. The one-column HMM2 contained one Dirac state that involved all non-crop land-cover using the search pattern (Table II-4b).

Finally, the result of the clustering analysis was mapped using the program ArcMap10 to visualize the crop sequence patterns from 1992 to 2003.

In addition, although the classification of agricultural districts was established, we further explored the major non-fixed length crop sequences in the territory of one cluster using the graphic output of a one-column ergodic HMM2 (Le Ber et al., 2006).

3. Results

3.1. Descriptive statistical analysis

In PCA, the first two components explained 23.8% and 12.3% of the total inertia, respectively. The first twenty-three principal components, which accounted for 80.1% of the total variability, were used to cluster the agricultural districts. Two-dimensional PCA scores plots and loading plots on PC1 vs. PC2 and PC3 vs. PC4 are shown in Fig. II-3. The agricultural districts score plot for PC1 vs. PC2 (Fig. II-3a, left) reveals two distinguished groups of agricultural districts. One group is projected on the negative dimension of PC1. According to the loading plot of crop sequences (Fig. II-3b, left), the occurrence of vineyards contributes most to this observed clustering. Another group is projected on the positive dimension of PC2, which correlates with the occurrence of wheat-based crop sequences. In the scores plot of agricultural districts of PC3 vs. PC4 (Fig. II-3a, right), three groups can be observed. The sugar beet-based crop sequences are heavily loaded for PC4 (Fig. II-3b, right), which separates the group that is projected on the negative dimension of PC4 from the others. The second group is projected on the positive dimension of PC4, which can be explained by the sunflower-wheat-based crop sequences, which have a high value of occurrences for PC4 loading. The occurrence of monoculture of maize is most strongly responsible for the discrimination of one group of agricultural districts that is projected on the positive dimension of PC3. Additionally, the occurrence of a 3-year fallow is partly responsible for this discrimination.

3.2. Clustering (merged) agricultural districts

In the first step, we used a visual aid, the bar graph of the distance values (Fig. II-4), to determine a wide range of the number of clusters. This distance value was the distance value between the two joining clusters that was used by Ward’s method. We looked for the jumps in the decreasing pattern in this bar chart. One possible drop occurs when the number of clusters is approximately 11 and another drop occurs at 25, i.e., the differences in height between two sizes of clusters after these values are all relatively small and approximately the same size. Next, adopting the cluster validation measures approach, which was implemented in the clValid package of Brock et al. (2011), we determined the most appropriate number of clusters within the range from 11 to 25. Table II-5 shows the result of internal and stability measurements that were based on different sizes of cluster. The results from the seven indices indicated that the number of clusters = 21, or perhaps 23, was suitable. Considering the small differences in the order of crop sequences and in their v-test value between the two new small clusters, which belonged to the same original cluster, we finally took 21 as the appropriate number of clusters for the AHC. Fig. II-5 is the visualization of the result of clusters, which was mapped using the program ArcMap.

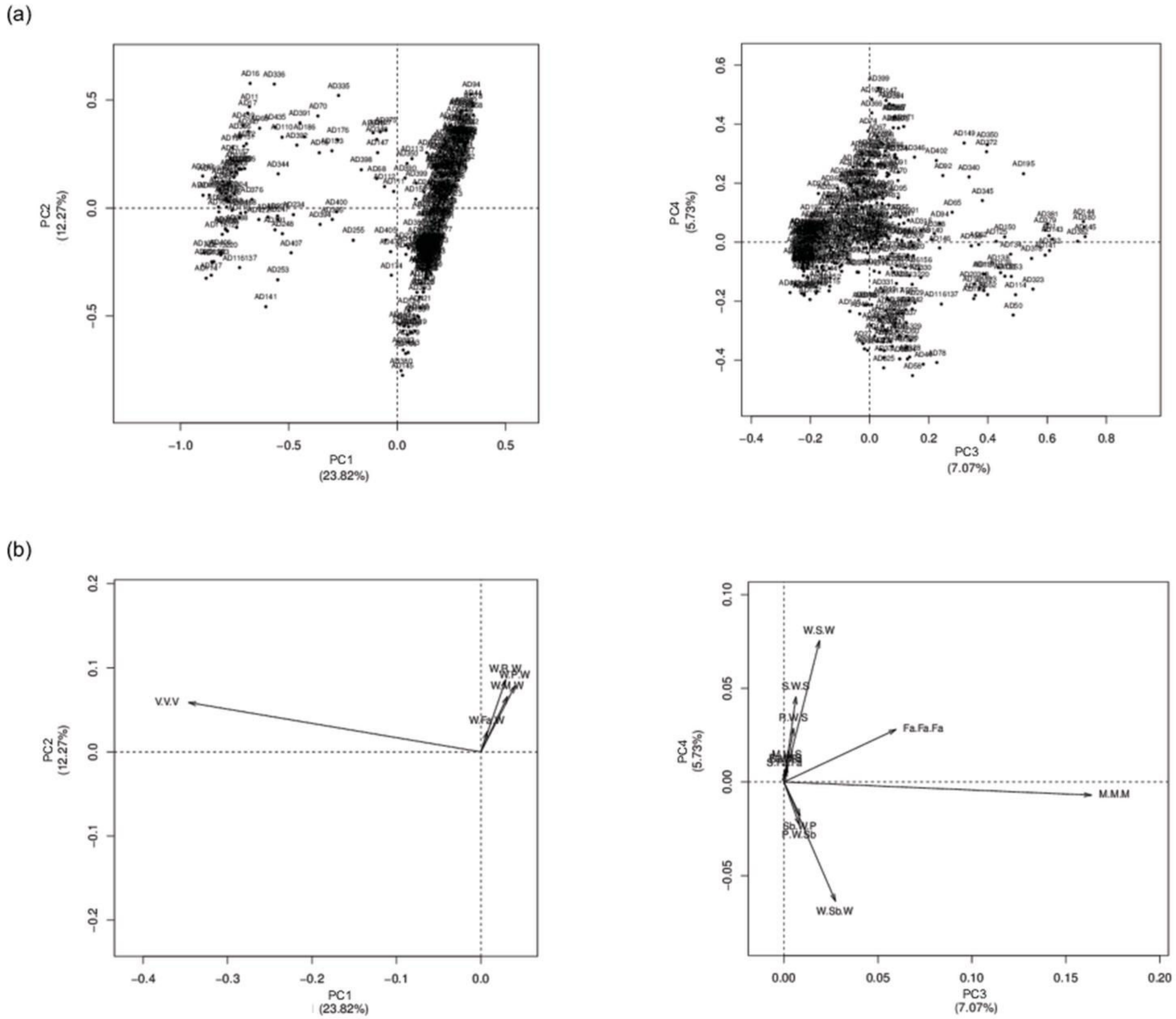


Fig. II-3. Principal component analysis based on the occurrences of 3-year crop sequences across 406 (merged) agricultural districts (AD) during 1992–2003. (a) PCA score plots of (merged) agricultural districts. (b) PCA loading plots of 3-year crop sequences. Left: on PC1 vs. PC2. Right: on PC3 vs. PC4. For visibility, only the crop sequences whose squared coefficients of correlation between variable and components >0.5 for PC1 vs. PC2 and >0.3 for PC3 vs. PC4 are displayed in plots.

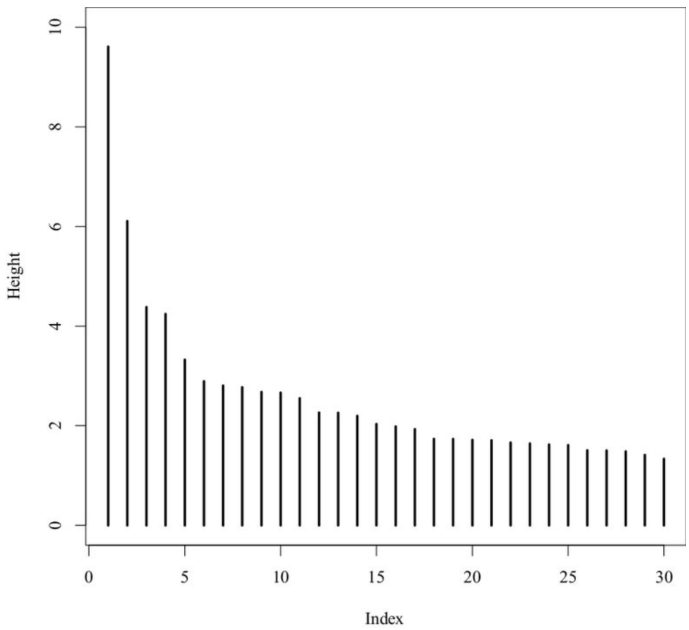


Fig. II-4. Bar plot of the distance values between the two joining clusters that was used by the Ward's method for hierarchical agglomerative clustering.

Table II-5
Internal and stability measurements on different size of clusters to choose an optimal number of clusters for the dataset. Four stability measures are the average proportion of non-overlap (APN), the average distance (AD), the average distance between means (ADM), and the figure of merit (FOM).

Number of clusters	Internal measures			Stability measures			
	Connectivity	Dunn	Silhouette	APN	AD	ADM	FOM
11	164.52	0.04	0.15	0.19	0.57	0.15	0.11
12	165.45	0.04	0.15	0.21	0.56	0.15	0.11
13	173.29	0.04	0.16	0.21	0.55	0.15	0.11
14	173.29	0.04	0.17	0.23	0.54	0.15	0.11
15	191.06	0.04	0.18	0.21	0.53	0.15	0.11
16	195.28	0.04	0.19	0.21	0.52	0.14	0.11
17	214.01	0.04	0.18	0.19	0.51	0.13	0.10
18	223.99	0.04	0.17	0.18	0.50	0.13	0.10
19	223.99	0.05	0.17	0.18	0.49	0.12	0.10
20	225.25	0.05	0.18	0.18	0.48	0.12	0.10
21	225.95	0.05	0.18	0.17	0.47	0.12	0.10
22	225.95	0.05	0.18	0.18	0.47	0.12	0.10
23	232.56	0.05	0.19	0.16	0.46	0.10	0.10
24	234.43	0.05	0.19	0.17	0.45	0.10	0.10
25	243.33	0.05	0.19	0.17	0.44	0.10	0.10
Criteria of well clustering	Minimized	Maximized	near 1	Close to 0	Minimized	Minimized	Minimized

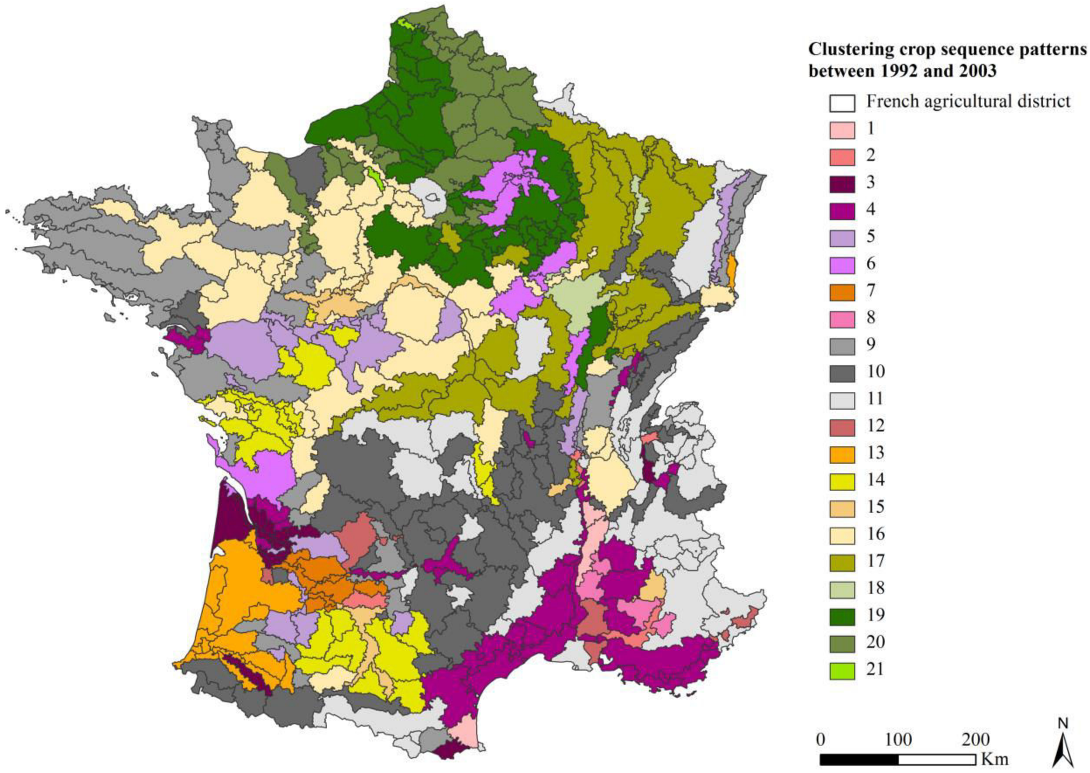


Fig. II-5. Spatial distribution of 3-year crop sequences in France (overseas departments not included) between 1992 and 2003. Clusters belonging to vineyard-based cropping systems are in the purple series. Clusters belonging to maize monoculture and maize-wheat-based cropping systems are in the orange series. Clusters belonging to temporary pasture and maize-based cropping systems are in the grey series. Clusters belonging to wheat and barley-based cropping systems are in the green series. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Description of the crop sequence patterns

The crop sequence patterns that are delimited in Fig. II-5 can be described by both the v-test values that were obtained as outputs of the function HCPC within the FactoMineR package and by the probabilities of occurrences of major 3-year crop sequences (Table II-6).

Based on the ten most frequent 3-year crop sequences that were identified in each cluster, four types of crop sequence patterns could be identified. The first type was vineyard-based cropping systems, which included the clusters 1, 2, 3, 4, 5, 6, 8 and 12. The second type was characterized by the predominance of maize monoculture and maize/wheat-based crop sequences. Clusters 7, 13, 15 and 16 belonged to this type. The third type was temporary pasture and maize-based cropping systems, which were possibly for livestock. This type included clusters 9, 10 and 11. The fourth type was wheat and barley-based cropping systems, which included the clusters 14, 17, 18, 19, 20 and 21. This pattern of agricultural districts was revealed in the previous PCA. Here, we further describe these 21 clusters using the v-test value.

3.3.1. Vineyard-based cropping systems

Four types of vineyard-based cropping systems were distinguishable. The presence of other cropping systems discriminated these types. The areas of clusters 1, 2, 4 and 12 were characterized by the predominant mixed systems of vineyards for wine and grape production and other fruit production. Maize monoculture and 3-year successions of sown pastures also occurred in this zone. The differences among these clusters were the occurrences of different fruits, which were managed as permanent crop areas. For example, peaches and apricots were widely grown in the agricultural districts of cluster 1. Apples, pears and plums were dominant in the zone of cluster 2. Other species of fruits were grown as specialty crops in clusters 4 and 12. Furthermore, the monoculture of durum wheat was an important characteristic of the cropping systems of cluster 4. Cluster 3 is the second type of vineyard-based cropping system. Vineyards were predominant in the agricultural districts of this cluster, whereas maize monoculture and maize-fallow-based crop sequences were also broadly implemented. Clusters 5 and 6 can be identified as the third type of vineyard-based cropping system, where vineyards were less frequent than in the zone of cluster 3. Additionally, this type co-existed with wheat and barley, which incorporated oilseed crops and sugar beet-based cropping systems. The appearance of beans and artificial pasture, which was based on alfalfa, in 3-year crop sequences was a remarkable characteristic of cluster 6. A small cluster (cluster 8) that involved four agricultural districts was revealed as the fourth type of vineyard-based cropping system. The occurrences of monoculture of durum wheat and other industrial crops discriminated this cluster from the others.

3.3.2. Maize monoculture and maize/wheat-based cropping systems

Maize monoculture was the dominant crop sequence within the agricultural districts of cluster 13. Fallow and vegetables were often integrated into the maize-based crop sequences in this zone. Clusters 7, 15 and 16 belonged to another type of maize-based cropping system. The surface of maize monoculture was important, whereas maize/wheat-based crop sequences and oilseed crops (sunflower and rapeseed)/wheat-based sequences also took a great proportion of growing areas.

3.3.3. Temporary pasture and maize-based cropping systems

Three large clusters, 9, 10 and 11, which included 137 (merged) agricultural districts, were characterized by the widespread adoption of successive temporary pasture and temporary maize crop sequences. Maize/wheat-based crop sequences and maize monoculture frequently occurred in the zone of clusters 9 and 10. The high values of v-test of three supplementary variables that were relevant to the occurrences of rocky areas, alpine meadows and herbaceous vegetation area emphasized that the temporary pasture and maize-based cropping systems in the zone of cluster 11 were most likely extremely extensive and different from the temporary pasture and maize-based cropping systems of clusters 9 and 10. The small cumulative probabilities of occurrences of the 10 most frequent 3-year crop sequences indicated that arable land under a rotational system occupied a small surface and that the extensive area of cluster 11 for agricultural land use was natural permanent grassland.

3.3.4. Wheat and barley-based cropping systems

Six clusters, which included 115 (merged) agricultural districts, belonged to this type of cropping systems. Cluster 14 specialized inbsunflower cultivation, and sunflower was often grown between two years of cereals.

The specialty of clusters 17 and 18 was rapeseed. Most likely, a typical 3-year “wheat-barley-rapeseed” rotation, which consists of three forms: “wheat-barley-rapeseed”, “barley-rapeseed-wheat” and “rapeseed-wheat-barley”, was broadly adopted in the zone of these two clusters. We can observe that maize/wheat-based crop sequences occurred frequently in the zone of cluster 17. The presence of 3-year successions of the cultivation of wheat and/or barley discriminated cluster 18 from cluster 17. The “wheat-barley-rapeseed” rotation was also implemented in the zone of cluster 19 and 21. The appearance of peas or sugar beet in 3-year wheat and barley-based crop sequences was an important characteristic of the cropping systems of these two clusters.

One remarkable crop sequence that discriminated cluster 21 from 19 is the 3-year sequence of nurseries. The introduction of sugar beet, peas or potatoes between two years of wheat and/or barley was an important characteristic of the cropping systems of cluster 20. The 4-year “wheat-sugar beet-wheat-peas” sequence most likely rotated during the study period in the zone of cluster 20.

Table II-6

Description of the characteristics of 21 clusters based on the v-test value obtained in AHC and the probabilities of occurrences of the 10 most frequent 3-year crop sequences estimated using one-column ergodic HMM2. Nomenclature used is: A (apples), Ap (apricots), B (barley), Bn (beans), Ch (cherries), Fa (fallow), Fo (berry orchard), Fs (orchard of other fruits, nut trees), G (grassland), H (herbaceous vegetation area), Id (industrial crops), M (maize), N (nursery), O (oats), Oc (other cereals), Ol (oilseed crops), Of (other fodder crops), OS (other seminatural areas including heathland, moors, hedgerow), Ov (other vegetables), P (peas), Pa (artificial pasture sown by alfalfa and clover), Pe (peaches), Pl (plums), Pm (alpine meadows), Pr (pears), Ps (potatoes), Pt (temporary pasture), R (rapeseed), Ry (rye), S (sunflower), Sa (6 major species of fruits and crops), Sb (sugar beet), Ss (mixed orchard of 6 major species), St (rocky areas), Tx (fiber crops), V (vineyards) and W (wheat). CS: crop sequences. AD: agricultural districts. v-test values of variables include both active and supplementary variables.

Cluster	1		2		3		4		5		6		7	
v.test value	PePePe	17	AAA	14	MMM	9	VVV	10	VVV	9	BSbSb	8	PlPlPl	19
	PePeM	16	PrPrPr	12	FaVV	8	VFaW	8	FaFaS	7	PaPaW	7	MFaOv	12
	ApApAp	14	FaOcPe	10	VVV	7	VVFa	7	SBW	7	PaWSb	7	OlOlS	12
	OcPW	13	OvOvA	10	FaFaV	6	VFaFa	7	SMW	7	WBPa	7	MSM	11
	AOvOv	12	OcPePe	10	PaPtM	6	WWV	6	WOcFa	7	BPaPa	7	PlPlM	10
	WOcOv	12	AAPe	10	PtPtOf	6	VVW	6	SSW	6	BOB	7	OcWOc	10
	OcOvM	12	OvAA	10	BnOcBn	6	FaFaV	5	FaSW	6	RBnSb	6	SOlW	9
	IdPM	12	FaFaPe	10	VFaM	6	ApApFa	5	ASS	6	PSBn	6	FaOvM	9
	SaPePe	12	OvOvPa	10	VFaV	6	FaVV	5	OcOcR	6	BnRR	6	SMS	9
	SApAp	12	ChChA	10	SPlPl	6	HHH	5	SFaS	6	PsSbBn	6	BOlM	8
The 10 most frequent 3-yr CS (%)	VVV	17	VVV	11	VVV	61	VVV	47	VVV	14	VVV	15	MMM	10
	PePePe	8	AAA	6	MMM	15	WWW	3	MMM	7	BRW	4	PlPlPl	5
	MMM	6	PlPlPl	3	FaFaFa	2	PtPtPt	2	WSW	3	WBR	4	FaFaFa	4
	ApApAp	4	MMM	3	PtPtPt	2	FoFoFo	2	FaFaFa	3	MMM	4	VVV	4
	FaFaFa	2	WWW	3	MMFa	1	MMM	2	WRW	2	RWB	4	WSW	3
	WSW	1	PaPaPa	2	MFaFa	0.5	ApApAp	1	MWM	2	WRW	4	SWS	3
	PaPaPa	1	FaFaFa	2	FaMM	0.4	FaFaFa	1	WMW	2	FaFaFa	2	MWM	2
	FoFoFo	1	PrPrPr	2	FaVV	0.4	PaPaPa	1	SWS	2	WPW	2	WMW	2
	OvOvOv	1	WSW	2	MPtPt	0.4	ChChCh	1	PtPtPt	2	WSW	2	MMW	1
	WMM	1	PtPtPt	2	VVFa	0.3	OvOvOv	1	MWPt	1	RWW	2	WMM	1
Number of AD	3		4		12		24		20		10		6	

Table II-6 (continued)

Cluster	8		9		10		11		12		13		14	
v.test value	IdIdId	19	StStSt	11	FoFoFo	15	MMW	8	PtPtPt	8	MMM	14	RWS	14
	FsFsFs	19	PmPmPm	10	ApApFo	9	MWM	8	BBPt	7	MFaFa	11	FaWS	14
	IdIdW	13	BPaPt	5	OvFaPa	8	PtMM	7	OcMPt	6	MMFa	11	SWS	12
	WIdId	11	BWPa	5	ApFoFo	8	WMM	7	OcPtPt	6	MFaM	9	SWFa	12
	IdIdFa	11	PaPaPt	5	VNW	8	PtPtM	6	BOcB	6	MOvOv	9	WSW	11
	SsSsAp	10	ORyB	5	NSN	8	MPtPt	6	BPtPt	6	OvOvM	9	WFaS	11
	FsIdId	10	PaPtPa	5	FaFaN	8	MOcM	6	MOcOc	6	FaMM	8	SWOc	10
	SSPa	10	HHH	4	FoFaFa	8	MPtM	6	BBOc	6	FaMFa	8	MWS	10
	IdIdFs	10	OcBPa	4	RNW	8	OcMW	5	OcOcM	6	MMOv	8	PWS	10
	IdIdPt	10	PaPtPt	4	FoFoFt	8	PtMPt	5	OcMOc	6	FaFaM	7	WBS	10
The 10 most frequent 3-yr CS (%)	VVV	28	PtPtPt	5	VVV	15	MMM	12	PtPtPt	16	MMM	56	WSW	11
	IdIdId	10	MMM	1	FoFoFo	8	PtPtPt	9	MMM	5	FaFaFa	4	SWS	7
	FsFsFs	6	OcOcOc	0.9	AAA	8	MWM	5	PaPaPa	2	PtPtPt	3	MMM	5
	WWW	6	PaPaPa	0.7	MMM	6	WMW	4	BPtPt	2	OvOvOv	2	WRW	3
	PaPaPa	2	BPtPt	0.5	PePePe	4	MMW	3	OcPtPt	2	MMFa	2	FaFaFa	3
	WSW	1	VVV	0.5	PtPtPt	2	WMM	2	PtPtM	1	MMOv	1	SWW	2
	FaFaFa	1	WWW	0.5	PrPrPr	2	PtPtM	2	MWM	1	MFaFa	1	VVV	2
	WFaW	1	OcPtPt	0.4	FaFaFa	2	MPtPt	2	MPtPt	1	FaMM	1	WWS	2
	FaWW	1	WMW	0.3	ApApAp	2	MWPt	2	WMW	1	OvMM	1	WMW	2
	WWFa	1	OPtPt	0.2	OvOvOv	2	PtMW	1	WPtPt	1	MOvM	0.9	SWR	2
Number of AD	4		32		57		48		6		16		21	

Table II-6 (continued)

Cluster	15		16		17		18		19		20		21	
v.test value	AAA	11	PWR	9	RWB	9	BBR	16	SbWB	14	WSbW	15	NNN	19
	ChPsPs	8	WRW	9	RWR	9	PaSM	12	BSbW	13	MWSb	14	IdWFa	14
	BnMS	8	RWM	8	BRW	9	FaPaR	12	PWB	12	PWSb	13	OBPs	14
	SsChCh	8	WWR	8	WBR	9	BPaS	12	WBSb	12	SbWPs	13	PTxR	14
	BBCh	8	PWM	7	BWB	8	PaBO	12	BPW	12	WPsW	13	BPsSb	14
	SBRy	8	WMW	7	FaRW	8	PaRW	10	WBP	12	SbWSb	12	FaRSb	14
	RRyM	8	RWW	7	MWR	8	WBB	10	SbWW	10	SbWP	12	SbPsSb	14
	ChChPs	8	MWM	7	RWFa	7	BOPa	9	SbWP	10	PsWSb	12	MPaP	14
	PtBRy	8	MWR	6	WRB	7	PaBB	8	WSbW	10	FaWP	12	PaPtR	14
	ASM	8	MPW	6	WFaR	7	FaBR	7	BPtW	9	WTxW	11	OOvW	14
The 10 most frequent 3-yr CS (%)	MMM	9	MMM	5	BRW	7	BRW	13	WPW	4	WSbW	9	WRW	5
	WSW	4	WMW	5	WBR	6	RWB	12	WSbW	4	WPW	6	WPW	5
	FaFaFa	4	WRW	4	RWB	6	WBR	10	WRW	3	WMW	3	BRW	3
	AAA	3	MWM	4	WRW	5	WBB	4	WMW	3	PWSb	3	RWW	3
	WRW	3	PtPtPt	3	PtPtPt	5	BBR	4	BRW	2	SbWSb	3	WBR	3
	SWS	2	WBR	2	RWR	3	FaFaFa	3	WBR	2	WPsW	2	WWW	3
	WMW	2	BRW	2	MMM	3	WRW	3	PWB	2	SbWP	2	RWB	3
	SWW	2	WPW	2	WMW	2	WWB	2	BPW	2	WRW	2	WSbW	2
	WWW	2	WSW	2	RWW	2	RWW	2	SbWB	2	MWM	2	WWR	2
	WWS	1	FaFaFa	2	MMW	1	BBB	2	RWB	2	WWW	2	NNN	2
Number of AD	6		43		30		3		30		29		2	

3.4. Exploration of major non-fixed length crop sequences: the example of cluster 17

The major land-cover categories in the thirty agricultural districts of cluster 17 were as follows: wheat, barley, rapeseed, maize, sunflower, temporary pasture, fallow, grassland, other semi-natural zone and perennial areas. Thus, a one-column ergodic HMM2 with nine Dirac states and one container state was performed. Fig. II-6 is the graphic output of the model, in which the probabilities of transitions between two land-cover categories are expressed by the width of the line that joins the two land-covers. One can see that the major crop sequences are:

(1) Three-year crop rotation “wheat-barley-rapeseed”, which is composed of three 3-year sequences that strictly rotate during the entire study period: barley-rapeseed-wheat
(shown in Fig. II-6b by polyline “B1-C2-A3-B4-C5-A6-B7-C8-A9-B10-C11-A12”), “wheat-barley-rapeseed” (polyline “A1-B2-C3-A4-B5-C6-A7-B8-C9-A10-B11-C12”), and “rapeseed-wheat-barley”(polyline “C1-A2-B3-C4-A5-B6-C7-A8-B9-C10-A11-B12 ”).

(2) Two-year strict crop rotation “maize-wheat”, which is composed of two rotating 2-year sequences, “maize-wheat” (polyline “D1-A2-D3-A4-D5-A6-D7-A8-D9-A10-D11-A12”) and “wheat-maize”(polyline “A1-D2-A3-D4-A5-D6-A7-D8-A9-D10-A11-D12”).

(3) Two-year crop rotation “rapeseed-wheat”, which is composed of two rotating 2-year sequences, “rapeseed-wheat” (polyline “C1-A2-C3-A4-C5-A6-C7-A8-C9-A10-C11-A12”) and “wheat-rapeseed” (polyline “A1-C2-A3-C4-A5-C6-A7-C8-A9-C10-A11-C12”).

(4) Monoculture of maize (line D1D12), wheat (line A1A12), and barley (line B5B12);

(5) Long-term fallow (lines F1F4 and F5F10) and temporary pasture (line G1G2);

(6) Two-year sequences, “rapeseed-wheat” and “maize-wheat”, and one year of wheat may interrupt the predominant 3-year crop rotation “wheat-barley-rapeseed”, such as “barley-rapeseed-wheat-rapeseed-wheat-barley-rapeseed-wheat-barley-rapeseed-wheat-”(polyline “B1-C2-A3-C4-A5-B6-C7-A8-B9-C10-A11-”), “rapeseed-wheat-barley-rapeseed-wheat-barley-rapeseed-wheat-maize-wheat-barley-rapeseed” (polyline “C1-A2-B3-C4-A5-B6-C7-A8-D9-A10-B11-C12”) and “wheat-barley-rapeseed-wheat-barley-wheat-barley-rapeseed-” (polyline “A1-B2-C3-A4-B5-A6-B7-C8-”).

Of note, we can identify the occurrence of major unfixed-length crop sequences and even the exact crop rotations within a spatial unit; however, the rate of their occurrences is impossible to quantify.

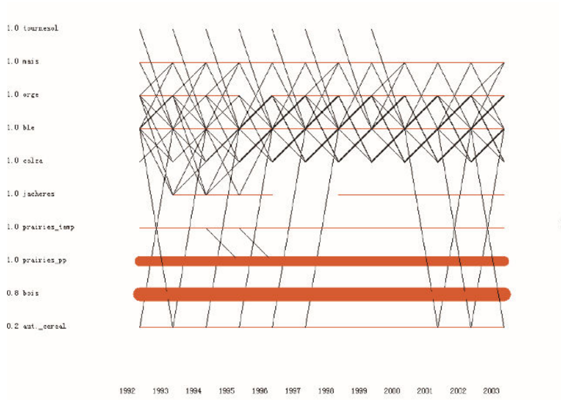
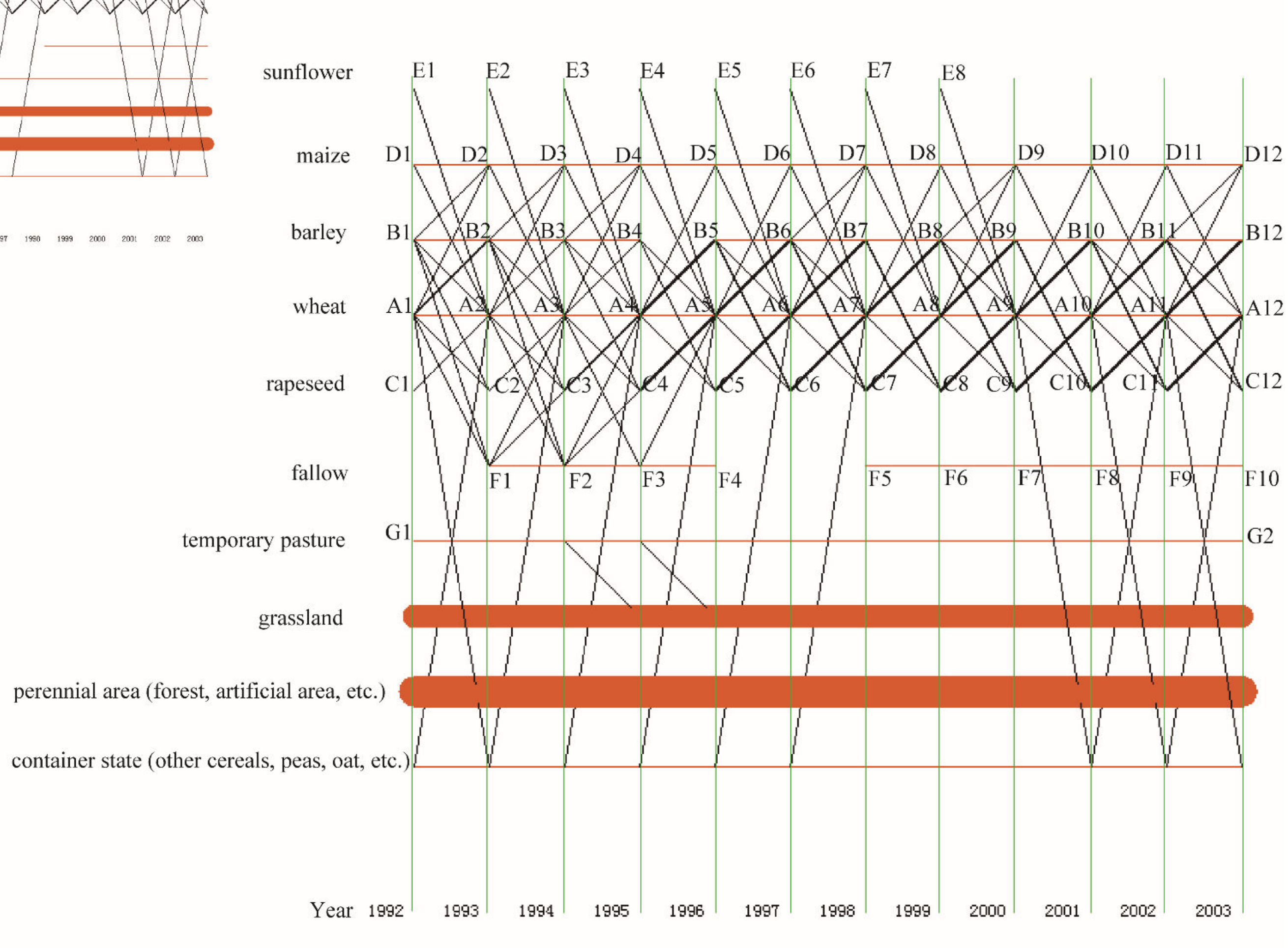


Fig. II-6. Graphic output of CARROTAGE. In order to improve the visibility and to guide the audience, we add a grid to give a coordinate for one land-cover in a given year. (a) Original graph: the a posteriori probabilities of transitions between states (diagonal and horizontal lines). Only the transitions whose probability is greater than 0.5% are displayed; (b) Modified graph with adding a grid to give a coordinate for one land-cover in a given year.

(a)

(b)



4. Discussion

4.1. A generic approach to describe regional time-space regularities in agricultural landscape

The modeling approach that is presented in this paper provides a tool to derive spatially explicit data regarding cropping patterns at a large regional scale from the sequential annual land-cover survey data. With this tool, users can (a) identify homogeneous zones in terms of fixed-length crop sequences across a large territory, (b) understand the characteristics of cropping systems within a region in terms of typical crop sequences, (c) identify the major crop sequences of a region according to the probabilities of occurrences, and (d) identify the most representative spatial units of each cluster.

The potential application of this modeling approach is as a tool to extract spatially explicit information regarding cropping patterns from time series data of land-cover for the environmental or economic assessment of agricultural production systems. This method can also be used for building historical data regarding cropping patterns, which can be integrated into the land-use change modeling framework for land planning and policy making.

4.2. Limitations of crop sequence-based modeling

The approach that has been proposed here, however, has several limitations. These limitations are primarily due to the simplified representation of the complex rotational cropping system.

First, we took the concept 'crop sequences', which is limited to the order of appearance of the crops during a fixed period, instead of the exploration of the exact cycle of crop rotations during the study period. Indeed, most agricultural land management practices are decided at the local scale by the farm holders under different biophysical constraints and socio-economic conditions. Joannon et al. (2008) indicated that farmers grew crops in a field of their farm over the years without implementing strict crop rotations and kept a degree of freedom in their choices. This observation may explain why a great number of crop sequences can be observed over a large area. Two observation-based studies confirmed this point. Leteinturier et al. (2006) observed 62,499 7-year crop sequences in an area of 255,461 hectares in the Wallonia area of Belgium. In another study in the central region of the United States, there were 24 crops that were observed in a database, and a total of 9,826,083 4-year crop sequences occurred from 2003 to 2010 (Plourde et al., 2013).

Second, because we adopted a temporal regularity mining tool that was based on hidden Markov models, we were required to define an observation symbol for the model. In our case, the observation symbol was crop sequence, which was composed of three components: the length of the sequence, the appearance of crops and the crop order. Our strategy of modeling the spatial distribution of crop sequences is to classify the agricultural districts, which are based on the occurrences of crop sequences within each spatial unit and on further mapping the result of clustering. Thus, to explore the major crop sequences within each spatial unit, we must define the unique length of sequences for all land units that are studied. However, as we know, in reality, the length of crop rotations ranges from 2 years to 12 years (long crop rotations are often observed in organic farming) (Mudgal and Lavelle, 2010). Therefore, the diversity in crop rotations in terms of the rotation length has been ignored in this study.

Third, based on expert knowledge, we chose a 3-year crop sequence as our observation symbol for all 406 (merged) agricultural districts. However, the fixed-length crop sequences do not indicate a great simplification of complex crop sequences in reality because monoculture and biennial, triennial and quadrennial crop rotations are widely adopted in the field cropping area for cereal and oilseed production in French mainland. Although this choice of the length of crop sequences may be unable to cover the complete cycles based on the long rotations, biennial, triennial and partly quadrennial rotations covers most areas of arable land. With the exception of expert knowledge regarding local cropping systems, the choice of the length of sequence as the observation symbol is also limited to both the temporal depth of data that are available regarding land-cover and the computing power. Moreover, we kept 2549 major crop sequences for clustering 406 (merged) agricultural districts. Potentially innovative crop sequences with rare occurrences were not specifically considered. More complex cropping patterns that involved winter cover crops, intercropping, etc. could not be investigated in this study because the records of the Teruti survey were performed every June between 1992 and 2003 and because each sampling point represents one land-cover type for a year.

4.3. Characteristic of the modeling approach and its potential application to other sources of land-cover data

One remarkable characteristic of this modeling approach is the use of historical national land-cover survey data for identifying crop sequences at a large regional scale. One benefit of using this type of survey data regarding land-cover with detailed crop information for exploring crop sequences is its time series continuity at the same location. This time series continuity allows the information regarding cropping patterns to be coupled with other agricultural statistics (i.e., the National Census of Agriculture, the Survey of the Structure of Agricultural Holdings, the Survey of Agricultural Practices) with fewer problems of time mismatch, which further improves the description and the assessment of the agricultural production systems. With the development of remote sensing techniques, land-cover data that are based on the temporal depth of remote sensing imagery are more available. Martínez-Casasnovas et al. (2005) proposed a method of mapping the main multi-year cropping patterns using crop maps that were acquired from supervised classification of the program Landsat imagery. The temporal depth of remote sensing imagery is often affected by the quality of the image archive, which suffers reductions in landscape views because of persistent cloud patterns and because of changes in the remote sensing system (Rindfuss et al., 2004). Several recent studies have made progress regarding crop classification using time series remotely sensed data for classifying multiyear agricultural land use or for investigating the changes in crop rotation patterns at a large regional scale (Wardlow et al., 2007; Brown et al., 2013; Plourde et al., 2013). Thus, if the remotely sensed multi-temporal land-cover data with maximally detailed land-cover types are available, then it is possible to perform our modeling approach to describe the past or current crop sequence patterns from a regional to a global scale. Ideally, if the data on multi-temporal land-cover covering the entire one year growing season for several years is accessible, then it will be possible to explore more complex cropping patterns, considering both the annual main crops and the cover crops. These high temporal-spatial resolution remote sensing data will provide more spatially temporally explicit and accurate data for investigating cropping systems.

We emphasize that because the tool we used for extracting crop sequences is a temporal data mining tool, the quality of the corpus of observed sequences strongly influences the model estimation of parameters. Constant and continuous land-cover and use data at a stable location are essential. CARROTAGE is not able to handle the corpus with missing values during the study period, and it is preferable to apply the hidden Markov models to large databases.

5. Conclusions

The modeling approach of the spatial distribution of crop sequences that is presented in this study is an empirical modeling method that combines a temporal regularity data mining tool that is based on the hidden Markov models with a classic unsupervised clustering technique for the annual national land-cover survey dataset. The patterns of crop sequences that are identified here satisfactorily represent the homogeneity of the major crop sequences within the zone under similar environmental and socio-economic conditions, as well as the heterogeneity of crop sequence patterns across the entire French mainland territory.

This work allows stakeholders, such as advisory services, agencies of agriculture and state agricultural organization, to evaluate the state of agricultural land-use over a long period. Therefore, these stakeholders may evaluate their role as driving forces in the state of agricultural production systems.

For future studies, two tasks should be performed: investigating the changes in crop sequence patterns and exploring the determinants of the changes, particularly linking the relation between farm types (e.g., the economically based EU Community typology for agricultural holdings) and crop sequence patterns.

This modeling approach can be considered a generic method for modeling the crop sequence patterns using observed land-cover and land-use data. It is possible to apply this approach in other cases using other sequential land-cover and land-use data. It is also possible to perform this approach at different spatial scales. Regarding the effect of the fast growth of investment on the collection of the time series land-cover and land-use data, with categories of crops that are distinguished by different organizations, such as the yearly Land-use/cover area frame statistical survey (LUCAS), which was funded and launched by Eurostat in 2001, obtaining observed data on cropping patterns becomes possible. However, the large volumes of data regarding land-cover and land-use have necessitated the development of innovative data processing and analysis systems for delivering accurate data for global change research.

The contribution of our modeling approach is to extract crop sequences from the sequential land-cover and land-use dataset to provide spatially explicit data regarding cropping patterns for the assessment of environmental impacts of agricultural production systems and for modeling agricultural land-use changes under the rotational system.

Acknowledgements

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Chapter III Characterizing historical (1992-2010) transitions between grassland and cropland in the French mainland through mining land-cover survey data

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Abstract

Grassland, as one of the largest ecosystems on the earth, supports various goods and services to humanity. Historically, humans have increased agricultural output primarily by cropland expansion and agricultural intensification. The cropland area was primarily gained at the expense of grassland and forests. Apart from grassland conversion, increasing consumption of calorie- and meat-intensive diets drives the intensification of livestock systems, which is shifting steadily from grazing to feeding with crops. To cope with the environmental degradation due to agriculture, various forms of 'green payment' were implemented to promote the adoption of sustainable farming practices over the last two decades in the European Union. The aim of this study is to monitor the recent transitions (1992-2010) between grassland and cropland during two Common Agricultural Policy reforms at the French mainland scale. We proposed an innovative approach to link grassland conversion to agricultural commodities and farming systems practices. We first assessed the grassland-to-cropland conversion and further investigated the crop sequence patterns that were observed to be dominant after the conversion through mining land-cover survey data Teruti and Teruti-Lucas. We found the trends of the transitions between grassland and cropland over the two time intervals: the loss of grassland (1992-2003) and restoration or re-expansion of grassland (2006-2010) in mainland France. Our finding on the crop sequence patterns after the grassland conversion reveals two notable evolutions of agricultural production systems. These evolutions were related to the increase in the proportion of cropland in the total agricultural land use. One evolution was most likely influenced by the demand for fodder: the conversion from grazing livestock to feeding livestock. Another evolution was the conversion from livestock production to field crop production. Our results indicate that the intensification of livestock farming systems continued over the last two decades in France. We conclude that, the approach developed in this study can be considered as a generic method for monitoring the transitions between grassland and cropland and further identifying the crop sequence patterns after the grassland conversion from time-series land-cover data.
Keywords: Conversion; Crop sequence patterns; Land-cover survey; Agricultural land-use change

1. Introduction

According to FAO (2013), permanent meadows and pasture (the synonym for grassland in our study) covered approximately 25% of the world's land surface over the last two decades. These land-cover types are among the largest ecosystems on the earth and support various goods and services. Grassland is an important source of livestock feed and of livelihood for stock raisers and herders, a habitat for wildlife, and a land component for the in-situ conservation of plant genetic resources.

Suttie et al. (2005) reviewed the characteristics, conditions, present use and issues of the natural grassland at the worldwide scale. They highlight that the condition of the world's grasslands is extremely varied; however, in many cases, it is far from satisfactory. Long-term historical data on grassland is scarce in most areas; thus, the degree of change or degradation must be inferred from the present conditions. Thanks to the increasingly available data on land cover and the improvement in the ability to detect changes in grassland cover, several recent studies investigate the accelerated conversion of grassland to cropland from the regional to national scale (Nitsch et al., 2012; Sylvester et al., 2013; Weeks et al., 2013; Wright and Wimberly, 2013). Remote sensing-based data, such as MODIS, were used to monitor either the area or the quality of grassland at a regional scale (Reeves et al., 2006; Xu et al., 2007). Additionally, Herrero et al. (2009) presented a typology of land use change and evolving livestock systems based on the theories of agricultural intensification and change. They distinguished several types of transitions: from pastoral to agro-pastoral systems, from agro-pastoral to mixed crop-livestock systems with different degrees of intensification and from mixed crop-livestock systems to specialized/industrial landless systems. Nevertheless, the location and the characteristics of the transitions have not been studied to address these questions: Where did grassland-to-cropland conversion occur more frequently: in the livestock zone or mixed livestock-crop zone? Which types of cropping systems replaced grassland areas?

Historically, to cope with the population growth, humans have commonly increased agricultural output by expanding cropland and intensifying agriculture (Lambin and Geist, 2006). Agricultural systems are already major forces of global environmental degradation. For example, cropland expansion occurs at the expense of grassland and forests (Morton et al., 2006; Sleeter et al., 2013). The consequences of the grassland-to-cropland conversion, such as loss of biodiversity, enhanced greenhouse gas emission, degradation of water quality, and increases in soil erosion have been investigated in many studies (Mignolet and Benoit, 2000; Guo and Gifford, 2002; Benoit and Simon, 2004; Foley et al. 2005). However, the intensification of livestock systems was ongoing in the most suitable areas in Europe, North American and South America, where traditional pastoral livestock systems were widespread and made extensive use of ecosystem services. Many of the problems of confinement production were eliminated (Tilman et al., 2002; Asner et al., 2004; Thornton, 2010). Increasing the consumption of calorie- and meat-intensive diets steadily drives the livestock system from grazing to feeding with crops (Naylor et al., 2005).

Responding to the pressures of the population growth and the increasing demand for food, fiber and biomass, sustainable intensification has been studied by agronomists, farmers and their allied partners (Mueller et al., 2012). Several countries, including the United States, European Union (EU) countries, Japan, Australia and China, have implemented various forms of 'green payment' to promote the adoption of sustainable farming practices over the last two decades (OECD, 2001). Successful cases that maintain environmental and landscape benefits were published. Drummond (2007) confirmed that most of the grassland expansion from cropland in the western Great Plains occurred during 1986-1992 when the Conservation Reserve Program (CRP) was implemented. In the EU, recent changes to the Common Agricultural Policy (CAP) encouraged more extensive grazing management in sheep and beef systems, but a continued trend towards intensification of dairy farming (Stoate et al., 2009). Mu et al. (2013) indicated that a net increase of 77,993 km^2 of grassland between 2001 and 2009, in addition to national restoration programs that guide human activities, caused 80.23% of the total net primary productivity increase in the Inner Mongolia grassland. However, the shortcomings of several agro-environmental policies cannot be neglected. For instance, the lower feed prices caused by the EU 1992 CAP reform have resulted in the continuation of the intensification of livestock production (European communities Court of Auditors, 2000). In Inner Mongolia, the net increase in grassland area, the increase in fragmentation and the decrease in heterogeneity in the grassland biome were observed between 1992 and 2004 (Ranjeet et al., 2009). Hence, it is critical that information about the processes, causes and consequences of land changes reach policy makers so that they can create more effective policies or revise old policies that impact our lives, particularly those policies regarding land-based activities (e.g., agricultural policy and forestry policy) (Lambin and Geist, 2006). Findings from land system science may be broadly useful for policy research and analysis.

France produces approximately a quarter of EU cereals, oilseeds and cattle. It is a net exporter with a net market balance of 9 billion euros (Huyghe, 2005). France is the largest producer of bovine meat and the second-largest producer of milk (whole fresh cow) in the EU during the last decade (Agreste, 2014b). In 2003, 81% of the total agricultural holdings were specialized: for dairy 12%, cattle rearing and fattening 12%, other grazing livestock 11%, pigs and poultry 2% (European Communities, 2005b). The grass and other forage plants made up 74% of the total dry matter available for feeding livestock animals in the year 2011 (Agreste, 2014b). FAO (2013) reports a decline in both grassland and cropland areas between 1992 and 2010 while the EU CAP 1992 and 2003 reforms were implemented. Faïq et al. (2013) reported a 6.3% decrease of grassland between 2006 and 2010 based on land-cover data from the EU Integrated Administration and Control System. To our knowledge, no published studies have investigated the temporal and spatial dynamics of the transition between grassland and cropland in France during the two CAP reforms at the national scale.

In this context, the aim of our study is to monitor the recent (1992-2010) transitions between grassland and cropland in mainland France. We first assess the grassland-to-cropland conversion and further investigate the crop sequence patterns that were observed to be dominant after the conversion through mining the historical land-cover survey time series. The grassland in this study comprises four land-cover types based on the nomenclature of the land-cover survey: permanent grassland (includes temporary pasture which is at least six years old at the year of survey), alpine meadows, herbaceous vegetation areas and grass orchard.

2. Materials and Methods

2.1 Study area and livestock sector in mainland France

Our study area is mainland France (excluding the island of Corse) in Western Europe, which covers 552 thousand square kilometers. The grassland is concentrated in northwestern, northeastern and central France (Huyghe et al., 2005). In the northern plain, permanent grassland consists mainly of pasture, but it does not predominate in the utilized agricultural area (UAA) whereas in central and mountainous regions of France, permanent grasslands with large areas of rough grazing are typical of the territory (Vidal, 2001). The intensively managed grasslands are primarily located in northwestern France (Palacio-Rabaud, 2000). Figure III-1 presents the location of grassland and fodder crop planting zones on the French mainland. Table III-1 outlines the evolution of the UAA at three temporal snapshots in the years of the national agricultural census: 1988, 2000 and 2010.

Table III-1
The evolution of the utilized agricultural area according to the national agricultural censuses in 1988, 2000 and 2010 in the French mainland (excluding the oversea departments and Corse).

	1988	2000	2010
Grassland (ha)	10,118,575	8,186,672	7,491,693
Arable land (ha)	17,063,244	18,342,696	18,260,916
Permanent crops (ha)	1,164,285	1,105,620	987,215
Utilized agricultural area (ha)	28,470,542	27,700,424	26,795,356

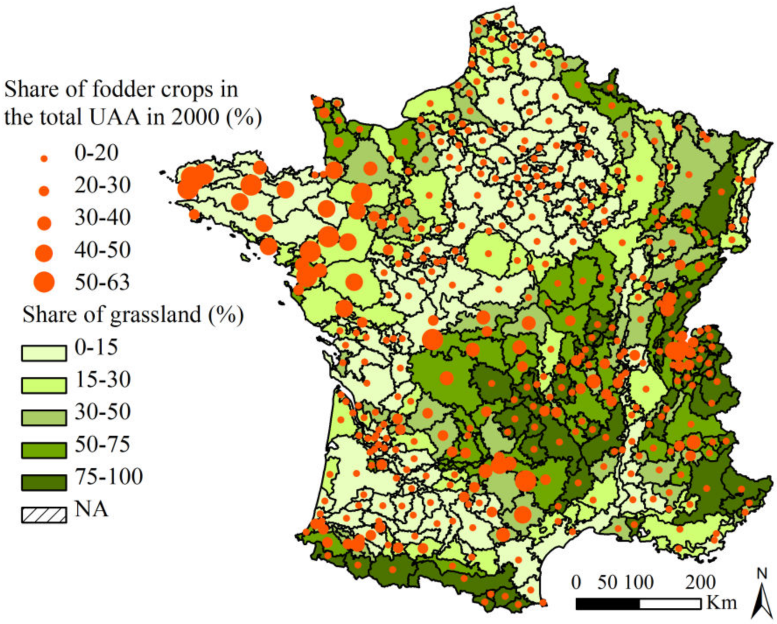


Fig. III-1. Map of the proportions of grassland and annual fodder crops in the total utilized agricultural area (UAA) in 2000. The land-cover data were derived from the agricultural census in 2000, which was conducted by the Ministry of Agriculture of France.

In addition, for the livestock sector, the agricultural holdings specializing in cow's milk production concentrated in the three regions of northwestern France: Brittany, Pays de la Loire and Lower Normandy where there were more than 46% of the total dairy cattle and farmers produced approximately half of cow's milk collected of the country in the year 2013. The production of sheep and goats is mainly located in the mountainous regions in the center of France and the French Alps. One third of the total beef cattle and mixed dairy/beef cattle were reared in Auvergne, Limousin and Bourgogne. Holdings specializing in granivore rearing (including both pigs and poultry) concentrated in Brittany and Pays de la Loire. 66% of the total pigs and 55% of the total broilers were reared in these two regions in 2000 (Agreste, 2014a).

The evolution of grazing livestock population and cow's milk collected in mainland France is given in Table III-2. In the period 1983 to 2010 the collection of cows' milk was rather stable. This is a direct consequence of the quota system and technical progress with a continuous adaptation of supply and demand for milk in the EU (Vidal, 2002). Overall, the grazing stock population has had a moderate decline during the last three decades. In particular, dairy stock sharply declined. The same applies to the sheep population. The number of goats has seen a slight increase over the same period. Approximately 80% of the dairy cattle holdings disappeared while the average number of cows per holding tripled between 1983 and 2010. Moreover, the total number of pigs increased by 26% between 1983 and 1997 (European Communities, 2000a). The average number of pigs per farm increased from 360 to 770 herds in the period between the 1987/1988 and the 1999/2000 censuses. A significant increase in population of pigs was observed in Brittany, La Manche and the several parts of Pays de la Loire while the decline in the number of pigs revealed in the rest of French mainland over the same period (Agreste, 2002). Changes in the structure of the livestock population were marked by several events such as the introduction of milk quotas in 1984 and the 1992 CAP reform (European Communities, 2000a).

Table III-2
The evolution of grazing livestock population and cow's milk collected in the French mainland from 1970 to 2010 (Source: Agreste, 2014a, 2014b; Eurostat, 2015).

	1970	1979	1983	1985	1990	2000	2010
Live bovine animals (thousand heads)	NA	23,550.0	23518.6	22,802.1	21446.0	20,088.9	19,599.0
Dairy cows (thousand heads)	7688.0	7451.9	7195.0	6,506.1	5271.0	4153.3	3718.0
Number of holdings with bovine animals (thousand holdings)	NA	NA	612.0	NA	458.0	282.0	200.0
Number of holdings with dairy cows (thousand holdings)	NA	NA	427.0	NA	227.0	128.0	83.0
Dairy cow number per holding	NA	NA	17.0	NA	23.0	33.0	45.0
Sheep (thousand heads)	10,065.0	12,969.0	13,035.0	12,001.0	11,071.0	9,324.0	7,955.0
Goats (thousand heads)	882.0	1,125.0	1,042.3	1,005.0	1,162.0	1,156.0	1,448.0
Collection of cow's milk (Mio tonnes)	18.5	23.7	26.1	25.5	24.1	22.6	22.9

2.2 Land-cover data

The land-cover data we used were derived from the annual French national land-cover survey database. Two time series data of land cover, which are named Teruti and Teruti-Lucas (Table III-3), were used in our study. These two annual surveys with two-level sampling were conducted by the French Ministry of Agriculture for two periods: 1992- 2003 and 2006-2010 (Ledoux and Thomas, 1992; Agreste, 2010b). At the first sampling level, the entire territory was segmented into 4700 (Teruti) and 32525 (Teruti-Lucas) grids; at the second sampling level, 36 or 10 sampling points were systematically distributed within a segment, respectively. All of the sampling points were surveyed during the summers of the two sub-periods. More details of the Teruti land-cover survey are provided by Xiao et al. (2014). For this study, two corpuses in which the sampling points were in rows and the records of land cover were in columns were used.

Table III-3
Summary of two land-cover datasets: Teruti and Teruti-Lucas land-cover survey. Nomenclature used: AD (agricultural district).

	Teruti (1992-2003)	Teruti-Lucas (2006-2010)
Nb. of sampling points	555,382	304,190
Nb. of land-cover types (crops) used in nomenclature	81 (36)	57 (29)
Minimum Nb. Of sampling points per AD	17	16
Maximum Nb. Of sampling points per AD	8,264	4,524
Area per sampling point	10 m^2	7 m^2

The benefits of using the historical land-cover survey are the following: (1) detailed nomenclature with explicit agricultural uses were available; (2) the ministry-conducted survey provides continuous sampling points, which ensure the representativeness at various spatial scales based on the occurrences and richness of crops.

Furthermore, we chose the French agricultural district (AD) as the spatial unit in this study. This zone was established by the French Ministry of Agriculture in 1946, which was mainly based on the homogeneous agricultural activities and partly based on the similar environmental conditions, such as the soil profile and climate (Richard-Schott, 2009). Mignolet et al. (2007), based on interviews with the regional chambers of agriculture, indicates that after more than 50 years of development of the socio-technical system, the principal agricultural activities within an agricultural district have remained homogeneous in the Seine Basin. Thus, the level of aggregation of Teruti sampling points was defined with respect to the zoning of the agricultural district. All 430 ADs in mainland France were incorporated into this study. Figure III-1 shows the spatial distribution of grassland and annual fodder crops with respect to the boundary of the agricultural district in 2000.

2.3 Data analysis

Because of the discontinuance of the land-cover survey in 2004 and 2005, we analyzed the transition between grassland and cropland for the two sub-periods separately. To investigate the crop sequence patterns that resulted after the grassland conversion, we merely considered the period of 1992-2003 because 2006-2010 is not long enough to support accurate temporal land-cover information for the study of cropping systems under rotation.

2.3.1 Transitions between grassland and cropland

Because our focus was on the transition between grassland and cropland, we first aggregated the land cover types of Teruti and Teruti-Lucas into eight general categories: urban, forest, water bodies, rocky areas, grassland (G), cropland (C) that includes arable land and permanent crops, other semi-natural areas and undefined areas. The category 'grassland' included permanent grassland, grass orchard, alpine meadows and herbaceous vegetation areas. Next, we counted the occurrence rate of 2-year land-use successions (LUSs) using sliding windows with a size of 2 years in the corpus for each AD. Thus, during 12 years, 11 overlapping 2-year LUSs can be observed. We then calculated the net change in the grassland cover as the absolute change from G to C (the occurrence rate of 2-year LUS: 'G-C') minus the absolute change from C to G (the occurrence rate of 2-year LUS: 'C-G').

Finally, we further characterized the transitions between grassland and cropland using Ward's Hierarchical Clustering Analysis (HCA) for 430 ADs in the French mainland. Two descriptive variables were used in the HCA: the net change in the grassland cover and the mean share of grassland in the total UAA (the average value of the 12 yearly shares of grassland in the total UAA). To compare the clusters, a multivariate analysis of variance (MANOVA) was conducted using the function 'manova' within R software (R Core Team, 2012).

2.3.2 Crop sequence patterns after the grassland conversion

To explore the crop sequence patterns following the grassland-to-cropland conversion, we removed 18 ADs where conversion did not occur from the corpus, according to previous identification. We retained all of the crops and grassland in individual categories and aggregated other land covers into four general categories: perennial natural surface (forest, water bodies and rocky areas), urban, other semi-natural areas and undefined areas. Next, we counted the occurrence of 4-year LUSs using sliding windows with a size of four years within each AD. Thirdly, we filtered all 4-year LUSs in the form of 'grassland-annual crops-annual crops-annual crops' from 4-year LUSs. In other words, we investigated the 3-year crop sequence patterns after the grassland-to-cropland conversion. These LUSs that involved a one year grassland followed by three successive years of annual crops were retained as descriptive variables to classify 412 ADs using principal component analysis (PCA) prior to HCA. Performing PCA on the raw data is an efficient technique for avoiding high correlations between variables, and it can improve the robustness of the clustering analysis (Josse and Husson, 2012). Therefore, HCA was applied on the first components of PCA, which explained 80% of the total inertia.

All of the hierarchical clustering analyses were based on the Euclidean distance and Ward criterion and were carried out using the R software package "FactoMineR" (Lê et al., 2008). We first chose a large range of clusters based on the evident drop in the bar graph of the distance values, which was drawn using the "Cluster" package within R. We then applied the R software "clValid" package (Brock et al., 2011) to obtain a suitable number of clusters within this range.

Finally, the result of the clustering analysis was mapped with the aid of ArcMap10 to visualize the spatial distribution of the net change in grassland and the crop sequence patterns after the grassland conversion.

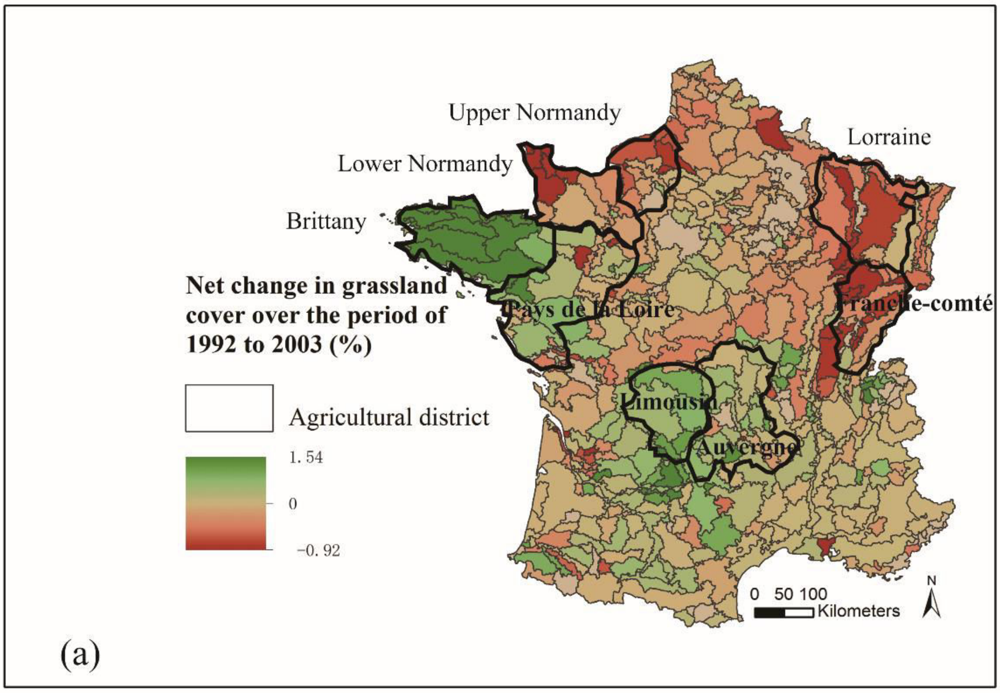
3. Results

3.1 Trends in the transition between grassland and cropland

Geographic and temporal variability in the phenomenon of the transition between grassland and cropland can be observed from 1992 to 2010 (Fig. III-2). The transition differed during the two time intervals. For the first subperiod (1992-2003), the transition between grassland and cropland revealed a west-east gradient (Fig. III-2a). The loss of grassland to cropland was mainly concentrated in northeastern France. The gain in the grassland from cropland occurred in two important livestock zones: Brittany and Pays de la Loire and Massif Central. Between 2006 and 2010, we observed a slight expansion in the grassland area at the expense of cropland in the Seine watershed, where the traditional field cropping zone is located (Fig. III-2b). This phenomenon could be explained by the implementation of the cross-compliance within the 2003 EU CAP reform in the year 2005. Cross compliance with requirements for the maintenance of the ratio of the permanent grassland in the total UAA at the national level has become obligatory (European Commission, 2003).

By comparing these two maps, we also observed that between 2006 and 2010, an absolute loss of grassland occurred in all of the traditional livestock zones, while grassland restoration occurred in field cropping zone, such as the Seine watershed.

Additionally, 430 ADs were classified into five clusters according to the net change in grassland cover and the mean grassland proportion of the total UAA from 1992 to 2003 (Fig. III-3). The agricultural districts within the clusters differ in the value of the net change in grassland and the grassland ratio in the UAA (Table III-4). We observed that the absolute loss of grassland to cropland not only occurred in the zone where the share of grassland in the UAA was modest (cluster 5), but it also occurred in the field cropping dominant zone (cluster 2) (e.g., the dark green area shown in Fig. III-3). Simultaneously, findings from our analysis indicate that a slight re-expansion of the grassland occurred in the zone where silage maize and temporary pasture-based cropping systems were dominant (cluster 4). This phenomenon can be explained by the adoption of the rotations involving long term temporary pastures (often more than five years) in these agricultural districts. Another zone where grassland slightly gained from cropland was in Massif Central, which is a traditional grazing livestock zone for cattle (cluster 3).



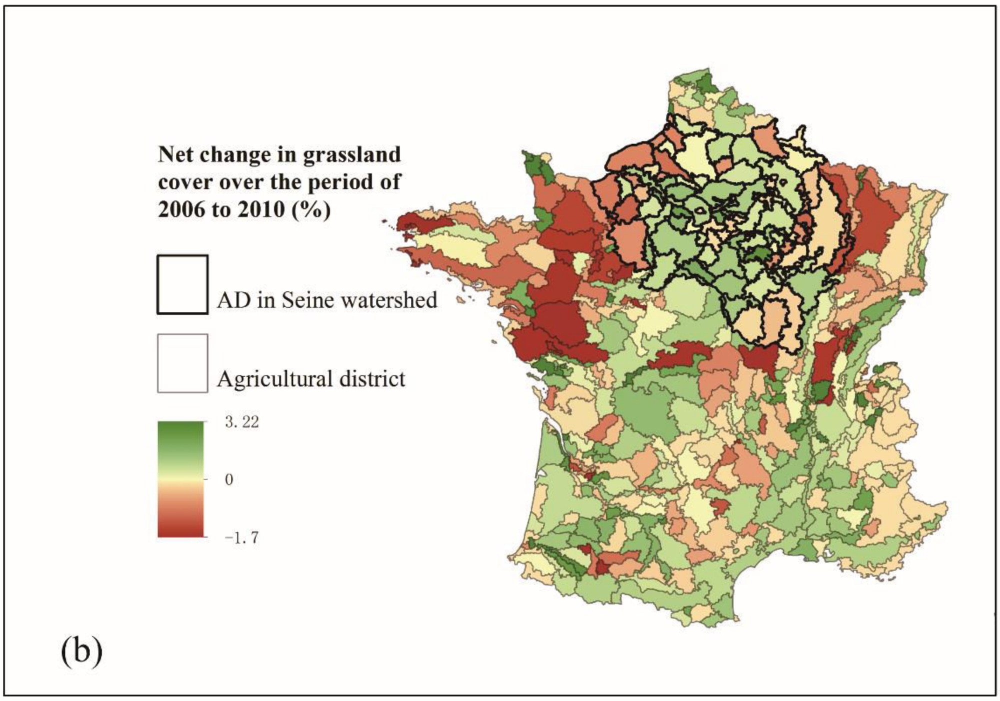


Fig. III-2. Map of the net changes in the grassland cover during 1992-2003 and 2006-2010. The administrative boundaries of the regions and geographical zones of Seine watershed are roughly highlighted by the bold lines.

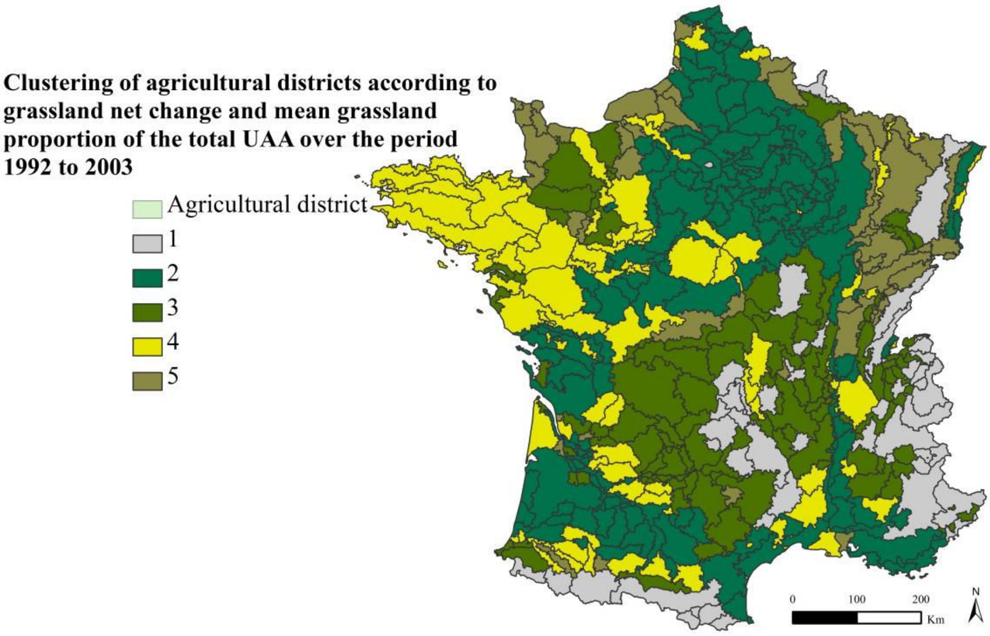


Fig. III-3. The map of the clustering analysis of 430 ADs according to the ratio of grassland in the total utilized agricultural area (UAA) and the net change in grassland from 1992 to 2003.

Table III-4
Comparison of the net change in grassland and the share of grassland in the total utilized agricultural area (UAA) across agricultural districts (ADs) that belong to different clusters (mean ± SD).

Attribute	Cluster (Number of ADs)					
	1 (50 ADs)	2 (148ADs)	3 (94ADs)	4 (84 ADs)	5 (54 ADs)	*p* value
Net change in grassland	0.02 ± 0.06	-0.03 ± 0.10	0.10 ± 0.14	0.15 ± 0.23	-0.28 ± 0.17	<0.0001
Share of grassland in the UAA	0.92 ± 0.07	0.10 ± 0.07	0.61 ± 0.13	0.24 ± 0.07	0.53 ± 0.15	<0.0001

3.2 Crop sequence patterns following the conversion

During 1992 to 2003 the grassland-to-cropland conversion concentrated in the Massif Central, northwestern and southwestern France and (Fig. III-4). Pflimlin et al. (2005) proposed a zoning of livestock systems in Europe which was set up according to the condition of soil and climate, land-use types and the areas under forage plants. Referring to this zoning, we observed that the conversion of grassland mainly occurred in forage crop areas (Brittany and Pays de la Loire), pastoral and maize areas (Lower Normandy), mixed crops-livestock areas (northern edge of Massif Central), grassland-based livestock areas (Franch-Comté, Massif Central) and field crop areas in southwestern France.

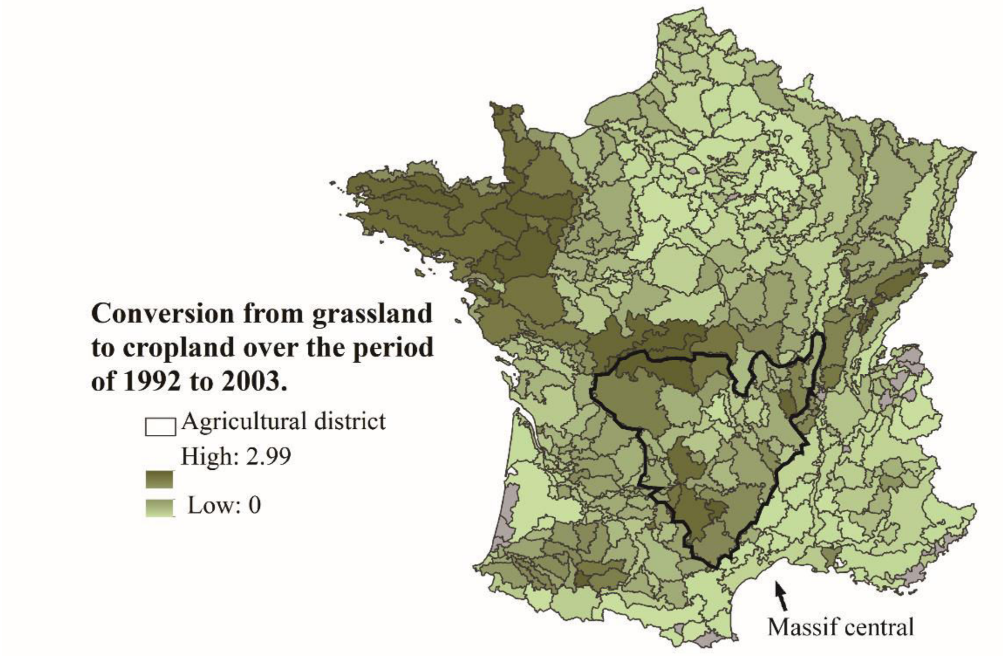


Fig. III-4. The map of the conversion rate of grassland into cropland according to the occurrence rate of 2-year land-use succession 'grassland-cropland' from 1992 to 2003. The approximate location of Massif Central is highlighted by the bold line.

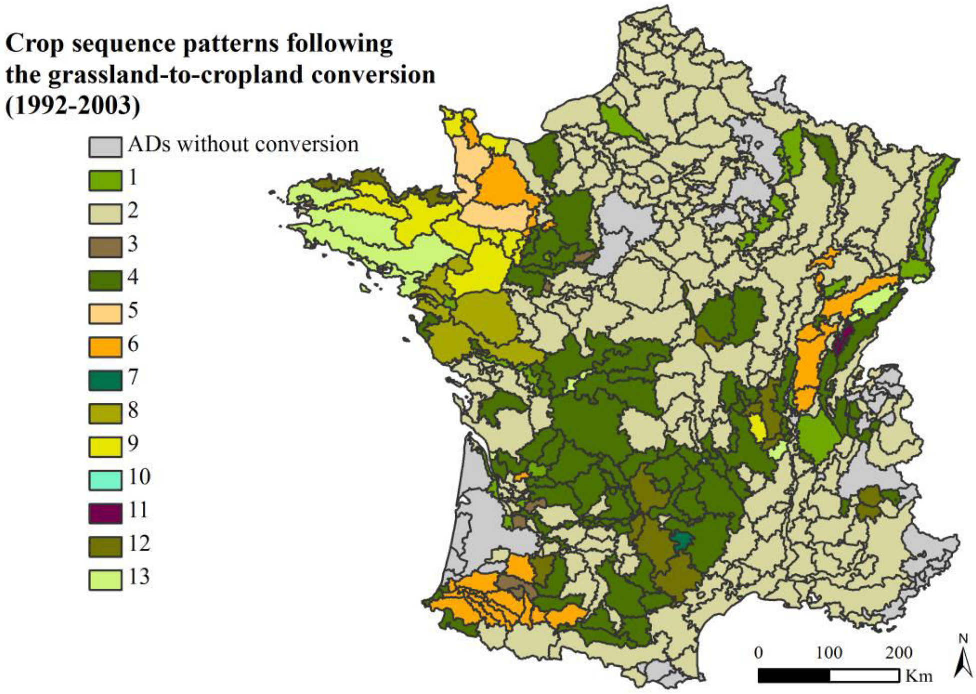


Fig. III-5. The map of clustering analysis of 390 ADs according to the occurrence rate of 4-year land-use successions in form of 3-year successive annual crops following grassland from 1992 to 2003.

The 390 ADs in which grassland was converted to arable land were classified into 13 groups (Fig. III-5). The 12-year averaged share of grassland in the total UAA was calculated for each cluster (Table III-5). In order to have a global view of farming systems (both crops and livestock) and the area under grassland within a region, we further grouped the crop sequence patterns of 13 clusters into four types with considering the 12-year averaged share of grassland in the total UAA and the zoning of livestock systems proposed by Pflimlin et al. (2005): (1) grassland predominant livestock area; (2) forage and grassland-based livestock area; (3) mixed crops-livestock area and (4) field cropping dominant area. We then describe the crop sequence patterns after the grassland conversion for these four types of farming systems separately.

The grassland-to-cropland conversion in the grassland dominant area

Grassland covered at least 50% of the total UAA in the zone belonging to clusters 4, 5, 10, and 11. A remarkable expansion of maize, wheat and the monoculture of maize cropping systems turned out to be dominant in the area that was converted from grassland in the zone of cluster 5. Clusters 4, 10 and 11 were characterized by the presence of temporary pasture and cereal-based cropping systems in the zone of grassland loss. This expansion of forage crops highlights the livestock intensification in the traditional extensive grazing livestock zone. Integrating wheat into the forage crop based rotations was a common phenomenon in the zone of three clusters. The weak occurrence rate of “grassland-annual crops-annual crops-annual crops” in the ADs of cluster 4 indicated less grassland-to-cropland conversion than that in the zone of clusters 10 and 11. The presence of monoculture of durum wheat differentiated cluster 10 from clusters 4 and 11.

The grassland-to-cropland conversion in forage and grassland-based livestock areas

The ADs belonging to clusters 6, 7, 8, 9, 12 and 13 were characterized by modest grassland combining with temporary pastures and cereal-based cropping zones as feed for livestock, which include ruminant, pigs and poultry. We observed a noticeable expansion of maize following the conversion of grassland in the zone of clusters 6, 8, 9 12 and 13. Forage maize was integrated into the temporary pasture-based cropping system or was associated with wheat-based crop sequences; additional amounts were grown as monoculture. In northwestern France, the gains in forage maize from grassland loss revealed a north-south gradient that was most obvious in Lower Normandy (cluster 6), moderate in Brittany (clusters 9 and 13) and less evident in Pays de la Loire (cluster 8).

Table III-5

Description of the characteristics of 13 clusters based on the occurrence rate of the 10 most frequent 4-year land use successions (LUSs) in form of ‘grassland-annual crops-annual crops-annual crops’ in the agricultural districts (ADs) within the same cluster. The sum of the occurrence rate of all 4-year LUSs in the ADs belonging to the same cluster equals to 1. The nomenclature is as follows: B (barley), Fa (fallow), G (grassland), M (maize), O (oats), Oc (other cereals), Ol (other oilseed crops), Pa (artificial pasture sown by alfalfa and clover), Pt (temporary pasture), R (rapeseed), Ry (rye) and W (wheat).

Cluster	1		2		3		4		5		6		7	
The 10 most frequent 4-year LUSs in form of ‘Grassland (G)-annual crops-annual crops-annual crops’ in the ADs belonging to the same cluster (%)	GMMM	0.11	GPtPtPt	0.02	GFaFaFa	0.13	GPtPtPt	0.10	GMMM	0.44	GMMM	0.23	GPtPtPt	0.58
	GMMW	0.01	GMMM	0.02	GPtPtPt	0.11	GMMM	0.04	GPtPtPt	0.19	GPtPtPt	0.11	GBPtPt	0.49
	GPtPtPt	0.01	GMMW	0.01	GMMM	0.05	GOcPtPt	0.02	GMWM	0.12	GMMW	0.04	GOcPtPt	0.36
	GMWM	0.01	GFaFaFa	0.01	GMPtPt	0.02	GMPtPt	0.02	GMMW	0.12	GMPtPt	0.04	GOcBPt	0.16
	GMMFa	0.01	GMWM	0.01	GMMPt	0.02	GBPtPt	0.02	GMPtPt	0.12	GMWM	0.03	GOcOcPt	0.13
	GMWB	0.01			GMWM	0.02	GWPtPt	0.01	GMMPt	0.06	GMMPt	0.02	GBBPt	0.09
	GMWPt	0.01			GFaOlOl	0.01	GOcOcOc	0.01	GMWPt	0.05	GFaFaFa	0.02	GBBB	0.07
	GMPtPt	0.01			GOcPtPt	0.01	GOPtPt	0.01	GPtPtM	0.02	GMWPt	0.01	GOcOcOc	0.05
	GFaFaFa	0.01			GOlFaFa	0.01	GMWM	0.01	GMWB	0.02	GWPtPt	0.01	GPtPtOc	0.05
	GMWR	0.01			GMMB	0.01	GMMW	0.01	GWMW	0.02	GWMW	0.01	GRyBPt	0.05
Mean share of grassland in the total UAA (12 year averaged)	35%		32%		17%		53%		52%		42%		41%	
Number of ADs	20		220		9		72		3		22		1	

Cluster	8		9		10		11		12		13	
The 10 most frequent 4-year LUSs in form of ‘Grassland (G)-annual crops-annual crops-annual crops’ in the ADs belonging to the same cluster (%)	GPtPtPt	0.16	GPtPtPt	0.22	GWWW	0.27	GPtPtPt	0.28	GPtPtPt	0.22	GPtPtPt	0.38
	GMPtPt	0.11	GMMM	0.12	GBOcOc	0.27	GBBPt	0.23	GOcPtPt	0.05	GMPtPt	0.09
	GMWPt	0.09	GMWM	0.1	GPtPtPt	0.27	GBBB	0.14	GBPtPt	0.04	GMMM	0.06
	GMMM	0.06	GMPtPt	0.1	GFaWPt	0.27	GBPtPt	0.11	GMMM	0.04	GMWM	0.04
	GWPtPt	0.05	GMMW	0.07			GOPtPt	0.07	GMPtPt	0.02	GMWPt	0.03
	GMPtM	0.03	GMWPt	0.06			GOBB	0.07	GOcOcPt	0.02	GMMW	0.03
	GMMPt	0.03	GMMPt	0.04			GBWB	0.04	GWPtPt	0.01	GMMPt	0.02
	GMWM	0.03	GWPtPt	0.04			GOcBPt	0.04	GMMPt	0.01	GPtPtM	0.02
	GBPtPt	0.03	GWMW	0.02			GBBW	0.04	GPaPaPa	0.01	GMMOc	0.02
	GMMW	0.02	GMWW	0.02			GOBPt	0.04	GMMW	0.01	GOcPtPt	0.02
Mean share of grassland in the total UAA (12 year averaged)	33%		43%		54%		70%		49%		35%	
Number of ADs	6		12		1		2		13		9	

The grassland-to-cropland conversion in mixed crops-livestock areas

The presence of mixed crops-livestock systems characterized the agricultural districts of cluster 1. The conversion of grassland to grow more cereals was observed in this zone. Maize and wheat-based crop sequences gained the most area from the conversion. Temporary pastures and maize-based forage livestock also expanded in the grassland conversion area.

The grassland-to-cropland conversion in field cropping dominant areas

The small share of grassland in the total UAA differentiated the ADs of cluster 3 from the other clusters. The most remarkable characteristic of the ADs belonging to this cluster was the conversion of grassland to retain three-year successive fallow or to integrate fallow into crop sequences. This gain in fallow area at the expense of grassland can be partly interpreted as the impact of the 1992 CAP reform, which required maintaining the ratio of fallow land in cropland. Moreover, other oilseed crops, such as soybean and flax, were integrated into the crop sequence. In this poor grassland zone, the conversion of grassland into cropland for forage or commerce continued between 1992 and 2003.

A large number of ADs were grouped in one cluster (cluster 2). The occurrence rate of grassland-to-cropland conversion was very low in the zone of this cluster.

4. Discussion

4.1 Comparison of crop sequence patterns after grassland-to-cropland conversion to existing cropping patterns

Here, we compare the crop sequence patterns after the grassland conversion that we identified to the existing cropping patterns that were investigated in a prior study of stationary crop sequence patterns (Xiao et al., 2014). In summary, the authors applied hidden Markov models to extract 3-year crop sequences (both annual and permanent crops were included) from Teruti datasets. Next, the average values of the occurrence of 2549 main 3-year crop sequences from 1992 to 2003 were used as descriptive variables to group 430 ADs into 21 clusters using hierarchical clustering analysis with Ward's criterion. Four cropping systems were further identified: maize monoculture and maize/wheat-based cropping systems, temporary pasture and maize-based cropping systems, wheat and barley-based cropping systems, and vineyard-based cropping systems. Generally, grassland-to-cropland conversion most frequently occurred in the zones with maize monoculture and maize/wheat-based cropping systems and temporary pasture and maize-based cropping systems. The major 3-year crop sequences following the grassland conversion (i.e., temporary pasture and maize-based crop sequences and maize/wheat-based crop sequences) were very similar to the existing dominant crop sequences. One year of cereals, such as oat or barley, which was planted as fodder crops were associated with the 3-year crop sequences. The occurrence of crop sequence patterns in the zone that gained from grassland conversion was likely due to the expansion of the existing cropping patterns of the region.

4.2 Drivers of grassland-to-cropland conversion

In the literature, the transitions between grassland and cropland in the EU countries and North America were primarily determined by climate change, soil quality, demographic conditions, economic returns of alternative land uses, and land-related policy implementation (Nitsch et al., 2012; Rashford et al., 2011; Sylvester et al., 2013). Here, we discuss the potential explanatory variables of the conversion based on a document analysis.

In general, regarding grassland conversion, the expansion of international trade in meat and recent changes to the industrial livestock system continue to push agricultural systems toward intensification in the more productive and populated areas while abandoning marginal zone (Naylor et al., 2005). On the other hand, some agricultural product development such as biofuel makes the concurrence of land source with grassland. For example, a recent study reveals a net loss of 1.3 million acres of grassland and the rapid development of corn ethanol and soy biodiesel from 2006 to 2011 in the western corn belt of the U.S. (Wright and Wimberly, 2013).

In our case of French mainland, the 1992 EU CAP reform played an important role in reducing the competitiveness of grassland against cropland. According to the analysis of the OECD (2004), the 1992 CAP reform implemented higher compensatory payments for maize than for the other cereals. It may be the principal driver of grassland conversion and the cultivation area expansion of maize in the period 1992-2003. The OECD report also states "much grassland has been classified as eligible for arable aid, on the grounds that it has traditionally been used to grow arable crops within long rotations." As the cropping systems in Brittany and Franche-Comté were dominant in long rotations involving temporary pasture, the high occurrence rate of grassland-to-cropland conversion that was observed in this zone is likely caused by this arable land aid. In the three regions specializing in cow's milk production: Brittany, Pays de la Loire and Lower Normandy, the grassland loss may be explained by under the EU quota system of milk, the decrease in both dairy cow numbers and agricultural holdings with dairy cattle from 1985 to 2010. The continuous concentration and intensification of pig production and the loss of the link between land and livestock production (Agreste, 2002, 2013) in the regions specializing in pig production i.e. Brittany, La Manche and Pays de La Loire should be correlated with the grassland-to-cropland conversion within the three regions. Because the farmers need less area to feed their animals and may reduce the grassland area, less fertile paddocks are abandoned or other commodities are produced.

Moreover, a rise in the world market prices of cereals (e.g., soft wheat, durum wheat, barley and maize) between 1992 and 1995 and a downward trend of the domestic producer prices of individual commodities for wheat, maize and sugar beet until 2005 in the EU countries (OECD, 2011) could have contributed to the grassland-to-cropland conversion.

4.3 Strengths and weaknesses of this study

We emphasize that an advantage of our study is the use of land-cover time series for detecting the transition between grassland and cropland. By inferring changes from two temporal snapshots, the time series land-cover data support a greater accuracy when investigating the enduring shift in land cover, as opposed to comparing the land cover maps at multiple temporal snapshots.

Furthermore, counting the occurrence rate of the land-use successions 'grassland-cropland' and 'cropland-grassland' to assess the transition between grassland and cropland can fully capture the shifts between these two land cover types during the entire study period. In France, when temporary pasture is grown for more than five years, it is classified as grassland. The transition between cropland and grassland is highly dynamic; the cropping system is dominant in long term temporary pasture and maize-based crop sequences. In this case, multiple changes occurred over the entire study period at the same location.

As suggested by Rashford et al. (2013), empirical models of grassland conversion have been limited by data availability. Advances in remote sensing have increased the availability of high temporal-spatial resolution land-cover data. However, the use of satellite imagery data to investigate grassland conversion still faces several challenges, such as remote sensing accuracy, sampling strategy, and computational constraints of big data. In this study, we attempted to explore the transitions between grassland and cropland using land-cover survey data. We described the trends of the transitions during two decades, rather than computing the extent and the point time of the transitions. One limitation of our study is that it is impossible to investigate the variability of conversions within an agricultural district because the sampling points were not geo-referenced within each district. Moreover, the land cover data that we used was based on the manual interpretation of aerial photos. Measurement errors likely occurred in distinguishing grassland from temporary pastures and artificial pastures. Unlike wall-to-wall land-cover data, land-cover data based on discrete sampling across the territory limits the precision regarding absolutely areas of transitions between cropland and grassland.

In addition, we emphasize that the approach presented in this study can be applied with remote sensing time-series data of land cover or land use, such as the land-use information within the Land Parcel Identification System of European Union and the Cropland Data Layer of the United States.

5. Conclusions

We sought to identify and characterize the transition between grassland and cropland during the period of the implementation of EU CAP reforms 1992 and 2003 in mainland France, which we summarize below.

- The transitions between grassland and cropland tended to be characterized by the loss of grassland (1992-2003) and the restoration or re-expansion of grassland (2006-2010) in mainland France.
- The crop sequence patterns that resulted after the grassland conversion reveal two notable evolutions of agricultural production systems. These evolutions were related to crop expansion in the UAA. One evolution was most likely due to the demand for fodder: the conversion from grazing livestock to feeding livestock. Another evolution was the conversion from livestock production to field crop production. Our results indicate that the intensification of livestock farming systems continued over the last two decades in mainland France.

We conclude that, monitoring grassland-to-cropland conversion and evaluating its impacts have been concerned in the research community of land change science for a long time. The innovation of our study is the linkage to agricultural commodities and farming systems practices. The findings of this study contribute to improve understanding of the process and pattern of human land management practices by agriculture affecting terrestrial biosphere. The approaches developed here can be considered as a generic method for monitoring the transitions between grassland and cropland and further identifying the crop sequence patterns that were observed to be dominant after the grassland conversion in the context of changing agri-environmental policy, development of agriculture, and shifts in the demand of agricultural products.

Acknowledgements

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Chapter IV Dynamics of crop sequence patterns between 1992 and 2003 in mainland France

Article prepared for the submission to *Land Use Policy*

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Abstract

The most substantial reforms to the European Common Agricultural Policy (CAP) began in 1992 and intensified in 2003. The successive CAP reforms have influenced relative incentives to commodities and therefore land use allocation in different ways. Numerous emerging studies investigated the changes in agricultural land in Europe in the form of agricultural land abandonment, cropland expansion, intensification of farming systems, and afforestation in the past two decades. However, crop sequences (CSs) as a vital and widespread agricultural land management practice and the changes in crop sequence patterns at a regional scale have been rarely investigated. The objective of this study was to investigate the spatio-temporal dynamics of crop sequence patterns between 1992 and 2003 in mainland France through mining time-series land-cover survey data. Our investigation was at two scales: the national scale by analyzing all 429 French agricultural districts and the assemblage of 90 representative agricultural districts and regional scales by analyzing three principal planting zones of cereals, oilseeds and protein crops (COP) separately. We segmented the entire study period into three non-overlapping subperiods: 1992-94, 1997-99, and 2001-03. We counted the occurrence rates of 3-year CSs within each district and subperiod. The Partial Triadic Analysis was then performed to assess the spatial variability of the crop sequence patterns during a different period and explore the temporal evolution of crop sequence patterns per district. We observed that crop sequence patterns at the national scale were substantially stable and represented merely subtle changes in crop sequence patterns revealed in several parts of the territory. The areas with maize-based CSs — particularly zones specializing in maize monoculture in southwestern and northeastern France — and oilseed crop (i.e., sunflower and rapeseed)-wheat and/or barley-based CSs in the west-central regions expanded throughout the whole study period, whereas the areas with pea/wheat-based CSs declined between the subsequent two subperiods in northern France. We also observed a steady increase in the occurrence of continuous fallow in all three COP planting zones over the entire study period while a decline in the occurrence of cereal-fallow-based CSs took place in the same zone.

Key words: Agricultural land-use change; Land management practices; Spatio-temporal analysis; Land-cover survey Teruti; Cropping system; Partial Triatic Analysis

1. Introduction

In the European Union (EU), agriculture is a large land user, occupying 47.2% of the total land area in 2000 (FAOSTAT, 2011), and plays an important role in many environmental and other land use issues, such as biodiversity conservation, carbon sequestration, nutrient cycling, soil protection, water management, and pollination (Stoate et al., 2009). In the past 25 years, the EU agricultural and agri-food sectors have had to adapt to ever-changing economic, market and policy environments (OECD, 2011). The sector is expected to provide a wider range of goods and services, including non-food products such as bioenergy and ecosystem services, which include wildlife conservation, pollinator management, climate regulation, pest control, soil retention and management of the quantity and quality of water resources (Power, 2010; van Zanten et al., 2014). Successive European Common Agricultural Policy reforms since 1986 have influenced relative incentives to commodities and, as a result, on land use allocation in different ways. In the early years, the CAP promoted the production of major grains, livestock and milk through a system of market interventions. This action resulted in the diversion of land from other uses into the production of these commodities. Subsequent reforms have removed much of the market interventions promoting crops and have replaced them with area payments for cereals, oilseeds and protein crops (COP) since 1992 and subsequent single payments introduced by the 2003 CAP reform (Stoate et al., 2001).

Changes in agricultural land in the EU in the form of agricultural land abandonment, cropland expansion, intensification in cropping systems and livestock systems, transitioning of grassland and arable land, and afforestation (Gellrich and Zimmermann, 2007; Griffiths et al., 2013; Lakes et al., 2009; Nainggolan et al., 2012; Neumann et al., 2011; Nitsch et al,., 2012; Ribeiro et al., 2014; Sklenicka et al., 2014) have captured the most attention from researchers in the last decade. However, as crop sequences (CSs) are a vital and widely implemented agricultural land management practice, the changes in crop sequence patterns at the regional scale have been rarely investigated. Prior experiments or field observation-based studies have proven the impact of changes in both the composition of CSs and the spatial distribution on yield, fertilizer requirement, water quality, solitary bee abundance and species richness, and soil pathogen dynamics (Le Féon et al., 2013; Leoni et al., 2014; Rabotyagov et al., 2010; Soon and Clayton, 2002). Monitoring the changes in crop sequence patterns at a regional scale contribute to the assessment of economic and environmental performance of agricultural production systems and thus is important for agri-environmental policy making and sustainable farming system design.

The lack of information on a continuous representation of land cover at the seasonal and inter-annual scales has limited the detection of spatially explicit data on crop sequence patterns for a long time. Recently, the availability of low-cost time-series data on land cover and progress in the classification of multiyear agricultural land-use data allow the monitoring of subtle changes in cropland (Brown et al., 2013; Chen et al., 2012; Wardlow et al., 2007; Zhong et al., 2011). Several recent studies have investigated the dynamics in crop rotation patterns from the regional to the national scale in the United States (Long et al., 2014a; Long et al., 2014b; Plourde et al., 2013; Stern et al., 2012). These USDA cropland layer data-based studies firstly identified the principal crop sequences or crop rotations and their planted area, and then the changes in the amount or relative proportion of these crop sequences or crop rotations were studied.

Moreover, France is the largest agricultural producer in the EU and produces about a quarter of cereals, oilseeds and cattle in the EU (Colson and Chatelier, 1997). The share of arable land in the total land area in mainland France was approximately 32.9% in 1992 and increased slightly to 33.7% in 2003 (approximate increase by 4.2 thousand km^2) (FAOSTAT, 2011).

The aim of this study was to investigate the spatio-temporal dynamics of crop sequence patterns between 1992 and 2003 in mainland France through mining time-series land-cover survey data. The beginning and end of the study period correspond to two years of EU CAP reforms. Inspired by ecology, we consider all CSs that occurred within the study area and period as a community of CSs. The occurrence rate of crop sequences is equal in "abundance." We studied the evolution of the CSs' community rather than studying the changes in the planting area of several specific or primary CSs. The Partial Triadic Analysis (PTA) (Thioulouse and Chessel, 1987; Thioulouse et al., 2004) was performed for this investigation. Numerous applications of this method can be found in the literature to study the spatio-temporal patterns in diverse research fields (Ernoult et al., 2006; Erös et al., 2012; Gourdol et al., 2013; Napoléon et al., 2012; Rolland et al., 2009).

Crop rotation is defined as the practice of growing a sequence of crops on the same land (Sebillotte, 1974; Sebillotte, 1990; Wibberley, 1996). It is characterized by the identified starter crops and cycle period (e.g., biannual, triennial, and quadrennial) (Dury et al., 2013). The term "crop sequences" is the order of appearance of annual crops during a fixed period. A crop sequence can be the partial or total development of a cycle of rotation, or even the basis of several cycles (Leteinturier et al., 2006). According to our prior study of the spatial distribution of crop sequences (CSs) at the regional and national scale in mainland France (Mignolet et al., 2007; Xiao et al., 2014), the length of sequences was fixed as three years.

2. Materials and methods

2.1 Study area

Our study area consists of mainland France (the island of Corsica is not included), covering 552 thousand square kilometers. Agricultural area as part of the total land area in mainland France decreased from 55.4% in 1992 to 54.2% in 2003 (FAOSTAT, 2011). The area of primary agricultural land use at the beginning, middle and end of our study period is described in Table IV-1. According to primarily the homogeneous agricultural activities and partly the similar environmental conditions such as soil profile and climate, the entire territory was subdivided into 430 French agricultural districts (ADs) by the French Ministry of Agriculture in 1946 (Richard-Schott, 2009). In our study, we used this zoning information to investigate the dynamics of crop sequence patterns. Figure IV-1 offers a look at the spatial distribution of agricultural land use and arable land in the 430 ADs in 2000.

Table IV-1
The area of main agricultural land use in mainland France in 1992, 1997 and 2003 (Agreste, 2004).

	Cereals (wheat, barley, oats, maize, rye and other cereals)	Sugar crops and oilseed crops (sugar beet, sunflower, rapeseed, textile crops and other oilseed crops)	Leguminous crops (peas, beans, broad beans, lupins)	Fallow	Pasture (temporary pasture, artificial pasture, permanent grassland and grass orchard
1992 (million hectares)	10.837	2.215	0.732	0.540	11.736
1997 (million hectares)	10.657	2.519	0.644	0.722	11.172
2003 (million hectares)	10.598	2.406	0.489	1.066	10.897

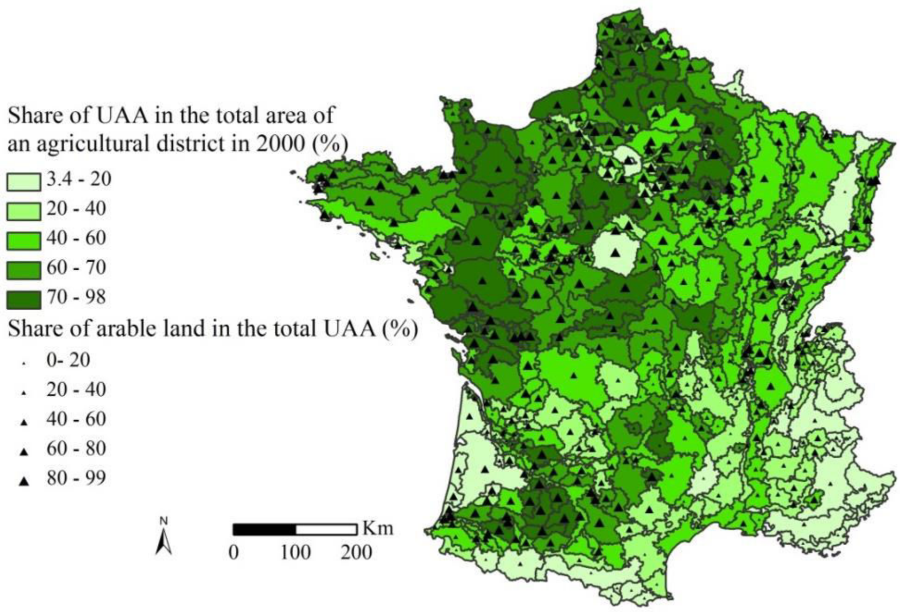

Fig. IV-1. Mapping the share of arable land (including temporary crops, temporary meadows and pasture, and fallow land) in the total utilized agricultural area (UAA) and the proportion of agricultural area in the total area of an agricultural district in 2000, based on the French national agricultural census.

2.2 Land-cover data

The sequential land-cover data used in this study was drawn from the Teruti databases. Teruti is a two-level sampling survey of land-cover, which was conducted by the French Ministry of Agriculture (Ledoux and Thomas, 1992). Details of this land-cover survey can be found in Xiao et al. (2014). A corpus of 555,382 sampling points that were labeled with their land cover during the period from 1992 to 2003 was used in this study.

2.3 Selection of representative agricultural districts

In this study, all 429 ADs (one AD in the Region of Paris was excluded in this analysis because of the high urban ratio) within the French mainland were analyzed. The selection of representative agricultural districts was based on our previous study of static crop sequence patterns (Xiao et al., 2014). In brief, we applied hidden Markov models to extract 3-year CSs (both temporary and permanent crops were included) from the Teruti datasets. Next, the average values of the occurrence of 2549 main 3-year crop sequences during the 1992–2003 period were used as descriptive variables to group the 430 ADs into 21 clusters using a hierarchical clustering analysis with Ward's criterion. We retained the ADs, which were sorted by cluster and the distance between each individual and the closest cluster center that comprised representative agricultural districts. These agricultural districts were identified using the function "desc.ind$spec" of package "FactoMineR" (Lê et al., 2008) within R (R Core Team, 2012). Major crops within each AD cluster are listed in Table IV-2. The method for identifying the major crops within one spatial unit can be seen in Xiao et al. (2014). The summary of this typology of 430 ADs and the 90 selected representative ADs are shown in Table IV-3.

2.4 Data preparation

As the aim of this study was to explore the shifts in 3-year crop sequence patterns following the 1992 EU CAP reform, we divided the entire study period into three non-overlapping subperiods: 1992-94, 1997-99, and 2001-03. This temporal division was defined considering the potential evolution of cropping systems during the period of implementation of two CAP reforms in 1992 and 2003. We then counted the occurrence rates of 3-year crop sequences within each district and subperiod. Finally, these data were arranged in a matrix that comprised three submatrices (a submatrix corresponded to one subperiod) in which one AD occupied a row, and each column corresponded to the occurrence rate of one 3-year crop sequence. These three submatrices were structured in the same manner: 429 ADs in rows and 4532 3-year crop sequences in columns.

2.5 Data analysis

The PTA is an extension of Principal Component Analysis (PCA) to analyze a three-way table, in other words, a series of two-way tables (e.g., a data cube, species × sites × time in ecology). The PTA searches for structures that are stable among the sequence of tables (Cadet et al., 2005), which is a three-step method: (1) an analysis of the interstructure (giving the weight of each table: a matrix of scalar products between tables "the vector covariance" is computed, and the eigenanalysis of this vector covariance matrix first gives an eigenvector, then the components of this first eigenvector are used as weights for the table to compute compromise); (2) an analysis of the compromise (compromise is computed as the weighted mean of the all tables in the series) by a PCA; (3) an analysis of intrastructure by projecting the rows and columns of the initial tables in the series as supplementary elements on the factor map of the PCA to visualize the trajectories (Thioulouse et al., 2004).

Table IV-2
Major crops in 21 clusters of 430 agricultural districts between 1992 and 2003. Nomenclature used is: A (apples), Ap (apricots), B (barley), Ch (cherries) Fa (fallow), Fo (berry orchard), Fs (orchard with other fruits i.e., single or mixed species, nut trees), Id (industrial crops), M (maize), Oc (other cereals), Ol (other oilseed crops including soybean, linseed, castor bean, etc.), Ov (other legumes), P (peas), Pa (artificial pasture sown by alfalfa and clover), Pe (peaches), Pl (plums), Pr (pears), Ps (potatoes), Pt (temporary pasture), R (rapeseed), S (sunflower), Sb (sugar beet), Tx (fiber crops), V (vineyards) and W (wheat).

Cluster	Major crops
1	V, W, M, Pe, S, Ov, Pa, Fa, B, Ap, Oc, R, A, P, Fs
2	V, W, M, A, Pa, S, B, Fa, Pt, Pl, Ov, Ch, Pe, Pr, Ol, Oc
3	V, M, Pt, Fa
4	V, W, Fa, M, Pt
5	W, M, Pt, V, S, Fa, B, Pa, R, Oc
6	W, V, B, M, S, R, Fa , P, Pa, Sb, Pt
7	M, W, Fa, S, B, Pt, Pa, Oc, Pl, V, Ov, Ol
8	V, W, Id, Pa, Fa, Fo, B, S
9	M, Pt, W, B, Fa, Ov, Oc, S
10	Pt, M, B, W, Oc
11	Pt, W
12	V, M, W, A, Pt, Fs, Fa, Ov, Pe
13	M, Pt, Fa, Ov
14	W, S, M, Fa, B, Pt, Pa, Oc, R, V, P, Ol
15	W, M, S, Fa, B, Pt, A, Pa, Oc, R, P, Ol
16	W, M, Pt, B, Fa, S, P, R
17	W, B, R, M, S, Pt, Fa
18	W, B, R, Fa, Pa, M, Pt
19	W, B, P, Sb, M, Fa, Pa, R, S, Ps, Pt, Tx
20	W, Sb, P, B, M, Ps, Fa, Ov, R, Pt, Tx
21	W, B, P, R, Fa, Sb, M, Ov, Ps, N, Tx, Pt

Table IV-3
Description of the characteristics of the 3-year crop sequence pattern-based typology of 430 agricultural districts and the representative agricultural districts. Nomenclature used is: A (apples), Ap (apricots), B (barley), Fa (fallow), Fo (berry orchard), Fs (orchard with other fruits i.e., single or mixed species, nut trees), Id (industrial crops), M (maize), Oc (other cereals), Ov (other legumes), P (peas), Pa (artificial pasture sown by alfalfa and clover), Pe (peaches), Pl (plums), Ps (potatoes), Pt (temporary pasture), R (rapeseed), S (sunflower), Sb (sugar beet), V (vineyards) and W (wheat). CS: crop sequences. AD: agricultural districts.

Cluster	Nb. of paragons/Nb. of total ADs	ID of representative ADs	First five dominant 3-yr crop sequences
1	3/3	AD242, 252, 240	VVV, PePePe, MMM, ApApAp, FaFaFa
2	4/4	AD200, 466, 211, 155	VVV, AAA, PlPlPl, MMM, WWW
3	3/12	AD129, 128, 114	VVV, MMM, FaFaFa, PtPtPt, MMFa
4	5/24	AD122, 469, 422, 119, 207	VVV, WWW, PtPtPt, FoFoFo, MMM
5	5/20	AD401, 444, 69, 151, 347	VVV, MMM, WSW, FaFaFa, WRW
6	5/10	AD17, 186, 336, 377, 11	VVV, BRW, WBR, MMM, RWB
7	5/6	AD400, 156, 396, 398, 402	MMM, PlPlPl, FaFaFa, VVV, WSW
8	4/4	AD243, 233, 462, 464	VVV, IdIdId, FsFsFs, WWW, PaPaPa
9	4/32	AD446, 84, 86, 148	MMM, PtPtPt, MWM, WMW, MMW
10	5/57	AD425, 450, 170, 445, 175	PtPtPt, MMM, PaPaPa, BPtPt, OcPtPt
11	5/48	AD237, 423, 166, 443, 236	PtPtPt, MMM, OcOcOc, PaPaPa, BPtPt
12	4/6	AD135, 404, 160, 467	VVV, FoFoFo, AAA, MMM, PePePe
13	6/16	AD382, 378, 143, 379, 150	MMM, FaFaFa, PtPtPt, OvOvOv, MMFa
14	5/21	AD349, 147, 375, 371, 348	WSW, SWS, MMM, WRW, FaFaFa
15	5/6	AD390, 350, 346, 459, 67	MMM, WSW, FaFaFa, AAA, WRW
16	5/43	AD332, 91, 199, 356, 201	MMM, WMW, WRW, MWM, PtPtPt
17	4/30	AD306, 205, 312, 178	BRW, WBR, RWB, WRW, PtPtPt
18	3/3	AD10, 311, 305	BRW, RWB, WBR, WBB, BBR
19	4/30	AD327, 41, 440, 321	WPW, WSbW, WRW, WMW, BRW
20	5/29	AD326, 23, 33, 43, 31	WSbW, WPW, WMW, PWSb, SbWSb
21	2/2	AD80, 24	WRW, WPW, BRW, RWW, WBR

In this study, the investigation of spatio-temporal dynamics was performed at two scales: (1) the national scale by analyzing all 429 ADs and the assemblage of 90 representative agricultural districts; (2) the regional scale by separately analyzing three principal zones of temporary crops, particularly COP cultivation (Fig. IV-2). Because of the computing power limit for handling very high dimensional data (i.e., 429 submatrices with 4532 columns *vs.* 90 submatrices with 2889 columns), PTA was only performed for the table of 90 representative ADs to explore the diversity of the temporal evolutions of crop sequence patterns per AD. Figure IV-2 shows the location of 90 representative agricultural districts and three principal temporary crop cultivation zones, which were linked to three different cropping systems.

A PTA was performed in two ways. Figure IV-3 illustrates our analytical strategy by using the analyses of the 90 representative ADs as example: (1) the PTA assessed the spatial variability of the crop sequence patterns in different periods (PTA in the matrix, which included three submatrices corresponding three subperiods — i.e., table-time: rows = ADs * columns = 3-year CSs); (2) it explored the temporal evolution of crop sequence patterns per AD (PTA on the matrix, which included 90 submatrices corresponding to 90 representative ADs — i.e., table-AD: rows = dates * columns = 3-year CSs). A PTA was completed by using the package ade4 (Chesssel et al., 2004; Dray et al., 2007) within R software (R Core Team, 2012).

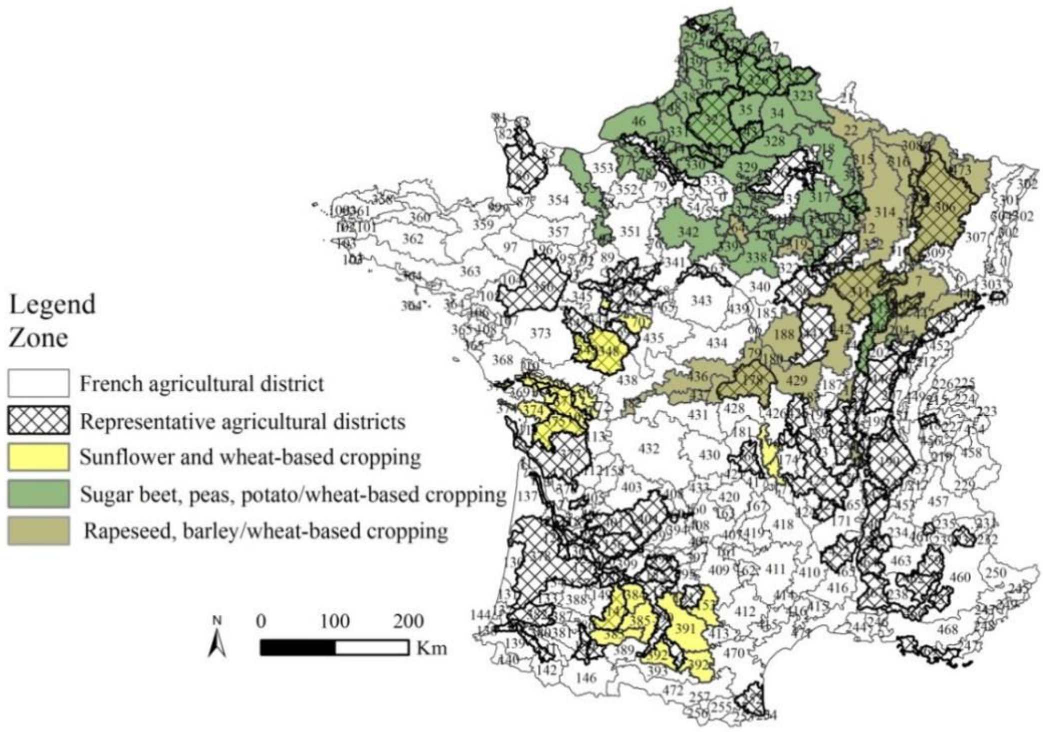

Fig. IV-2. Map of 430 French agricultural districts. The 90 representative agricultural districts are highlighted by crosshatches. Three cropping areas that are illustrated in this study are shown here. Sunflower and wheat-based cropping systems were dominant in the zone shown in yellow. Two main zones for cereals, rapeseed, and leguminous crop growing are displayed in green. The label of each area corresponds to the ID of an agricultural district.

In addition, the analysis of all 429 agricultural districts was initially performed using the first method shown in Fig. IV-3. The coordinates of the ADs of each initial submatrix on the PCA factor plane on the first principal axes, which explained 80% of the total inertia of the compromise, were used as descriptive variables to build a table in which the AD per subperiod (429× 3=1287 individuals) was placed in rows and their four coordinates on the principal axes were in columns. Ward's hierarchical clustering analysis (HCA) measuring

Euclidean distance was performed on this table. The suitable number of clusters was chosen according to seven indices (internal measure and stability measure), which were measured using the package 'clValid' (Brock et al., 2011). The result of the HCA was then mapped for each subperiod separately using ArcMap 10.

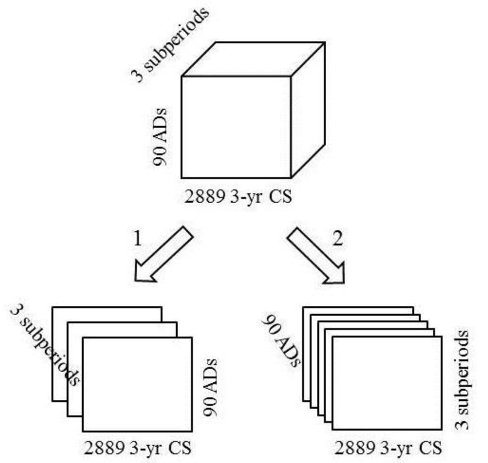

Fig. IV-3. Graphic illustration of our data analysis strategy by PTA, for instance, at the national level by analyzing the assemblage of 90 representative agricultural districts (ADs).

3. Results

3.1 Temporal variability of crop sequence patterns in mainland France

Figure IV-4 illustrates the detection of the similarities between subperiods concerning the occurrences of 3-year CSs within 429 ADs. The first two eigenvalues produced from the interstructure analysis explain 67.4% and 5.3% of the total inertia, respectively (Fig. IV-4a). The similar coordinates of the submatrices on the first axis of the interstrucuture plot indicates a strong common structure of crop sequence patterns between three subperiods (Fig. IV-4b). A weaker weight of submatrices from the 1992-94 period also suggests the more particular crop sequence patterns across the entire territory than the two subsequent subperiods.

For the analysis of the compromise, the first four principal axes accounted for 80.7% of the total inertia. Among them, the first two principal axes explained approximately 67% of the total inertia (Fig. IV-4c). Considering the large number of variables (i.e., 4532 3-year crop sequences), this analysis provided a good summary of the temporal variability of the spatial distribution of crop sequences through the three subperiods. The projection of observations on the first two principal axes-related planes of the compromise analysis reveals the two distinct assemblages of the ADs: one assemblage is located in the negative part of the first axis and another large assemblage is in the center of the plot (Fig. IV-4d). The first assemblage of ADs was characterized by the predominance of the monoculture of maize and maize-wheat-based CSs and continuous temporary pasture. Oilseed crops (sunflower and rapeseed), sugar beet- and wheat/barley-based CSs were dominant in the ADs of the second assemblage (Fig. IV-4e).

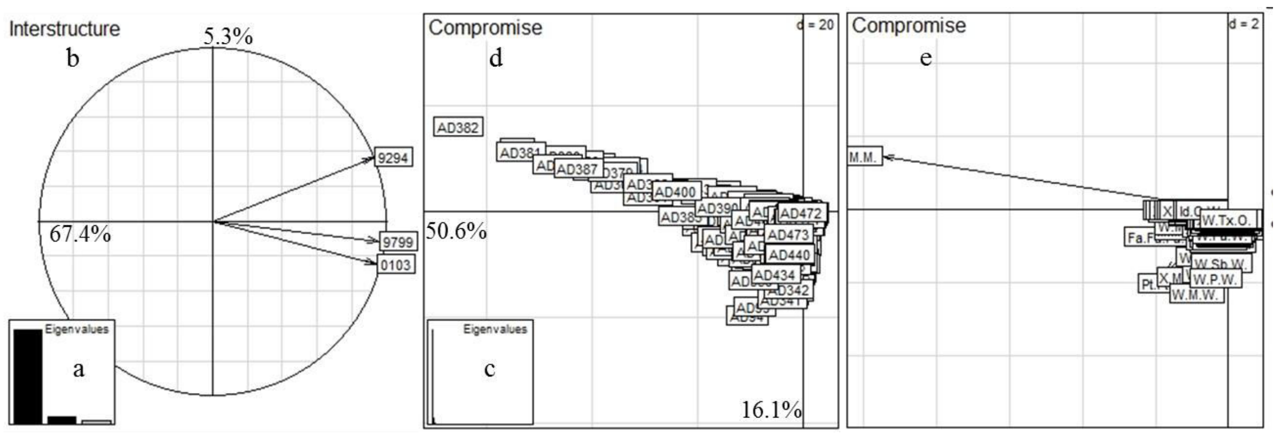

Fig. IV-4. Results of the PTA on the table of the occurrence of crop sequences in 429 ADs: PTA of table time. a. Eigenvalue histogram based on the diagonalization of the matrix of vector correlations. b. The interstructure plot, displaying the three subperiods, and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Projection of 429 ADs on the compromise analysis plane defined by the first two principal axes. e. Coordinates of the variables (3-year CSs) on the plane of the compromise analysis. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

We thus retained the coordinates of the ADs of each initial submatrix on the factor plane of the compromise analysis regarding the first four principal axes for further clustering analysis. With the aid of seven indices computed using clVlid, we defined 14 as the appropriate number of clusters for the HCA. The result of the AHC was visualized by mapping the clusters of 429 ADs per subperiod via ArcMap (Fig. IV-5). The characteristics of the 14 clusters were described using the descriptive statistics of the occurrence of the ten most frequent 3-year crop sequences (Table IV-4).

The changes in crop sequence patterns over three subperiods can be identified by the changes in the cluster of an AD between two subperiods. Comparing the series of maps of the spatial distribution of crop sequences over three sampling periods (Fig. IV-5), we notice that:

(1) The expansion of the cultivation zone with maize-based cropping systems, particularly cropping systems dominated by a monoculture of maize in southwestern and northeastern areas over the three subperiods;

(2) The expansion of planting areas of sunflower-wheat-based cropping systems between the subperiods 1992-94 and 1997-99 in the southwestern and central regions;

(3) The expansion of the areas where the 3-year crop rotation of wheat-barley-rapeseed was predominant between the subperiods 1992-94 and 1997-99 in the central regions;

(4) The reduction of growing zones for sugar beet- and/or pea-wheat/barley-based cropping systems between the two subsequent subperiods in the north-central regions;

(5) The expansion of growing areas of rapeseed/wheat-based CSs, in particularly "wheat-barley-rapeseed" rotation, between the early two subperiods in the west-central regions.

We also observed higher temporal variability in crop sequence patterns in the ADs where there was a high ratio of field cropping in the total UAA. Most changes in AD clusters occurred between the subperiods 1992-94 and 1997-99 (Table IV-5). Indeed, the crop sequence patterns in a large share of the ADs were likely stable over the course of the three subperiods because most ADs did not change the cluster (Fig. IV-6).

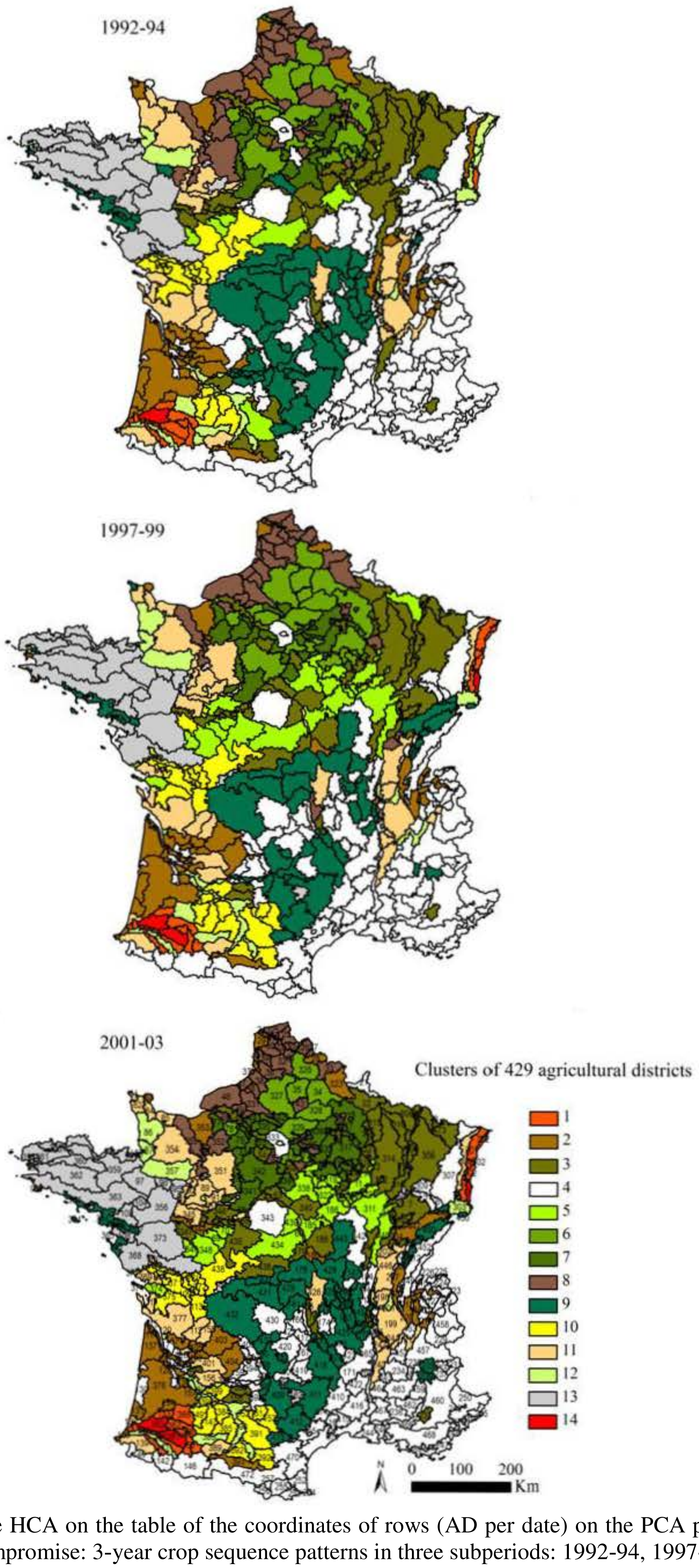

Fig. IV-5. Results of the HCA on the table of the coordinates of rows (AD per date) on the PCA plane on the first four principal axes of the compromise: 3-year crop sequence patterns in three subperiods: 1992-94, 1997-99, and 2001-03.

Table IV-4
Descriptive statistics of the 14 clusters of agricultural districts according to the occurrence rate of the ten most frequent 3-year crop sequences.

Cluster(Number of ADs)	1 (35)		2 (129)		3 (134)		4 (338)		5 (44)		6 (42)		7 (63)	
The occurrence rate (mean ± sd) of the ten most frequent 3-year crop sequences (%)	MMM	23.5±3.4	MMM	2.8±1.0	BRW	1.5±1.4	PtPtPt	0.4±0.5	BRW	3.4±2.1	WSbW	5.6±2.5	WPW	2.9±2.0
	FaFaFa	1.6±1.4	PtPtPt	0.9±0.9	WBR	1.4±1.3	MMM	0.3±0.5	WBR	3.3±2.1	WPW	4.7±2.4	BRW	2.5±1.8
	PtPtPt	1.6±1.2	MWM	0.5±0.9	WRW	1.3±1.0	PaPaPa	0.2±0.5	WRW	3.3±2.0	PWSb	2.0±1.1	WRW	2.5±1.6
	MMFa	1.0±0.9	FaFaFa	0.4±0.7	RWB	1.2±1.1	WWW	0.2±0.4	RWB	2.7±2.1	SbWP	1.8±0.9	WBR	2.0±1.4
	MWM	0.7±1.0	WMW	0.4±0.6	FaFaFa	0.9±1.0	FaFaFa	0.2±0.4	WSW	2.4±1.9	SbWSb	1.6±1.3	WWW	1.9±2.3
	WMM	0.6±0.9	WMM	0.3±0.4	MMM	0.9±0.8	OcOcOc	0.1±0.9	FaFaFa	1.4±1.0	WMW	1.6±1.5	WMW	1.8±1.4
	MMW	0.6±1.0	MMW	0.3±0.4	WMW	0.7±0.6	OvOvOv	0.1±0.4	RWW	1.3±0.9	WWW	1.5±1.2	WSbW	1.5±1.4
	OvOvOv	0.4±0.7	MMFa	0.2±0.5	WSW	0.7±0.9	IdIdId	0.1±0.5	WWR	1.1±0.8	BPW	1.3±1.0	RWB	1.5±1.1
	MFaFa	0.4±0.4,	OvOvOv	0.2±0.4	PtPtPt	0.7±0.7	MWM	0.1±0.2	MMM	1.1±0.9	PWB	1.3±1.0	RWW	1.4±1.5
	MFaM	0.4±0.6	PaPaPa	0.2±0.4	MWM	0.6±0.6	WSW	0.1±0.2	RWR	1.0±0.9	BSbW	1.2±0.8	FaFaFa	1.3±1.1
Cluster (Number of ADs)	8 (103)		9 (127)		10 (60)		11 (93)		12 (48)		13 (64)		14 (7)	
The occurrence rate (mean ± sd) of the ten most frequent 3-year crop sequences (%)	WMW	2.1±1.6	PtPtPt	3.4±1.4	WSW	5.4±2.4	MMM	4.6±1.6	MMM	11.1±2.9	PtPtPt	7.4±3.7	MMM	35.8±3.6
	WSbW	1.8±1.4	MMM	0.5±0.5	SWS	4.1±2.2	MWM	0.3±0.5	PtPtPt	2.0±2.0	MWM	3.5±3.4	FaFaFa	3.1±2.0
	WPW	1.6±1.2	BPtPt	0.4±0.4	MMM	3.7±2.3	PtPtPt	0.2±0.5	MWM	1.7±1.8	WMW	3.0±3.2	PtPtPt	1.5±1.1
	MWM	1.3±1.1	MWM	0.3±0.6	WRW	1.7±1.5	WMW	0.2±0.4	MMW	1.2±1.2	MMM	1.9±1.0	MMFa	1.1±1.0
	MWB	0.9±1.0	WMW	0.3±0.5	PtPtPt	1.7±1.1	FaFaFa	0.2±0.4	WMM	1.1±1.0	MMW	1.2±1.0	MFaFa	0.7±0.8
	BMW	0.9±0.8	PtPtM	0.3±0.4	FaFaFa	1.6±1.3	MMW	0.1±0.9	FaFaFa	1.0±1.2	PtPtM	1.0±0.8	FaMM	0.5±0.3
	SbWB	0.8±0.8	OcPtPt	0.3±0.3	SWR	1.2±1.1	WMM	0.1±0.4	WMW	0.8±0.9	PtMW	1.0±1.0	PtFaFa	0.5±1.1
	WBM	0.7±0.8	WPtPt	0.3±0.3	WMW	1.1±1.0	WSW	0.1±0.5	WSW	0.5±0.9	WMM	1.0±1.1	WMM	0.5±0.6
	BSbW	0.7±0.8	PaPaPa	0.2±0.4	MWM	1.0±1.0	WRW	0.1±0.2	PtMM	0.5±0.9	MPtPt	0.9±0.6	MWM	0.4±0.6
	WBSb	0.7±1.0	MMW	0.2±0.5	RWS	0.9±0.9	SWS	0.1±0.2	WRW	0.5±0.9	MWPt	0.9±0.8	MMW	0.4±0.4

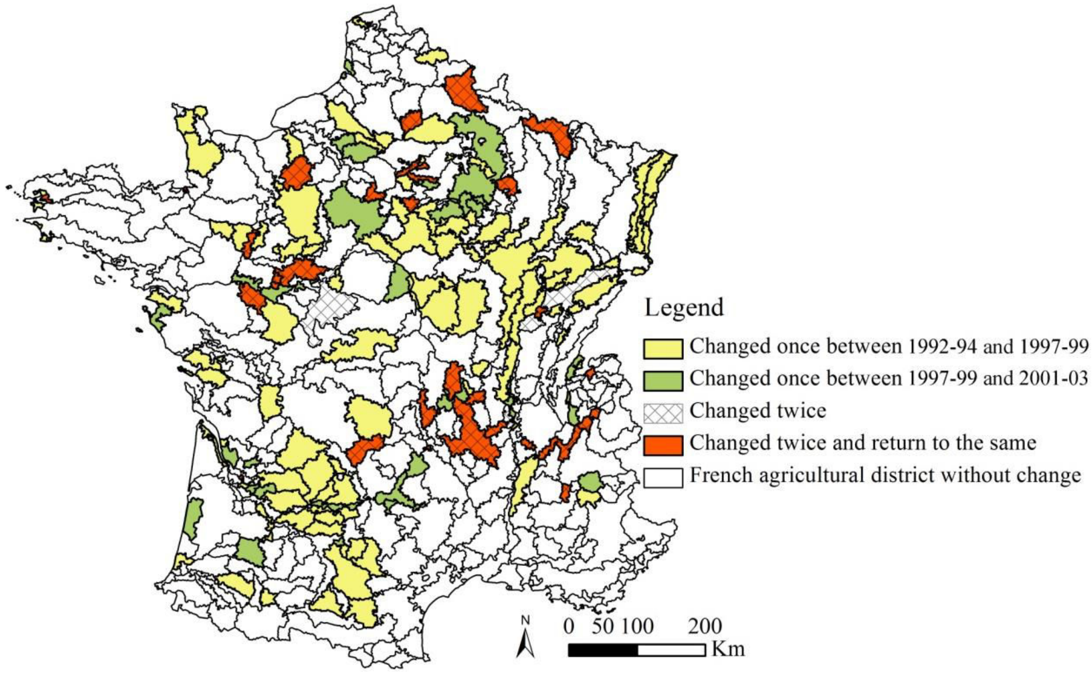

Fig. IV-6. Mapping the frequency of changes in agricultural district clusters across three subperiods: 1992-94, 1997-99, and 2001-03.

Table IV-5
Summary of the changes in clusters of 429 ADs across three subperiods.

	Number of ADs with change in cluster (% of the total ADs)	Number of ADs without change in cluster
1992-94 to 1997-99	126 (29.4%)	303
1997-99 to 2001-03	65 (15.2%)	364
1992-94 to 2001-03	128 (29.8%)	301

36 ADs changed twice, 274 ADs never changed, 27ADs changed twice and returned to the initial cluster during the subperiod of 2001-03.

3.2 Diversity of the temporal evolution of crop sequence patterns per agricultural district: an analysis based on 90 representative agricultural districts

For the analysis of the interstructure, the first and the second eigenvalue account for 34.8% and 13.8% of the total inertia, respectively (Fig. IV-7a). The moderate accounted for the inertia with the first two eigenvalues, and the non-distinguished assemblage of ADs regarding to the interstructure plot (Fig. IV-7b) indicates the spatial variability of the crop sequence patterns within an AD over the three subperiods.

The first principal axis of the compromise analysis explained 98.2% of the total inertia (Fig. IV-7c). Thus, it provides an accurate summary of the common spatial patterns of the occurrence of crop sequences within 90 ADs over three subperiods. The crop sequences patterns within 90 ADs during the subperiod 1992-94 differed slightly from the subsequent two subperiods (Fig. IV-7d). The 3-year successive fallow, maize, and temporary pasture, maize/wheat-based and sunflower/wheat-based CSs and the wheat-barley-rapeseed rotation strongly correlated to the negative part of the first axis. The second axis was characterized by 3-year successive temporary and artificial pasture, and 3-year CSs that included two cereals with one year of peas or fallow correlated with the positive values, 3-year fallow, and rapeseed/wheat-based CSs (Fig. IV-6e and IV-6f).

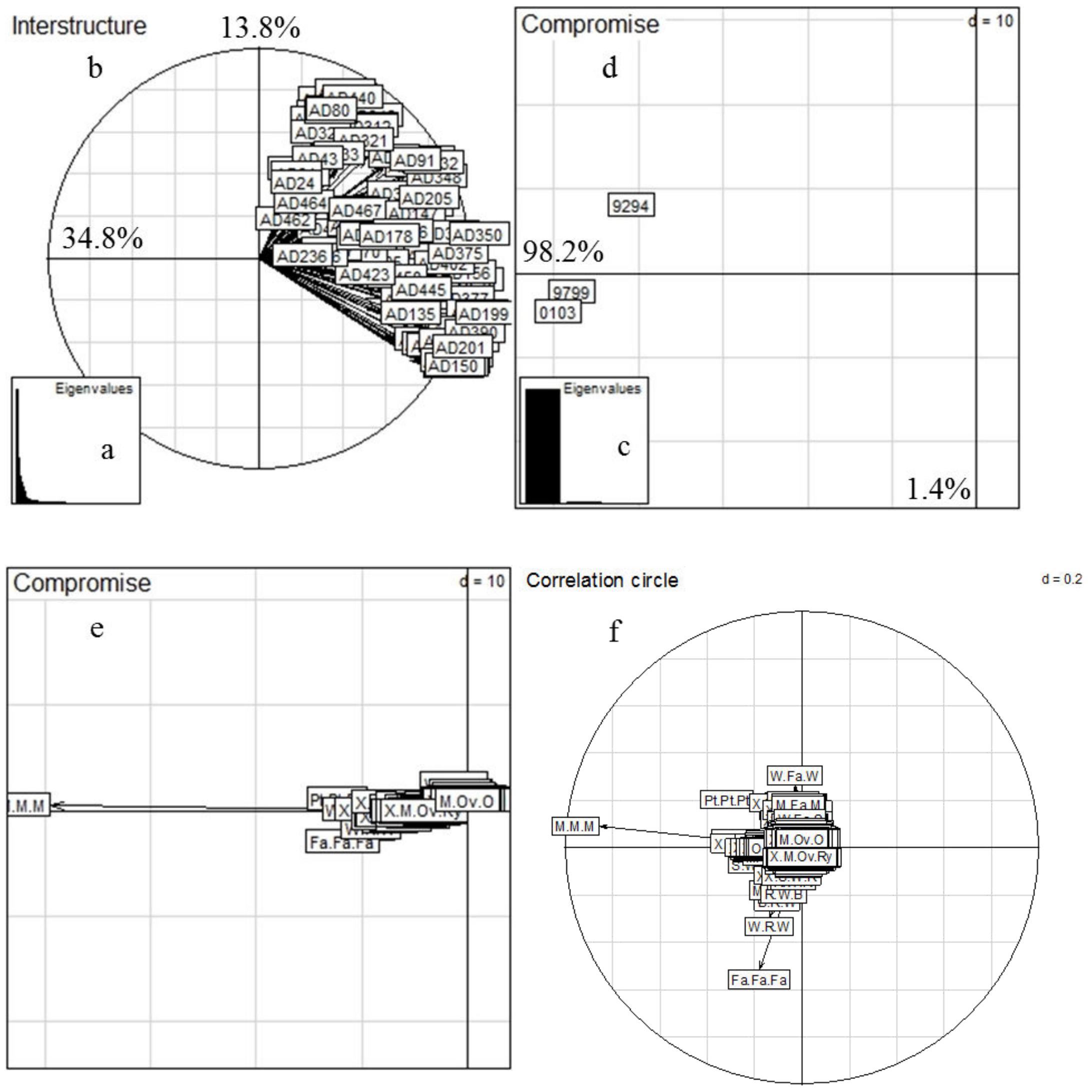

Fig. IV-7. Results of the PTA on the table of the occurrence of crop sequences within 90 ADs: PTA of table-ADs. a. Eigenvalue histogram based on the diagonalization of the matrix of vector correlations. b. The interstructure plot displaying the 90 ADs and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Projection of three subperiods on the compromise analysis plane defined by the first two principal axes. e. Coordinates of the variables (3-year CSs) on the compromise analysis plane. f. Loading plot of the variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

The intrastructure step was performed by separately projecting the rows (three subperiods) on the first two principal axes (Fig. IV-8) and columns (2889 CSs) on the first two principal components of the compromise analysis of PTA per AD. Thus, the changes in the position of the subperiod on the plane indicate the modifications in crop sequence patterns within an AD over time. The annual crop-related crop sequence patterns in the ADs — belonging to clusters 1, 2, 3, 4, 5, 8 and 12, where the vineyard-based cropping systems were dominant, and clusters 10 and 11 with the predominance of sown pastures and temporary pasture-cereal-based CSs (cf. Table 2) — appear stable across the three subperiods. In contrast, the higher dynamics of crop sequence patterns within an AD occurred in the ADs where wheat- and barley-based cropping systems were dominant, i.e., ADs belonging to the clusters 14, 17, 18, 19, 20, and 21. Among them, the ADs where sunflower- and wheat-based CSs (i.e., cluster 14) were dominant revealed the highest dynamics of crop sequence patterns over the study period. Within the remaining ADs, in which maize monoculture and maize/wheat-based CSs (i.e., clusters 9, 13, 15, 16) and mixed vineyard and temporary crop-based cropping systems (i.e., clusters 6 and 7) were dominant revealed moderate dynamics of crop sequence patterns.

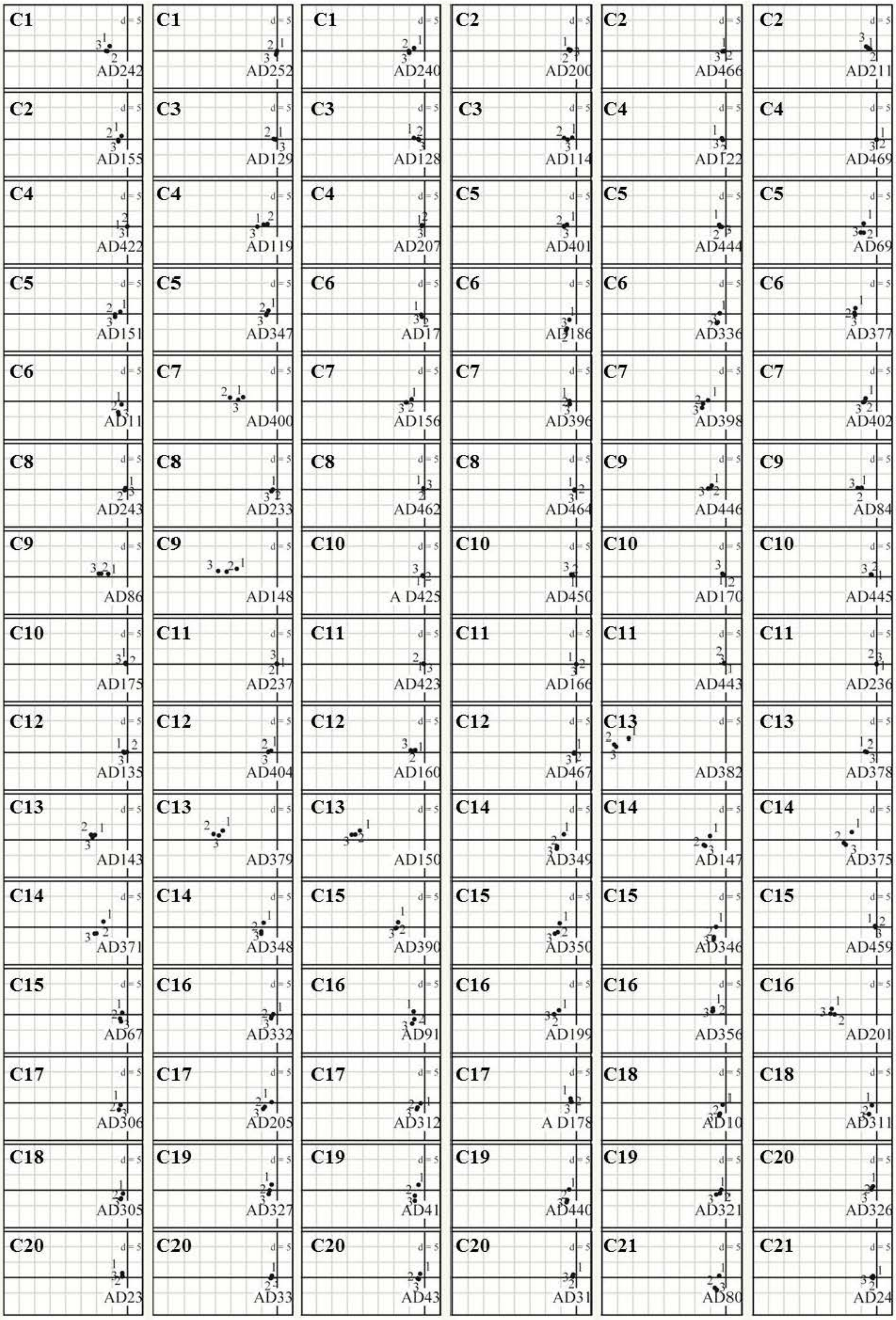

Fig. IV-8. Intrastructure plot of the PTA on the table of the occurrence of crop sequences within 90 ADs: PTA of table-ADs. The rows of each submatrix of the sequence in the compromise analysis are projected on the first two principal axes. Note: d in the upper right corner of each plot shows the scale of the x and y axes. “C1” to “C21” represent the clusters of ADs that were referenced in Table 2. “1”, “2”, and “3” represent the subperiods 1992-94, 1997-99, and 2001-03, respectively.

3.3 Temporal dynamics of crop sequence patterns in three principal zones of COP cultivation

In this section, we focus on the variability of the temporal evolution of annual crop-related 3-year CSs within an AD in the homogeneous zones that were identified according to the 12-year averaged occurrence of 3-year crop sequences. These three zones included 119 ADs and accounted for approximately 40% of the total arable land of mainland France in 2000.

3.3.1 Zone specializing in sunflower/wheat-based CS cultivation

Based on our prior study of the spatial distribution of crop sequences in the French mainland, the 21 ADs were clustered into one cluster that was characterized by the predominance of sunflower/wheat-based CSs. The 21 ADs accounted for 4.4% of the total land area (24.3 thousand km^2) and 8.2% of the total French mainland's arable land in the year 2000. A PTA was performed on a matrix, including 21 submatrices in which three subperiods were in rows and 1707 CSs were in columns to investigate the diversity of the temporal evolution of crop sequence patterns per AD over time.

The first and the second eigenvalue produced by the interstructure analysis explain 68.5% and 6.9% of the total inertia, respectively (Fig. IV-9a). The high value of inertia is explained by the first two eigenvalues confirmed the strong common structure of crop sequence patterns within the 21 ADs over the three subperiods. Five ADs that were projected onto the positive part of the second axis were slightly different from the other ADs based on the crop sequence patterns (Fig. IV-9b). This suggested that the temporal evolution of crop sequence patterns within these five ADs, particularly in ADs 176 and 427 (two ADs located in Auvergne in the center of mainland France; see Fig. IV-2) differed from the other ADs. The first axis of the compromise analysis explained 96.1% of the total inertia (Fig. IV-9c). Thus, it provided a good summary of the crop sequence patterns in 21 ADs. The three subperiods strongly correlated to the negative part of the first axis of the compromise analysis (Fig. IV-9d), and the first subperiod was the opposite of the other two subperiods on the second axis. The crop sequence patterns within the subperiod 1997-99 were very similar to those of the subperiod 2001-03. The high occurrence rate of CSs, including one year of fallow into sunflower/wheat-based 3-year CSs, mainly differentiated the subperiod 1992-94 from the two subsequent subperiods (Fig. IV-9e and IV-9f). The higher occurrence rate of the "sunflower-wheat" 2-year rotation, monoculture of maize, 3-year successive fallow, and rapeseed/wheat-based CSs partly resulted in this difference.

The overall trends of the temporal evolution of crop sequence patterns within an AD were: (1) the expansion of oilseed crops (sunflower and rapeseed)/wheat-based CSs and 3-year successive fallow between the subperiods 1992-94 and 1997-99 (see Fig. IV-10; all points labeled "1" are located in the second quadrants and the majority of points labeled "2" are located in the third quadrants or the negative part of the first axis); (2) the expansion of maize monoculture and sunflower/wheat-based CSs between the first two subperiods (Fig. IV-10; all points labeled “1” and “2” are located in the second quadrant, e.g., ADs 153, 383 and 427); and (3) the decrease in the area with oilseed crop/wheat-based CSs between the subperiods 1997-99 and 2001-03 in the most ADs (Fig. IV-10; the positions of points labeled “2” shift to the positions of points labeled “3” in the direction of the plot center).

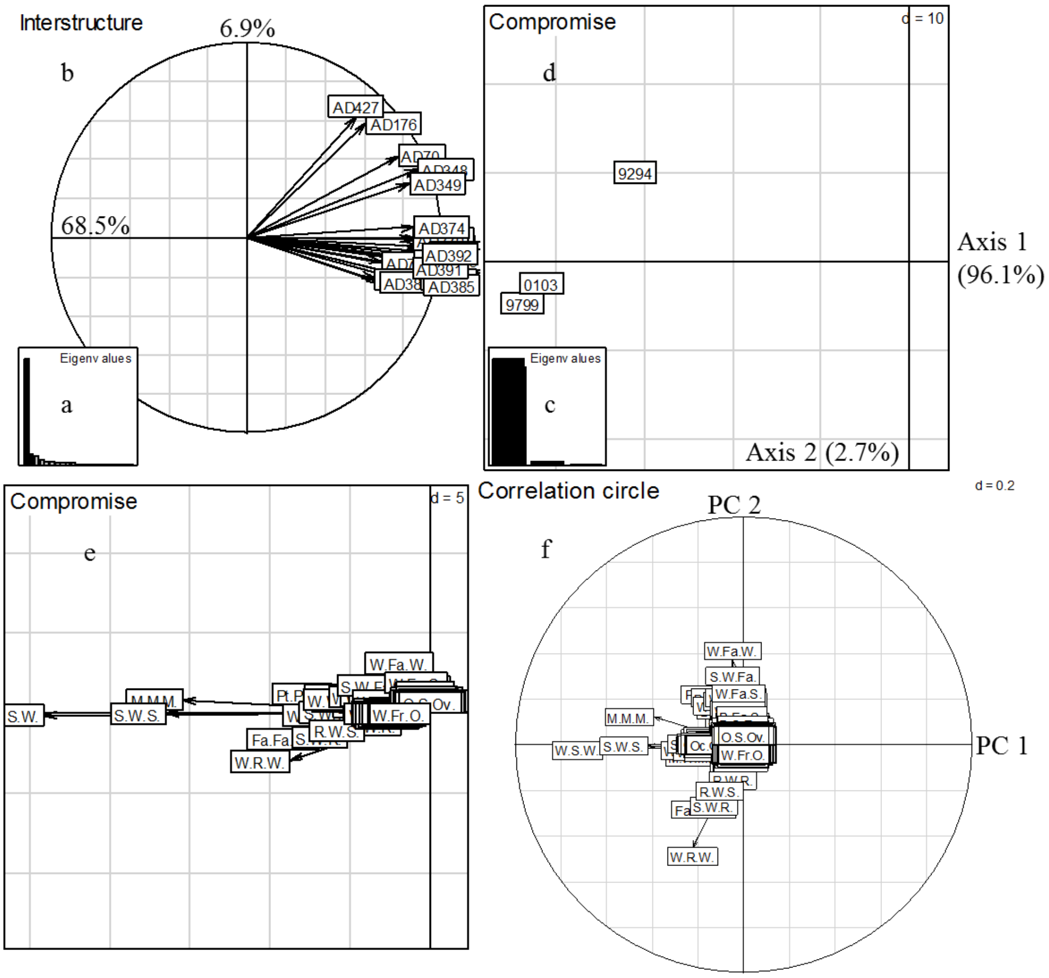

Fig. IV-9. Interstructure analysis of the PTA on the table of the occurrence of crop sequences within 21 ADs belonging to cluster 14: PTA of table-ADs. a. Eigenvalue histogram based on the diagonalization of the matrix of vector correlations. b. The interstructure plot, displaying the 21 ADs and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Projection of three subperiods on the compromise analysis plan defined by the first two principal axes. e. Coordinates of the variables (3-year CSs) on the compromise analysis plane. f. PC 1 and 2 loading plot of the variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

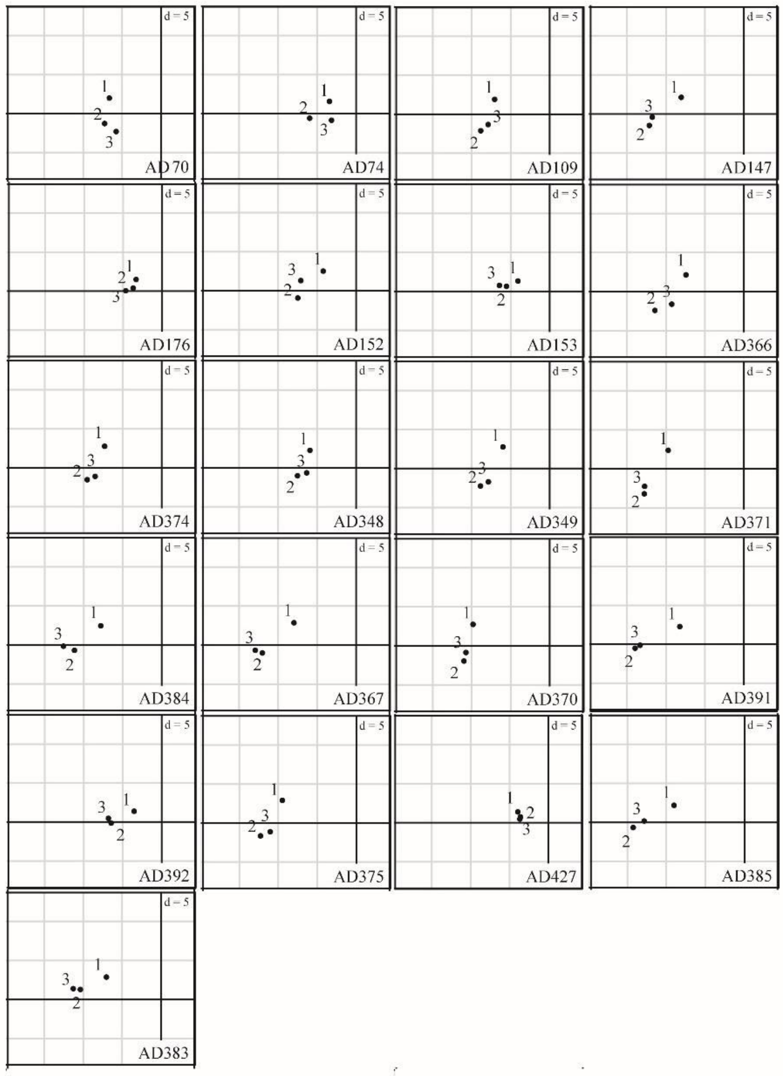

Fig. IV-10. Intrastructure plot of the PTA on the table of the occurrence of crop sequences within 21 ADs: PTA of table-ADs. The rows of each submatrix of the sequence in the compromise analysis are projected on the first two principal axes. Note: d in the upper right corner of each plot shows the scale of the x and y axes. “1”, “2”, and “3” represent the subperiods 1992-94, 1997-99, and 2001-03, respectively.

3.3.2 Zone specializing in the inclusion of rapeseed in wheat- and barley-based CS cultivation

The 34 ADs were characterized by the predominance of wheat/barley and rapeseed-based CSs. These ADs accounted for 10.5% of the total land area (57.9 thousand km^2) and 10.2% of the total French mainland's arable land in 2000. A PTA was performed on a matrix that included 34 submatrices, in which three subperiods were in rows and 1509 CSs were in columns to investigate the diversity of the temporal evolution of crop sequence patterns per AD over time. The first and the second eigenvalue produced from the interstructure analysis explain 55.6% and 14.9% of the total inertia, respectively (Fig. IV-11a). The high value of explained inertia by the first two eigenvalues confirmed the strong common structure of crop sequence patterns within the 34 ADs over the three subperiods.

The first axis of the compromise analysis explained 96.6% of the total inertia (Fig. IV-11c). Thus, it provided a good summary of the crop sequences patterns in 34 ADs. The three subperiods strongly correlated to the negative part of the first axis of the compromise analysis (Fig. IV-11d). Similar to the temporal dynamics of crop sequence patterns identified for the sunflower/wheat-based CSs dominant zone, the crop sequence patterns within the subperiod 1992-94 differed from the subsequent two subperiods. The high occurrence of rapeseed/wheat-based CSs, (i.e., the "wheat-barley-rapeseed" rotation, "rapeseed-wheat" rotation), 3-year successive temporary pasture, and maize monoculture negatively correlated to the first principal component of the compromise analysis (Fig. IV-11e and IV-11f). The occurrence rate of the CSs, including one year of fallow in the wheat/barley-based 3-year CSs and 3-year successive temporary pasture, negatively correlated to the second principal component.

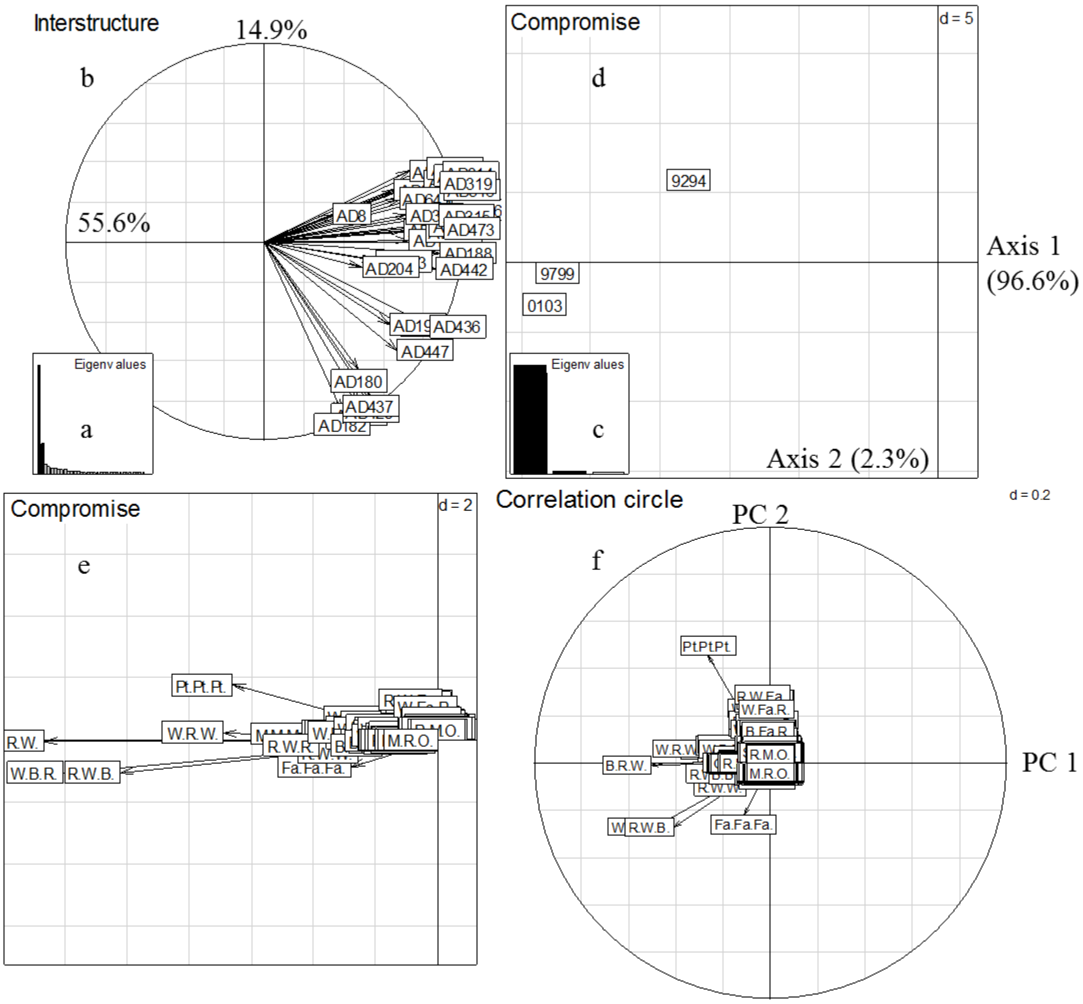

Fig. IV-11. Interstructure analysis of the PTA on the table of the occurrence of crop sequences within 34 ADs belonging to cluster 17 and 18: PTA of table-ADs. a. Eigenvalue histogram based on the diagonalization of the matrix of vector correlations. b. The interstructure plot, displaying the 21 ADs and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Projection of three subperiods on the compromise analysis plan defined by the first two principal axes. e. Coordinates of the variables (3-year CSs) on the compromise analysis plane. f. PC 1 and 2 loading plot of the variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

The intrastructure plot represents the temporal evolution of crop sequence patterns per AD (Fig. IV-12). All points labeled “1” corresponding to the subperiod 1992-94 are located in the second quadrant. In the majority of ADs, the changes of the position of the subsequent two subperiods are in the direction of the negative halves of the two axes. The increase in the occurrence rate of rapeseed/wheat-based CSs (i.e., “wheat-barley-rapeseed” rotation, “rapeseed-wheat” rotation, and monoculture of maize) primarily resulted in the trajectory from the first subperiod to the third subperiod. This trajectory partly resulted from the decrease in the occurrence rate of the CSs, including one year of fallow in the wheat/barley-based 3-year CSs and the expansion of 3-year successive fallow. In several ADs (e.g., ADs 311, 316 and 319), the trajectories between the subperiods 1997-99 and 2001-03 are in the direction of the positive half of the first axis. The decrease in rapeseed/wheat-based CSs’ planting made the temporal evolution of the crop sequence patterns within these ADs different from the others.

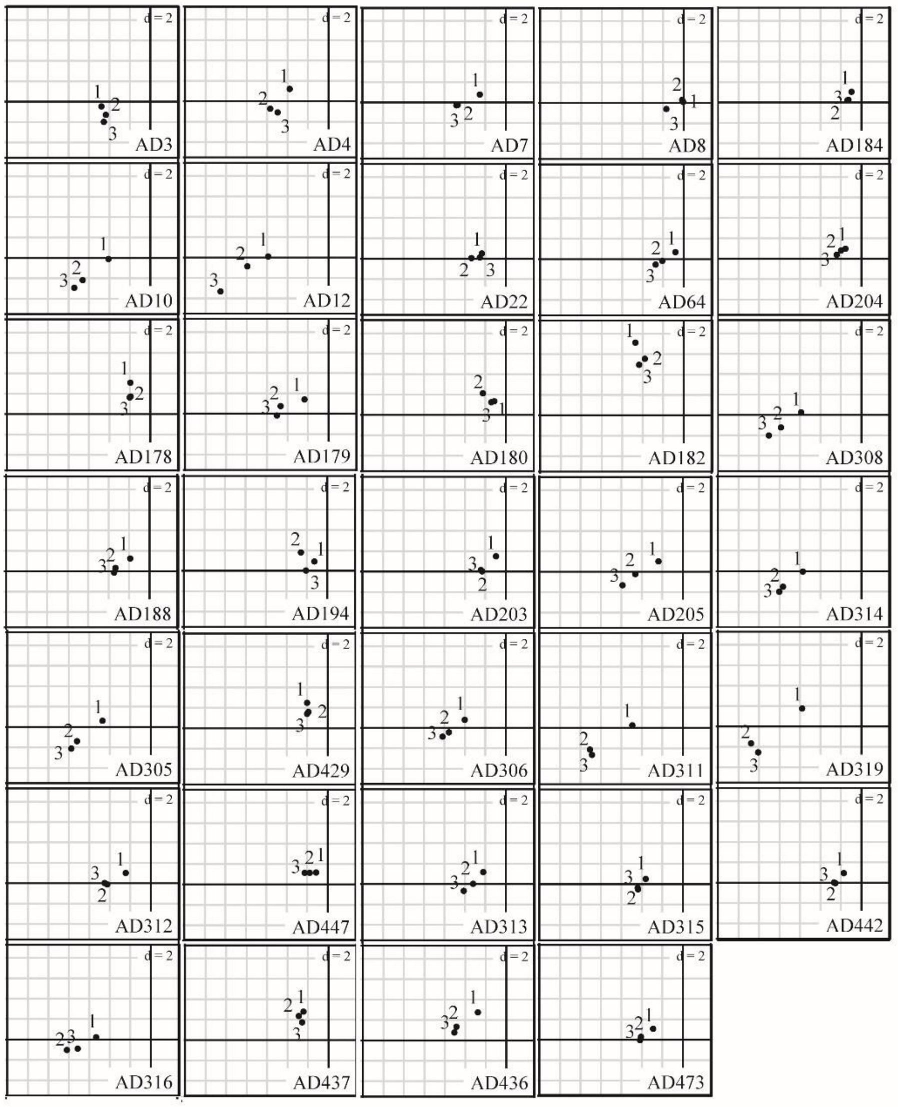

Fig. IV-12. Intrastructure plot of the PTA on the table of the occurrence of crop sequences within 34 ADs: PTA of table-ADs. The rows of each submatrix of the sequence in the compromise analysis are projected on the first two principal axes. Note: d in the upper right corner of each plot shows the scale of the x and y axes. “1”, “2”, and “3” represent the subperiods 1992-94, 1997-99, and 2001-03, respectivel

3.3.3 Zone specializing in the inclusion of sugar beet, peas or potatoes in wheat and/or barley-based CS cultivation

The 64 ADs were characterized by the predominance of wheat/barley and sugar beet, potatoes, pea-based 3-year CSs. These ADs accounted for 12.5% of the total land area (68.9 thousand km^2) and 21.6% of the total French mainland's arable land in 2000. A PTA was performed on a matrix including 64 submatrices, in which three subperiods were in rows and 2355 CSs were in columns, to investigate the diversity of the temporal evolution of crop sequence patterns per AD over time.

The first and the second eigenvalue produced from the interstructure analysis explain 49.2% and 8.4% of the total inertia, respectively (Fig. IV-13a). Compared to the two other zones that were previously studied, the moderate value of explained inertia by the first two eigenvalues and the non-distinct assemblage of ADs on the interstructure plot (Fig. IV-13b) indicated the weaker common structure of crop sequence patterns within the 64 ADs over the three subperiods. In other words, the crop sequence patterns within this zone revealed higher temporal variability than the other two field cropping zones.

The first axis of the compromise analysis explained 94% of the total inertia (Fig. IV-13c). Thus, it provided a good summary of the crop sequences patterns within 64 ADs. The scattered positions of the three subperiods on the plane of the compromise analysis also indicated the different temporal dynamics of crop sequence patterns within this zone from the two previously studied zones (Fig. IV-13d). The changes in crop sequence patterns were likely to have occurred through the entirety of the periods. The high occurrence of sugar beet and/or pea-wheat-based CSs and the "maize-wheat" rotation negatively correlated to the first principal component of the compromise analysis (Fig. IV-13e and IV-13f). The occurrence rate of the CSs including one year of fallow, peas into wheat/barley-based 3-year CSs positively correlated to the second principal component. The negative half of the second principal component was characterized by the rapeseed/wheat-based CSs and 3-year successive fallow and wheat.

The trajectories of the three subperiods of the majority of the 64 ADs on the plane of the compromise analysis reveal a common structure (Fig. IV-14). The points labeled "1" corresponding the first subperiod are located in the second quadrants. The positions corresponding the second subperiod are changed in the direction of the negative halves of the two axes. These changes are characterized by the increase in planting area of rapeseed/wheat-based, sugar beet and/or pea-wheat-based and maize/wheat-based CSs and 3-years of successive fallow. The changes in the position of subperiod corresponding to the period 2001-03 are in the direction of the negative half of the second axis and the positive half of the first axis. These changes were correlated to the decrease in the growing of pea/wheat-based CSs (e.g., Sb-W-P, B-P-W) between the subperiods 1997-99 and 2001-03. In addition, we observed the crop sequence patterns within several ADs (e.g., ADs 25, 26, 28, 29, 39 and 40 located in the north of France: Nord-Pas-de-Calais, see Fig. IV-2) which appear stable over the time.

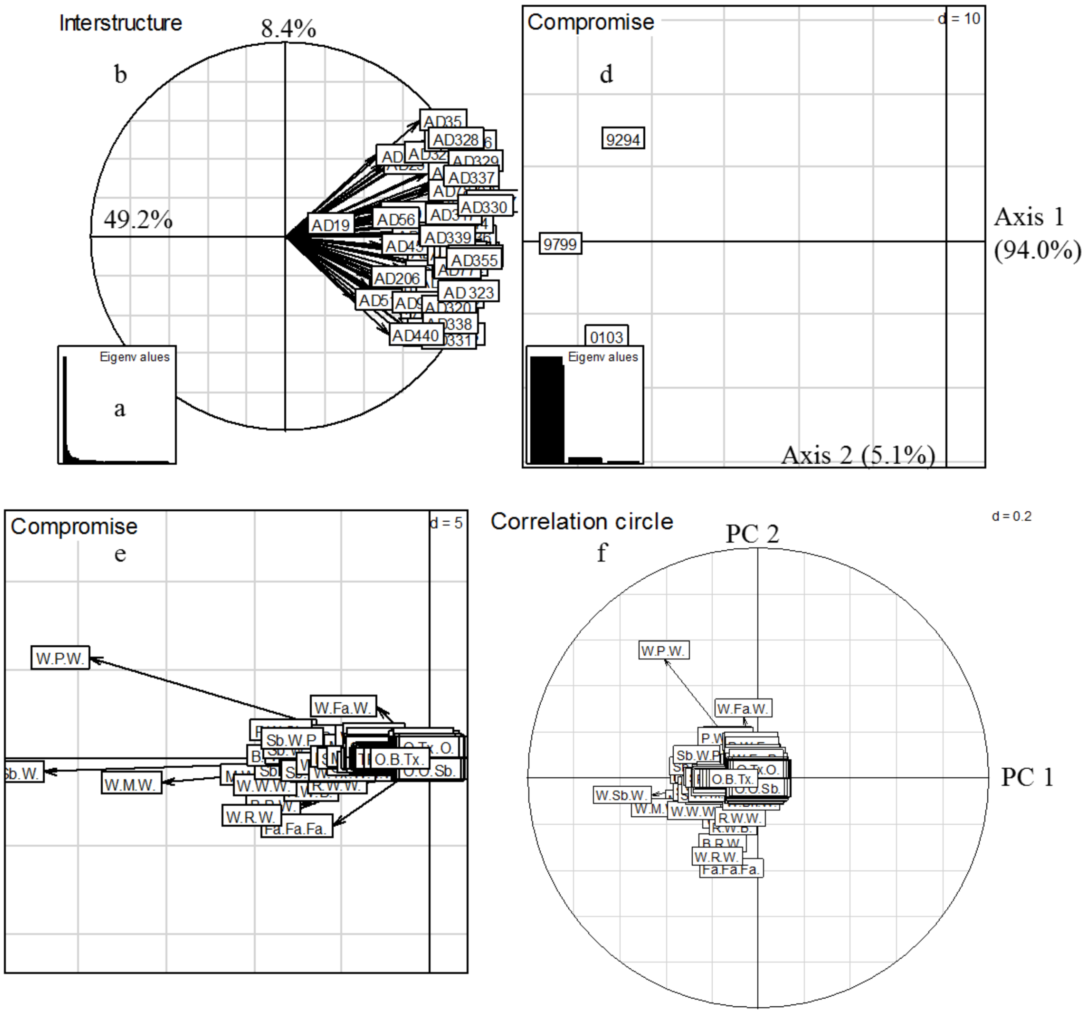

Fig. IV-13. Interstructure analysis of the PTA on the table of the occurrence of crop sequences within 64 ADs belonging to cluster 19 and 20: PTA of table-ADs. a. Eigenvalue histogram based on the diagonalization of the matrix of vector correlations. b. The interstructure plot, displaying the 21 ADs and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Projection of three subperiods on the compromise analysis plan defined by the first two principal axes. e. Coordinates of the variables (3-year CSs) on the compromise analysis plane. f. PC 1 and 2 loading plot of the variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

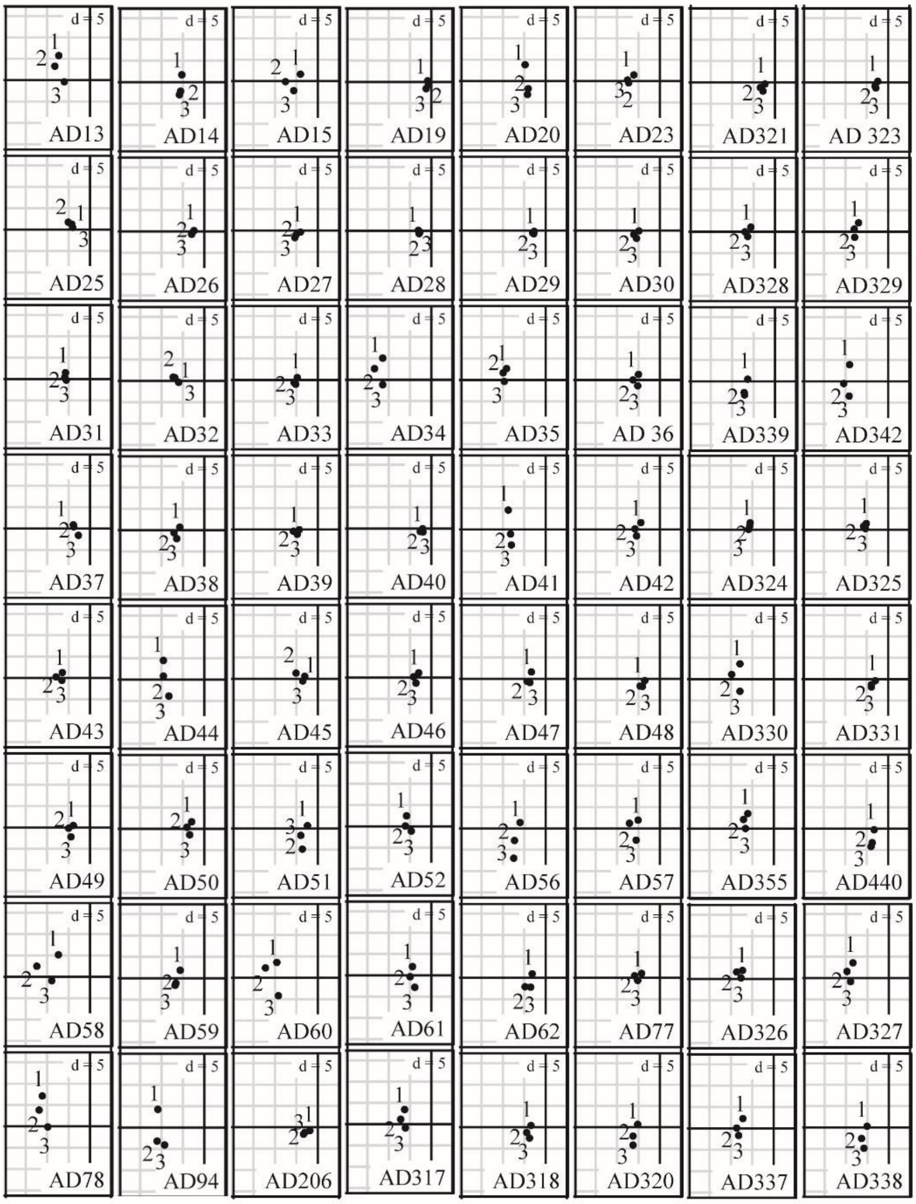

Fig. IV-14. Intrastructure plot of the PTA on the table of the occurrence of crop sequences within 64 ADs: PTA of table-ADs. The rows of each submatrix of the sequence in the compromise analysis are projected on the first two principal axes. Note: d in the upper right corner of each plot shows the scale of the x and y axes. “1”, “2”, and “3” represent the subperiods 1992-94, 1997-99, and 2001-03, respectively

4. Discussion and Conclusions

The major results of this study on spatio-temporal dynamics of crop sequence patterns at the national and regional scales are summarized below:

- The crop sequence patterns in a large portion of the ADs were likely stable. Hence, in general, crop sequence patterns at the national scale were stable during the period of the two EU CAP reforms in 1992 and 2003. Subtle changes in crop sequence patterns were observed in several parts of the territory. Crop sequence patterns within the regions using different cropping systems were modified by a variety of different pathways.
- The annual crop-related crop sequence patterns in which vineyards were dominant were likely to be stable during the entire study period.
- Field cropping zones revealed higher temporal variability of crop sequence patterns than the fodder crops and sown pasture-based livestock zones.
- The temporal evolutions of crop sequence patterns in the agricultural districts of a homogeneous zone, which was identified according to the averaged occurrences of crop sequences within the same study period, were very similar.
- Oilseed (i.e., sunflower and rapeseed) crop-, wheat- and/or barley-based CS planting zones expanded over almost the entire study period. The most evident expansion of oilseed crop/wheat-based CSs took place between the subperiods 1992-94 and 1997-99.
- Areas with pea/wheat-based CSs decreased between the subperiods 1997-99 and 2001-03 in the northern France.
- The zone specializing in planting maize monoculture and maize/wheat-based CSs evidently expanded between the two subsequent subperiods in southwestern and northeastern France. Maize/wheat-based CSs also increased in the zone where sugar beet and pea/wheat-barley-based CSs were dominant between the earlier two subperiods. Simultaneously, a monoculture of maize expanded in the other two COP growing zones.
- Increases in area with a 3-year successive fallow were observed in all three COP planting zones between the subperiods 1992-94 and 1997-99. Meanwhile, the reduction in occurrences of cereal-based CSs, including one year of fallow in 3-year CSs, were observed in the same zone.

One notable change in crop sequence patterns concern the fallow. The “set-aside” plan within the 1992 CAP reform required farmers to set aside a proportion of eligible land in exchange for a payment per hectare of land set aside (European Commission, 2003). The proportion of land to set aside was fixed every year depending on market conditions (from 5 to 15%) (Dussol et al., 2003). Dussol et al. (2003) reported an increase of 983,000 hectares of fallow between 1988 and 2000 in mainland France. The authors also indicated that fallow land mainly expanded in areas converted from fodder crop production (including both permanent meadows and pasture and temporary fodder crops). In our study, we observed an immediate increase in area of continuous fallow in all three COP cultivation zones. The increase continued over the entire study period. At the same time, a reduction in the occurrence of cereal-fallow-based CSs took place in the same zone. In the other words, the fixed set-aside area increased whereas the rotational set-aside land declined. It appears that the implementation of the 1992 CAP reform achieved its purpose of maintaining the ratio of fallow land in the total UAA. However, the complete loss of fallow from some cereal-based systems has been continued.

Another important change was related to peas, which had positive rotation effects for sustainable agriculture. As pointed by Bues et al. (2013), pea production in Europe peaked between 1987 and 1999. Since then and particularly associated with the 2003 CAP reform, the area cultivating peas has continued to decline in all member states except Spain. Our finding also indicated the same trend: an initial increase and then decrease in the planting area of pea/wheat-based CSs in northern France over the three subperiods. The increase in the planting area in the early period was correlated with the higher area-related direct payments for peas, faba beans and lupins than for other crops, which was introduced by the 1992 CAP reform. These interventions temporarily increased pea and faba bean production but have not changed the underlying economic drivers: (1) the use of protein-rich grain in animal feed has increased dramatically as well as the imports of soya bean have increased; (2) the comparative advantage of using land to grow wheat instead of protein crops has increased during the last three decades; (3) the decrease in demand for human consummation; and (4) protein crops are confronted with a range of agronomic challenges such as yield instability.

In addition, due to the increasing amount of time-series data available on land-cover and use at high temporal-spatial resolution, the improvement in the ability to detect changes in land management practices is increasingly notable in our research community (Rounsevell et al., 2012). Our study confirms the possible utilization of land-cover survey data for studying the changes in agricultural land management practices. The Partial Triadic Analysis appears to be a very powerful tool for investigating the spatio-temporal dynamics of agricultural land-use patterns. When monitoring the shifts in crop sequence pattern-related cropping systems, the explained inertia from the first two eigenvalues in the "interstructure" step of the Partial Triadic Analysis on a matrix in which sampling dates are in rows and all observed CSs were in columns can be considered as an indicator of the dynamics of crop sequence patterns within a region — i.e., the high value of explained inertia assumes a strong common structure of crop sequence patterns over the time; in other words, low temporal variability of crop sequence patterns.

We conclude that, the findings in this study provide some insights on the process and pattern of shifts in local agricultural activity-related land-use dynamics in the context of agricultural policy reform. The approach presented here can be considered as a tool for monitoring changes in crop sequence-related cropping systems through mining time-series land-cover data at a large regional scale. Information about regional crop sequence pattern modification is useful for decision-making and policy efficiency evaluation by policy makers and agricultural system stakeholders. It can also be used as input data for other modeling frameworks to assess economic and environmental performance of agricultural production systems.

Chapter V Dynamics of the relationships between crop sequence patterns and biophysical and socio-technical-economic conditions from 1992 to 2003 in mainland France

Article prepared for the submission to ***Landscape and Urban Planning***

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Abstract

The direct payments introduced by the 1992 European Common Agricultural Policy (CAP) reform began the shift from product support to producer support, resulting in farm holders adjusting their planning to market opportunities. This study explored the dynamics of the relationships between crop sequence patterns (CSP) and the biophysical and socio-technical-economic conditions during the period of the 1992 CAP reform and Agenda 2000 implementation (1992-2003) in mainland France using land-cover survey and agricultural census data. The STATICO method was applied to analyze these relationships and their temporal variations. Our investigation was at two scales: the national scale by analyzing all 429 agricultural districts (ADs) within mainland France and the regional scale by separately analyzing three principal planting zones for cereals, oilseeds and protein crops. We segmented the entire study period into three non-overlapping subperiods and then calculated the occurrence rates of 3-year crop sequences within each AD and subperiod. We found that farm size-related factors, the use of tractors with different power sizes, the share of irrigated land in the total utilized agricultural area, and the ratio of farm holders with different legal status play an important role in the overall CSP within a zone at both the national and regional scales. Some socio-technical-economic factors (e.g., irrigation, the share of legal entities in the total farm holders, the use of powerful tractors, and the large farm ratio) were strongly correlated with the CSP in one subperiod whereas the influence was less in another subperiod. This suggests possible shifts in these factors within the study area.

Key word: Cropping system; Agricultural landscape; Land-cover survey Teruti; Agricultural census; STATICO

1. Introduction

Agriculture is not the main economic activity in the European Union (EU), but it represents the main usage of land, occupying approximately 47.2% of the total land area in 2000 (FAOSTAT, 2011) and plays an important role in many environmental and other land use issues (Stoate et al., 2009).

The intensification and scale enlargement of farming that have changed the agricultural landscape after the World War II was initially driven by the large-scale application of synthetic fertilizers, mechanization and subsidies from the European Common Agricultural Policy (CAP) (van Zanten et al., 2014). Since the 1990s, further intensification, scale enlargement and specialization, and land abandonment in less-favored areas caused by the globalization of commodity markets and CAP reforms has occurred across Europe (Stoate et al., 2009; van Zanten et al., 2014). Many emerging studies modeled agricultural land-use change in relation to the shifts in agricultural management practices in Europe during the past two decades — for example, changes in the agricultural intensity at the European Union scale (Temme and Verburg, 2011), multi-scale scenarios of dynamics in the European livestock sector (Neumann et al., 2011), dynamics of farming systems in the Portuguese High Nature Value Farmland (Ribeiro et al., 2014), agricultural abandonment in the Italian Alpine area (Cocca et al., 2012), and the co-evolution of landscape patterns and agricultural intensification in Dutch dairy farming (van Apeldoorn et al., 2013). Drivers of the changes were also investigated in these studies. However, crop rotations as vital and widely implemented agricultural management practice, their changes and related driving factors have been rarely studied. Only several recent studies (Stern et al., 2012; Plourde et al., 2013; Long et al., 2014a; Long et al., 2014b) have aimed to identify primary crop rotations and quantify the changes in their planting areas in certain regions of the United States.

Crop rotation is defined as the practice of growing a sequence of crops on the same section of land (Sebillotte, 1990; Wibberley, 1996). The term “rotation” implies a cycle and is characterized by the identified starter crops and cycle period (e.g., biannual, triennial, and quadrennial) (Leteinturier et al., 2006; Dury et al., 2013). The term “crop sequences” (CSs) mentioned in this study is the order of appearance of annual crops during a fixed period (Leteinturier et al., 2006). Crop rotation has been practiced in temperate Europe agriculture since at least the 18th century to eliminate the need for a fallow period. Traditional rotations in Europe included a legume seed or forage crop, which served as a nitrogen source, and a sod crop (legume or grass) for the maintenance of organic matter (Liebman and Dyck, 1993).

The agronomic, environmental and economic effects of crop rotations have been well documented (Krupinsky et al., 2006; Rabotyagov et al., 2010; Bell et al., 2012). Integrating crop rotations in the place of a single crop into a modelling framework for assessing environmental and economic performance of agricultural production systems is receiving increased attention in the research community (Beaudoin et al., 2005; Heard et al., 2005; Gaiser et al., 2009; Rode et al., 2009; Salmon-Monviola et al., 2012; Ouyang et al., 2013). In the context of the establishment of new agricultural and environmental policies, farmers are to be paid for re-establishing and increasing ecosystem services on agricultural land (Tilman et al., 2002; Miller, 2008). The positive effects of crop rotations have once more come to the attention of researchers (Merrill et al., 2012; Le Féon et al., 2013). Monitoring the changes in crop sequence patterns at a regional scale contribute to the assessment of economic and environmental performance of agricultural production systems and thus is important for agri-environmental policy making and evaluation and sustainable farming system design.

Major modifications to EU agricultural policies were first introduced by the 1992 CAP reform (Mahé and Roe, 1996) and were further consolidated by Agenda 2000. Before 1992, support was predominately delivered via intervention in domestic markets that varied by crop and influenced which crop was to be planted. The area payments introduced to compensate for reductions in intervention prices in 1992 did not favor a specific cereal over another, but oilseed producers received a higher payment per hectare than did grain producers. These payments were important in determining whether to plant cereals or oilseeds or to set land aside, but the payments were not relevant for the allocation of land between individual cereals or oilseeds (Andersen et al., 2007). In other words, the direct payments introduced by the 1992 CAP reform was decoupled from a requirement to produce a specific crop, with the result that farm holders adjust their planning to market opportunities.

France is the largest agricultural producer in the EU and produces approximately a quarter of cereals, oilseeds and cattle in the EU. It is a net exporter with a net market balance of nine billion euros (Colson and Chatelier, 1997; Huyghe, 2012). The national implementation of the 1992 CAP reform in France was from 1993 to 1999. The direct area payment for oilseeds started in 1992 and the level of payment has been adjusted as the same level for cereals since 2000. The total intervention was 4.39 billion € in 1993 and increased to 6.65 billion Euros (€) in 1999. The share of CAP aid for the total agricultural income has increased from 2.6% in 1990 to 28.5% in 1999. The average payments for cereals, oilseeds, protein crops and land to set aside were €323.90, €558.90, €468, and €410.40 per hectare in 1999, respectively (Desriers, 2000). Changes in the policy had an impact on the relative incentives to commodities and thus on land use allocation. The study of Dussol et al. (2003) that was based on analyzing the French Agricultural Censuses indicated an increase of 2.3 million hectares in planting areas of cereals, oilseeds and protein crops (COP) and fallow and a decline of 3.5 million hectares in areas under grassland and fodder crops between 1979 and 2000. Nevertheless, information derived from the agricultural census did not allow the authors to further investigate the impact of 1992 CAP reform on the evolution of land cover.

The objective of this study was to explore the temporal variation in the relationships between crop sequence patterns (CSP) and the external conditions during the period of the 1992 EU CAP reform and Agenda 2000 implementation (1992-2003) using sequential land-cover survey and agricultural censuses data. Inspired by ecology, we consider all of the crop sequences that occurred within the study area and period as a community of crop sequences. The occurrence rates of the crop sequences represent equal "abundance." Hence, exploring the relationships between CSP and the biophysical and socio-technical-economic conditions and the temporal variation of the relationships can be considered the fundamental ecological issue: a description of species-environment relationships and the changes in the relationships. The STATICO (Simier et al., 1999; Thioulouse et al., 2004) method was performed for this exploration. Numerous applications of this method can be found in the literature to study the dynamics of species-environment relationships in diverse research fields (Carassou and Ponton, 2007; Mendes et al., 2009; Shieh and Chi, 2010; Padial et al., 2012). In addition, according to our prior studies of the spatial distribution of crop sequences at the regional and national scale in France (Mignolet et al., 2007; Xiao et al., 2014), the length of sequences was fixed at three years.

2. Materials and methods

2.1 Study area

Our study area consists of mainland France (the island of Corsica is not included) in Western Europe, which covers 552 thousand square kilometers. In France, the share of agricultural land use in the total land area was 55.4% in 1992 and 54.2% in 2003. The proportions of arable land in the agricultural area increased from 59.5% to 62.2% (FAOSTAT, 2011). Due to homogeneous agricultural activities primarily and partly similar environmental conditions such as soil profile and climate partly, the entire territory was subdivided into 430 French agricultural districts (ADs) by the French Ministry of Agriculture in 1946 (Richard-Schott, 2009). In our study, we used this zoning for the investigation of the temporal dynamics of the relationships between crop sequence patterns and external factors. Our investigation was at two scales: (1) the national scale by analyzing all 429 agricultural districts (one AD in the Region of Paris where agriculture was not a main land user was excluded in this analysis) within the French mainland; and (2) the regional scale by analyzing three principal zones for COP cultivation (Fig. V-1). These three zones included 119 ADs and accounted for approximately 40% of the total arable land of mainland France in the year 2000.

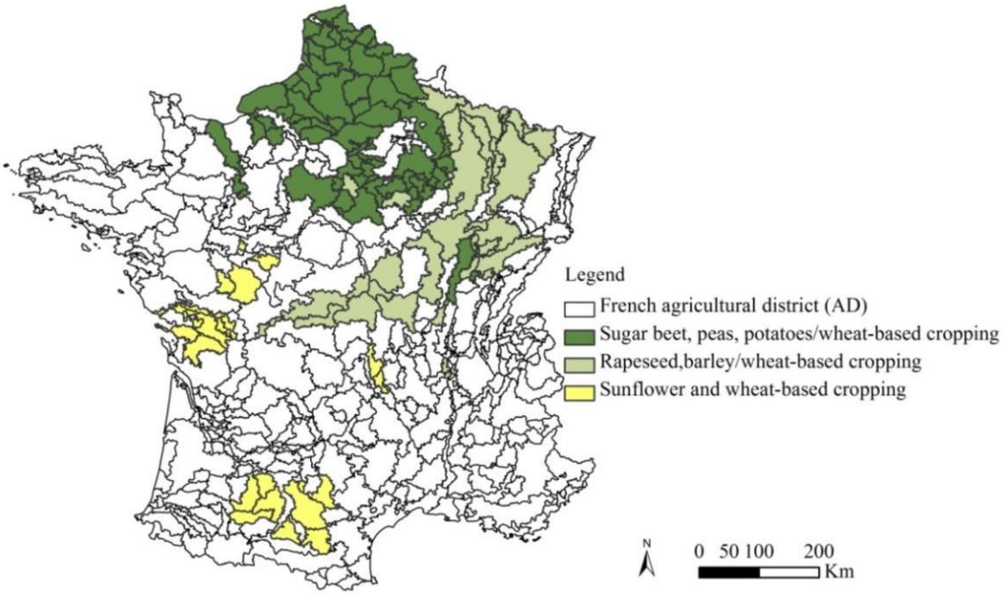


Fig. V-1. Map of 429 French agricultural districts and three principal planting zones of cereals, oilseeds, and protein crops. These three homogenous areas, in terms of the major 3-year annual crop-related sequences, were identified in our prior study (Xiao et al., 2014).

2.2 Data

Three datasets, including the occurrence rates of 3-year crop sequences within an AD, the biophysical condition, and the socio-technical-economic conditions within an AD, were used in this study. Because the agricultural districts differ widely by absolute scale, most indicators were either standardized by dividing by the total utilized agricultural area (UAA), the total number of farm holders, the total labor force, or expressed as proportions.

2.2.1 Crop sequence patterns

Historical land-cover data used in this study was derived from the Teruti database (Ledoux and Thomas, 1992) provided by the Statistics Center of the French Ministry of Agriculture. It contains sampling point-based observations of land-cover types in June on the French mainland from 1992 to 2003. A common approach to characterizing changes in cropping sequences is to partition the data into non-overlapping blocks (Plourde et al., 2013; Long et al., 2014). In this study, we divided the entire study period into three non-overlapping subperiods: 1992-94, 1997-99, and 2001-03. We then counted the occurrence rates of 3-year CSs within each district and subperiod. This temporal division was defined to capture the potential evolutions of cropping systems, which should be related to the CAP reforms in 1992 and 2003 and Agenda 2000. Finally, the data were arranged in a matrix that comprised three submatrices (each submatrix corresponded to one subperiod) in which one AD occupied a row, and each column corresponded to the occurrence rate of one 3-year CS. These three submatrices were structured in the same manner: 429 ADs in rows and 4532 3-year CSs in columns.

2.2.2 Biophysical conditions

With the aid of ArcInfo, we developed a spatial database that included the layers of biophysical variables. Given the limit of data availability, only landform and climate were included in this study to characterize the biophysical condition for agricultural production within an AD. Our data source is a digital elevation model (DEM, with a cell size of 250 m × 250 m), the SAFRAN climate database (on a 8 km × 8 km grid, daily records from the 1st January 1992 to the 31th December 2003), and the CORINE land-cover 2000 (Service de l'Observation et des Statistiques of the French ministry for the environment). An intersected layer that was obtained by intersecting the layers of the CORINE land-cover 2000, SAFRAN and the French agricultural districts was used as a basic layer. All of the biophysical variables were calculated only for the agricultural area, according to the CORINE land-cover 2000 within each agricultural district.

Slope and elevation related to the profile of the landform were extracted from the DEM. The overlay between the agricultural districts and agricultural land from the CORINE land-cover was rasterized with a resolution of 250 m. The mean elevation and associated standard deviation within the zone were then quantified using the function "Zonalstats" within ArcInfo. To calculate the slope, we used the function "Slope" within ArcInfo. The slope values were then classified into five classes: [0-2.5%] (slope 1), (2.5%-5%] (slope 2), (5%-7.5%] (slope 3), (7.5%-10.0%] (slope 4) and 10.0% or over (slope 5). The classified grid was vectorized and intersected with the basic layer. Within each agricultural district, the proportion of different classes of slope was further calculated.

Based on the daily weather data, 12 agro-climatic indicators that determinate the crop growth can be calculated to differentiate the regional climates across the entire territory. They are (1) total yearly precipitation (mm) (Prcp), (2) total yearly evapotranspiration (mm) (Evap), (3) accumulated P-PET = precipitation minus potential evapotranspiration (ET) from May to August (mm) (PPETma), (4) yearly P-PET (PPET), (5) total yearly solar radiation (SoRad), (6) number of days with frost risk (DFrsk), (7) number of days with the daily maximal temperature exceeding 30ºC (DHeat), (8) yearly mean temperature (TempM), (9) accumulated temperature (higher than 0 ºC, for the months March-July) for spring crops (ATMarJul), (10) number of days with the daily mean temperature exceeding 0ºC (D0, growing season for major crops, e.g., wheat, barley and rapeseed), (11) the number of days with the daily mean temperature exceeding 5ºC (D5, growing season for maize), (12) the number of days with the daily mean temperature exceeding 25ºC (D25, for instance, if mean air temperature exceeds 25ºC, it will be critical for wheat to survive). Moreover, the temperature threshold for crop frost risk differs between crop types and for one crop type between growing stages. We considered only one temperature threshold: 0 ºC. The input data for calculating the number of days with frost risk is the daily minimum temperature. To describe the regional climate, all indicators were calculated as 12-year averages. The calculation of the agro-climatic indicators firstly considers the SAFRAN 8 km grid. We then computed area-weighted averages of variables for each agricultural district.

2.2.3 Socio-technic-economic conditions

The pre-selection of socio-economic and technological-related variables was based on the literature review on the studies of the driving forces of agricultural land-use change and the diversity of farm types at the regional scale (e.g., Briassoulis, 2000; Köbrich et al., 2003; Hietel et al., 2007; Serra et al., 2008; Riberio et al., 2014). Thirty variables (Table V-1) were chosen and derived from publicly accessed information on French Agricultural censuses from 1988 and 2000 that was at the departmental level (Accessed at: http://agreste.agriculture.gouv.fr/spip.php?page=dc_research&id_rubrique=464&). We disaggregated the data to the AD level by computing the area-weighted average of variables. The demographic information based on the Population Census was at the commune level (Accessed at: http://www.insee.fr/fr/themes/detail.asp?reg_id=0&ref_id=fd-rp19682008&page=fichiers_detail/RP19682008/telechargement.htm). They were aggregated into the AD level. Data for 1988 was used to describe the conditions during the first subperiod 1992-94. The conditions during the subsequent two subperiods were represented using the 2000 census data.

2.3 Data analysis

Each pair of tables corresponded to two types of information: the occurrence rates of CSs and the biophysical and socio-technical-economic conditions within an AD and one subperiod. The series was therefore composed of three pairs of tables. The sampling ADs (in rows) were the same for the two tables of one pair and for the three pairs. To investigate the temporal variability in the relationships between crop sequence patterns and the external factors, the STATICO method was applied to this series of tables using R software (R Core Team, 2012) package "ade4" (Chesssel et al., 2004; Dray et al., 2007).

The STATICO method was applied in three steps: (1) a normed principal component analysis (PCA) of the external factors and the centered PCA of the CS data were separately performed on each table of the series, (2) a PCA–PCA co-inertia analysis (Dolédec and Chessel, 1994; Thioulouse, 2011) of each pair of tables was performed to produce a cross-table, and (3) a partial triadic analysis (PTA) (Thioulouse and Chessel, 1987; Thioulouse et al., 2004) was performed on the series of CSs and external factors cross-tables. The compromise analysis of this PTA gave an ordination of the crop sequences and an ordination of the external factors, which represented the stable structure of the relationships between CSP and external factors across the series. In the intrastructure step of the PTA, the CSs and external factors of each pair of tables were projected as supplementary elements on the plane of the compromise analysis, allowing us study the reproducibility of the structure across the three subperiods.

Table V-1
Socio-technical-economic variables.

Variable	Symbol	Description
Population density (inhabitants/km^2)	Popudt	
Percentage of total employees in agricultural, manufacturing, and tertiary sector (%)	Agriemp, Indemp, Tertemp	Labor population age is from 25 to 54 years. French economy consists of four sectors: agriculture, manufacturing, tertiary and public construction.
Share of female employees in agricultural sector (%)	Fagrisct	
Number of tractors by four types per UAA	Tractors55, Tractor55, Tractor80, Tractor135	Four classes of tractors according to the power: less than 55, [55, 79], [80, 134] and 135 or more DIN horsepower (DIN hp).
Ratio of areas of UAA by four types of legal status of the farm organization (%)	LegInd, LegGAEC, LegEARL, LegOth	Four types of legal status of holder: individual holders (LegInd), group holders (GAEC), legal entities (EARL), and other (LegOth).
Livestock density (four types of livestock: dairy and beef cattle, pigs, poultry, and sheep and goats) per one square kilometer of UAA) (LSU)	Cattledt, Sheepdt, Pigsdt, Poultrydt	The livestock units (LSUs) were calculated according to the LSU coefficient proposed by Eurostat (http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:Livestock_unit_)
Total labor force per hectare of UAA (annual work units/ha)	AWUs	Including both family and non-family labor forces
Ratio of the areas of UAA by six classes of the size of the farms (%)	Fss20, Fs20, Fs50, Fs100, Fs150, Fs300	Six classes of the size of farms: less than 20, [20, 50], [50, 100), [100, 150), [150, 300), and 300 or more hectare.
Mean farm size (ha)	FsM	Mean farm size = Total arable land divided by total farms with arable land.
Percentage of principal operators of four age groups (%)	Ages40, Age40, Age55, Age65	Classification according to (Bernier, M., 2005): under 40 years, [40, 55], (55, 64] and 65 years and over. Farm holders under 40 years have subsides from government for set-up (Benjamin et al., 2006).
Ratio of irrigated land of the total UAA in the census year (%)	Irri	Available data is at the admistrative regional scale.

3. Results

3.1 The dynamics of the relationships between CSP and socio-technical-economic and biophysical conditions at the national scale

The STATICO was performed on a series of paired tables to investigate the temporal evolutions of the relationship between the CSP and socio-economic and biophysical conditions within all 429 ADs. Each pair of tables consisted of one table of 4532 CSs (in columns) and another table of 48 socio-technical-economic and biophysical variables (in columns). Both of the tables had the same rows (one AD per sampling subperiod).

The first two eigenvalues produced by the eigenanalysis of this series of cross-tables explain 89.2% and 9.7% of the total inertia, respectively (Fig. V-2a). The similar coordinates of the submatrices on the first axis of the interstrucuture plot indicates a strong common structure of the relationships between CSP and external conditions across the three subperiods (Fig. V-2b). A weaker submatrix weight for 1992-94 means that the corresponding tables are less structured and have weaker importance in defining the compromise.

For the analysis of the compromise, the first two principal axes accounted for 83.1% of the total inertia (Fig. V-2c), which supports a good summary of the common structure in the relationships between CSP and external variables over the three subperiods. The factor map of the PCA of the compromise for the CSs (Fig. V-2d) reveals four distinct assemblages of CSs: (1) a monoculture of maize and three-year successive temporary pastures located in the second quadrant and a maize monoculture that isolates from the others CSs; (2) wheat-barley-based CSs, particularly the "wheat-barley-rapeseed" rotation and sugar beet/pea-wheat CSs and a three-year successive fallow located in the first quadrant; (3) maize/wheat-based CSs, sunflower/wheat-based CSs located on the positive half of the second axis; and (4) many CSs are close to the origin and thus have no importance in the graphic. Meanwhile, the factor map of the compromise analysis for the external variables (Fig. V-2e) reveals two gradients: a farm structure-related gradient along the first principal component and a landform-related gradient along the second principal component. Figure V-2f shows the correlation circle of the PCA on the table for compromise. The positive half of the first component was characterized by the high ratio of large farms (Fs150, Fs100) and farms with large mean sizes. The negative half of the first component was correlated with the ratio of small farms (Fs20, Fss20), the use of low-powered tractors (tractors with power between 55 and 79 DIN hp), and the share of irrigated land in the total UAA. The second component was mainly positively correlated with the use of tractors with moderate power (Tractor80), flat landform (Slope 1) and the ratio of legal entities among total farm holders but was negatively correlated with sloping land with high elevation, more days with frost risk and more yearly solar radiation.

Hence, the stable relationships between the abundant CSs-related cropping patterns and external conditions at the national scale can be summarized as follows:

(1) The monoculture of maize was associated with the high share of irrigated land in the total UAA, the high share of small farms with plain landform, and the significant use of tractors with moderate power;

(2) Including rapeseed or sugar beet in wheat-barley-based CSs and three-year successive fallow were frequently implemented within the plain zone with larger mean farm size, higher ratio of farms with 100 hectares or more, and a higher ratio of legal entities among the total farm holders;

(3) Maize/wheat-based and sunflower/wheat-based CSs were associated with the use of tractors with moderate power, plain landform, number of days with the daily mean temperature exceeding 5ºC, and a high share of legal entities as farm holders;

(4) Continuous temporary pasture was positively associated with the share of irrigated land in the total UAA, plain landform, use of tractors with moderate power, and ratio of small farms.

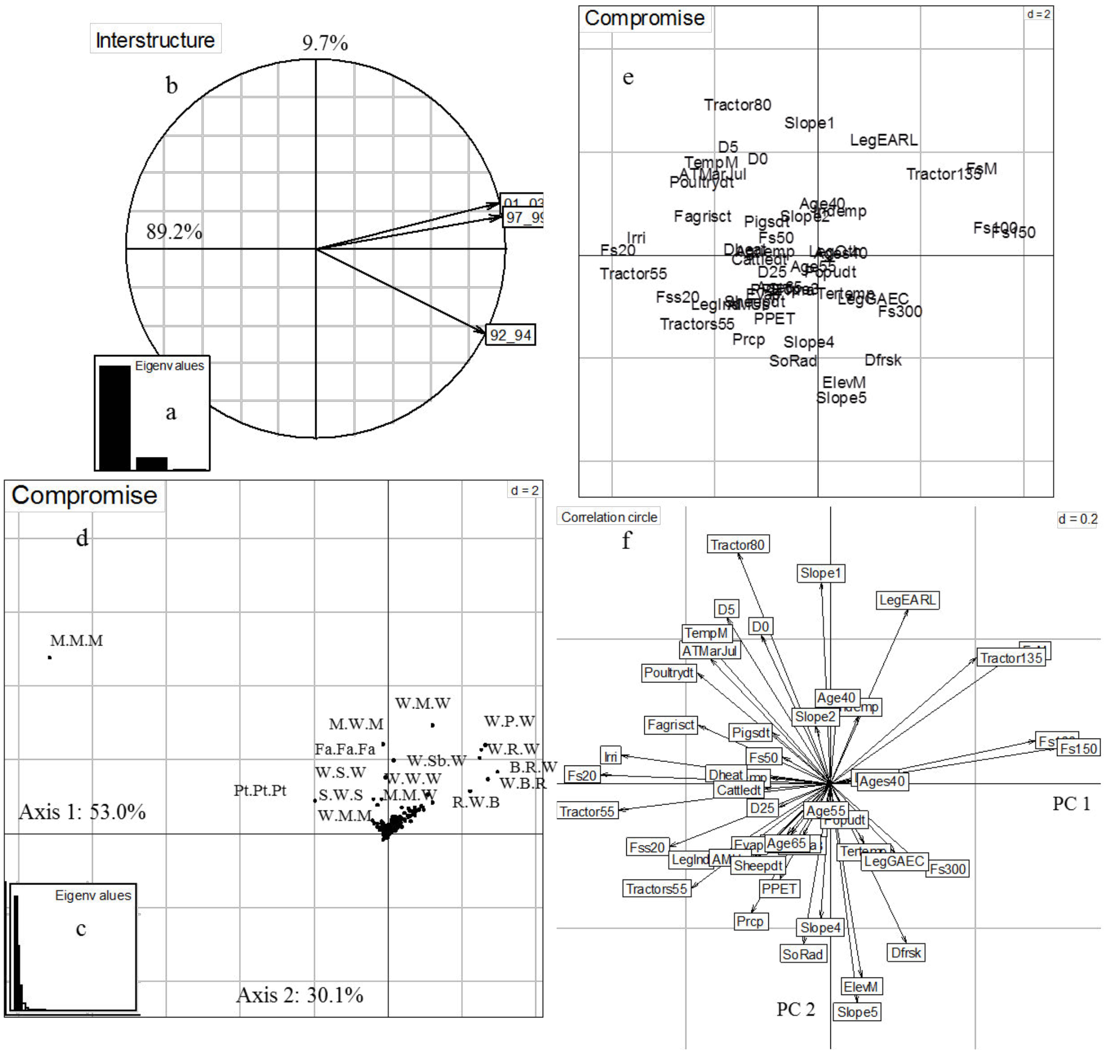


Fig.V-2. Results of the STATICO on the paired tables of 429 ADs. a. Scree plot of eigenvalues based on the diagonalization of the RV matrix. b. The interstructure plot, displaying the three subperiods and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Compromise analysis principal axes map (4532 CSs). The most abundant CSs were indicated with labels. e. Compromise analysis principal axes map (48 socio-technical-economic and biophysical variables). f. PC 1 and 2 loading plot of the 48 socio-technical-economic and biophysical variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

The trajectories factor maps indicated that the relationships between the most abundant CSs in the assemblage and external factors differed between sampling subperiods (Fig. V-3). The stable structure of the crop sequence pattern-external condition relationships was well expressed by the two investigations of the subperiods 1997-99 and 2001-03. During the first subperiod, different crop sequence patterns emerged. Pea/wheat-based CSs were major CSs while oilseed crops (rapeseed and sunflower) /wheat-based CSs were not abundant. In comparison to the first subperiod, maize/wheat-based CSs and a monoculture of maize were implemented more during the subsequent two subperiods. During the first subperiod, field crop-based crop sequence patterns were mainly associated with farm size-related factors, the use of tractors with moderate power, and plain landform. During the subsequent two subperiods, the relationships between the most abundant CSs and external factors were similar. The most abundant CS and monoculture of maize were positively associated with the use of tractors with moderate power, ratio of irrigated land, plain land form, and ratio of small farms. The inclusion of rapeseed and sugar beets in wheat-barley-based CSs showed abundance within the plain zone with a high ratio of farms of 150 hectares or more, large mean farm size, a high ratio of legal entities in the total number of farm holders, and significant use of powerful tractors. Maize/wheat-based and sunflower/wheat-based CSs were also major CSs and they were positively associated with the use of tractors with moderate power, plain landform, and ratio of legal entities in the total number of farm holders.

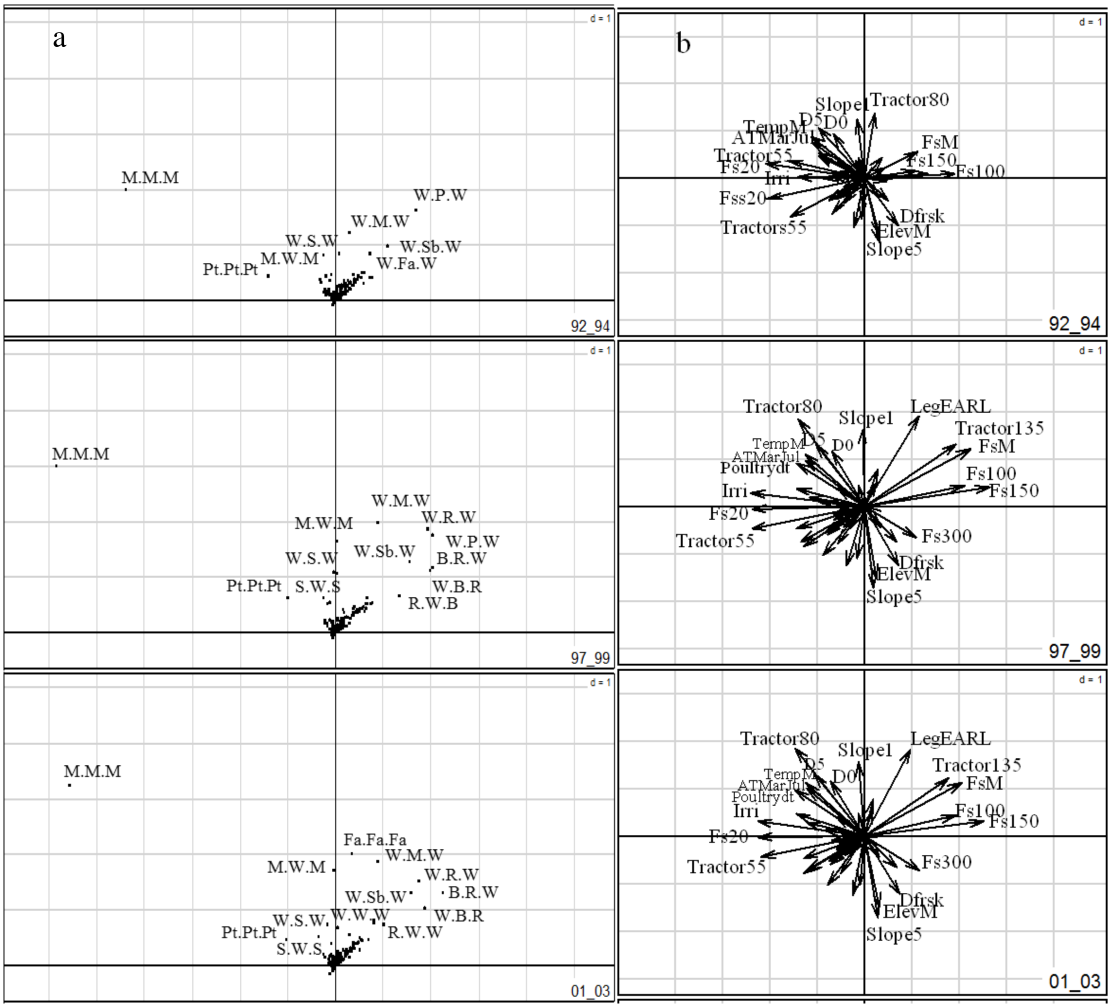


Fig. V-3. Results of the intrastructure step of the STATICO analysis on the paired tables of 429 ADs. The three plots on the left (a) show the 3-year CSs for each set of dates (three subperiods: 1992-94, 1997-99 and 2001-03), and the three plots on the right (b) show the socio-technical-economic and biophysical variables at the same dates. Only the most abundant were highlighted using letters. (c) Projection of columns of each table (socio-technical-economic and biophysical variables) as supplementary elements on the plane of the compromise analysis. The scale of the grid in each plot is given by the value d in the upper right corner of the plot.

3.2 The dynamics of the relationships between the CSP and socio-technical-economic and biophysical conditions at the regional scale: STATICO on the paired tables of three major zones for COP cultivation

3.2.1 Zone specializing in sunflower/wheat-based CS cultivation

Based on our prior study of the spatial distribution of crop sequences in mainland France, 21 ADs were clustered into one cluster, which was characterized by the predominance of sunflower/wheat-based CSs (Xiao et al., 2014). STATICO was performed on a series of paired tables, including three submatrices in which sampling ADs in each subperiod were in rows and 1707 CSs and 48 external factors were in columns, respectively.

For the interstructure step, the first two eigenvalues produced from the eigenanalysis of this series of cross-tables explained 94% of the total inertia (Fig. V-4a). The subperiod 1992-94, with the shortest arrow (Fig. V-4b), is less structured and thus less important than the other two subperiods in the construction of compromise.

The first two axes of the compromise analysis explained approximately 83% of the total inertia (Fig. V-4c). It therefore summarized the stable structure of the relationships between crop sequence patterns and the external conditions within the zone specializing in sunflower/wheat-based CSs well. The factor map of the compromise analysis for the CSs (Fig. V-4d) reveals the abundance of “sunflower-wheat” rotations and maize-based CSs (i.e., maize monoculture, maize/wheat-based CSs, and wheat-based CSs associating with rapeseed or other oilseed crops). The factor map for the external factors (Fig. V-4e) reveals a gradient of temperatures along the first axis. With the compromise analysis, out of the 48 external factors taken into account, only a few were confirmed as correlating with the crop sequence patterns (Fig. V-4f). The first principal component of the compromise analysis was characterized by warm climate (high yearly mean temperatures and longer growing season for crops), and a high share of irrigated land in the total UAA for the negative half and by the number of days with frost risk for the positive half. The second component was primarily associated with the landform, mean farm size, poultry density and legal status of farm-related factors. The correspondence with CSs allowed the identification of these CSs, which responded to the external factors. The most dominant CS “sunflower-wheat” rotation was frequently implemented within the zone with higher yearly mean temperatures, a longer growing season for crops, a higher ratio of irrigated land in the total UAA, and a higher use of moderate power tractors. Another predominant CS, a monoculture of maize, dominated within the plain, warm and wet zone (more PPET) with a high density of poultry, large mean farm size, a high ratio of legal entities at total farm holders, and a high share of irrigated land. Including two years of rapeseed or/and sunflower in wheat-based CSs were positively associated with plain landform, a high poultry density, large mean farm size, a high ratio of legal entities of the total farm holders, and more PPET. Other oilseed crops (other than rapeseed and sunflower)/wheat-based CSs were also major CSs in the sunflower specialized zone. They were frequently grown within warm and steeping zones with a high ratio of individual farms and significant use of tractors with low power. Including one year of maize or sunflower into successive wheat-based CSs and a monoculture of wheat (durum wheat) were predominant within the steeper zone with high elevation, a high ratio of individual farms, a high use of tractors with low power, and more days with frost risk. Maize/wheat-based CSs were positively associated with plain landform, ratio of employees in manufacturing sector, and number of days with frost risk.

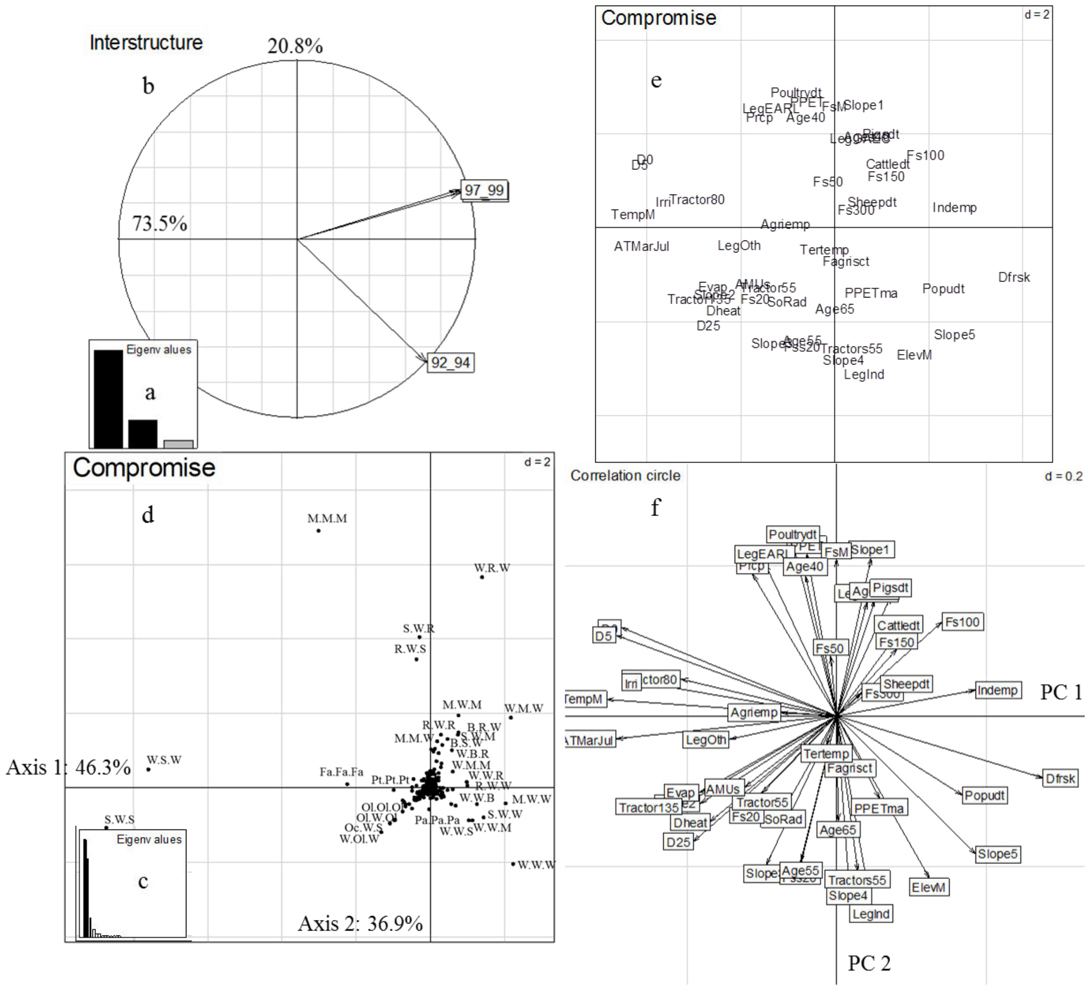


Fig. V-4. Results of the STATICO on the paired tables of 21ADs belonging to the zone specializing in sunflower/wheat-based crop sequences' cultivation. a. Scree plot of eigenvalues based on the diagonalization of the RV matrix. b. The interstructure plot, displaying the three subperiods and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Compromise analysis principal axes map (1707 CSs). The most abundant CSs were indicated with labels. e. Compromise analysis principal axes map (48 socio-technical-economic and biophysical variables). f.

PC 1 and 2 loading plot of the 48 socio-economic and biophysical variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

Figure V-5 indicated the relationships between the predominant CSs and the external factors within the zone specializing in sunflower/wheat-based CSs in each sampling subperiod. During the first subperiod, the most dominant CSs, a monoculture of maize and sunflower/wheat-based CSs were positively associated with the agro-climatic condition (i.e., mean temperature, duration of the growing season, precipitation and PPET, and the ratio of middle-aged principal farm operators (40-55 years old).

During the second subperiod, rapeseed/wheat-based CSs presented high abundance while sunflower/wheat-based CSs and maize monoculture were the major CSs within this zone. These rapeseed/wheat-based CSs were directly associated with plain landform, a high density of poultry, a high ratio of legal entities in the total number of farm holders and large mean farm size. The “Sunflower-wheat” rotation was not only positively associated with agro-climatic condition but also with the share of irrigated land in the total UAA and the use of powerful tractors (Tractor135). Moreover, two successive wheat-based CSs and a monoculture of wheat (durum wheat) and wheat and other oilseed crop-based CSs presented as major CSs within this subperiod. The successive wheat-based CSs were associated with hilly zones with a higher ratio of individual farms and more days with frost risk. Wheat/other oilseed crop-based CSs were frequently grown within the steeping zone with more days with heat (the number of days with the daily mean temperature exceeding 25 ºC), and a significant use of powerful tractors.

During the third subperiod, the crop sequence pattern-external condition relationships were similar to the second subperiod. Rapeseed/wheat-based CSs were still major CSs but they were less abundant than in the second subperiod. Meanwhile, maize/wheat-based CSs presented more abundance and they were associated with plain landform, large mean farm size, a high ratio of farms with 100 hectares or more, a high density of poultry, and a high ratio of legal entities in the total farm holders.

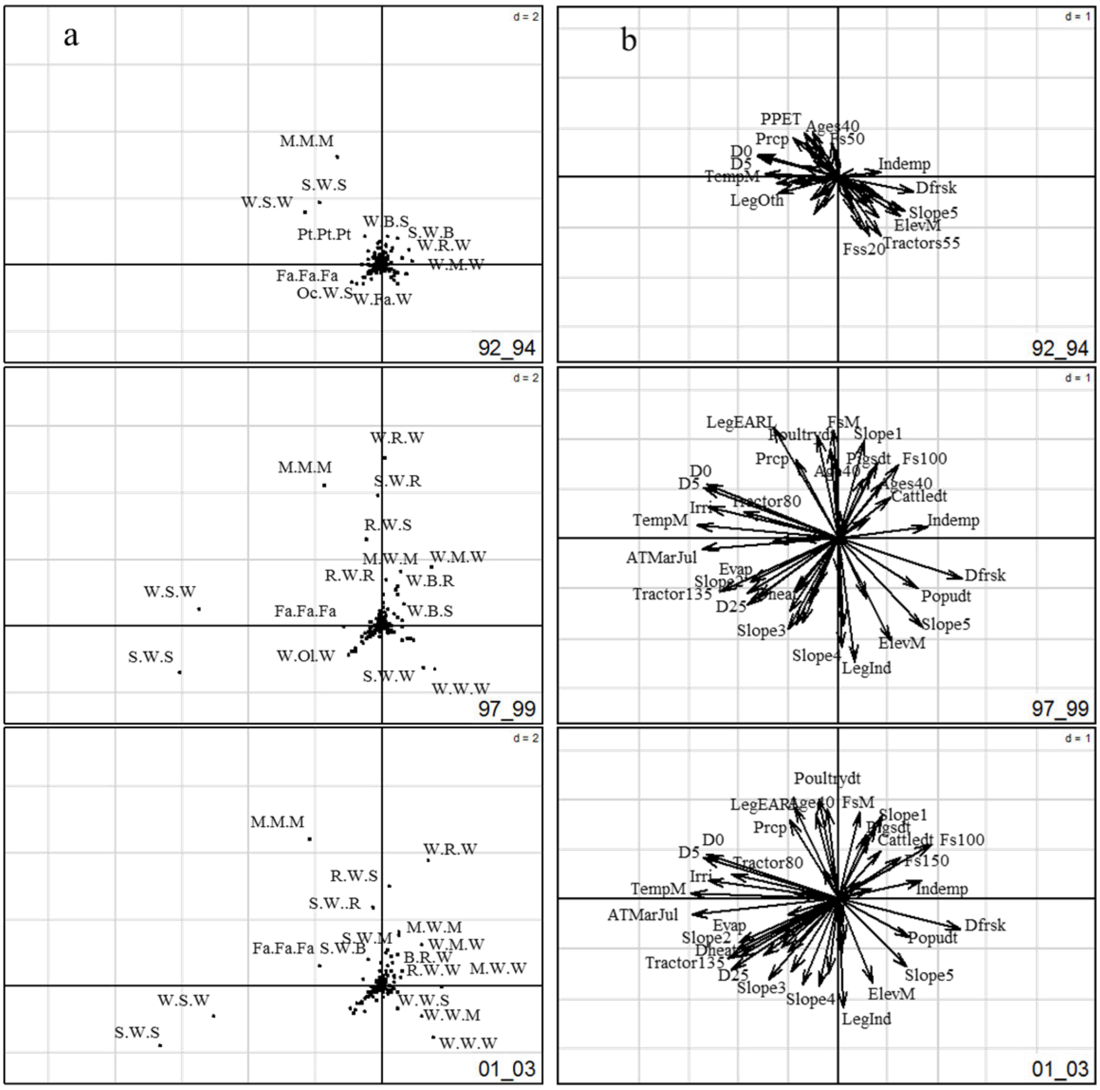


Fig. V-5. Results of the intrastructure step of the STATICO analysis on the paired-tables of 21 ADs belonging to the zone specializing in sunflower/wheat-based crop sequences' cultivation. The three plots on the left (a) show the 3-year CSs at each set of dates (three subperiods: 1992-94, 1997-99 and 2001-03), and the three plots on the right (b) show the socio-technical-economic and biophysical variables at the same dates. The scale of the grid in each plot is given by the value d in the upper right corner of the plot. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

3.2.2 Zone specializing in the inclusion of rapeseed in wheat-and barley-based CS cultivation

The 34 ADs were characterized by the predominance of wheat/barley- and rapeseed-based CSs. A PTA was performed with a matrix including 34 submatrices, in which three subperiods were in rows and 1509 CSs were in columns, to investigate the diversity of the temporal evolution of crop sequence patterns per AD over time.

For the interstructure step, the first two eigenvalues produced from the eigenanalysis of this series of cross-tables explained approximately 97% of the total inertia (Fig. V-6a). The submatrix of the subperiod 1992-94 was less structured and therefore the compromise was less influenced by this submatrix (Fig. V-6b). The second subperiod 1997-99, with the largest coordinate on the first axis, is clearly more important than the other three, meaning that the compromise will be more influenced by this subperiod. The first principal component of the compromise analysis was clearly dominant and accounted for 82% of the total inertia — in contrast with the second component, which accounted for 10.7% of the total inertia and was much less significant (Fig. V-6c). Thus, the PCA of the compromise summarized the common structure of the relationships between crop sequence patterns and the external conditions over the three subperiods well. Fig. V-6d and V-6e show the PCA factor maps of the compromise for crop sequences and external factors, respectively. The wheat-barley-rapeseed rotation was the opposite of the continuous temporary pasture on the first axis. The loadings of the variables on the first two components (Fig. V-6f) allowed us to explore the variables that accounted for the difference. The first principal component positively correlated with the ratio of very large farms (Fs150, Fs300), the use of powerful tractors (Tracotr135), and number of days with frost risk. It was negatively correlated with a high density of sheep, warm climate (ATMarJul, D5, D0, TempM), a high total yearly evapotranspiration, a high ratio of individual farms and a high share of elderly farm operators (Age65), and a high share of irrigated land in the total UAA. Therefore, the stable part of the crop sequence-external condition relationships can be summarized as follows:

(1) The most abundant CSs of the zone, the "wheat-barley-rapeseed" rotation and the "rapeseed-wheat" rotation, were associated with high use of powerful tractors, a high ratio of very large farms, and more days with frost risk;

(2) Continuous temporary pasture was frequently implemented within zones with higher sheep density, warmer climate, a higher ratio of individual farms, a higher share of elderly farm operator, and a higher share of irrigated land in the total UAA.

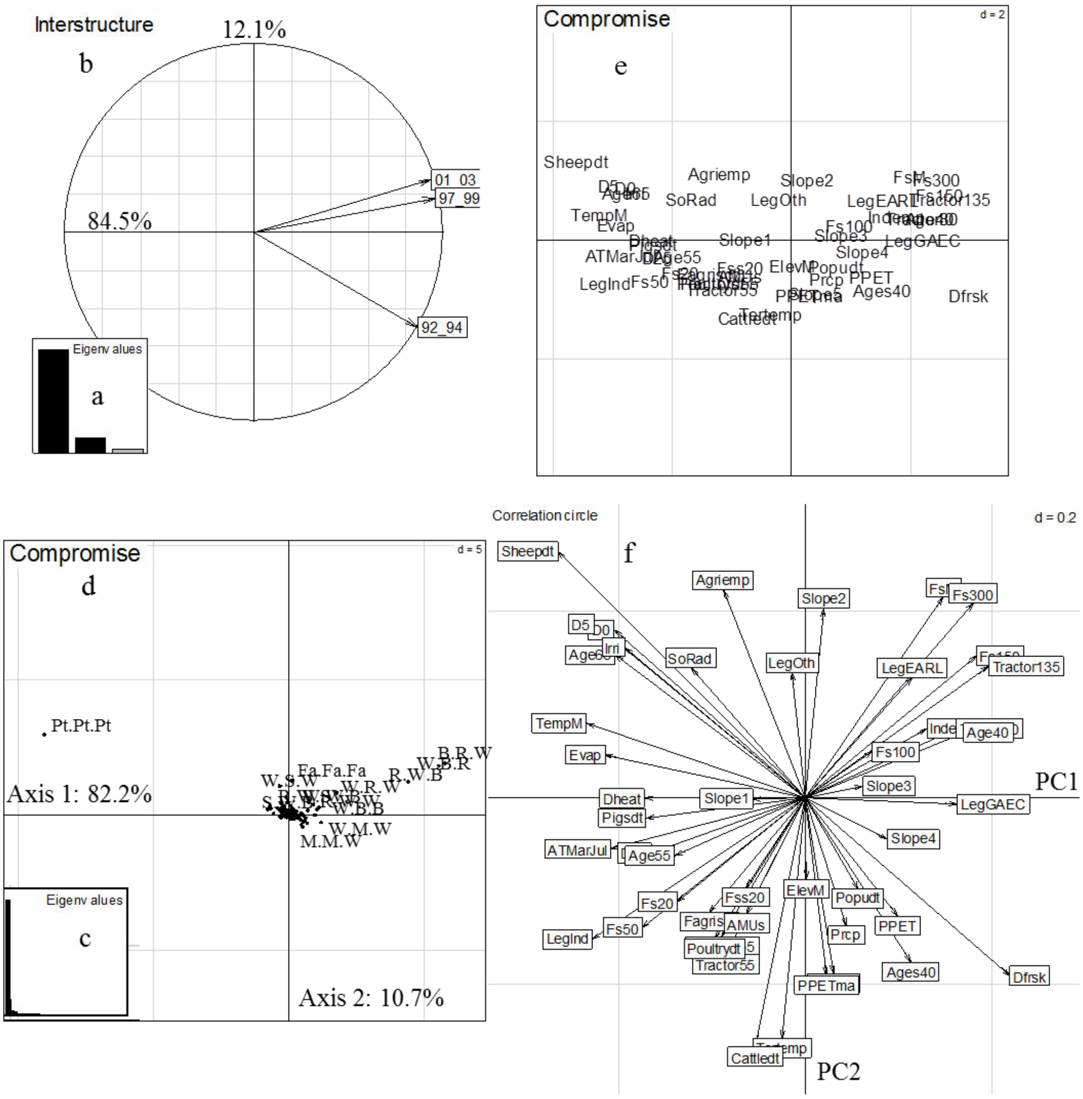


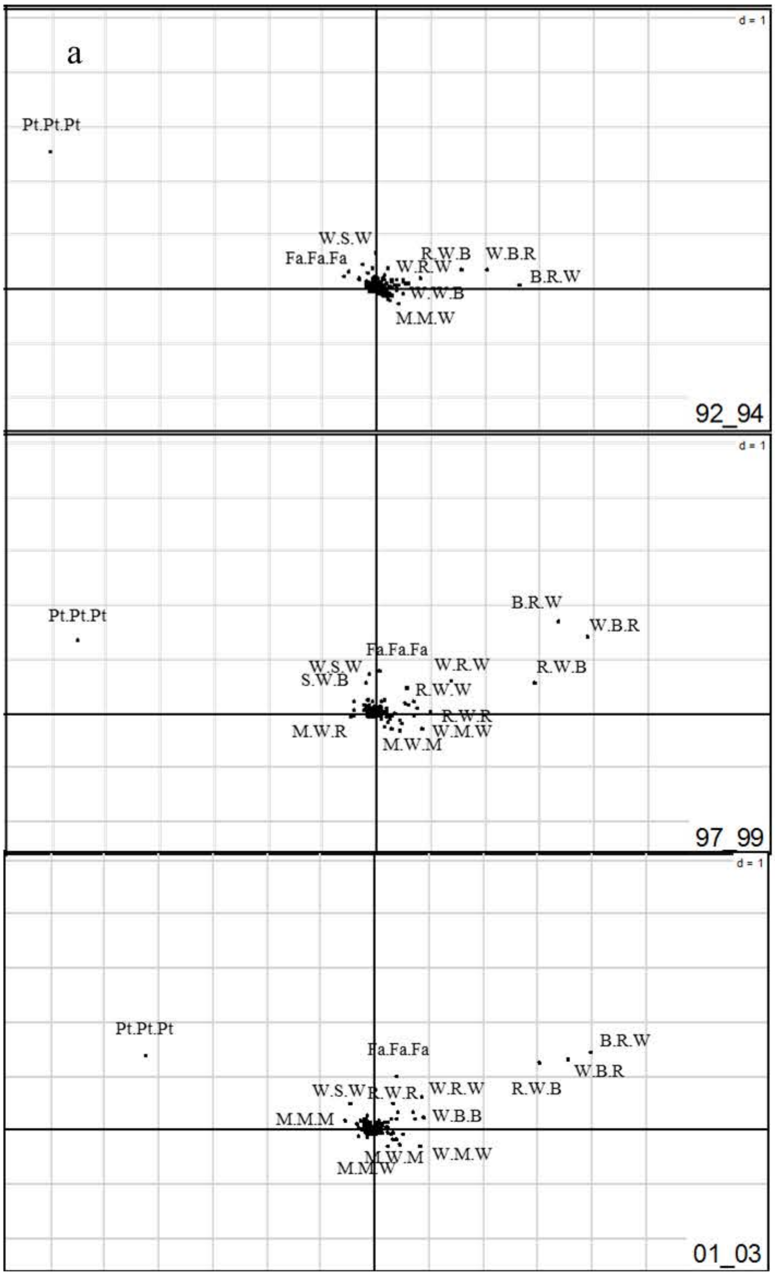
Fig. V-6. Results of the STATICO on the paired tables of 34 ADs belonging to the zone specializing in the inclusion of rapeseed in wheat-and barley-based CS cultivation. a. Scree plot of eigenvalues based on the diagonalization of the RV matrix. b. The interstructure plot, displaying the three subperiods and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Compromise analysis principal axes map (1509 CSs). The most abundant CSs were indicated with labels. e. Compromise analysis principal axes map (48 socio-technical-economic and biophysical variables). f. PC 1 and 2 loading plot of the 48 socio-technical-economic and biophysical variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

The trajectory factor maps (Fig. V-7) indicated that the relationships between the crop sequence patterns and external factors differed between subperiods.

During the first subperiod, the most abundant CS, three year successive temporary pastures, was positively associated with sheep density and warm climate with a long growing season for crops. Rapeseed/wheat-based CSs (e.g., “wheat-barley-rapeseed” and “rapeseed-wheat” rotations) were major CSs during this subperiod and they were positively associated with the use of moderate power tractors (Tractor80), the number of days with frost risk and the ratio of farms with 100 hectares or more.

During the second subperiod, the most abundant CSs were continuous temporary pasture and the “wheat-barley-rapeseed” rotation. The former was associated with warm climate and a long growing season for crops, a high ratio of old operators, a high sheep density, a high ratio of individual farms, and a high share of irrigated land. The latter was positively associated with the use of powerful tractors, the ratio of very large farms (Fs150, Fs300), and the number of days with frost risk. In addition, continuous fallow was a major CS during this subperiod. They were frequently implemented within the zone with a large mean farm size, a high ratio of farms with 300 hectares or more.

In general, the relationships between crop sequence patterns and the external factors during the third subperiod were very similar to the second subperiod. We noted that a monoculture of maize presented as a major CS during this subperiod. It was associated with a high ratio of individual farms, the ratio of medium-sized farms (Fs50), and a high share of elderly principal operators (Age65).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Fa.Fa.Fa
R.W.B
W.B.R
W.R.W
B.R.W
W.W.B
M.M.W
92_94
d = 1
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W.B.R
Pt.Pt.Pt
Fa.Fa.Fa
W.R.W
W.S.W
R.W.B
S.W.B
R.W.W
R.W.R
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W.M.W
M.W.M
97_99
d = 1
Pt.Pt.Pt
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Fa.Fa.Fa
W.B.R
R.W.B
W.S.W
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01_03

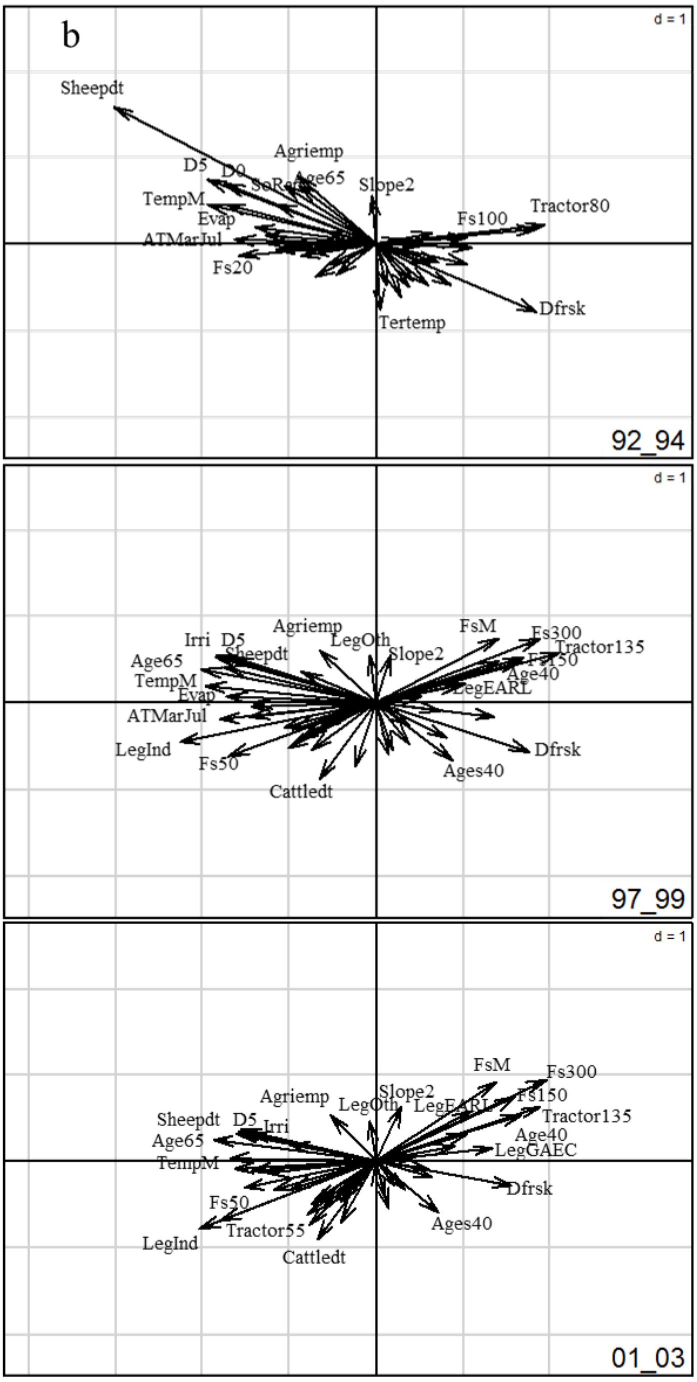

Fig. V-7. Results of the intrastructure step of the STATICO analysis on the paired tables of 34 ADs belonging to the zone specializing in the inclusion of rapeseed in wheat-and barley-based CS cultivation. The three plots on the left (a) show the 3-year CSs at each date (three subperiods: 1992-94, 1997-99 and 2001-03), and the three plots on the right (b) show the socio-technical-economic and biophysical variables at the same dates. The scale of the grid in each plot is given by the value d in the upper right corner of the plot. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

3.2.3 Zone specializing in the inclusion of sugar beet, peas or potatoes in wheat and/or barley-based CS cultivation

The 64 ADs were characterized by the predominance of wheat/barley and sugar beet-, potato-, and pea-based 3-year CSs. A PTA was performed on a matrix including 64 submatrices, in which three subperiods were in rows and 2355 CSs were in columns, to investigate the diversity of the temporal evolution of crop sequence patterns per AD over time.

For the interstructure step, the first and the second eigenvalue produced from the interstructure analysis explain 76.1% and 17.8% of the total inertia, respectively (Fig. V-8a). The weaker inertia explained by the first two eigenvalues of the 64 ADs that belong to the cluster that specialized in sugar beets, peas or potato-wheat and/or barley-based CSs rather than the two previously studied clusters indicate that a higher temporal variation of the crop sequence pattern-external condition relationship. The interstructure plot (Fig. V-8b) shows that the relationships between crop sequence patterns and the external factors within this zone revealed to be the strongest in the subperiod 1997-99, followed by 2001-03 and 1992-94 in decreasing order of importance in the construction of compromise.

The share of the total inertia explained by each of the first two axes of the compromise PCA was 60.9% and 12.5%, respectively (Fig. V-8c). Figure V-8d and V-8e show the factor maps of the compromise PCA, CSs and the external factors, respectively. The abundant CSs of the zone, sugar beet/wheat-based associated with potato or pea CSs, are the opposite of the rapeseed/wheat-based and maize/wheat-based CSs on the bottom part of the factor map. Out of the 48 external factors taken into account, only a few factors were found to be associated with the structure of crop sequence patterns (Fig. V-8f). The first component was positively correlated with the ratio of large farms (Fs150, Fs300), mean farm size, the ratios of two types of farm holders (legal person and other legal entity) and the use of powerful tractors (Tractor135). The density of pigs and cattle, the ratio of small farms, the use of tractors with low power, AMUs, and precipitation-related conditions (e.g., Prcp, PPET, PPETma) were negatively correlated with the first component. The second component was mainly positively associated with the ratio of employees in the tertiary sector and population density. High poultry density, a high yearly mean temperature, more days with the daily mean temperature exceeding 25 ºC, a high share of irrigated land in the total UAA, a high ratio of farms operated by elderly farmers characterized the negative half of the second component.

Hence, the stable structure of the relationships between crop sequence patterns and the external factors within the zone can be summarized as follows:

(1) sugar beet/wheat-based CSs were primarily associated with the higher ratio of employees in the tertiary sector and a higher population density. Among them, the inclusion of potatoes in sugar beet/wheat-based CSs were grown within the zone with a higher ratio of small farms

(Fs20), a higher use of tractors with low power, a higher AMUs and a higher density of pigs and cattle. Sugar beet/wheat-based CSs associated with peas or a second wheat or sugar beet CSs was positively associated with the use of powerful tractors, the ratio of very large farms, and the ratios of two types of farm holders (legal entities and individual holders);

(2) maize/wheat-based CSs were positively associated with the density of pigs, cattle and poultry, the ratio of small farms, the use of tractors with low power, AMUs, precipitation-related conditions, yearly mean temperature, and the ratio of individual farms;

(3) rapeseed/wheat-based CSs were positively associated with the ratio of large farms (Fs150, Fs 100), the ratio of legal entities of the total farm holders, the ratio of elderly farm operators (Age55, Age65), the share of irrigated land, and mean daily temperature.

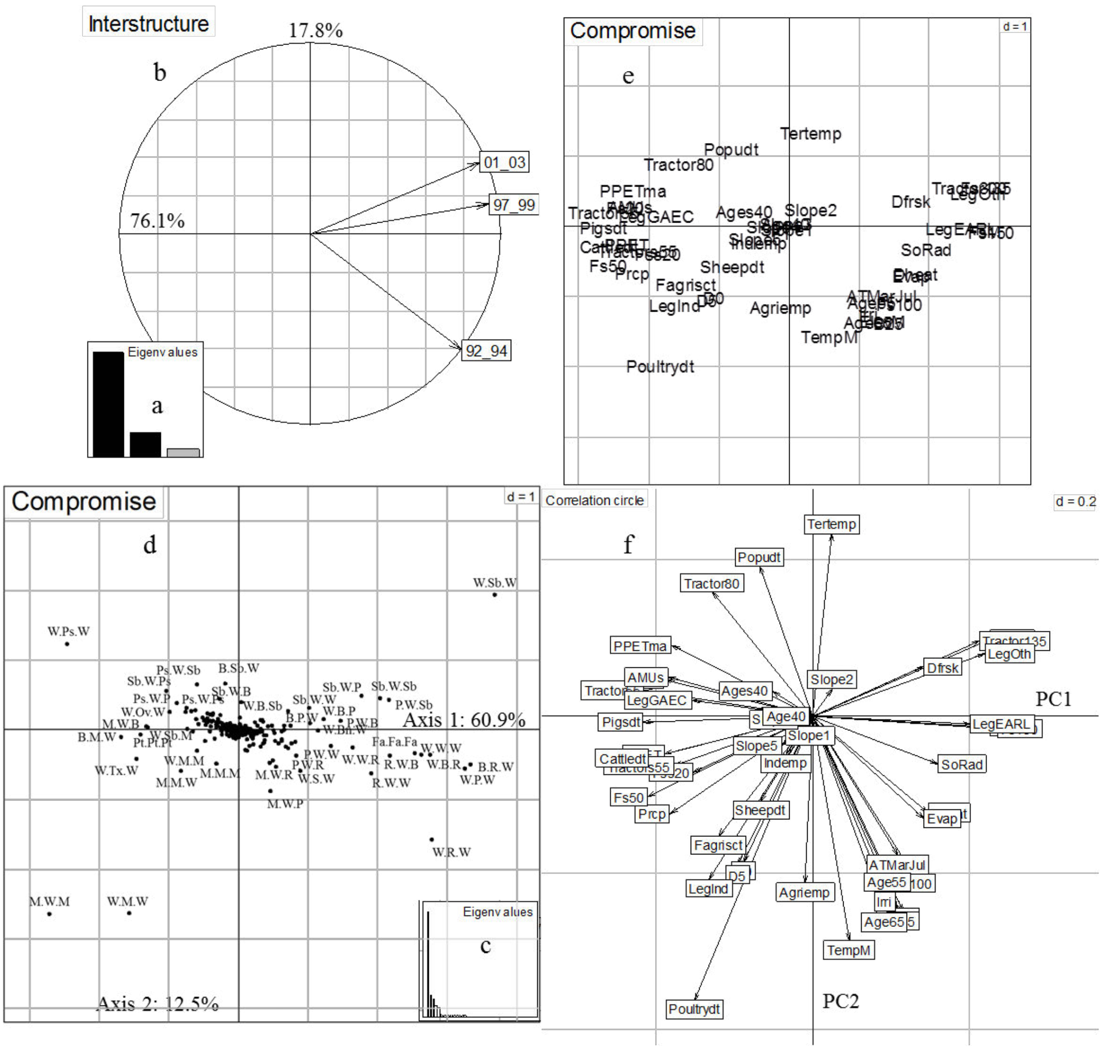

Fig. V-8. Results of the STATICO on the paired tables of 64 ADs belonging to the zone specializing in the inclusion of sugar beet, peas, or potatoes in wheat and/or barley-based CS cultivation. a. Scree plot of eigenvalues based on the diagonalization of the RV matrix. b. The interstructure plot, displaying the three subperiods and the importance of the corresponding submatrices in the definition of the compromise (coordinates of the points on the first axis). c. Scree plot of eigenvalues of the compromise analysis. d. Compromise analysis principal axes map (2355 CSs). The most abundant CSs were indicated with labels. e. Compromise analysis principal axes map (48 socio-technical-economic and biophysical variables). f. PC 1 and 2 loading plot of the 48 socio-technical-economic and biophysical variables. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

The trajectory factor maps indicated that the relationships between the most abundant CSs in the assemblages and external factors differed between subperiods (Fig. V-9). The structure of the relationships between crop sequence patterns and external factors is the strongest during the second subperiod.

During the first subperiod, inclusions of one year of peas or potatoes in wheat-based CSs, maize/wheat-based and sugar beet/wheat-based CSs were abundant. Among them, pea/wheat-based and sugar beet/wheat-based CSs were frequently implemented within the zones with high ratios of large farms (Fs100, Fs150) and a high ratio of other legal entities as the farm holder. In contrast, maize/wheat-based and potato/wheat-based CSs were frequently implemented within the zones with a high ratio of small farms and a high use of tractors with low power. Moreover, potato/wheat-based CSs were associated with a high ratio of employees in the tertiary sector and a high population density, whereas maize/wheat-based CSs were positively associated with yearly mean temperatures and the share of employees in agricultural sector.

During the second subperiod, the “maize-wheat” rotation was one of the most abundant CSs. It was associated with a high density of poultry and pigs, a high ratio of farms with medium size (Fs50), and a high yearly mean temperature. Rapeseed/wheat-based CSs were also abundant and were positively associated with large mean farm sizes, the ratio of very large farms (Fs150, Fs300), the use of powerful tractors, and the ratio of legal entities in the total number of farm holders. In addition, sugar beet/wheat-based CSs involving potatoes or peas remained abundant. Potato-related CSs were positively associated with the use of tractors with moderate power, population density, and the ratio of employees in the tertiary sector. The inclusion of peas in sugar beet/wheat-based CSs were associated with a high ratio of large farms (Fs300), a high ratio of employees in tertiary sector, and a high use of powerful tractors.

During the third subperiod, crop sequence patterns revealed two evident changes: continuous fallow was one of the most common CSs within the zone, and pea-related CSs were no longer major CSs. Continuous fallow was implemented under similar conditions to rapeseed/wheat-based CSs.

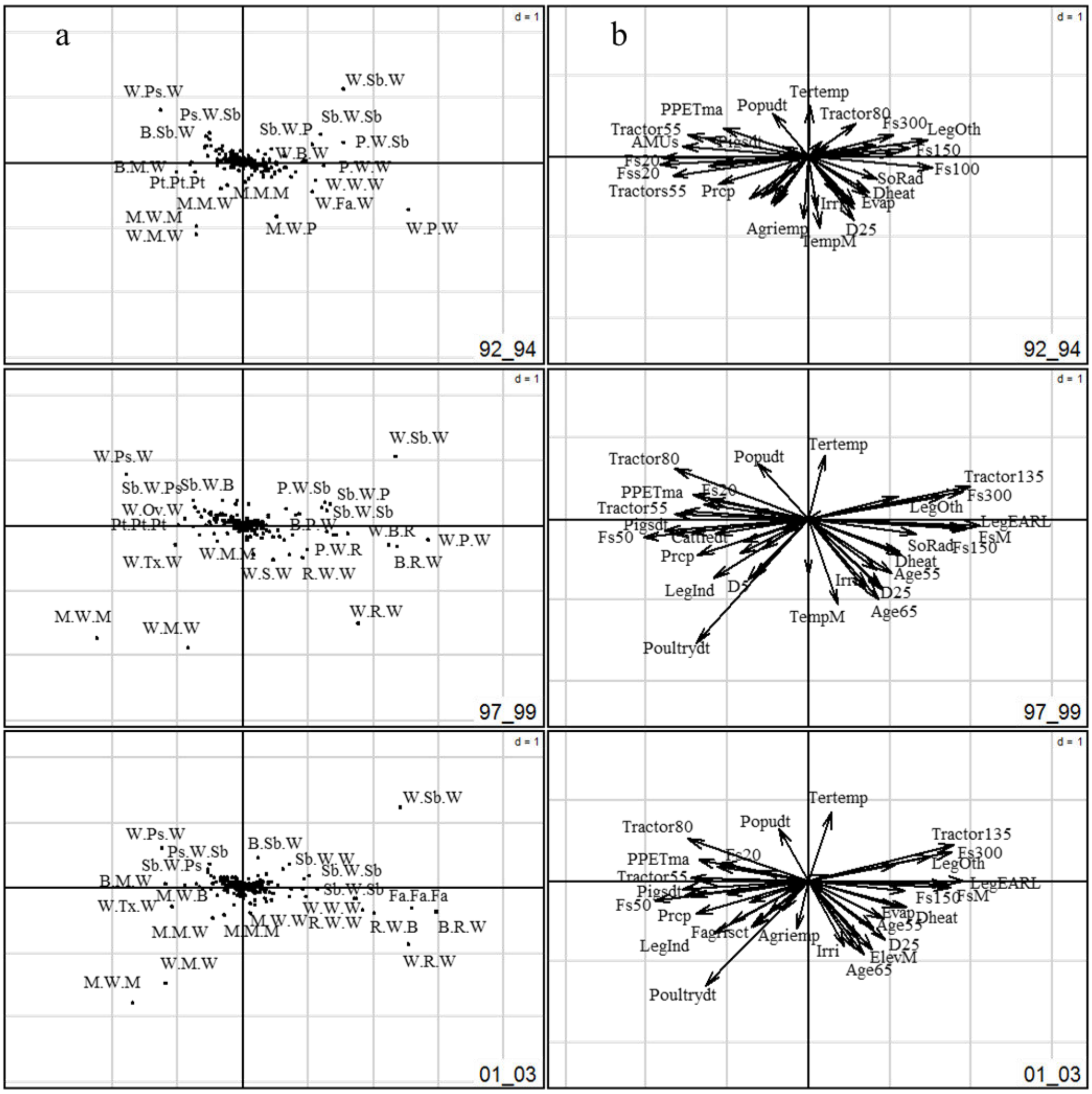

Fig. V-9. Results of the intrastructure step of the STATICO analysis on the paired-tables of 64 ADs belonging to the zone specializing in the inclusion of sugar beet, peas, or potatoes in wheat and/or barley-based CS cultivation. The three plots on the left (a) show the 3-year CSs at each set of dates (three subperiods: 1992-94, 1997-99 and 2001-03), and the three plots on the right (b) show the socio-economic and environmental variables at the same dates. The scale of the grid in each plot is given by the value d in the upper right corner of the plot. Note: d in the upper right corner of each plot shows the scale of the x and y axes.

4. Discussion and conclusions

We sought to investigate the temporal variation of the relationships between major crop sequence-related cropping patterns and the biophysical and socio-technical-economic conditions during the period of the implementation of the 1992 EU CAP reform and Agenda 2000 in mainland France. Our investigation was at two scales: the national scale with all 429 ADs and the regional scale focusing on three principal planting zones for cereals, oilseeds and protein crops. The major findings in this study can be summarized as follows:

- At the national scale:

(1) From 1992 to 2003, the most abundant 3-year CSs were maize monoculture, continuous temporary pasture, continuous fallow, "wheat-barley-rapeseed" rotation, and included one-year oilseed crops (sunflower and rapeseed) or maize or sugar beet in two-year wheat- or wheat-barley-based CSs;

(2) Major factors that were associated with abundant CS-related cropping patterns were primarily farm size (i.e., mean farm size, the ratio of farms by different classes), the use of tractors, and the share of irrigated land in the total UAA, and secondary, landform (slope, elevation), the number of days with frost risk, solar radiation, and the ratio of legal entities as the total farm holders;

(3) The stable part of the crop sequence-external factor dynamics is as follows. The cereal- and oilseed-based CSs, continuous temporary pasture and fallow were frequently grown within flat zones with low elevation. Maize monoculture and continuous temporary pasture were positively associated with the ratio of small farms (20 to 50 ha), the use of tractors with low power (55 to 79 and 80 to 134 DIN hp), and the share of irrigated land in the total UAA. Rapeseed/wheat-based CSs (e.g., "wheat-barley-rapeseed" rotation, "rapeseed-wheat" rotation) were associated with a high ratio of farms with 100 hectares or more, large mean farm size, a high ratio of legal entities as the total farm holders, and a high use of tractors with medium power (80 to 134 DIN hp). Maize/wheat-based and sunflower/wheat-based CSs were positively associated with the use of tractors with moderate power, the number of days with the daily mean temperature exceeding 5ºC (growing season for maize), and the share of legal entities in the total farm holders.

(4) Three-year CS-related cropping patterns were highly persistent during the period of implementation of the 1992 EU CAP reform and Agenda 2000. Only a very limited number of CSs (e.g., oilseed/wheat-based CSs, maize-based CSs such as monoculture of maize, "maize-wheat" rotation and the inclusion of peas in wheat-based CSs) exhibited an evident variation of their occurrence rates over the three subperiods. The external factors that most influenced the crop sequence patterns also changed over the three subperiods. For instance, the ratio of legal entities as farm holders, the share of irrigated land in the total UAA, the use of powerful tractors, mean farm size, and the ratio of farms with 150 to 300 hectares become correlated with the wheat-barley-based CSs while the ratio of farms with the sizes of less than 20 hectares no longer correlated with continuous temporary pasture nor monoculture of maize since the second subperiod.

- At the regional scale:

(1) In the zone specializing in sunflower/wheat-based CSs, the stable part of crop sequence-external factor and their dynamics can be summarized as follows. The most dominant CS, the "sunflower-wheat" rotation, was frequently implemented within the warm zone with a high ratio of irrigated land in the total UAA and a high use of tractors with medium power. A monoculture of maize dominated in the plains, warm and wet zones with a high density of poultry, large mean farm size, a high ratio of legal entities as the total farm holders, and a high share of irrigated land. Including two years of oilseeds (rapeseed, sunflower) in wheat-based CSs were positively associated with low slope, a high poultry density, large mean farm size, a high ratio of legal entities as farm holders, and more PPET. Other oilseed crops (other than rapeseed and sunflower)/wheat-based sequences were major CSs in the sunflower specialized zone. They were frequently grown within warm and steeping zones with high ratios of individual farms and a high use of tractors with low power. Including one year of maize or sunflowers into successive wheat-based CSs and a monoculture of wheat were predominant within the steeper zones with high elevation, a high ratio of individual farms, a high use of tractors with low power, and more days with frost risk. Maize/wheat-based sequences were also major CSs and were positively associated with plain landforms, the ratio of employees in the manufacturing sector, and the number of days with frost risk. Temperature-related factors always played the major role in the overall crop sequence patterns within the zone. However, we noted that the use of powerful tractors, the ratio of legal entities and individual farms as the total farm holders, poultry density, the share of irrigated land in the total UAA, and mean farm size became important factors influencing the cropping patterns within the zone since the subperiod 1997-99.

(2) In the zone specializing in the inclusion of rapeseed in wheat- and barley-based CSs, the stable part of the crop sequence-external factor relationships and their dynamics are as follows. The most abundant CSs, including rapeseed or maize in wheat- and barley-based CSs and continuous fallow, were positively associated with the use of powerful tractors (135 DIN hp or more), the number of days with frost risk and the ratio of large farms (150 to 300 hectares). Continuous temporary pasture was associated with high sheep density, a high ratio of individual farms, a high ratio of elderly farm principal operators (65 years and over), a warm climate with high evapotranspiration, and a high share of irrigated land in the total UAA. During the subperiod 1992-94, sheep density was strongly associated with continuous temporary pasture while rapeseed/wheat-based CSs were correlated with the use of medium power tractors, but these two factors became less important during the subsequent two subperiods. Meanwhile, the use of powerful tractors, the ratio of large farms (150 hectares or more) and the ratio of farm operators from 40 to 55 years old became the most important factors for planting rapeseed/wheat-based CSs. Continuous temporary pasture was mainly associated with the ratio of individual farms, the ratio of elderly farm operators (65 years and over) and the share of irrigated land of the total UAA except for temperature-related factors, which were major factors influencing the distribution during the entire study period.

(3) In the zone specializing in the inclusion of sugar beets, peas or potatoes in wheat- and/or barley-based CSs, the stable part of crop sequence-external factor dynamics was as follows. Sugar beet/wheat-based CSs were primarily associated with the higher ratio of employees in the tertiary sector and a higher population density. Among them, the inclusion of potatoes in sugar beet/wheat-based CSs were grown within the zone with a high ratio of small farms (20 to 50 hectares), a high use of tractors with low power, a high number of annual work units and a high density of pigs and cattle. Sugar beet/wheat-based CSs associated with peas or a second wheat or sugar beet CS were positively associated with the use of powerful tractors, the ratio of very large farms (300 hectares or more), and the ratios of legal entities and individual holders as the total farm holders. Maize/wheat-based CSs were positively associated with the density of pigs, cattle and poultry, the ratio of small farms, the use of tractors with low power, annual work units, precipitation-related conditions, yearly mean temperature, and the ratio of individual farms. Rapeseed/wheat-based CSs were positively associated with the ratio of large farms (100 to 300 hectares), the ratio of legal entities as the total farm holders, the ratio of farm operators at the age of 55 years and over, the share of irrigated land in the total UAA, and mean daily temperature. During the subperiod 1992-94, the ratio of very small farms (less than 20 hectares), the use of tractors with low power and annual work units played a major role in the distribution of potato- and maize-related sequences while the inclusion of rapeseed, peas, or sugar beets in wheat-based CSs were positively associated with the ratio of other legal status in the total number of farm holders and the ratio of large farms (100 to 150 hectares). However, these factors were no longer important during the subsequent subperiods. The use of medium and high powered tractors, the density of poultry and pigs, the ratio of very large farms (300 hectares or more), mean farm size, the ratio of legal entities as farm holders, and the ratio of elderly farm operators became the most important factors influencing the overall cropping patterns.
(4) Temporal variation of the crop sequence pattern-external condition relationship within the zone specializing in the inclusion of sugar beets, peas or potatoes in wheat and/or barley-based CSs was higher than in the other two zones.

Dussol et al. (2003) reported that the expansion of COP planting areas primarily occurred in the zones specializing in COP cultivation such as the eastern basin of Paris and partly in traditional dairy cattle farming and mixed crop-livestock farming zones in western, southwestern and eastern France. Our findings are consistent with the authors. Furthermore, our results offer more details of the evolution. For instance, in the zone specializing in the inclusion of rapeseed in wheat- and barley-based CSs, rapeseed/wheat-based CSs increase between the subperiods 1992-94 and 1997-99 and slightly decreased between 1997-99 and 2001-03, but they remained the most abundant CSs.

With the results of our analyses, we found that farm size-related factors (mean farm size, the ratio of farms of different sizes), the use of tractors with different power sizes, the share of irrigated land in the total UAA, and the ratio of farm holders with different legal entities play an important role in the overall crop sequence patterns within one zone at both the national and regional scale. For biophysical factors that were stable during the study period, we found that landform-related factors (slope, elevation) were the only major factors influencing the spatial distribution of crop sequences within the zones with significant variation in morphological conditions such as the sunflower specialist zone, whereas agro-climatic variables were major factors influencing crop sequence patterns within all of the three COP cultivation zones. These biophysical factors appear to be structuring factors because they were associated with the crop sequence patterns during all three subperiods. Some socio-technical-economic variables (e.g., irrigation, the share of legal entities in the total number of farm holders, the use of powerful tractors, and the ratio of large farms) were correlated with the crop sequence patterns during one subperiod but becoming less correlated during another subperiod. These data suggest possible shifts in these factors. The relationships between the changes in the external factors and the dynamics of crop sequence patterns need to be further explored in the future.

Here, we indicate several limitations of this study. First, we used 12-year averaged climate indicators to describe the regional agro-climate. We therefore ignored the exploration of the eventual modifications in crop sequences after the occurrence of extreme weather during the last growing season at the local scale, which could be a mitigation of farm holders. Second, because of the limits on accessibility of the data on soil profiles and the structure of agricultural holdings other than the national agricultural census, soil profile was excluded in this study, and data on farm structure drawn from the 2000 Agricultural Census was used to describe the subperiods 1997-99 and 2001-03. The French 2000 Census of Agriculture was carried out from October 2000 to January 2001. The reference periods for crop data and seasonal or occasional employment and for livestock data were for the agricultural year 1999/2000 (from 1 November 1999 to 31 October 2000) and the day of enumeration, respectively. Hence, using 1999/2000 Agricultural Census data to describe the conditions during 2001-03 may disregard the temporal variation of farm structures and further lead to some bias in the investigation of the dynamics of crop sequence patterns-biophysical and socio-technical-economic condition relationships.

In addition, using descriptive methods such as ordination to study the driving forces of land-use/cover change (LUCC) can be found in the literature (Thenail, 2002; Mottet et al., 2006; Hietel et al., 2007). In comparison to numerous studies using predictive methods such as regression models to study the driving forces of LUCC, descriptive methods have the following advantages: (1) Descriptive methods do not differentiate between "explained" and "explanatory" variables and they therefore avoid a constraint in the application: "explanatory" variables in predictive methods must be independent (in the statistical sense) and linearly independent; and (2) descriptive methods can be used without constraint on the ratio between the number of samples and the number of variables (Thioulouse, 2011). In our case of studying complex cropping patterns across a large region with an enormous number of crop sequences, creating a classification of changes in crop sequence patterns as the conventional classification of land-use change (e.g., the transition from forest to arable land and the expansion of built-up areas represent different types of land-use change) is not feasible. We thus considered containing all identified crop sequences as a "community of crop sequences" and apply the ordination method to describe the association between the assemblage of crop sequences and the biophysical and socio-technical-economic factors. The STATICO method performs a simultaneous analysis of a series of paired tables and supports users by offering a clear graphic representation of species-environment relationships and its evolution in time. This result appears efficient for achieving our goals and allows us to understand the patterns in both the distribution of crop sequences and the biophysical and socio-technical-economic conditions and crop sequence-external factor relationships within a given zone and period and the temporal variation of these patterns and relationships with one analysis.

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Chapter VI General discussion and conclusions

Land is a key parameter in global environmental change (Kongsager and Reenberg, 2012). Land-use activities-whether converting natural landscapes for human use or changing management practices on human-dominated lands-have transformed a large proportion of the planet's land surface (Foley et al., 2005). Land-change science that seeks to understand the human and environment dynamics giving rise to changed land covers and uses has emerged as a foundational element of global environment change and sustainability science (Rindfuss et al, 2004). Significant progress has been made in deepening understanding of the land system over the last few decades (Reenberg, 2009) promoted by 'The Global Change and Terrestrial Ecosystem' and 'Land Use Land Cover Change' communities under the IGBP and IHDP programmes. However, the identification of dynamics in land management that are not reflected in land cover change remains a challenge (Lambin et al., 2000; Lambin and Geist, 2006; Rounsevell et al., 2012). Meanwhile, a research field 'landscape agronomy' emerges to deal with research issues in agricultural landscape dynamics and enhance the interdisciplinary integration of farming systems in wider landscape and land system research (Benoît, Davide et al., 2012). The main objective of this thesis was to investigate the crop sequence patterns (in both spatial and temporal aspects) and the relationships between crop sequence patterns and biophysical and socio-technic-economic conditions in mainland France through mining long-term census data (e.g. land-cover survey and agricultural censuses). This study can be considered as an empirical analysis of past subtle changes in agricultural land use.

In this chapter we first summarized the major results of the thesis. Next, we discussed the strength and limitations of our work from the point of view of data used and methodology. Finally, we gave a perspective of this thesis research.

1. Summary of thesis findings

French agricultural district (AD) is agro-eco-region zoning that was established by the French Ministry of Agriculture in 1946. The entire territory of French mainland was divided into 430 ADs. Common wheat was the staple crop in the French mainland. It was often rotated with the secondary crops such as other cereals (e.g. barley, maize), root crops (e.g. sugar beet, potatoes), oilseed crops (e.g. sunflower, rapeseed), and legumes (e.g. peas, beans) in the zones specialized in arable crop production. In the zones specialized in livestock and mixed crops-livestock, successive temporary pasture and maize-based crop sequences (CSs) were predominant. Maize as another staple crop was often planted as monoculture or embedded in successive temporary pasture or rotated with wheat and/or barley. The lengths of major crop sequences ranged from two to four years in most of the ADs. Long crop sequences (five years or more) were often implemented within the zone specialized in grazing livestock in which cereals (e.g. wheat, maize, barley, oats, etc.) are inserted in successive temporary pasture.

The 2549 3-year CSs were first identified as major crop sequences across the entire territory from 1992 to 2003. These ADs were then grouped into 21 clusters according to the similarity of the probabilities of occurrences of major 3-year CSs. The occurrence referred here is the averaged occurrences of crop sequences within the study period. Four cropping systems were further identified: vineyard-based cropping systems, maize monoculture and maize/wheat-based cropping systems, temporary pasture and maize-based cropping systems and wheat and barley-based cropping systems. The 90 representative ADs and three principal planting zones of cereals, oilseeds, and protein crops (COP) (accounting for approximately 40% of the total arable land of mainland France in the year 2000) that belong to three clusters were also identified according to this typology of ADs.

The investigation of spatio-temporal dynamics of 3-year crop sequence patterns by segmenting the period 1992-2003 into three subperiods at the national scale indicates that: (1) the crop sequence patterns in a great part of ADs were likely stable. Hence, in general, crop sequence patterns at the national scale were stable; (2) the annual crops-related sequence patterns in which vineyard was predominant seems to be stable during the study period; (3) field cropping zones revealed higher temporal variability of crop sequence patterns than the fodder crops and sown pasture-based livestock zones; (4) the areas under maize-based cropping systems, in particular zones specialized in maize monoculture, expanded in southwestern and northeastern throughout the whole study period; and (5) the areas under peas/wheat-based CSs declined between the subperiod 1997-99 and 2001-03 in northern France. Moreover, our investigation at the regional scale confirm that the temporal evolutions of crop sequence patterns in the ADs of a homogeneous zone which was identified previously as one cluster of ADs were very similar. The crop sequence patterns within the zone specialized in sugar beet and/or peas or potatoes-wheat/barley-based CSs (SbPP) revealed higher temporal variability over the three subperiods than the crop sequence patterns in the two zones specialized in rapeseed/wheat-barley-based (RWB) and sunflower/wheat-based (SW) CSs cultivation. Areas under 3-year successive fallow evidently expanded in all of the three principal zones of COP cultivation between the subperiods 1992-94 and 1997-99 whereas the occurrence of cereals-based sequences including one year fallow decreased. The planting area of rapeseed/wheat-based CSs expanded between the subperiods 1992-94 and 1997-99 within the three zones. Maize/wheat-based CSs also increased in the zone SbPP during the same period while maize monoculture expanded in the other two zones. In the zone SbPP, the area under sugar beet and/or peas-wheat-based CSs increased between the two early subperiods whereas the decrease in the planting areas under peas/wheat-based CSs occurred between the two later subperiods. The planting area of sunflower/wheat-based CSs increased between 1992-94 and 1997-99 whereas the occurrence rate of oilseed crops (sunflower and rapeseed)/wheat-based CSs decreased between the subperiods 1997-99 and 2001-03 in the most ADs within the zone SW. The decline in the areas under rapeseed/wheat-based CSs was also observed in several ADs of the zone RWB between the subperiods 1997-99 and 2001-03.

At the national scale, major factors that were associated with the abundant CSs-related cropping patterns were primary, farm size-related factors, the use of tractors by different power class, and the share of irrigated land in the total UAA, and secondary, landform (slope, elevation), climate (i.e. number of days with frost risk, solar radiation), and the ratio of legal entities in the total farming holders. The temporary crops-based CSs were frequently grown in the flat zone with low elevation. Among them, maize monoculture and continuous temporary pasture were positively associated the ratio of small farm (20 to 50 hectares), the use of tractors with low power (55 to 79 DIN hp), and the share of irrigated land in the total UAA. Maize/wheat-based and oilseed crops/wheat-based CSs were correlated with the high share of legal entities in total farming holders while rapeseed/wheat-based CSs were positively associated with the ratio of big farms (100 to 300 hectares), mean farm size, and the use of tractors with medium power (80 to 134 DIN hp and 135 DIN hp or more) and maize and/or sunflower-wheat-based CSs were correlated with high use of tractors with moderate power (80 to 134 DIN hp) and the duration of maize growing season. Of note, the relationships between crop sequence patterns and socio-technic-economic and biophysical conditions have changed over the three subperiods. Biophysical-related conditions like flat landform, the duration of growing season were highly correlated with the temporary crops-related cropping patterns over the three subperiods. The high use of tractors with high power (135 DIN hp or more), the high ratio of legal entities in the total farming holders, big mean farm size, the high ratio of big farms, and high density of poultry became highly correlated with the occurrence of rapeseed-wheat/barley-based CSs while the share of irrigated land in the total UAA was positively correlated with the occurrence of maize monoculture and successive temporary pasture during the later two subperiods though.

At the regional scale, (1) crop sequence patterns within the zone SbPP were primarily associated with precipitation-related condition, farm size-related factors (mean farm size, the ratio of farms with big size and small size), the ratio of two types of farming holders (legal entities and other legal status), the use of tractors by two class (135 DIN hp and more and 55-79 DIN hp), annual work units (AMUs), density of pigs and cattle, and partly with temperature-related factors, poultry density, population density, the ratio of old farm operators (65 years old and over), the share of irrigated land in the total UAA, and the ratio of employees in tertiary sector. The most abundant CSs, sugar beet/wheat-based CSs were often planted within the zones with the higher ratio of employees in tertiary sector and higher population density. Among them, inclusion of potatoes in sugar beet/wheat-based CSs were grown within the zone with high ratio of small farms, high use of tractors with low power, high AMUs and high density of pigs and cattle. Inclusion of peas or a second wheat or sugar beet in sugar beet/wheat-based CSs were positively associated with the use of powerful tractors, the ratio of farms with very big size, and the ratios of two types of farming holders: legal entities and individual holders. Maize-wheat-based CSs as major CSs within the zone were positively correlated with the density of pigs, cattle and poultry, the ratio of farm with small size, the use of tractors with low power, AMUs, precipitation-related conditions, yearly mean temperature, and the ratio of individual farms. During the first subperiod, the ratio of small farms (less than 20 hectares and 20-50 hectares), the ratio of big farms (100 to 300 hectares), the use of tractors with low power, AMUs and the share of other legal status in the total farming holders were the most important factors correlating with the crop sequence patterns. During the later two subperiods, the use of medium and high power tractors, density of poultry and pigs, the ratio of very large farms (300 hectares or more), mean farm size, the ratio of legal entities in farming holders, and the ratio of old farm operators became the most important factors influencing the overall cropping patterns; (2) Crop sequence patterns within the zone RWB were strongly associated with temperature-related condition, the ratio of individual farms in the total farming holders, the share of very big farms (150 hectares or more), the use of tractors with high power, sheep density, irrigation, and the ratio of old farm operators. The most abundant CSs i.e. “wheat-barley-rapeseed", "rapeseed-wheat" rotations and successive fallow were positively associated with the use of powerful tractors, number of days with frost risk and the ratio of very big farms (150 to 300 hectares) whereas continuous temporary pasture was frequently implemented within the zone with higher sheep density, warmer climate, higher ratio of individual farms, higher share of old farm operator, and higher share of irrigated land in the total UAA. Temperature-related factors were always major factors correlating with the crop sequence patterns within this zone over the three subperiods. But sheep density and the use of tractors with medium power became less associated with the crop sequence patterns during the later two subperiods. Meanwhile, the use of powerful tractors, the ratio of large farms, the ratio of farm operators by two classes (40-55 years old and 65 years old and over), and the share of individual farms in the total farming holders became major factors correlating with the crop sequence patterns; and (3) Crop sequence patterns within the zone SW were strongly correlated with temperature and precipitation-related condition, slope, mean farm size, the use of tractors, poultry density, irrigation, and the ratio of legal entities in the total farming holders. The most dominant CS, "sunflower-wheat" rotation, was frequently implemented within the warm zone with high ratio of irrigated land in the total UAA, and high use of tractors with medium power. Another predominant CS, maize monoculture, dominated in the flat, warm and wet zone with high density of poultry, big mean farm size, high ratio of legal entities in total farming holders, and high share of irrigated land. Wheat-based CSs including two years of oilseeds (rapeseed, sunflower) were positively associated with plain landform, high poultry density, large mean farm size, high ratio of legal entities in farming holders, and more PPET while maize/wheat-based sequences, major CSs in the zone, were positively associated with plain landform, the ratio of employees in manufacturing sector, and number of days with frost risk. Our result confirms that temperature-related factors always played the major role in the overall crop sequence patterns within the zone. But the use of powerful tractors, the ratio of legal entities and individual farms in the total farming holders, poultry density, the share of irrigated land in the total UAA, and mean farm size have become important factors influencing the cropping patterns since the subperiod 1997-99.

In addition, we confirm the trends of the transitions between grassland and cropland over the two time intervals: the loss of grassland (1992-2003) and restoration or re-expansion of grassland (2006-2010) in the French mainland. Our finding on the crop sequence patterns after the grassland conversion revealed two notable evolutions of agricultural production systems. These evolutions were related to the increase in the proportion of cropland in the total agricultural land use. One evolution was most likely influenced by the demand for fodder: the conversion from grazing livestock to feeding livestock. Another evolution was the conversion from livestock production to field crop production. Our results indicate that the intensification of livestock farming systems continued over the last two decades in mainland France.

2. Strength and limitations of the thesis

2.1 Data remarks

One important thing to note here is that land-cover data used in this thesis was derived from annual land-cover survey databases. We found Teruti and Teruti-Lucas datasets to be a reliable source for investigating crop sequence pattern s at the regional to national scale because of the continuity of sampling in every June for several decades, systematic sampling points across the entire territory, and aerial photo interpretation-based land-cover classification with denoting specific agricultural cover types (e.g. wheat, maize, temporary pasture, etc.). In the case of French mainland, sole cropping under rotational systems and monocropping are widely implemented while multiple cropping is limited in the zones specialized in spring sowing crops (e.g. sugar beet, potatoes, peas) with planting cover crops in winter for the purposes of nitrogen fixation and preventing soil erosion. Thus, land-cover survey in June-based sequential data is an accurate source for studying main temporary crops-related crop sequence patterns. This data has been used in various fields for the case studies in France, e.g. predicting land use allocation, testing species responses to landscape fragmentation and disturbance, modeling spatial distribution of soil organic carbon stocks (Devictor et al., 2008; Martin et al., 2011; Chakir and Le Gallo, 2013). However, sampling points of Teruti survey are not geo-referenced but only are located at the smallest administrative division ("commune" in French) and there are few points sampled in certain communes. We have to aggregate data at higher level than commune. It results in be impossible to represent crop sequences at the field level which is the smallest and most fundamental decision unit for farming holders.

With the increasing available data on agricultural land use and progress in crop-specific classification of remote sensing, several emerging researches investigate field-level crop sequence patterns at the regional scale. For the case study in the EU, field data can be derived from the Integrated Administration and Control system (IACS) which was adopted for the administration of the EU agricultural direct payments to farmers under the CAP. IACS records cover the whole UAA and include precise locations and sizes of parcels. Land Parcel Identification System (LPIS) is one of the four components of IACS to identify the parcels on which aid applications are made and their areas. A study the crop sequence patterns in Northern Germany (Steinmann and Dobers, 2013) has demonstrated the feasibility of the use of this type of information for exploring crop sequence patterns and their evolutions following the implementation of 2003 CAP reform. Plourde et al. (2013) and Long et al. (2014a, 2014b) identified crop sequence patterns and the dynamics of specific crop sequences-based patterns in several states using Cropland Data Layers produced by USDA. In comparison to survey and farming holder declaration-based agricultural land-use data, remote sensed data permits estimating the area of major crop sequences and the changes in area in a wall-to-wall and accurate way, in particular, multi-seasonal and various resolution data allows the investigation of crop sequence patterns under multi-cropping (e.g. double cropping (Brown et al., 2013), strip cropping (Long et al., 2014b).

In addition, the exclusion of soil profiles in the analysis of crop sequence patterns-biophysical and socio-technic-economic condition relationships (Chapter V) was due to the lack of data on soil covering the study area of the thesis at the time. The data on the soil typological units (STUs) components of soil map units (SMUs) included in the SPADE-2 (the European soil profile analytical database) (Hollis et al., 2006) of the 1: 1,000,000 Soil Geographic Database of Europe (SGDBE) for France was derived from expert judgment using SPADE-1 profiles to attribute data to representative STUs. The paucity of data in SPADE-1 profiles for France results in large data gaps in SPADE-2 (Hannam et al., 2009). Hence, it was insufficient for our aim of characterizing soil within an AD for agricultural production by the year 2013. To our knowledge, for the future work potentially available data on soil profiles such as content of organic carbon, total nitrogen, and water pH of topsoil can be derived from the French National Soil Quality Monitoring Network in which soil property is observed on a 16 km regular grid covering the French metropolitan territory (Arrouays et al., 2011).

2.2 Methodological remarks

In this thesis work, the methods based on statistical and data mining technique were applied in both alone and combined ways. First, the methodologies presented here for representing crop sequence patterns consist of three major steps: (i) stationary representation of crop sequence patterns within a given area and period; (ii) dynamic representation of crop sequence patterns over the given period and (iii) dynamic representation of crop sequence patterns-biophysical and socio-technic-economic conditions relationship over the given period. In the first step (Chapter II), we classified all of the spatial units (i.e. 406 (merged) ADs in this case) within the given area (French mainland) according to the similarity of the probabilities of occurrences of major fixed-length (3-year in this case) crop sequences during the period 1992-2003. Hidden Markov models were applied via CARROTAGE to identify major crop sequences. The homogeneous zones (it means the clusters of agricultural districts) and the representative ADs (90 ADs) identified in this step were used as study areas in the Chapter IV and V. The potential application of the modeling approach presented in Chapter II is as a tool to extract spatially explicit information about cropping patterns from time series data of land-cover for the environmental or economic assessment of agricultural production systems. Furthermore, the crop sequence patterns following grassland-to-cropland conversion were studied through classifying ADs according to the occurrence rates of LUSs that involved one year grassland followed by three successive years of annual crops (Chapter III). The occurrence rates of 4-year LUSs were counted using sliding windows with a size of 4 years within each AD. In the second and third step, inspired by ecology, we considered all of the crop sequences which occurred within the study area and period as a community of crop sequences. The occurrence rate of crop sequence is equal “abundance”. Two advanced statistical techniques: Partial Triadic Analysis and STATICO were applied for studying the dynamics of crop sequence patterns (Chapter IV) and the dynamics of crop sequence patterns-biophysical and socio-technic-economic conditions relationships (Chapter V), respectively. The investigation of dynamics of crop sequence patterns was performed at two scales: (i) the national scale by analyzing both all of the 429 ADs and the assemblage of 90 representative ADs; (ii) the regional scale by separately analyzing three principal zones of temporary crop, particularly, COP cultivation. The investigation at the national scale allows us general understanding of where and when the changes occurred and to compare the diverse dynamics of crop sequence patterns under different cropping systems whereas the study at the regional scale allow us to estimate whether it exists the similarity of dynamics of crop sequence patterns across the given several subperiods within the spatial unit of a homogeneous zone which was identified according to the averaged occurrences of crop sequences within the same study period. The “multiscale” analysis in the thesis was done in terms of multiple spatial extents i.e. entire French mainland or an assemblage of ADs (the cluster of ADs identified in Chapter II) with respecting unique spatial resolution (i.e. AD).

Second, we took the concept 'crop sequences' in this thesis, which was limited to the order of appearance of the crops during a fixed period, instead of the exploration of the exact cycle of crop rotations and their related changes within the given period. Indeed, most agricultural land management practices are decided at the local scale by the farm holders under different biophysical constraints and socio-technic-economic conditions. Joannon et al. (2008) indicated that farmers grew crops in a field of their farm over the years without implementing strict crop rotations and kept a degree of freedom in their choices. Several observation-based studies confirmed that a great number of crop sequences occurred over a large area while there were only a limit number of crop portfolios within the region (Leteinturier et al., 2006; Plourde et al., 2013; Steinmann and Dobers, 2013). Our results also support this point. Annual crops-related sequential cropping systems observed in this thesis seem to be a combination of fixed-sequence systems and dynamic cropping systems (dynamic cropping systems concept adopted from Tanaka et al. (2002)). Some wheat-based sequences e.g. "maize-wheat", "sunflower-wheat", "rapeseed-wheat", "wheat-barley-rapeseed", "sugar beet-wheat-barley", "maize-wheat-barley", and "sugar beet-wheat-peas-wheat" were widely rotated in the primary field cropping zones. Meanwhile, some secondary crops were embedded in these wheat-based sequences or some of these sequences were joined to make several other sequences on the occasion which was motivated by both market and policy incentives and time rationing among crops. Dury et al. (2013) point out a typology of crop sequence patterns with four types according to 30 irrigated arable farms survey in three regions of mainland France. The authors demonstrate the spatio-temporal dynamics of cropping-plan decision-making at the farm level. Hence, in comparison to investigating the changes in crop rotation patterns, exploring the evolution of the patterns of fixed-length crop sequences which are foundational sequences of cropping systems within one zone and one period is more rational and feasible for monitoring the changing land management practice-driven agricultural land-use change.

In addition, the more detailed discussions of the methodologies proposed in this thesis have been given separately in Chapters II - V.

3. Perspectives

We conclude that, the approaches developed in this thesis permit representing crop sequence patterns at the large regional scale in both the stationary and dynamic way using time series land-cover data with denoting specific agricultural cover types. It contributes to assess the environmental and economic performance of agricultural production systems, monitor the evolution of cropping systems following the implementation of agricultural and environmental policies for evaluating policy effectivity, and explore modification in agriculture-relevant terrestrial systems and their impacts. The findings of this thesis contribute to improve understanding on: (1) the diverse dynamics of temporal crop-relevant sequence patterns under different cropping systems; (2) the co-evolution of crop sequence patterns and agricultural intensification such as the increase in field size and feeding livestock density, the implementation of tractors with great power, and irrigation; and (3) the process and pattern of human activities by agriculture affecting terrestrial biosphere.

It is evident that much additional research is required to do. Here, we suggest some areas as follows:

First, as indicated by Verburg and Chen (2000) and Kok and Veldkamp (2001), the existence of the scale dependency and the effects of both the spatial extent and spatial resolution in modeling land-cover/use change, choosing other spatial resolution in modeling crop sequence patterns should be considered in the future work. In the case of mainland France, the spatial unit accounting both agro-ecological conditions and administrative level such as small French agricultural district (small agricultural region mentioned in (Teillard et al., 2012), territorial unit that is created by intersecting agricultural district with NUTS3 level "French department", and in total, there are 713 small French agricultural districts) could be a suitable choice since information on socio-economic conditions are available at the municipality's level for public and agricultural policies in France are nationally set up and they are also locally (EU NUTS3 level) completed in order to fit with local stakes and environmental preoccupations (Desjeux et al., 2007).

Second, being time-series data, numerous approaches can be applied for analyzing sequential land-cover record. When geo-referenced land-cover data with denoting specific agricultural cover types are available, a typology of crop sequences by clustering time series data (Warren Liao, 2005) can be created and various techniques used frequently in the field of land-change modeling (Bürgi et al., 2004; Lesschen et al., 2005; Verburg et al., 2004) such as regression models and chi-squared tests can be further applied to test the crop sequence patterns and the explanatory factors relationship, driving forces of changes in crop sequence patterns or even more predicting future crop sequence patterns.

Third, spatial autocorrelation should be analyzed since spatial autocorrelation will occur in any spatially explicit study of land use/cover change (Overmars et al., 2003). Lesschen et al. (2005) summarized the techniques used in land change modeling to detect spatial autocorrelation and account for spatial autocorrelation in regression models. Long et al. (2014b) inspired some spatial analysis technique like point pattern analysis to assess the spatial dependency among fields in each of the crop sequences of interest by year. On the other hand, recent progresses in specifying spatial features through weighting matrices and spatial eigenfunctions of multivariate multiscale spatial analysis in the field of community ecology (Dray et al., 2012) also provide advanced approach for studying crop sequence-the external conditions relationship.

Fourth, in order to explore the relationships between cropping system dynamics and the implementation of CAP reforms, more economic variables related to CAP subsides (source: CAP declarations, see Teillard et al., 2012) should be integrated in the analysis. We can also enlarge the research objective by studying crop management systems or even more livestock sector to investigate the dynamics of the whole farming systems.

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Appendix I Exploring changes in crop sequence patterns in northern of France

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Abstract

After two decades development of land change science, the interest of research has moved from the investigation of fast and distinct land-cover conversion toward studying subtle changes within land-cover categories such as shifts in land management practices. In this context, we propose an investigation of the changes in crop sequences between 1992 and 2003 in one of the main areas of field crops production in France using national land-cover and use survey data Teruti. The objective of our study is to combine a temporal data mining technique with the classical statistical technique for investigating the changes in the probabilities of occurrence of major crop sequences over time in northern of France. A temporal data mining tool CARROTAGE based on second-order Hidden Markov Model was performed to identify the homogeneous periods in terms of the probabilities of occurrence of crop sequences. One-way ANOVA or Friedman test were applied to compare the mean values of the probabilities of occurrence of major 3-year crop sequences according to different sub- periods. Tukey HSD method or two-tailed Wilcoxon signed rank test were used for further multiple comparisons between two successive sub-periods. Our study confirms that there were some notable shifts in crop sequence patterns between 1992 and 2003 in northern of France. For example we find the increase in planting area of rapeseed in 1990's and rapeseed was often associated in the wheat and barley based crop sequences. Rapeseed, wheat and barley based crop sequences were predominant in the study area over the 12 years. We also observed that, during the whole period, the area of long term fallow (3-year land-use succession under fallow) increased. Similarly, maize-wheat based crop sequences significantly increased at the beginning of the study period.

1. Introduction

Research on land-use/cover change emerged in the research agenda on global environmental change several decades ago with the realization that land-surface processes have a broad range of impacts on climate, ecosystem goods and service. All impacts are not negative though as many forms of land-use/cover changes are associated with continuing increases in food, fiber and energy production, in resource-use efficiency, and in wealth and well-being [1]. The emergence of "land-change science" took on the task of demonstrating the role of land change in its own right within the Earth system.

Over the last two decades, numerous researchers have improved monitoring and measurement of land-cover change, the understanding of the driving forces of land-use change, and predictive models of land-use/cover change. Research has therefore moved toward investigating on subtle changes within land-cover categories (in other words land-cover modification) such as soil erosion, shifts in land management practices, etc. [2]. Lambin et al. [3] pointed out that changes in the management of agricultural land use, including changes in levels of inputs and the effect of this on profitability or the periodicity of complex land-use trajectories, e.g., fallow cycles, rotation systems, causes frequently land-cover modification. Recently, one of the most significant forms of land–cover modification, land intensification, has increasingly been noticed by researchers [4-6]. However, in existing modeling frameworks of land-use/cover change, especially agricultural land-use change, few models integrate agricultural land management practices such as crop rotations [7].

Crop rotations are the practice of growing a sequence of crops on the same land [8]. Because of the multiple benefits of the crop rotations such as increasing crop yields, decreasing the incidence of plant diseases and weed, maintaining soil fertility, improving the soil structure, preserving biodiversity, crop rotations are a very old practice and are implemented widespread. In the context of the establishment of new economic, agronomic and governmental policies, farmers will be paid for re-establishment and increase of ecosystem services on agricultural land [9]. The positive effect of crop rotations has re-noticed by researchers [10-11].

In this context, we propose an investigation of the changes in crop sequences in one of the main areas of field crops production in France (red zone in Fig. AnI-1) using national land-cover and use survey data. This area covers 52, 995 km^2 and involves 31 French agricultural districts. It is characterized by the wheat, barley, rapeseed and maize based cropping system [12]. We use the concept 'crop sequences' in this study, which is defined as the partial or total development of a cycle of rotation or even the basis of several cycles and it is limited to the order of appearance of the crops during a fixed period [13].

The objective of our study is to combine a temporal data mining technique with the classical statistical technique for investigating the changes in the probabilities of occurrence of major crop sequences over time in northern of France.

2. Materials and methods

2.1 Data

The sequential land-cover data was derived from Teruti databases. Teruti is an annual two-level sampling survey of land-cover conducted by the French Ministry of agriculture. 15579 aerial photos have been taken in every June during the survey period. The area of one sampling point is about 100 hectares. A corpus with the sampling points in row and the records of land-cover types for the period 1992-2003 in column was used in this study. The French agricultural district was used as spatial unit in our study. Two adjacent agricultural districts were merged in one since they are lack of sampling points. Thus, there were 30 spatial units studied.

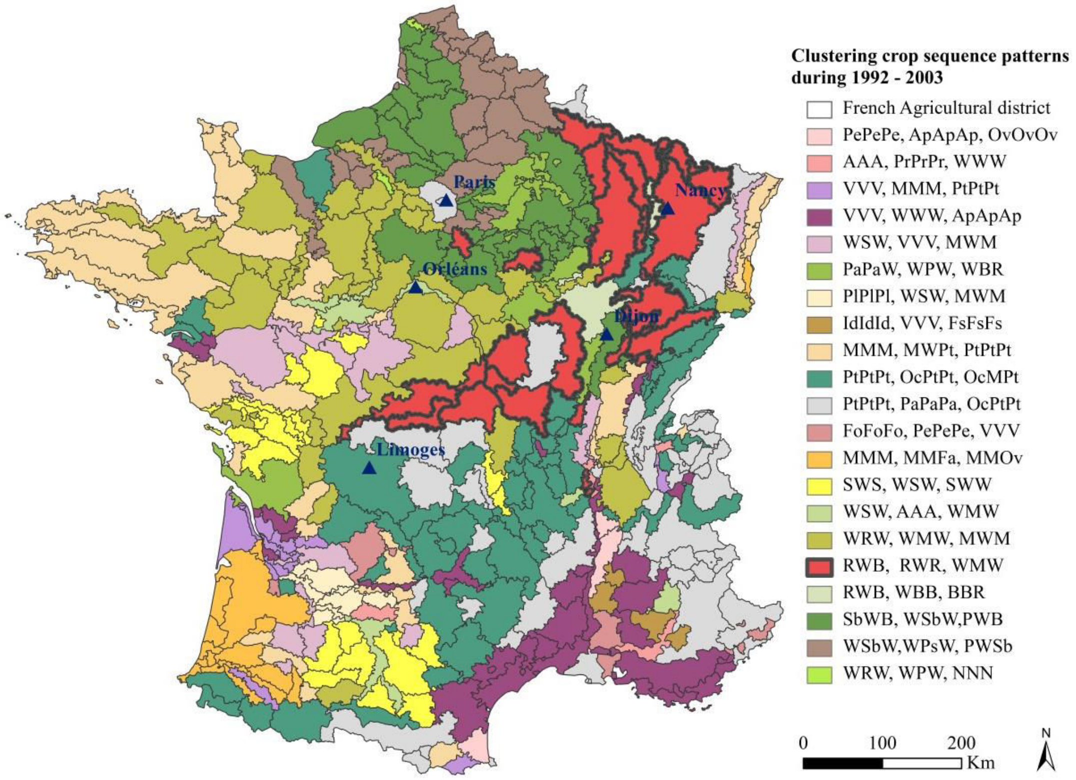

Fig. AnI-1. Location of the study area. The map of clustering crop sequence patterns is adopted from XIAO et al. (2014). Nomenclature used in legend is: A (apples), Ap (apricots), B (barley), Bn (beans), Ch (cherries), Fa (fallow), Fo (berry orchard), Fs (Orchard of other fruits e.g. single or mixed species, nut trees), G (grassland), Id (industrial crops), M (maize), N (nursery), O (oat), Oc (other cereals), Ol (oilseed crops), Of (other fodder crops), Ov (other legumes), P (pea), Pa (artificial pasture sown by alfalfa), Pe (peaches), Pl (plums), Pm (alpine meadows), Pr (pears), Ps (potatoes), Pt (temporary pasture), R (rape seed), Ry(rye), S (sunflower), Sb (sugar beet), V (vineyards), W (wheat).

2.2 Identifying major crop sequences over the different homogeneous periods

A temporal data mining tool CARROTAGE [14] based on second-order Hidden Markov Model (HMM2) was performed to identify the homogeneous periods in terms of the probabilities of occurrence of crop sequences. The corpus of 12 years of land-cover and use record of 30 spatial units called training sequence was used to adjust the model parameters of HMM2. Firstly, we applied left-right HMM2 of CARROTAGE with 3-year land-use succession as observation symbol on the corpus which contains 31 agricultural districts for extracting the temporal segmentation of study period in which the distribution of 3-year land-use successions (LUSs) is stationary [14]. As our study period covers 12 years, for the first running, the number of states defined for HMM2 was 12 and then we reduced one state for each following running. The results of the probabilities of transitions between states show that the segmentation of 12 years into 5 states is rational. Secondly, we applied the 5-state left-right HMM2 with 3-year LUS as observation symbol to estimate the probabilities of occurrence of all 3-year LUSs within each agricultural district. Thirdly, we made an inventory table of all 3-year LUSs which occurred over the 5 sub-periods across 31 agricultural districts. In this table, the most frequent and broadly distributed 3-year crop sequences (the LUSs involve 3-year successively appeared crops) were selected for further analyzing the changes in the occurrences of crop sequences according to the sum of probabilities of occurrence and the number of the presence in 30 spatial units during 5 states.

2.3 Statistical analysis

The normal distribution of data sets was tested using the Shapiro-Wilk test. The homogeneity of variance was tested by the Levene's test [15]. One-way ANOVA was performed to compare the mean values of the probabilities of occurrence of major 3-year crop sequences according to 5 different periods in the situation where the two assumptions of one way ANOVA were respected. The further multiple comparisons using Tukey HSD method was also made if the one-way ANOVA was significant. Otherwise, Friedman test prior to two-tailed Wilcoxon signed rank test without correction for multiple comparisons was performed. All of these tests were carried out using the R software [16] 'Rcmdr' package [17]. Statistical significance was accepted at the 95% confidence level ($P<0.05$).

3. Results

With the aid of left-right HMM2, the whole period of 12 years was segmented into 5 sub-periods in terms of homogeneous 3-year land-use successions. These 5 sub-periods are: 1992-1994, 1994-1996, 1996-1998, 1998-2000, and 2000-2003. Totally, there are 3570 3-year LUSs which occurred over the 5 sub-periods across 31 agricultural districts. The 18 most frequent and widespread distributed 3-year crop sequences (Table AnI-1) were identified as major crop sequences for further analysis of changes in the probabilities of occurrence.

The mean values of probabilities of occurrence of crop sequences and derived indexes at five temporal states are presented in Table AnI-2. The most important findings in comparison of means of probabilities of occurrence of major crop sequences were the increase in the occurrence of rapeseed relevant crop sequences during the 3 first temporal states (correspond to the period of 1992 to 1998). A typical and widely cultivated crop rotation "wheat-barley-rapeseed" in Europe which is presented by three forms of sequences "barley-rapeseed-wheat", "rapeseed-wheat-barley" and "wheat-barley-rapeseed" were planted increasingly during the year 1992 to 1998. The 3-year crop sequences that consist of rapeseed and wheat were noted to be significantly increased during the same period (except for rapeseed-wheat-wheat, it increased during 1996-2000). Nevertheless, they decreased between 1998 and 2003. Similarly, maize-wheat based crop sequences significantly increased at the beginning of the study period. A reduction of adoption of maize-wheat based crop sequences appeared in the year of 1996 to 2000. In addition, there was a trend toward an increase in area of fallow during the whole period apart from a brief reduction in the year of 1994 to 1998.

4. Conclusions

There were some notable shifts in crop sequence patterns between 1992 and 2003 in northern of France. This study confirm the increase in planting area of rapeseed in 1990's and further explore the related crop sequences which were the representation of the land-use decision of farming holders. Rapeseed was often associated in the wheat and barley based crop sequences. Rapeseed, wheat and barley based crop sequences were predominant in the study area over the 12 years. We also observed that, during the whole period, the area of long term fallow (3-year land-use succession under fallow) increased. Similarly, maize-wheat based crop sequences significantly increased at the beginning of the study period.

We plan several follow up studies in the thesis work. One is to build a multi-criteria approach to estimate the changes in crop sequence patterns, e.g. study the changes in return time of special crops (potatoes, maize, rapeseed), the changes in the richness of crop sequences within an area, etc. And then we will apply the approach at the national scale. Finally, we will study the driving forces of the changes in crop sequence patterns using data of national agricultural census, soil survey and historical weather records.

Table AnI-1
List of the 18 most frequent and widespread distributed 3-year crop sequences within the whole study area based on the probabilities of occurrence during 12 years and the number of presence at 5 temporal states. Nomenclature used is: B (barley), Fa (fallow), M (Maize), Pt (temporary pasture), R (rapeseed), W (wheat).

3-year crop sequences	probability of occurrence	the number of presence
B-R-W	0.019	143
W-B-R	0.018	145
R-W-B	0.017	143
Pt-Pt-Pt	0.015	137
W-R-W	0.014	147
R-W-R	0.008	136
M-M-M	0.007	144
W-M-W	0.004	135
R-W-W	0.004	128
M-M-W	0.004	132
M-W-B	0.004	131
Fa-Fa-Fa	0.004	122
W-W-B	0.004	128
W-B-B	0.003	126
W-B-M	0.003	133
M-W-M	0.003	132
W-W-R	0.003	130
W-M-M	0.003	128

Table AnI-2
The mean value of probabilities of occurrence of 12 major 3-year crop sequences which had significant difference of probabilities of occurrence among five historical sub-periods. Nomenclature used is: B (barley), Fa (fallow), M (Maize), Pt (temporary pasture), R (rapeseed), W (wheat).

	State1	State2	State3	State4	State5	p-value
B-R-W	0.012 ± 0.012	0.014 ± 0.013*	0.018 ± 0.017*	0.021 ± 0.017	0.021 ± 0.017	< 0.001
R-W-B	0.009 ± 0.008	0.012 ± 0.012	0.014 ± 0.013	0.021 ± 0.019	0.018 ± 0.016	< 0.001
W-B-R	0.009 ± 0.009	0.013 ± 0.013	0.020 ± 0.017	0.017 ± 0.016	0.020 ± 0.016	< 0.001
R-W-W	0.002 ± 0.002	0.003 ± 0.004	0.004 ± 0.004	0.005 ± 0.004	0.006 ± 0.005	< 0.001
W-W-R	0.002 ± 0.002	0.003 ± 0.003	0.004 ± 0.003	0.003 ± 0.002	0.003 ± 0.002	< 0.001
W-M-W	0.003 ± 0.003	0.004 ± 0.003	0.005 ± 0.005	0.005 ± 0.005	0.006 ± 0.006	< 0.001
W-W-B	0.002 ± 0.002	0.003 ± 0.003	0.004 ± 0.004	0.003 ±0.003	0.004 ± 0.003*	0.043
M-W-B	0.003 ± 0.003	0.004 ± 0.004	0.004 ± 0.004	0.003 ± 0.002*	0.004 ± 0.004	0.013
M-M-W	0.003 ± 0.003	0.005 ± 0.005*	0.004 ± 0.004	0.003 ± 0.003*	0.004 ± 0.003	0.044
Fa-Fa-Fa	0.003 ± 0.004	0.004 ± 0.004*	0.004 ± 0.004*	0.005 ± 0.004*	0.007 ± 0.006**	< 0.001
W-R-W	0.008 ± 0.008	0.014 ± 0.010**	0.018 ± 0.011**	0.018 ± 0.011	0.012 ± 0.008**	< 0.001
R-W-R	0.004 ± 0.006	0.006 ± 0.007**	0.010 ± 0.010**	0.008 ± 0.006	0.005 ± 0.005**	< 0.001

p refers to Friedman's test.
* $p < 0.05$ and ** $p < 0.001$ refer to comparison with the previous state analyzed by Wilcoxon signed rank test.

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Appendix II List of arable crops-related land-cover types in Teruti land-cover survey database

Temporary crop	Symbol	Permeant crop	Symbol
Barley	B	Apricots	Ap
Beans	Bn	Apples	A
Fallow	Fa	Berry orchard	Fo
Vegetable and root fodder	Fr	Cherries	Ch
(cabbages for fodder, carrots for fodder, swedes turnip, etc.)			
Maize (grain maize and maize for forage)	M	Peaches	Pe
Other industrial crops (tobacco, chicory, hops, medicinal plants, spice crops, aromatic crops, etc.)	Id	Pears	Pr
Oats	O	Plums	Pl
Other cereals (including rice, sorghum, triticale, buckwheat, etc.)	Oc	Mixed orchard of six major species	Ss
Other oilseed crops (including soybean, linseed, castor bean, etc.)	Ol	Six major species of fruits and crops	Sa
Other vegetables (cabbages, haricot bean, lentils, carrots, strawberry, melons, etc.)	Ov	Orchard of other fruits (single or mixed species, nut trees)	Fs
Other fodder crops (rapeseed for fodder, vetches, etc.)	Of	Orchard of other fruits and crops	Ft
Peas	P	Nursery (wood nursery, ornamental plants)	N
Temporary pasture (mainly sown by gramineous no more than five years)	Pt	Vineyards	V
Artificial pasture (mainly sown by legumineous like alfalfa, trefoil, clover, sainfoin, birdsfoot, etc.)	Pa	Mixed vineyards and orchard of six major species	Vv
Potatoes	Ps	Mixed vineyards and crops	Vc
Rapeseed	R		
Rye	Ry		
Sugar beet	Sb		
Sunflower	S		
Fibre crops (flax, hemp, etc.)	Tx		
Wheat(common wheat and durum wheat)	W		

Appendix III Major unfixed-length crop sequences within the 16 homogenous zones of mainland France

(16 homogenous zones correspond to the 16 clusters of ADs identified in Chapter II. For the location of the 16 zones, see Fig. II-5). Nomenclature used is: A (apples), Ap (apricots), Ch (cherries), Fo (nut trees), Fs (berry orchard), Ft (orchard of other fruits and crops), G (grassland, including alpine meadows, herbaceous vegetation area, high-productive natural pasture and wooded meadows), OS (other semi-natural areas including heathland, moors, hedgerow), Pe (peaches), Perennial areas (Per, including forest (F), artificial areas (U), water bodies (Wa) and rocky areas (St)), Pl (plums), Pr (pears), Sa (mix six major species of fruits and crops), Sb (sugar beet), Ss (mixed orchard of six major species), V (vineyards).

Cluster 1: Monoculture of maize, successive artificial pasture, fallow and other legumes, rotations "sunflower-wheat" and "maize-wheat", 2-year sequences "fallow-wheat", "rapeseed-wheat", "peas-wheat" and "other cereals-wheat" only or plus following by one year barley or other cereals are major crop sequences within the three ADs of cluster 1.

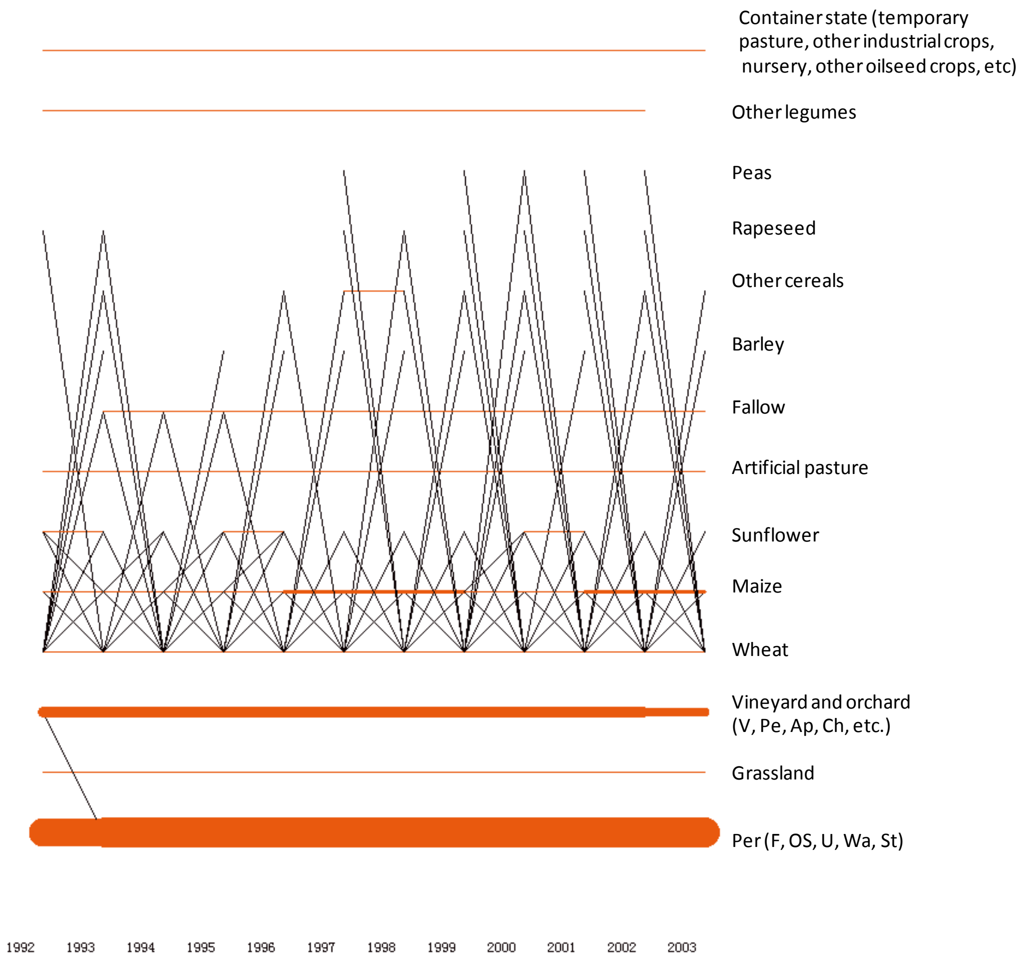

Fig. AnII-1. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 2: Monoculture of maize and wheat (durum wheat), successive sown pastures (both artificial and temporary pasture), other oilseed crops, and fallow, 2-year rotations "sunflower-wheat" and "maize-wheat", two year succession of other legumes, 2-year sequences "potatoes-wheat" and "rapeseed-wheat", and two year successive barley and/or wheat preceding one year sunflower are major crop sequences within the four ADs of cluster 2.

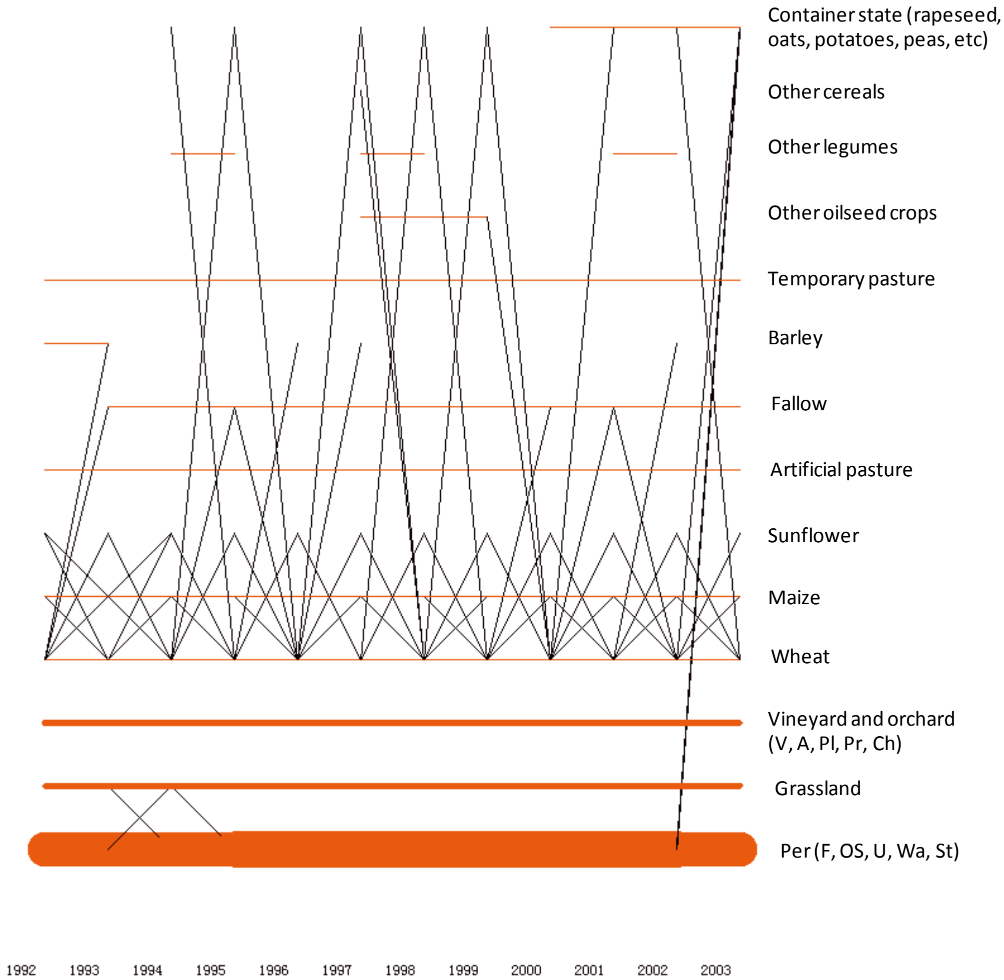

Fig. AnII-2. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 3: Monoculture of maize, successive temporary pasture and fallow, and sequences with embedding fallow, wheat, and other legumes in successive maize are major crop sequences within the 16 ADs of cluster 3.

Cluster 4: Monoculture of maize, wheat (durum wheat), other legumes, other cereals and other industrial crops, successive temporary pasture, artificial pasture and fallow, and sequences with including fallow, maize or sunflower in wheat-based CSs are major crop sequences within the 25 ADs of cluster 4.

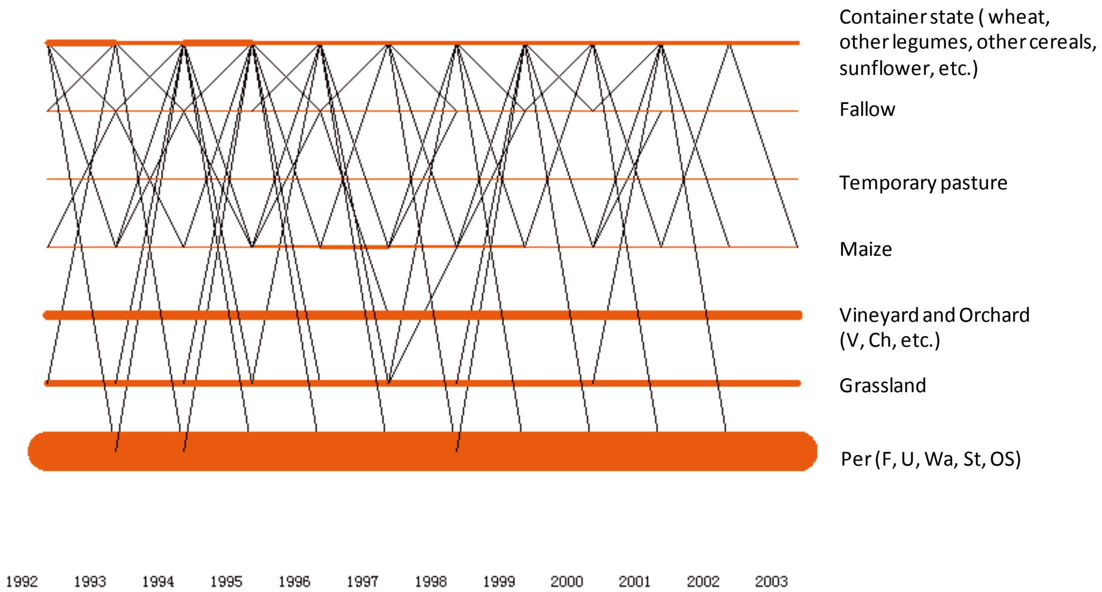

Fig. AnII-3. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.02% are displayed.

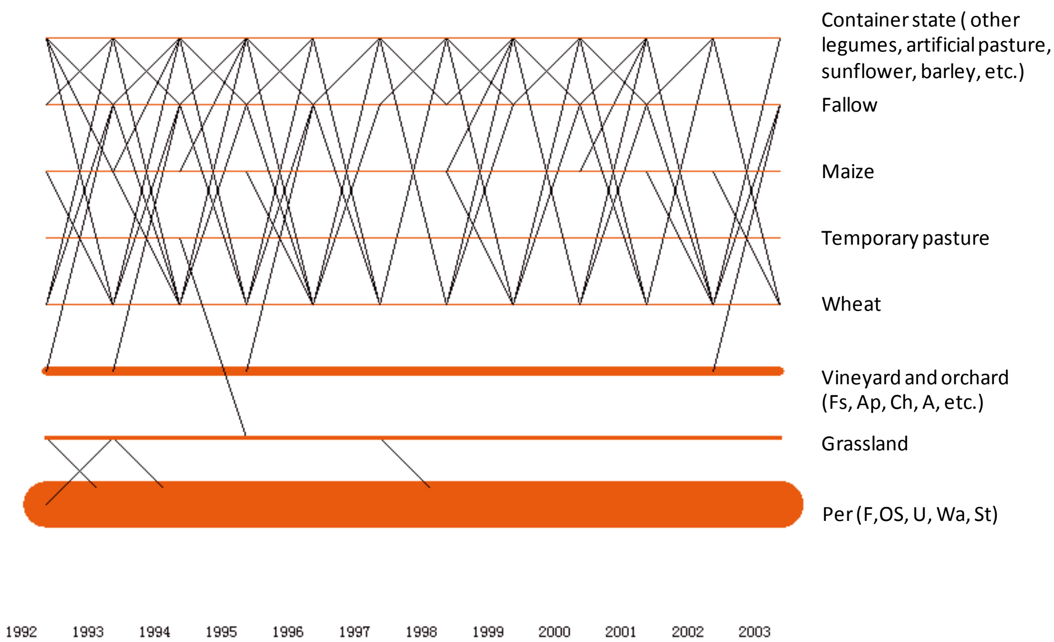

Fig. AnII-4. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.02% are displayed.

Cluster 5: Monoculture of maize, other legumes and wheat, successive temporary pasture and fallow, “maize-wheat”, “sunflower-wheat”, “rapeseed-wheat”, “wheat-barley-rapeseed” rotations, 3-year sequence “temporary pasture-maize-wheat”, and sequences with the inclusion of fallow, rapeseed or wheat in sunflower-wheat-based CSs are major crop sequences within the 21 ADs of cluster 5.

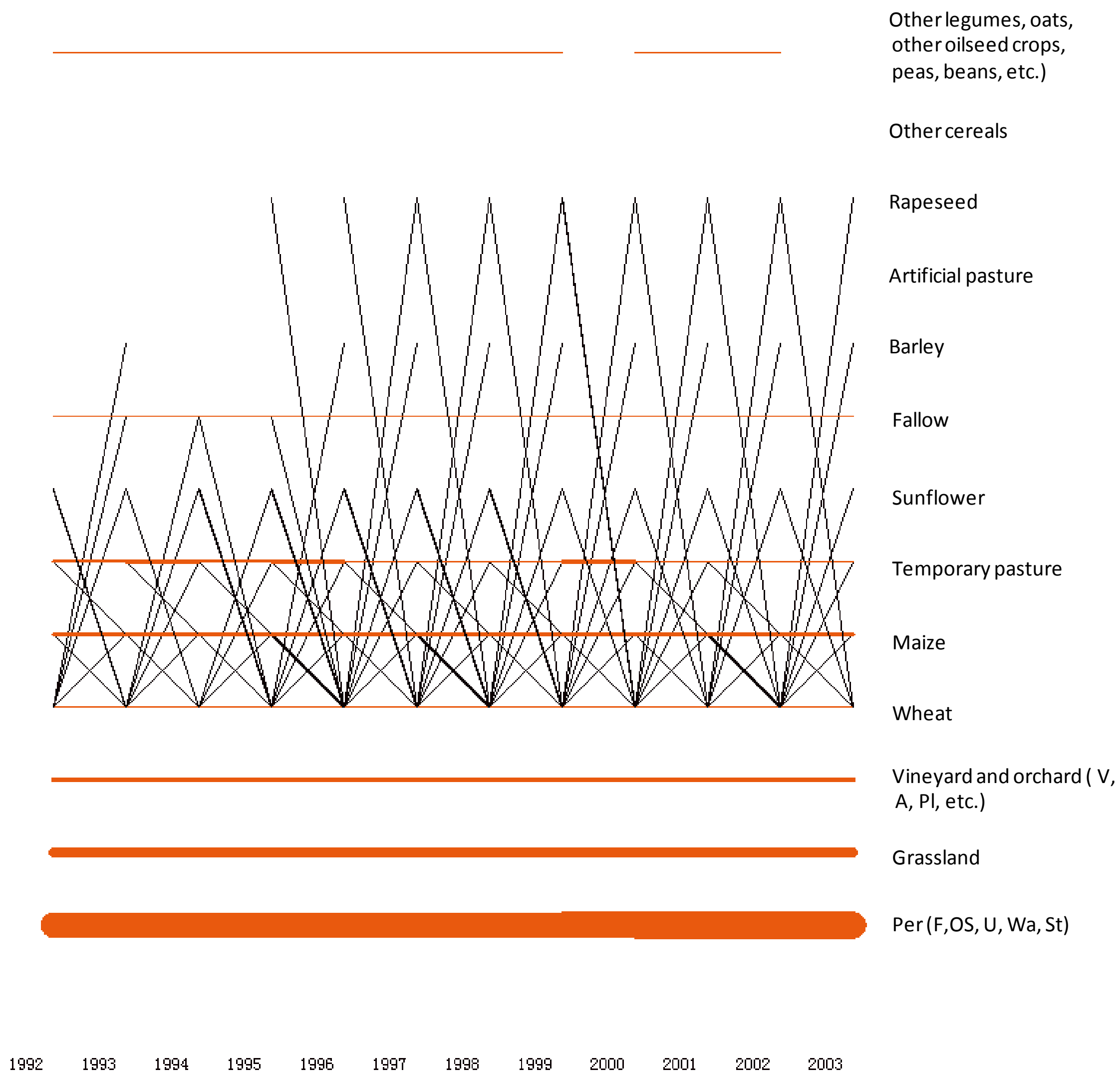

Fig. AnII-5. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.1% are displayed.

Cluster 6: Monoculture of maize and wheat, successive artificial pasture, barley and fallow, rotations "sunflower-wheat", "rapeseed-wheat", "wheat-barley-rapeseed", 3-year and 4-year sequences "peas-wheat-barley", "peas-wheat-sugar beet-wheat", "peas-wheat-rapeseed-wheat", and sequences with embedding one year rapeseed, peas or wheat in the rotation of "wheat-barley-rapeseed" are major crop sequences within the 10 ADs of cluster 6.

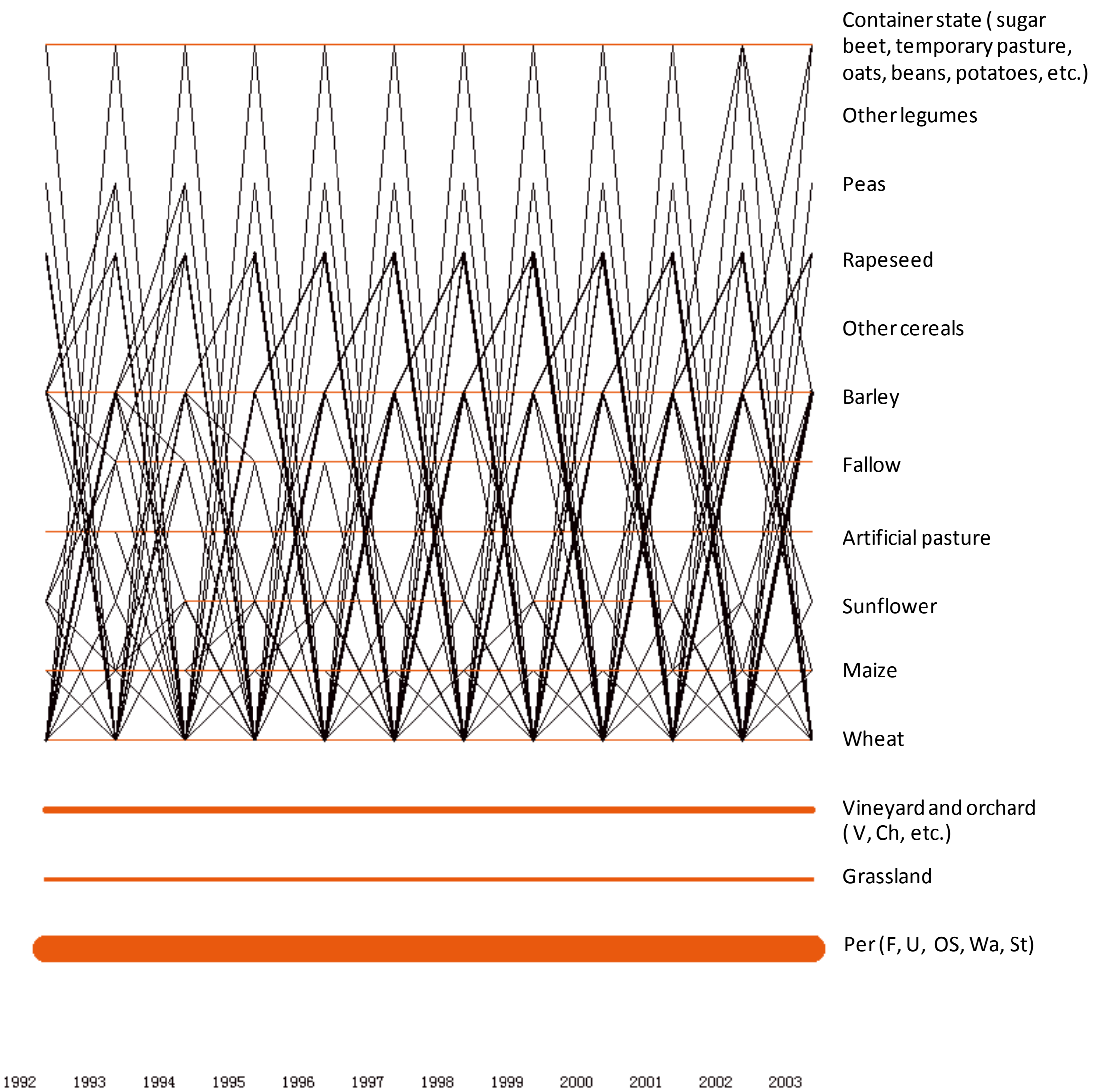

Fig. AnII-6. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 7: Monoculture of maize, wheat and sunflower, successive sown pasture (both temporary and artificial pasture) and fallow, 2-year rotations "sunflower-wheat", "maize-wheat", "other cereals-wheat", and "other oilseed crops-wheat", and sequences with embedding one year other cereals, barley, sunflower, fallow or wheat in maize monoculture and "sunflower-wheat" rotation with embedding barley are major crop sequences within the six ADs of cluster 7.

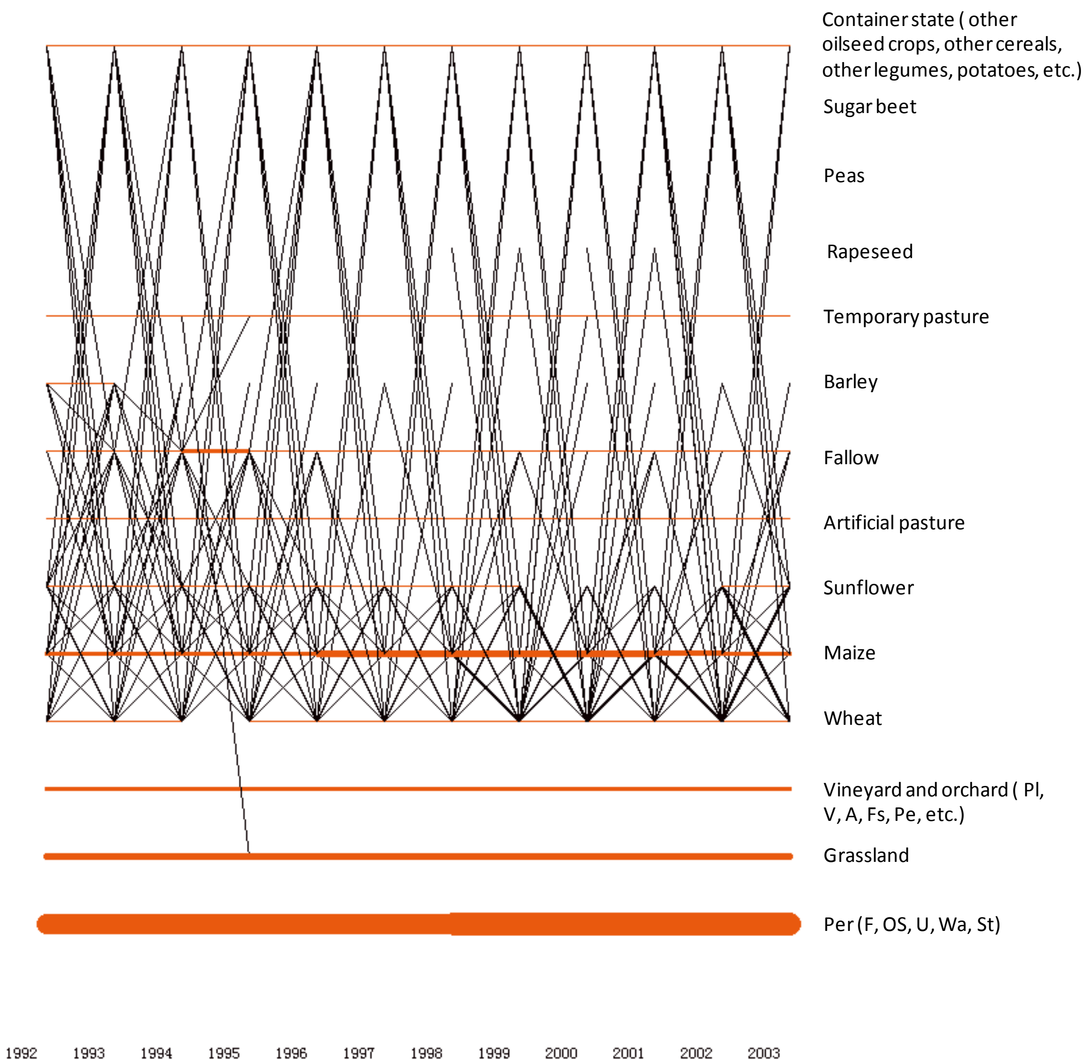

Fig. AnII-7. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 8: Monoculture of wheat (durum wheat) and other industrial crops, successive artificial pasture and fallow, 2-year rotations "sunflower-wheat" and "fallow-wheat", and sequences with including one year fallow, sunflower, peas or rapeseed in wheat monoculture are major crop sequences within the four ADs of cluster 8.

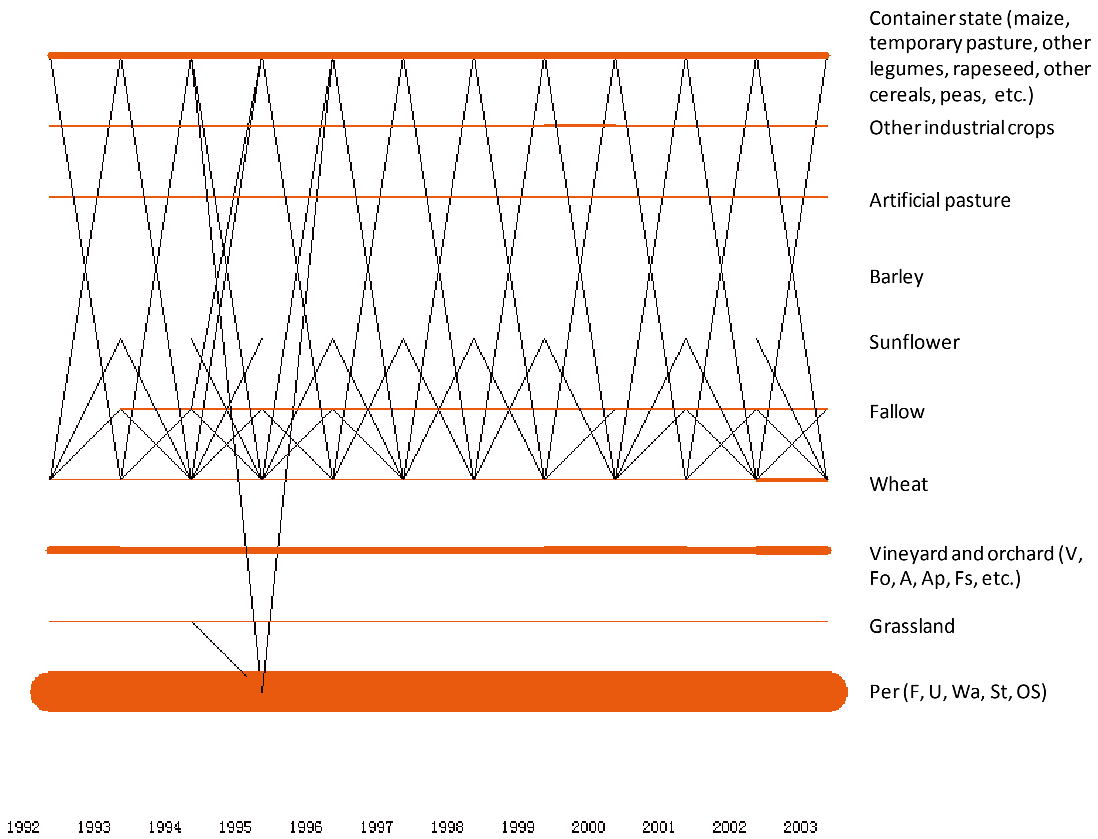

Fig. AnII-8. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 9: Monoculture of maize, other legumes and wheat, successive temporary pasture and fallow, 2-year rotations "maize-wheat", 3-year rotations "maize-maize-wheat", "maize-wheat-temporary pasture" and "maize-wheat-barley", and sequences with including one year maize, wheat, barley, other cereals or "maize-wheat" in successive temporary pasture are major crop sequences within the 39 ADs of cluster 9.

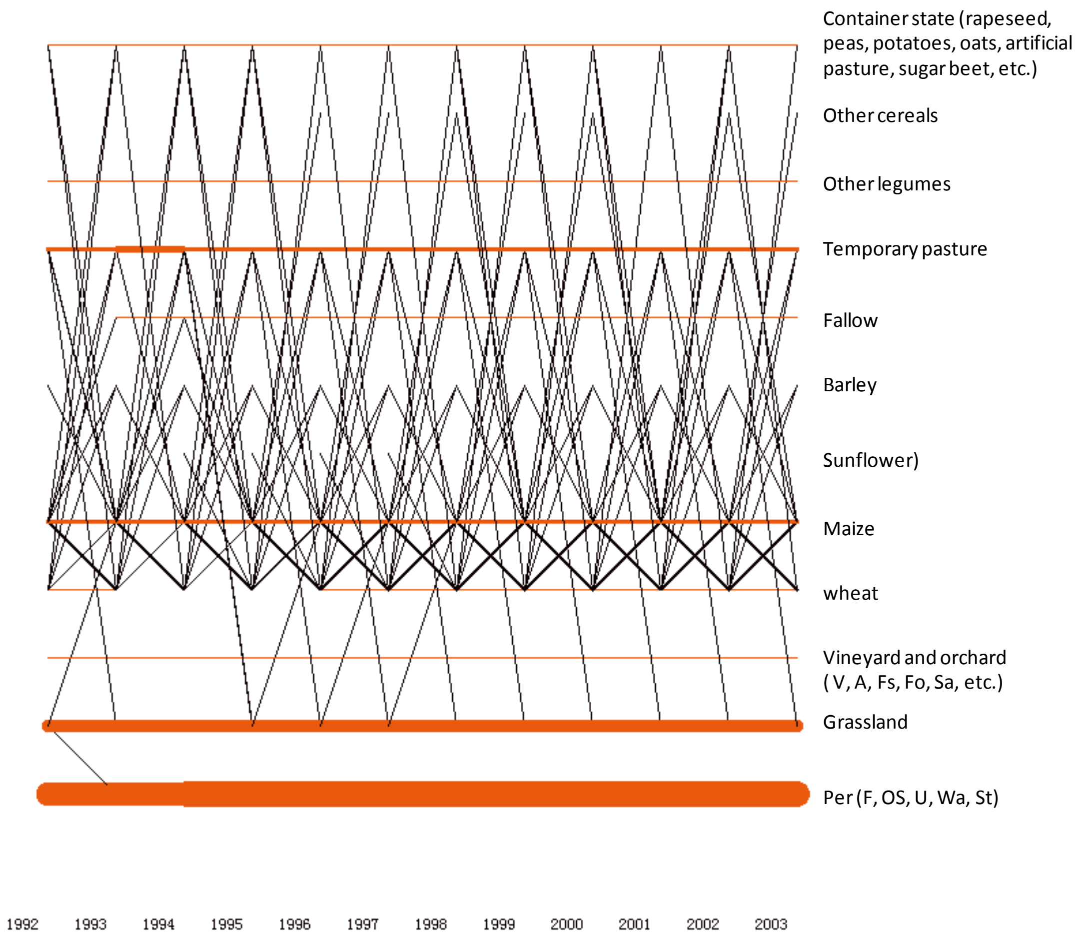

Fig. AnII-9. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 10: Monoculture of maize, barley and other cereals, successive temporary and artificial pasture, 2-year rotations “maize-wheat”, and sequences with including one year maize, wheat, barley or other cereals in successive temporary pasture are major crop sequences within the 59 ADs of cluster 10.

Cluster 11: Successive temporary pasture, monoculture of maize and other cereals, and sequences with embedding wheat in successive other cereals or wheat are major crop sequences within the 51 ADs of cluster 11.

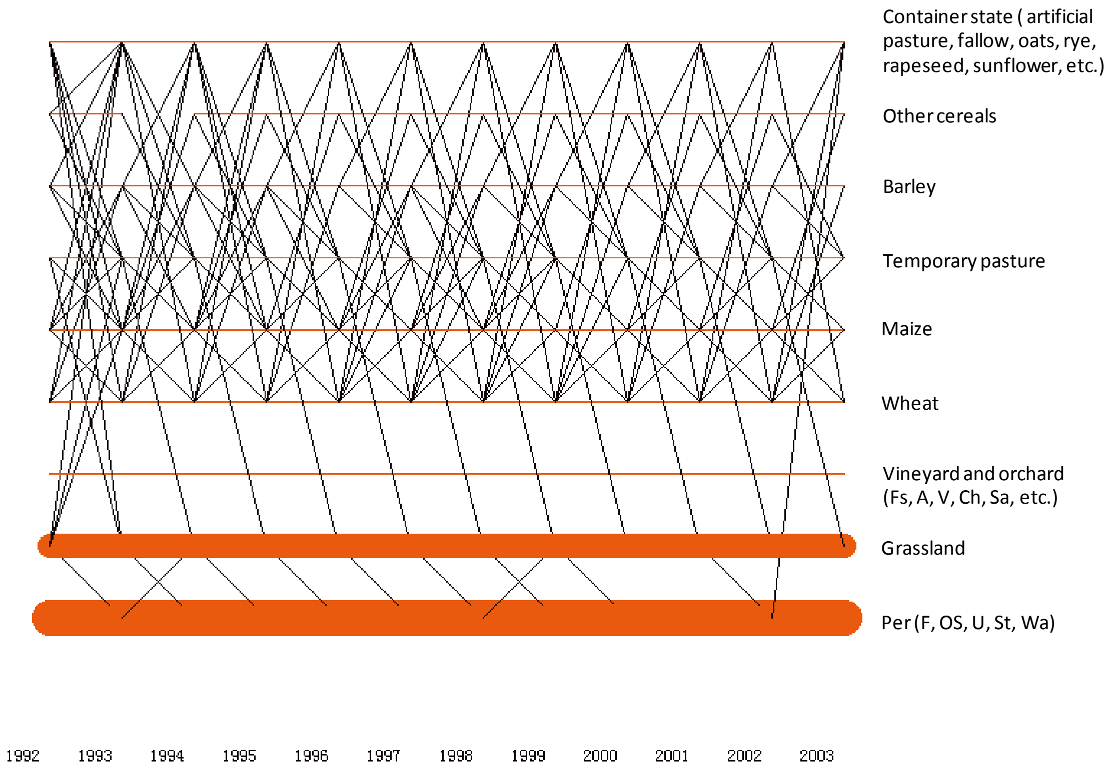

Fig. AnII-10. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.02% are displayed.

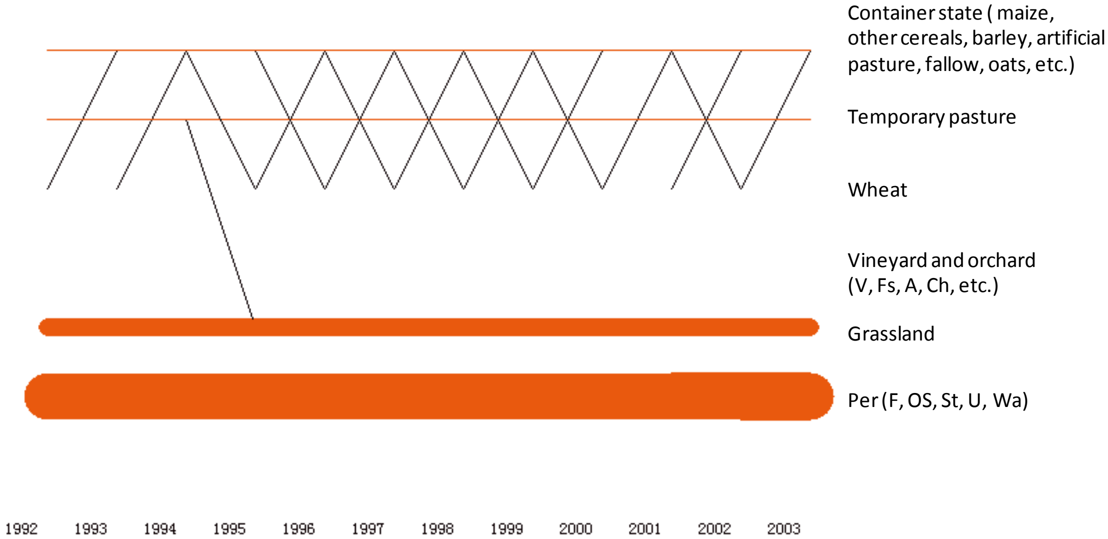

Fig. AnII-11. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 12: Successive temporary pasture, fallow and other cereals, monoculture of maize, other legumes and wheat, 2-year sequences “maize-wheat” and “sunflower-wheat”, and sequences with embedding barley, other cereals or temporary pasture in successive maize are major crop sequences within the six ADs of cluster 12.

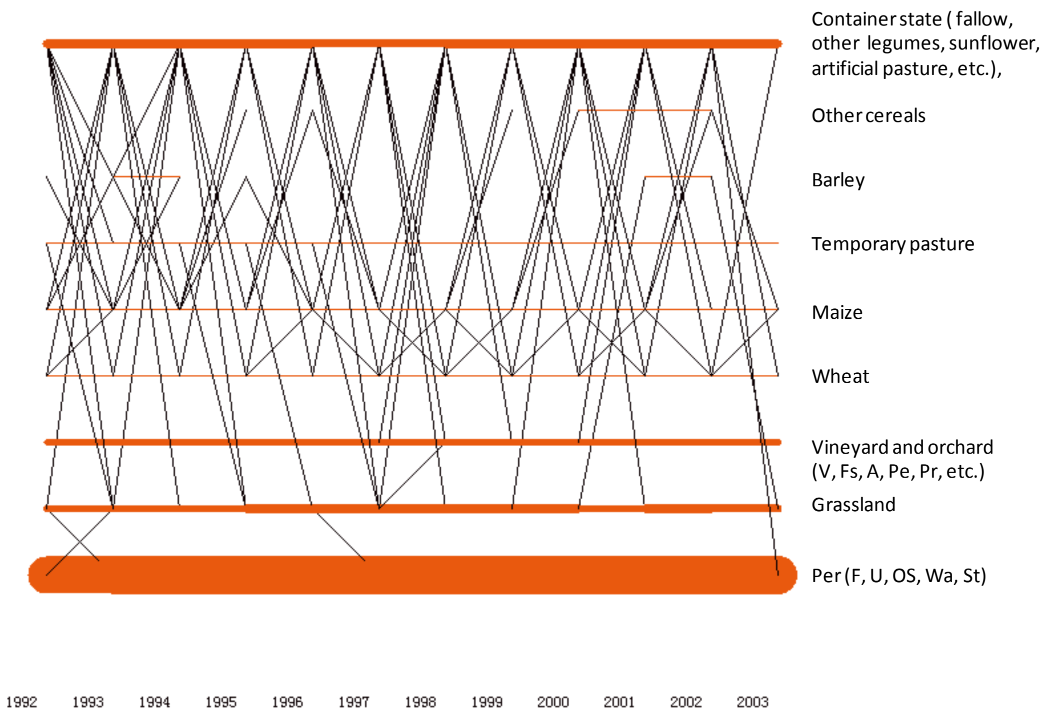

Fig. AnII-12. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.02% are displayed.

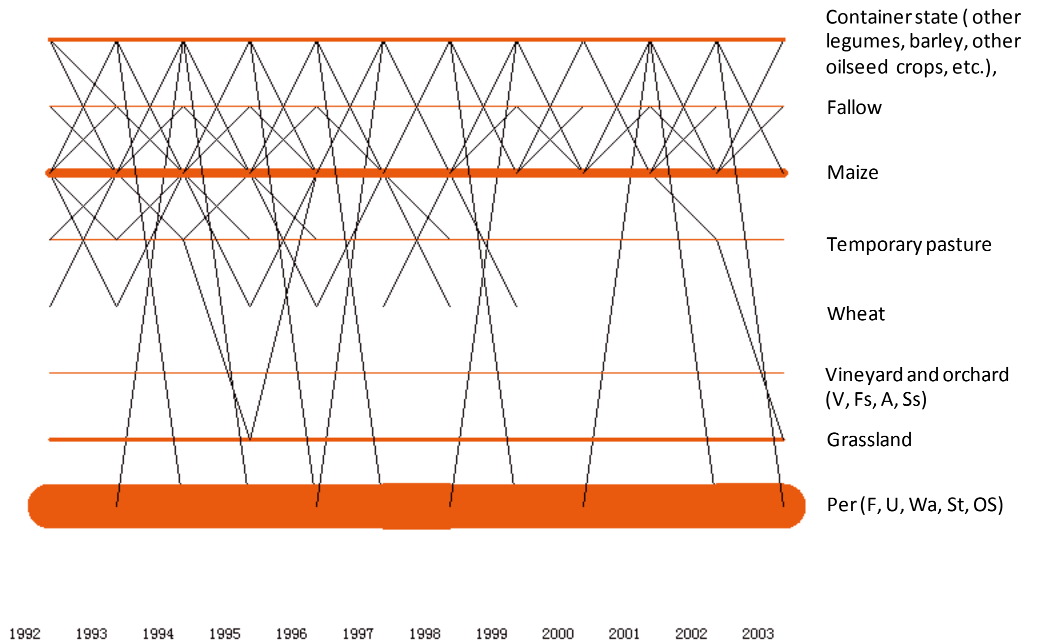

Fig. AnII-13. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.02% are displayed.

Cluster 13: Monoculture of maize and other legumes, successive temporary pasture and fallow, 2-year sequences “maize-wheat” and “sunflower-wheat”, and sequences with embedding one year or 2 or 3-year successive fallow, other legumes and temporary pasture or one year wheat in maize monoculture are major crop sequences within the 16 ADs of cluster 13.

Cluster 14: Two-year rotations “sunflower-wheat”, and “maize-wheat”, monoculture of maize and wheat, successive sown pastures (temporary and artificial pasture) and fallow, 3-year rotations “wheat-barley-sunflower” and “wheat-wheat-sunflower”, 4-year rotation “rapeseed-wheat-sunflower-wheat”, and sequences with embedding sequences “maize/rapeseed/peas-wheat” or one year barley or fallow in “sunflower-wheat” rotation are major crop sequences within the 21 ADs of cluster 14.

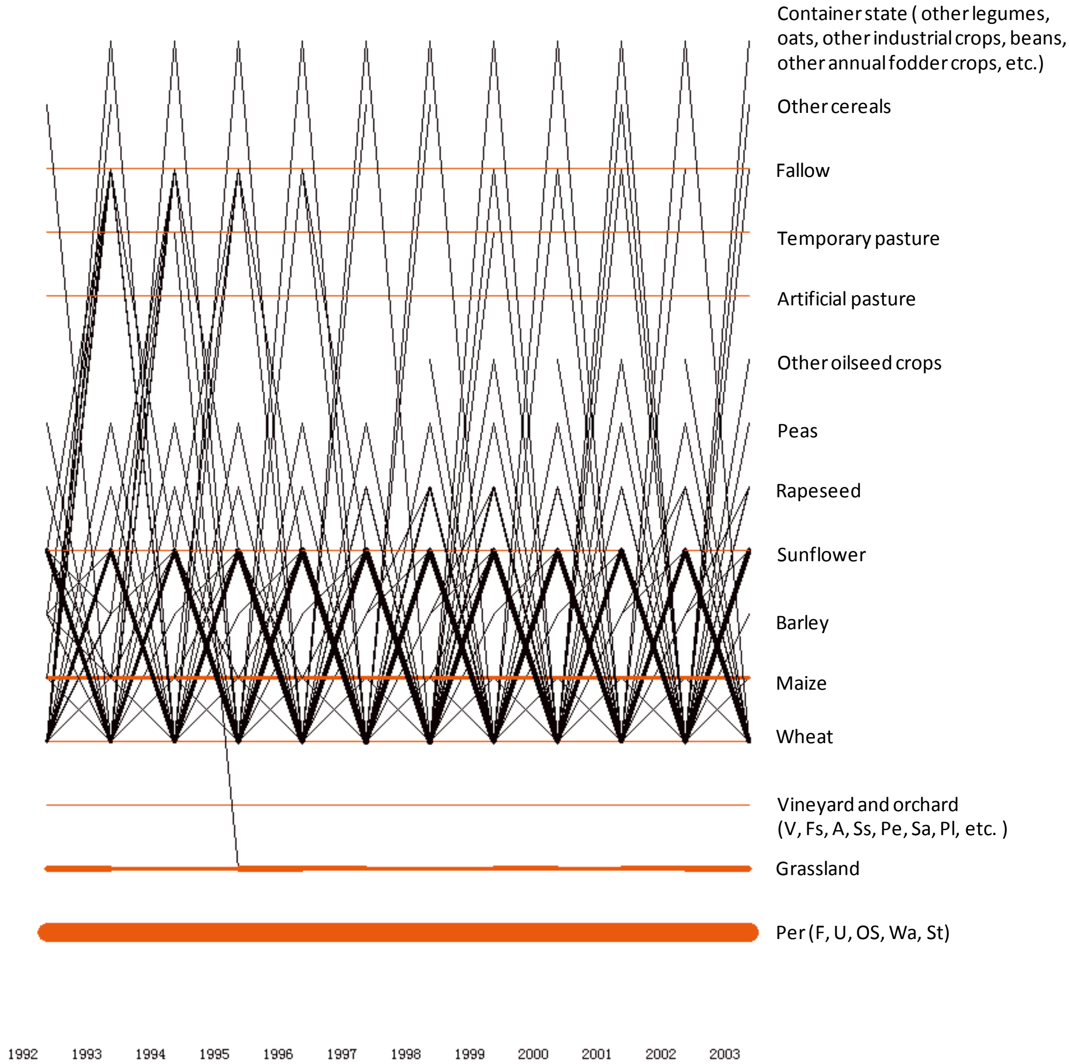

Fig. AnII-14. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 15: Monoculture of maize and wheat (durum wheat), successive temporary and artificial pasture, other oilseed crops, sunflower, other legumes and fallow, 2-year rotations “sunflower-wheat”, “rapeseed-wheat” and “maize-wheat”, 3-year rotations “wheat-wheat-sunflower”, “wheat-wheat-rapeseed” and “rapeseed-wheat-barley”, 4-year rotation “rapeseed-wheat-sunflower-wheat”, sequences with embedding other oilseed crops in maize monoculture, and sequences with including fallow in “sunflower-wheat” and “rapeseed-wheat” rotations are major crop sequences within the six ADs of cluster 15.

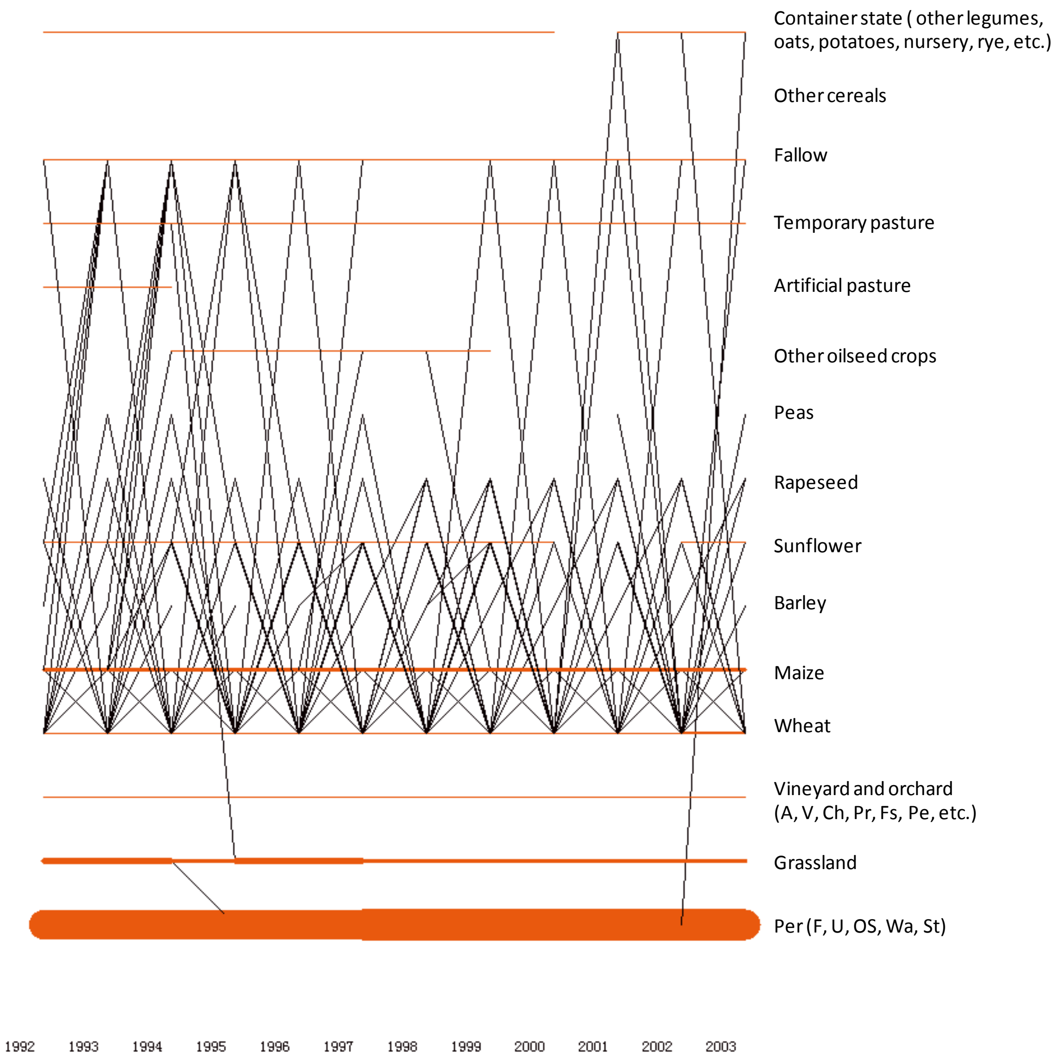

Fig. AnII-15. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 16: Monoculture of maize and wheat, successive temporary pasture and fallow, 2-year rotations "maize-wheat", "rapeseed-wheat" and "sunflower-wheat", 3-year rotations "barley-maize-wheat", "wheat-barley-rapeseed", "rapeseed-wheat-wheat" and "peas-wheat-wheat", 4-year rotation "maize-maize-wheat-maize", sequences with embedding maize and/or wheat in successive temporary pasture, and sequences with including peas or peas-wheat in successive wheat, "maize-wheat" and "rapeseed-wheat" rotations are major crop sequences within the 43 ADs of cluster 16.

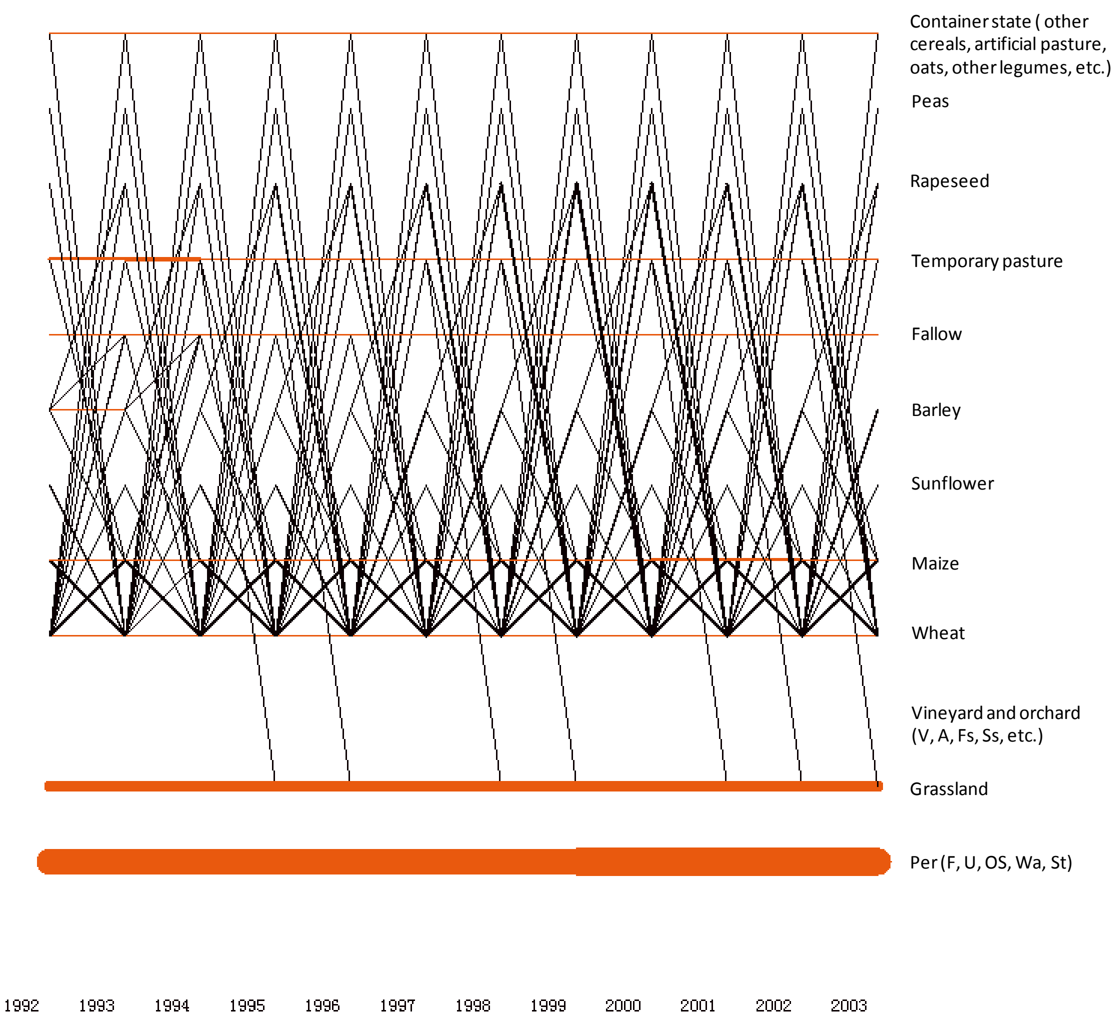

Fig. AnII-16. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 18: Three-year rotations “wheat-barley-rapeseed”, monoculture of barley and wheat, successive temporary and artificial pasture and fallow, 4-year rotation “barley-barley-rapeseed-wheat”, 2-year sequence “maize-barley”, and sequences with including fallow or “rapeseed/maize-wheat” in “wheat-barley-rapeseed” rotation are major crop sequences within the three ADs of cluster 18.

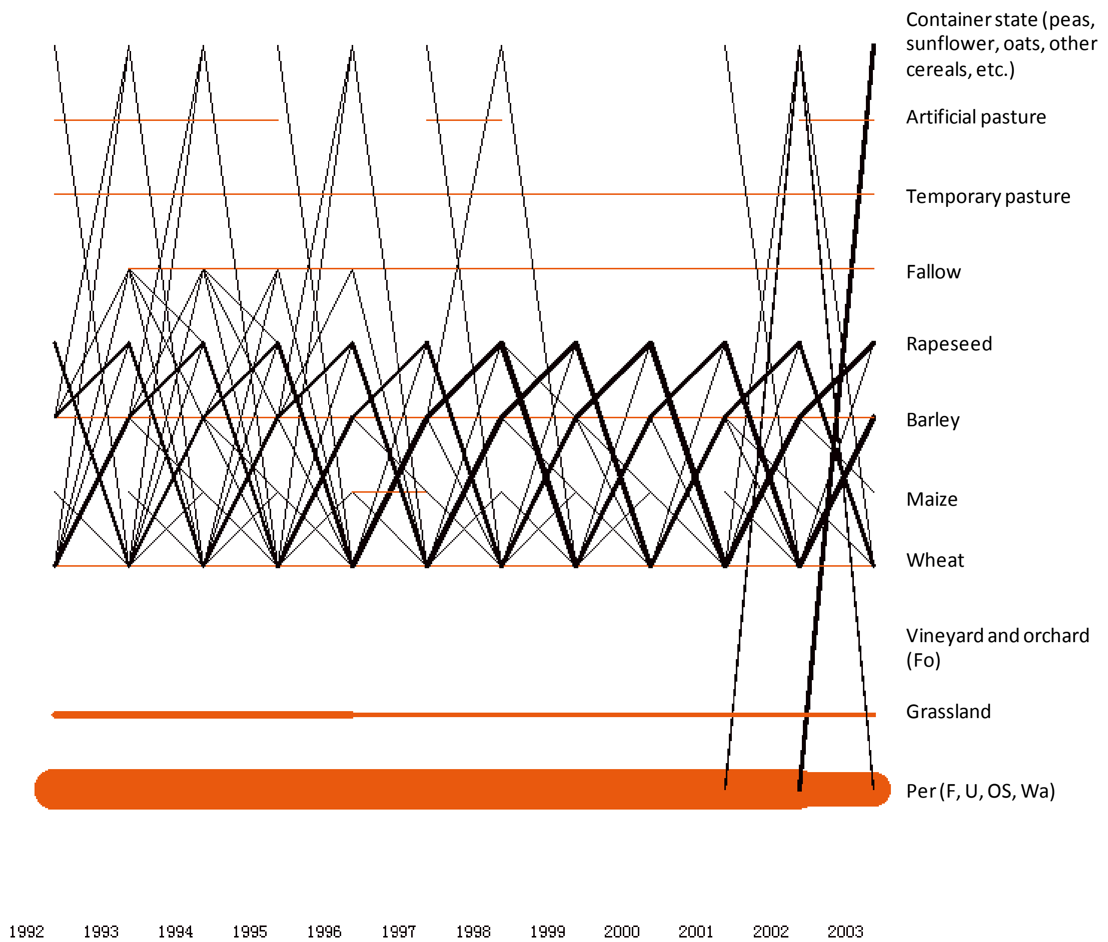

Fig. AnII-18. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 19: Monoculture of maize and wheat, successive artificial pasture, fallow and barley, 2-year rotation “maize-wheat”, 3-year rotations “sugar-beet-wheat-barley/wheat”, “wheat-barley-rapeseed”, and “barley-maize-wheat”, 4-year rotation “sugar beet-wheat-peas-wheat”, and sequences with embedding peas in “wheat-barley-rapeseed” rotation are major crop sequences within the 34 ADs of cluster 19.

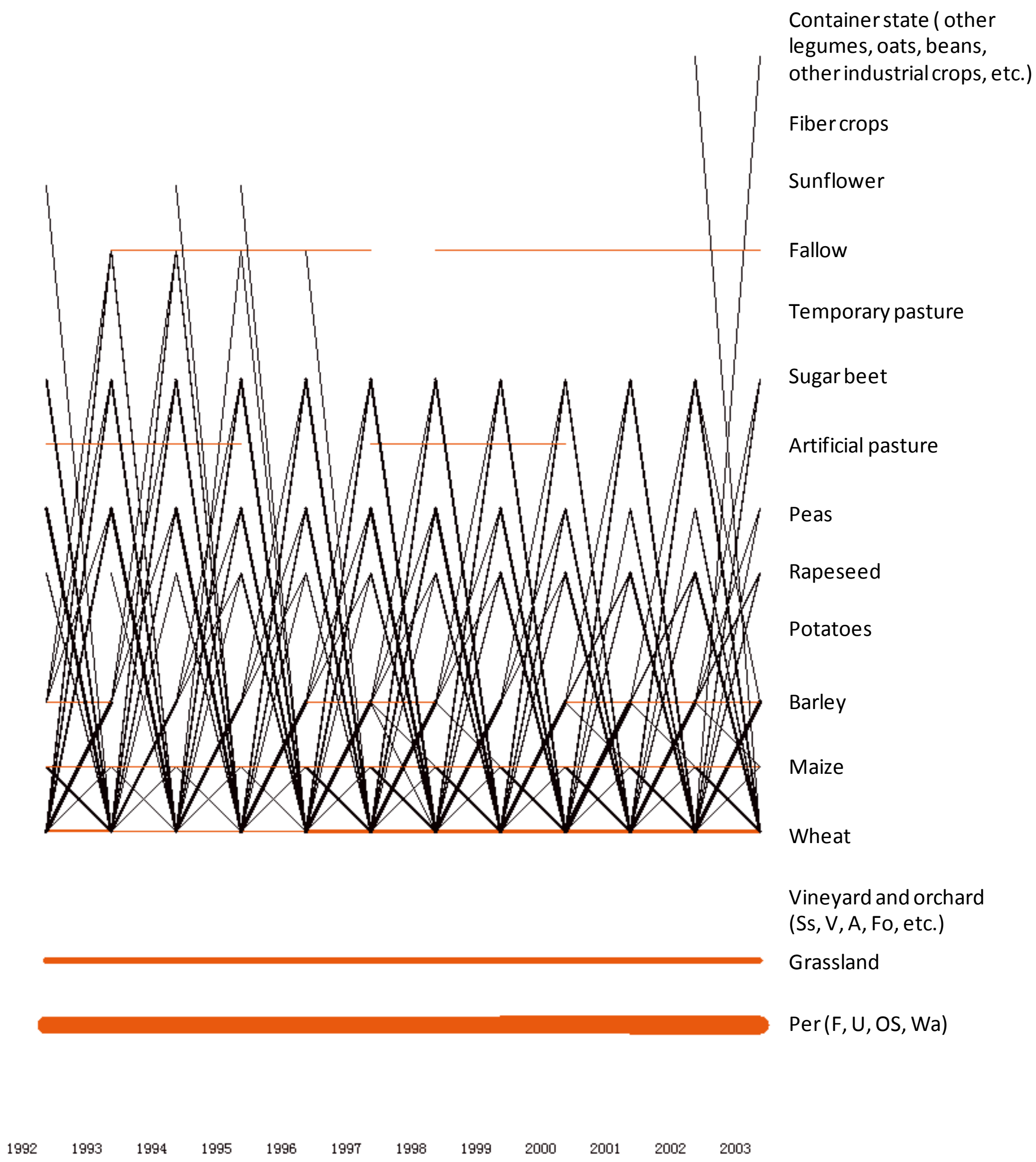

Fig. AnII-19. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.1% are displayed.

Cluster 20: Monoculture of maize and wheat, successive temporary pasture, fallow and barley, 2-year rotations "maize-wheat" and "sugar beet-wheat", 3-year rotations "sugar beet-wheat-barley/wheat", and 4-year rotations "sugar beet-wheat-peas-wheat" and "potatoes-wheat-sugar beet-wheat" are major crop sequences within the 30 ADs of cluster 20.

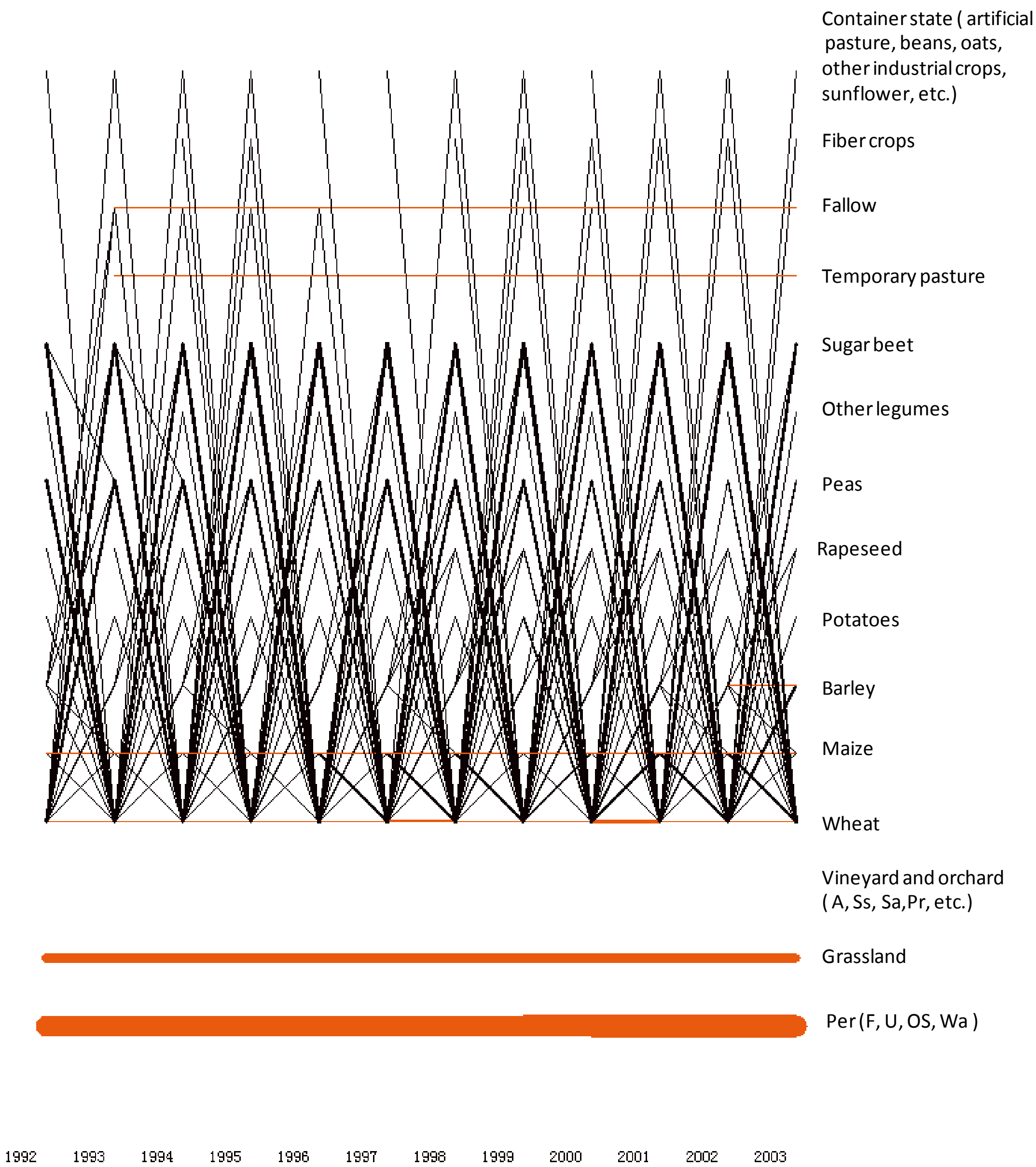

Fig. AnII-20. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.05% are displayed.

Cluster 21: Monoculture of wheat, successive temporary pasture, nursery, fallow and barley, 2-year rotation "maize-wheat", 3-year rotations "wheat-barley-rapeseed" and "sugar beet-wheat-barley", 4-year rotation "peas-wheat-rapeseed-wheat", and sequences with embedding peas or fallow in "wheat-barley-rapeseed" rotation or one year maize, fallow or peas in successive wheat are major crop sequences within the two ADs of cluster 21.

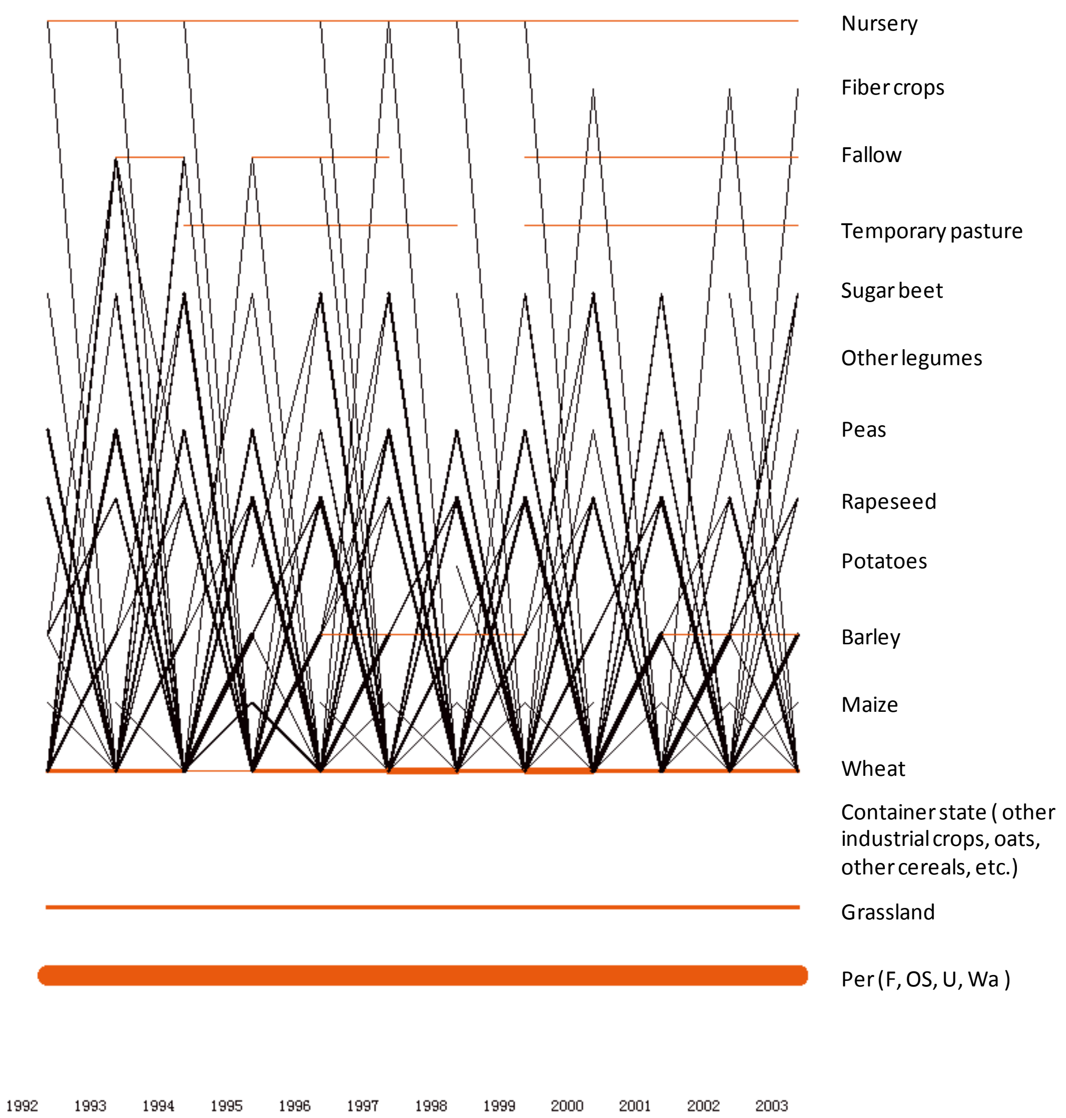

Fig. AnII-21. Graphic output of CARROTAGE. The a posteriori probabilities of transitions between states are described by diagonal and horizontal lines. Only the transitions whose probability is greater than 0.1% are displayed.

Appendix IV Publication and conference participation

Publication in scientific journal

Xiao, Y., Mignolet, C., Mari, J.-F., Benoît, M., 2014. Modeling the spatial distribution of crop sequences at a large regional scale using land-cover survey data: A case from France. Computers and Electronics in Agriculture 102, 51-63. doi:10.1016/j.compag.2014.01.010

Xiao, Y., Mignolet, C., Mari, J.-F., Benoît, M. Characterizing historical (1992-2010) transitions between grassland and cropland in mainland France through mining land-cover survey data. Journal of Integrative Agriculture 14(8), 1511-1523. doi: 10.1016/S2095-3119(15)61103-0

Oral presentation at international conference

Xiao, Y.*, Mignolet, C., Mari, J.-F., Benoît, M., 2014. Spatio-temporal dynamics in crop sequence patterns at national scale: the French case study based on historical land survey data. 2nd Global Land Project Open Science Meeting, Berlin, Germany. URL: http://www.glp-osm2014.org/abstracts_01.php

Xiao, Y.*, Mignolet, C., Mari, J.-F., Benoît, M., 2013. Data mining on land-cover survey datasets to explore grassland conversion in France. 4th International Symposium for Farming Systems Design, Lanzhou, China. URL: http://www.fsd2013.com/uploadfile/2013/0906/20130906122245145.pdf

Xiao, Y.*, Mignolet, C., Mari, J.-F., Benoît, M., 2012. Modeling the spatial distribution of cropping systems at a large regional scale: a case of crop sequence patterns in France between 1992 and 2003. 12th Congress of the European Society for Agronomy, Helsinki, Finland. URL: http://www.esa12.fi/Abstracts.pdf

Résumé étendu

Cette thèse contribue à un récent courant de recherche international centré sur la « Land Change Science », soit la science des changements d'usages des sols (Rounsevell ***et al.,*** 2003)[1] dont le programme « Global Land Project » est la plus récente réalisation. Pour notre part nous centrons notre recherche sur les changements dits « subtils » d'usage des sols, ceux liés aux successions de culture. Elle alimente les avancées récentes en agronomie des territoires (Benoît, Rizzo ; 2014 ; Leenheradt et al, 2010)[2]. Dès les écrits fondateurs en agronomie (Sebillote, 1974)[3], la succession de culture est l'un des deux objets-clés des agronomes qui étudient l'efficacité d'utilisation des territoires par les agriculteurs. Ici, nous proposons d'innover dans deux directions :

- L'échelle de travail retenue : l'ensemble du territoire français,
- L'utilisation d'une base de données spécifique à la France, Terruti.

L'information spatialement explicite sur les systèmes de culture est indispensable pour évaluer les impacts environnementaux des systèmes de production agricole (Tilman et al., 2002 ; van Ittersum et al., 2008)[4]. Toute caractérisation des changements dans l'usage des sols agricoles pour l'analyse de la performance des politiques publiques agricoles et environnementales exige également ce type de données pour les entrées du modèle. Ainsi, les dynamiques des changements de successions de culture sont à la fois des produits de décisions humaines à divers niveaux d'organisation, exploitation, filières, politique européenne, et des facteurs de nombreux fonctionnements agronomiques et environnementaux, tels que biodiversité, qualité des eaux, dynamique des adventices et des ravageurs des cultures

Les réformes les plus importantes de la politique agricole commune européenne (PAC) ont commencé en 1992 et se sont intensifiées en 2003 (EC, 2000)[5]. Les paiements directs introduits par la Convention de la

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[1] Rounsevell, M., Annetts, J., Audsley, E., Mayr, T., Reginster, I., 2003. Modelling the spatial distribution of agricultural land use at the regional scale. Agric. Ecosyst. Environ. 95, 465-479.

[2] Benoît M. , D. Rizzo, E. Marraccini, H. Rapey, C. Thenail, A.C. Moonen, S. Lardon, M. Galli , P. Caron, N. Silvestri, E. Bonari , 2012. Landscape Agronomy: Conceptualizing a new research field in landscape ecology. *Landscape Ecology.*10 (27) : 1385-1394
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, 131-138.

[3] Sebillotte M, 1974. Agronomie et agriculture. Essai d'analysse des tâches de l'agronome. Cahiers ORSTOM, série Biologie, 24, 3-25.

[4] van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). Agricultural Systems 96, 150-165.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671-677.

[5] European Communities, 2000. Thirty years of agriculture in Europe-Arable land, increased size of holdings and changes in crop rotation. Statistics in focus No. 12/2000. Luxemburg.

réforme de la PAC de 1992 ont acté le passage du soutien au produit calculé par unité de surface des diverses productions au soutien au producteur via une aide unique. En sus de ces bouleversements juridiques sur les aides publiques liées aux choix des couverts végétaux, les agriculteurs ajustent leur planification aux opportunités du marché. Les réformes successives de la PAC ont influencé les incitations relatives aux productions et donc l'affectation des terres agricoles. De nombreuses études récentes ont étudié les changements dans l'usage des sols agricoles en Europe sous la forme de l'abandon des terres agricoles, l'expansion des terres labourées, l'intensification des systèmes de production, et le boisement de terres (van Zanten ***et al.,*** 2014)[6]. Cependant, la succession de cultures (SC) comme une pratique centrale et généralisée de gestion des terres agricoles et les changements dans les choix de successions des cultures à l'échelle régionale ont été rarement étudiées, cet objet est au cœur de cette thèse.

Dans le contexte de l'évolution de la politique agricole, du développement des systèmes de productions agricoles, de préoccupation croissante pour la durabilité dans l'agriculture, l'objectif principal de cette thèse est d'instruire l'organisation des successions de cultures, à l'échelle de l'ensemble de la France et sur un recul décennal. Nous aborderons cet objet de recherche tant en terme de cinétiques localisées, où nous nous centrerons sur les modalités de ces évolutions, qu'en terme de dynamiques où nous centrerons notre recherche sur les des variables explicatives tant du milieu physique que des conditions socio-technico-économiques. Ce travail de « fouille de données » est appliqué à la France métropolitaine entière, en utilisant les bases de données publiques disponibles. Notre étude couvre la période 1992-2003 où s'implémenta la réforme de la Politique Agricole Commune de 1992 et l'Agenda 2000 en France.

Cette thèse comprend six chapitres, y compris l'introduction générale "Chapitre I". Chaque chapitre aborde une des questions de recherche annoncées ci-dessus :

- *Le chapitre I* présente le contexte scientifique du travail de thèse et décline les objectifs de la recherche avec la réalisation des tâches réalisées à l'unité d'accueil INRA SAD UPR 055 ASTER de Mirecourt. Nous justifions l'originalité de la recherche et nous la contextualisons sur le plan politique : la période d'étude correspond à la mise en œuvre de la PAC à partir de 1992 et à la mise en place de l'Agenda 2000. Les concepts principaux sont présentés (système de culture ; rotation de culture et succession de culture).
- Dans le *chapitre II,* nous présentons une exploration innovante de données stochastiques qui vise à décrire la distribution spatiale des successions de cultures à grande échelle régionale. L'exploration de données est effectuée par des modèles de Markov cachés et une analyse de classification non-supervisée qui traite, séquentiellement sur la période observée (de 1992 à 2003), les données de l'enquête sur la couverture des sols sur le territoire français nommée Teruti. Les 2549 successions de

[6] van Zanten, B., Verburg, P., Espinosa, M., Gomez-y-Paloma, S., Galimberti, G., Kantelhardt, J., Kapfer, M., Lefebvre, M., Manrique, R., Piorr, A., Raggi, M., Schaller, L., Targetti, S., Zasada, I., Viaggi, D., 2014. European agricultural landscapes, common agricultural policy and ecosystem services: a review. Agronomy for Sustainable Development 34, 309-325.

cultures de trois ans ont d'abord été identifiées comme les principales successions de cultures à travers l'ensemble du territoire, qui comprenait 406 régions agricoles. Le choix d'une longueur de trois ans pour identifier ces successions est lié à la forte occurrence de cette durée parmi l'ensemble des successions de cultures traitées. Une première étude stationnaire sous forme d'une classification hiérarchique a permis de regrouper l'ensemble des 406 régions agricoles de France, en 21 groupes sur la base des occurrences moyennes de 12 années de ces successions de culture. Ainsi, se dégage une figure cartographique de la France agricole en 21 territoires aux agrégats de successions de culture contrastés. Au sein de ce territoire, quatre systèmes de culture, 90 régions agricoles, parangons des 430 régions agricoles françaises définies par la statistique agricole, et trois régions principales appartenant à cinq des 21clusters, regroupant les cultures de céréales, oléagineux et protéagineux, ont été plus particulièrement étudiés. L'approche de modélisation qui est présentée dans cette recherche fournit un outil pour extraire les associations de modes de culture à grande échelle à partir de données de séries chronologiques sur la couverture des sols. Avec cet outil, les utilisateurs peuvent (a) identifier les zones homogènes en termes de successions de cultures de longueur fixe sur un grand territoire, (b) comprendre les caractéristiques des systèmes de culture dans une région en termes de successions de cultures typiques, et (c) identifier les principales successions de culture d'une région selon les probabilités d'occurrences.

- Dans le *chapitre III,* nous nous focalisons sur les transitions récentes (1992-2010) entre les prairies permanentes et les terres cultivées pendant deux réformes de la PAC de 1992 et de 2003 à l'échelle du continent français. La question est ici celle du retournement des prairies permanentes et de l'usage futur de ces anciens territoires en herbe. Nous avons proposé une approche innovante pour relier la conversion de prairies permanentes en terres labourées et les pratiques de gestion des sols agricoles. Nous avons d'abord évalué la conversion des prairies en terres cultivées en étudiant les patrons de successions de cultures qui ont été observés comme dominants après la conversion à travers les données de l'enquête Teruti et Teruti-Lucas. Nous avons trouvé deux périodes de réalisation des transitions entre les prairies permanentes et les terres labourées: la perte importante de prairies (1992-2003) et la restauration modeste des prairies permanentes (2006-2010) en France métropolitaine. Notre conclusion sur les patrons de successions de cultures après la conversion de prairies permanentes révèle deux évolutions notables de systèmes de productions agricoles. Ces évolutions sont liées à l'augmentation de la proportion de terres cultivées dans la surface agricole utile totale. Une telle évolution a probablement été influencée par la demande de fourrage: la conversion prairies à usage de pâturage pour le bétail en terre labourées servant à produire des fourrages annuels. Une autre évolution est la conversion complte de la production animale à la production de grandes cultures. Nos résultats indiquent que l'intensification des systèmes d'élevage a continué au cours des deux dernières décennies en France Métropolitaine. Nous concluons que, l'approche développée dans cette étude peut être considéré comme une méthode générique pour surveiller les transitions entre les prairies et les terres cultivées et identifier en outre les modèles de successions de cultures après la conversion de prairies permanentes à partir de données d'enquête de la couverture des sols.

- Dans le *chapitre IV*, nous étudions la dynamique spatio-temporelle des patrons de successions de cultures entre 1992 et 2003 en France métropolitaine en utilisant les données de l'enquête Teruti. Notre étude a été menée à deux échelles: (1) l'échelle nationale en analysant toutes les 430 régions agricoles françaises et l'assemblage des 90 régions agricoles, parangons de ces 430 régions agricoles françaises, et (2) l'échelle régionale en analysant trois des 21 clusters (voir chapitre 2) regroupant les principales zones de plantation de céréales, oléagineux et de protéagineux séparément. Cette recherche a été menée en segmentant la période étudiée en trois sous-périodes : 1992- 1994, 1997-1999, 2001-2003. Nous avons compté les occurrences de successions de cultures de trois ans dans chaque région agricole et dans chaque sous-période. Une analyse triadique partielle (Partial Triatic Analysis) a ensuite été effectuée pour évaluer la variabilité spatiale des patrons de successions de cultures au cours d'une période et explorer l'évolution temporelle des patrons de successions de cultures par région agricole. Nous avons observé que les patrons de successions de cultures à l'échelle nationale étaient essentiellement stables et présentaient seulement des changements subtils dans les patrons de successions de cultures dans plusieurs parties du territoire. Nous avons montré qu'au niveau national, les zones de culture révèlent des plus grandes variabilités au cours du temps que les successions de culture liées aux fonctionnements d'élevage : cultures fourragères et prairies temporaires. Les surfaces en successions de cultures basées sur le maïs, en particulier en monoculture, s'étendent de plus en plus dans le sud-ouest et le nord-est sur toute la période, alors que les régions dominées par les successions de culture pois/blé déclinent fortement entre les deux dernières sous-périodes dans tout le Nord de la France. Les analyses menées séparément pour les trois zones retenues montrent que les patrons de successions de culture dans la zone spécialisée en betterave à sucre et/ou pois ou pomme de terre – blé/orge montrent une plus grande variabilité temporelle au cours des trois sous-périodes que les successions de culture des deux zones spécialisées sur les successions de culture colza/blé-orge et tournesol/blé. Les évolutions temporelles des patrons de successions de cultures dans les régions agricoles appartenant au même cluster sont très similaires ce qui confirme la validité de ces clusters.
- Dans le *chapitre V*, une recherche des dynamiques d'évolution de successions de culture en lien avec des conditions biophysiques et socio-technico-économiques a été menée. Nous avons segmenté la période étudiée en trois sous-périodes : 1992- 1994, 1997-1999, 2001-2003. STATICO a été utilisé pour analyser ces relations et représenter graphiquement leurs variations temporelles. Notre étude était conduite à deux échelles comme au chapitre IV. Nous avons montré que les facteurs liés à la taille des exploitations, l'utilisation de tracteurs, et la surface irriguée, ainsi que le ratio des types d'associations dans les exploitations jouent un rôle important dans l'organisation des successions de cultures d'une zone aux deux échelles. Les relations entre les successions de cultures et les conditions externes changent au cours des trois sous-périodes. Ainsi, la taille moyenne des exploitations, la part des

exploitations de plus de 100 hectares et l'usage des tracteurs les plus puissants deviennent des facteurs majeurs corrélés avec les patrons de successions de culture à la fois à l'échelle de la France entière et des trois zones étudiées. A l'opposé, la densité d'élevages avicoles et le ratio d'unité de travail humain (UTH) par exploitation deviennent des facteurs importants influençant les patrons de successions de cultures à l'échelle France entière et à celle de deux des trois zones seulement pendant les deux dernières sous-périodes.

- Dans le *chapitre VI*, nous concluons sur les principaux apports de ce travail de thèse et évoquons les perspectives de recherches. Les résultats ont permis de franchir une étape supplémentaire dans la compréhension de la diversité des patrons de successions de cultures sous différents systèmes de culture à l'échelle de la France. Nous évoquons plusieurs pistes de recherche dans le champ de l'analyse spatiale et de la modélisation (modélisation à multi-échelles, modèle de régression et d'autocorrélation spatiale, analyse multidimensionnelle dans le domaine de l'écologie des communautés, etc.).

Cette recherche mériterait des améliorations sur les données mobilisées, en particulier le sol n'a pu être pris en compte comme variable explicative des patrons de séquences de culture. Nous proposons une utilisation ultérieure des méthodes mobilisées qui ont montré leur capacité à cartographier les grandes tendances d'évolution en France et à identifier les principales variables explicatives de ces évolutions des patrons des successions de culture. Les apports de cette thèse contribuent à améliorer notre compréhension des processus qui organisent les successions de culture en France et construisent par ces pratiques agricoles très dynamiques, dans le temps et l'espace, des impacts forts sur le territoire agricole français qui connaît, depuis deux décennies, de fortes tendances à se spécialiser et à simplifier ces patrons de successions de culture.

Abstract In the context of changing agricultural policy, the development of agricultural production systems, increasing concern for agricultural sustainability and shifts in agricultural land management practice-related land-use change, the main objective of this thesis was to mine crop sequence patterns (CSP) and the relationships between CSP and the biophysical and socio-technical-economic (BSTE) conditions in mainland France from historical census data. Our study period 1992-2003 covers the implementation period of the 1992 European Union Common Agricultural Policy reform and Agenda 2000 in France. The 2549 3-year crop sequences (CSs) were first identified as major CSs within all 430 agricultural districts (ADs) in mainland France during this period. We then classified these ADs into 21 clusters according to the 12-year average occurrences of these CSs. Four cropping systems, 90 representative agricultural districts and three principal planting zones of cereals, oilseeds, and protein crops belonging to five clusters identified previously were further defined. Moreover, our study of CSP after grassland conversion confirmed two types of evolution: grazing-livestock-to-feed-livestock and livestock-production-to-field-crop-production conversion. Next, we segmented the study period into three subperiods: 1992-94, 1997-99 and 2001-03 to explore the dynamics of CSP and CSP-BSTE condition relationships. We found that, at the national scale, field cropping zones revealed higher temporal variability of CSP than the fodder crop and sown pasture-based livestock zones. The areas with maize-based CSs, and maize monoculture in particular, expanded in the southwestern and northeastern areas over the whole period, whereas the areas with peas/wheat-based CSs declined between the two subsequent subperiods in northern France. Separate investigations for three zones indicated the CSP within the zone specializing in sugar beet- and/or pea- or potatoes-wheat/barley-based CSs, which revealed higher temporal variability over the three subperiods than the CSP in the two zones that specialized in rapeseed/wheat-barley-based and sunflower/wheat-based CS cultivation. The temporal evolutions of CSP in the ADs belonging to the same cluster were very similar. We also found that farm-size-related factors, the use of tractors with different power sizes, the share of irrigated land in the total utilized agricultural area, and the ratio of farm holders with different legal status play an important role in the overall CSP within one zone at two scales. Of note, the relationships between CSP and BSTE conditions have changed over the three subperiods. For example, the mean farm size, the share of farms with 100 hectares and more and the use of powerful tractors became major factors correlating with the CSP within both the French mainland and three zones, while poultry density and the ratio of legal entities among the total farm holders became important factors influencing CSP within the French mainland and two of the three zones during the subsequent two subperiods. We conclude that the approaches developed here permit the representation of CSP at the large regional scale in both stationary and dynamic ways using time series land-cover data denoting specific agricultural cover types. The findings of this thesis contribute to improving the understanding of the process and pattern of human land management practices by agriculture affecting the terrestrial biosphere.
Key words: Crop sequence; Cropping system; Agricultural land-use change; Land-cover survey Teruti and Teruti -Lucas; Agricultural census; Spatio-temporal analysis

Résumé L'objectif principal de cette thèse est d'instruire l'organisation des séquences de culture, à l'échelle de l'ensemble de la France et sur un recul décennal, tant en terme de cinétiques localisées qu'en terme de dynamiques liées à des variables explicatives du milieu physique et socio-technico-économiques. Ce travail de «fouille de données »est appliquéàla France entière, en utilisant les bases de données publiques disponibles. Notre étude couvre la période 1992-2003 où s'implémenta la réforme de 1992 de la Politique Agricole Commune européenne et l'agenda 2000 en France. A partir d'une fouille de données sur l'ensemble des points Terruti disponibles en zone agricole sur cette période, 2549 séquences de culture de trois années furent identifiées. Ensuite, une première étude stationnaire sous forme d'une classification a permis de regrouper l'ensemble des 430 régions agricoles (RA) de France, en 21 groupes sur la base des occurrences moyennes de 12 années de ces successions de culture. Quatre successions de culture, 90 RA, parangons des 430 RA, et trois régions principales appartenant àces trois clusters regroupant les cultures de céréales, colza et cultures de protéagineux ont étédéfinis. Deux approches de cinétiques des successions ont étéréalisées : Une étude envisageant les successions de culture qui suivent les retournements de prairies permanentes. Une recherche des dynamiques d'évolution de successions de culture en lien avec des conditions externes. Cette recherche a étémenée en segmentant la période étudiée en trois sous-périodes : 1992- 1994, 1997-1999, 2001-2003. Nous avons montré qu'au niveau national, les zones de culture révèlent des plus grandes variabilités au cours du temps que les séquences liées aux fonctionnements d'élevage, cultures fourragères et pâtures semées. Les surfaces en séquences de cultures basées sur le maïs, en particulier en monoculture, s'étendent de plus en plus dans le sud-ouest et le nord-est sur toute la période, alors que les régions dominées par les séquences de culture pois/blédéclinées entre les deux dernières sous périodes dans tout le Nord de la France. Les analyses séparées pour les trois zones retenues montrent que les patrons de séquences de culture dans la zone spécialisée en betterave à sucre at/ou pois ou pomme de terre-blé/orge montrent une plus grande variabilité temporelle au cours des trois sous-périodes que les séquences de culture des deux zones spécialisées sur les séquences de culture colza/blé-orge et tournesol/blé. Les facteurs liés àla taille des exploitations, l'utilisation de tracteurs, et la surface irriguée, ainsi que le ratio des types d'associations dans les exploitations jouent un rôle important dans l'organisation des séquences de culture d'une zone à deux échelles. Les relations entre les séquences de culture et les conditions externes changent au cours des trois sous-périodes. Ainsi, la taille moyenne des exploitations la part des exploitations de plus de 100 hectares et l'usage des tracteurs les plus puissants deviennent des facteurs majeurs corrélés avec les patrons de séquences de culture à la fois à l'échelle de la France entière et des trois zones. A l'opposé, la densité d'élevage avicoles et le ratio d'Unité de travail humaine par exploitation deviennent des facteurs importants influençant les patrons de séquences de culture à l'échelle France entière et à celle de deux des trois zones seulement pendant les deux dernières sous-périodes. Nous proposons une utilisation ultérieure des méthodes mobilisées qui ont montré leur capacité à cartographier les grandes tendances d'évolution en France et à identifier les principales variables explicatives de ces évolutions. Les apports de cette thèse contribuent àaméliorer notre compréhension des processus qui organisent les séquences de culture en France et construisent par ces pratiques agricoles très dynamiques des impacts forts sur le territoire agricole français.
Mots-clés: Successions de cultures ; Système de culture; Changement d'usage du sol agricole ; Enquête de l'occupation du sol Teruti ; Recensement agricole ; Analyse spatio-temporelle