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Land use mosaics in Mediterranean rainfed agricultural areas as an indicator of collective crop successions: Insights from a land use time series study conducted in Cap Bon, Tunisia

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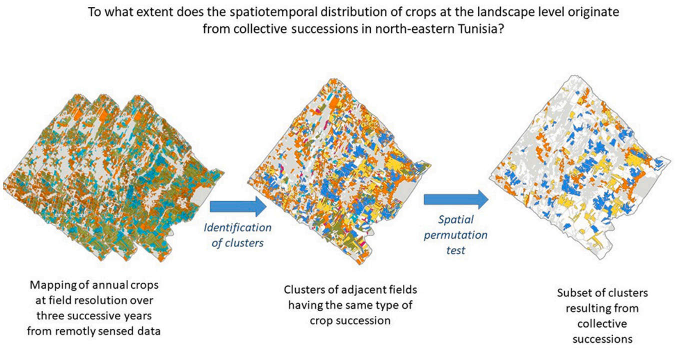
HIGHLIGHTS

- In North Africa, collective successions applied to groups of fields contribute to the homogenization of crop distribution at the landscape level.
- Remotely sensed land use time series allow the identification of clusters of adjacent fields with the same type of crop succession.
- It is possible to assess whether a cluster results from a collective succession using a spatial permutation test.
- The approach developed is a tool to help define land use scenarios that take into account collective successions for better farmers' acceptability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: In cultivated landscapes, land use patterns related to the diversity of crops, their spatial arrangement into patches and their succession over several years influence many biophysical processes and the production of ecosystem services and disservices. Understanding the determinants of these patterns is a prerequisite for the development of acceptable alternative land use patterns. Most studies deem crop distribution patterns at the landscape level to be the result of individual allocations of crop successions to fields designed at the farm level. However, in some parts of the world, there are collective crop successions that apply to groups of adjacent fields on different farms.

OBJECTIVE: The objective of this study was to examine the extent to which the spatiotemporal distribution of crops at the landscape scale relates to collective crop successions.

METHODS: The study was based on a Mediterranean rainfed agricultural landscape (67.7 km^2) located in northeastern Tunisia, in which collective successions respond to constraints related to agricultural land fragmentation. Combined with field mapping, remotely sensed land use time series were used to identify three-year crop sequences, classify them into crop succession types and identify clusters of adjacent fields with the same type of crop succession. We assumed that such a cluster was the result of a collective succession if the

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determinants of the individual crop succession locations did not explain its size (expressed in the number of fields). We related such determinants to the characteristics of the fields and their land-use environment and defined them statistically. Then, we developed a spatial permutation test to distinguish clusters resulting only from the determinants of the individual crop succession locations from those resulting from collective succession.
RESULTS AND CONCLUSIONS: The results show that the collective successions mainly comprised biennial successions (wheat sown alternately with legumes, spices or forage crops). These successions were synchronized between adjacent fields based on wheat cultivation; all fields in the same cluster had wheat in the same year. Collective successions were secondarily comprised of fodder-dominant successions. These collective successions involved approximately 40% of the fields and their total area in the study area. These fields belonged to different clusters ranging in size from two to 96 adjacent fields.
SIGNIFICANCE: The developed approach is a tool for mapping the likely presence of collective successions and considering this factor in the definition of sustainable land use scenarios at the landscape level for better soil and water management.

1. Introduction

In cultivated landscapes, land use patterns related to the diversity of land use types and their spatial arrangement into patches impact many biophysical processes, such as water, erosion, contaminants or gene fluxes (Joannon et al., 2006; Viaud et al., 2008; Wohlfahrt et al., 2010; Colin et al., 2012; Jiang et al., 2021). Land use patterns also impact biotic diversity (Joannon et al., 2008; Fahrig et al., 2011), which in turn impacts plant health, crop protection (Steinmann and Dobers, 2013; Scheiner and Martin, 2020) and, consequently, crop production. Characterizing land use patterns and their determinants is a prerequisite for the development and assessment of the impact of acceptable alternative land use scenarios and is a major challenge for landscape agronomy (Benoît et al., 2012; Rizzo et al., 2013). Landscape agronomy focuses more precisely on land use patches related to the distribution of crops and crop successions in the landscape, where a crop succession refers to the ordered sequence of crops in a given area. For example, a patch of interest may be a continuous area of adjacent fields with a given crop or combination of crops during a crop cycle. It may also be a continuous area of adjacent fields with a given crop succession or combination of crop successions, with each crop succession being described by a fixed or flexible crop sequence or combination of crop sequences recurring over time (Joannon et al., 2008; Thenail et al., 2009).

In the field of landscape agronomy, two main types of land use pattern approaches have been developed. The first type of approach assumes that crop distribution patterns at the landscape level result from farmers' decisions regarding the allocation of crops to fields (Joannon et al., 2008; Peltonen-Sainio et al., 2017; Thenail et al., 2009; Sorel et al., 2010). Studies, therefore, focus on characterizing the spatiotemporal allocations of crops to fields by farmers and their determinants. The objective is to understand how and why the crops chosen by farmers are distributed each year among the different agricultural fields of their farms and succeed each other over time within the same field. In these studies, farmers' crop allocation decisions are sometimes expressed as decision rules. These studies are mainly based on data acquired from farm surveys, expert opinions, literature reviews or a combination of all three. The knowledge gained may then be used to simulate the spatial distribution of crops or crop successions on a matrix of real or virtual fields. (Baudry et al., 2003; Joannon et al., 2008; Thenail et al., 2009; Castellazzi et al., 2010). The second type of approach aims to describe spatiotemporal patterns at the landscape level using a time series of crop location data obtained from a census or remote sensing. For example, using crop location data acquired by remote sensing and cross-referenced in a geographic information system, Martinez-Casasnovas et al. (2005) mapped homogeneous units with respect to the frequency of main crops over several successive crop cycles. Based on data mining involving spatial and temporal clustering methods, other studies have segmented the landscape into homogeneous units that exhibit similar combinations of land use successions (Lazrak et al., 2010; Mari et al., 2013; Xiao et al., 2014). The combination of these two types of approaches can lead to a better characterization and understanding of land use patterns. As shown by Schaller et al. (2012), in a study conducted on the landscape of the Niort Plain in France, the stochastic regularities of the landscape identified through data mining are partly explained by decision rules shared by a set of farmers concerning the allocation of crops to fields.

The technical, economic and social constraints and opportunities to which farmers are subjected shape the range of opportunities available for allocating crops to fields. The well-known driving factors behind crop selection and the allocation of land to different crops are as follows: (1) the environmental conditions and characteristics of the fields (e.g., precipitation and temperature, soil properties, slope, field size, land-use environment, distance from the farm's headquarters, and access to water resources); (2) the agronomic characteristics of the crops (e.g., return period), (3) the agro-economic characteristics of the farms (e.g., farm size, labour and equipment resources, and economic orientation) and farmers' global objectives; and (4) the socio-economic environment of the farm (e.g., market prices) (Ekasingh and Ngamsomsuke, 2009; Thenail et al., 2009; Sorel et al., 2010; Dury et al., 2013; Ren et al., 2016; Peltonen-Sainio et al., 2018).

In the studies mentioned above, the spatiotemporal allocation of crops to fields is implicitly considered as designed at the farm level and considers the preferences of the farmer while taking into account a range of opportunities and constraints. Farmers' individual decisions regarding the allocation of crops to fields may lead to groups of adjacent fields with the same type of crop succession, depending on the spatial distribution of crop succession allocation factors over the field mosaic and the specialization of crop successions to their allocation factors (Thenail et al., 2009).

However, groups of adjacent fields with the same type of crop succession may also result from collective crop succession. In this paper, we define a collective crop succession as a crop succession designed and managed at the level of a set of fields distributed among several farms as opposed to an individual crop succession designed and managed at the level of a farm. To our knowledge, the issue of collective crop succession and the resulting spatial patterns have been less studied, apart from studies conducted in the fields of agrarian geography and landscape history. In these fields of study, the collective crop successions that were characteristic of the old European open field system of agriculture have been extensively described (Caput, 1956; Meynier, 1958; Watteaux, 2005; Calvo-Iglesias et al., 2009; Renes, 2010; Leturcq, 2014). Open field systems of agriculture were used in Europe over several centuries. Schematically, such systems had the following main characteristics. Arable land was extremely fragmented, and the fields were unfenced. The agrosystem was based on (i) mixed crop and livestock farming, including grain-growing, (ii) the implementation of crop successions characterized by two- or three-year cycle periods (repetition of a biennial or triennial sequence), and (iii) the free grazing of crop residues and fallow land. Crop successions were mainly collective for free grazing and were managed at the landscape scale as follows. The cultivated landscape was divided into blocks of small unfenced agricultural fields that were distributed among the cultivators. Crops were distributed over different arable areas, each of which was composed of one or more blocks of fields. Crop successions were carried out among these areas. Therefore, adjacent fields belonging to the same block had the same biennial or triennial crop sequence, and these sequences were synchronized between fields. The management of the open-field system was regulated by community-based social structures that determined the scheduling of agricultural activities in each of the crop blocks (dates of sowing, harvesting, grazing of crop residues, etc.)

Numerous studies focusing on the Middle East and North Africa also attest to the existence of collective crop successions in the context of open field systems of agriculture in peasant societies in past centuries (de Planhol, 1956; Meynier, 1958; Fay, 1979; Kark and Grossman, 2003; Lazarev, 2005; Renes, 2010; Lazarev, 2014). In North Africa, the presence of open-field systems of agriculture was still recorded in the middle of the twentieth century in some regions of Morocco, Algeria and Tunisia (Renes, 2010). An example of an open-field system, comparable in outline to the European open-field system described above, was described in the Rif Mountains of Morocco during the second half of the 20th century (Fay, 1979, Lazarev, 2005 et 2014). The description mentions the fragmentation of arable land into many small individual unfenced fields, biennial or triennial crop successions organized around blocks of adjacent fields to allow free grazing of crop residues and fallow land by farmers' herds, and village assemblies to design and regulate the management of the system. This system was then considered to be rapidly deteriorating or even disappearing. Various factors explaining this evolution were identified, including population growth, the collapse of communitarian social structures, the expansion of arable land, the disappearance of free grazing areas, the modernization of agriculture and the intensification of cropping and livestock systems.

Despite these predictions, collective crop successions applied to groups of adjacent fields on different farms still exist today in some regions of North Africa. In Morocco, the presence of collective crop successions in the aforementioned Rif region is still documented today (Sabir et al., 2019). In northeastern Tunisia, in the Cap Bon Peninsula, collective crop successions have recently been observed in the context of an open field landscape with highly fragmented agricultural land (Mekki et al., 2018a). However, in both cases, individual and collective crop successions coexist, and their respective impacts on crop distribution patterns at the landscape scale are not known. This lack of knowledge limits the definition of crop distribution scenarios in the landscape that respond to the production and environmental challenges facing these regions (soil erosion, limited water resources, low yields, etc.) while being acceptable to farmers.

Therefore, the objective of this study was to examine to what extent the spatiotemporal distribution of crops reveals the existence of collective crop successions in a Mediterranean rainfed agricultural landscape. We sought to answer the following question: “Do clusters of adjacent fields with the same type of crop successions originate from collective succession?” The case study was an agricultural watershed located in the Cap Bon peninsula in northeastern Tunisia. We characterized the spatiotemporal distribution of crops from land use time series collected by remote sensing at the agricultural field scale. We observed this distribution through the sizes of clusters of adjacent fields with the same type of crop succession. We assessed whether a cluster was the result of a collective succession by using a spatial permutation test that takes into account factors related to field characteristics that explain the allocation of an individual crop succession to a field. The results were then discussed in light of our knowledge of farmers' practices from the literature and from informal interviews conducted during our fieldwork.

2. Materials and methods

2.1. Study area

The study area (67.7 km^2) belongs to the Lebna watershed (210 km^2; 36°43′N–36°53′N, 10°40′E–10°58′E) located in the Nabeul Governorate in northeastern Tunisia (Fig. 1). The Lebna watershed extends from 0 to 637 m in altitude on the southeastern slope of the Abderrahman jebel. The climate regime is at the boundary between subhumid and semiarid conditions (IAO, 2002). The study area is located in the most cultivated part of the watershed and corresponds to altitudes below 200 m. The northern and western parts of the study area are located in a hilly area with altitudes ranging from 80 m a.s.l. to 200 m a.s.l. and include a large network of wadis (i.e., intermittent rivers). The southern and eastern parts belong to a plain area (0 m to 80 m altitude). A sebkha, i.e., a floodable depression in which evaporite-salt minerals accumulate borders the southeastern section of the study area.

This area is characterized by soil with highly contrasted water holding capacity depending on soil texture and depth. The soil distribution presents a complex soil pattern in relation to the geology of the watershed, which shows alternating sandstones and marls in the landscape (IAO, 2002; Ciampalini et al., 2012; Gomez et al., 2012). As demonstrated by Lagacherie et al. (2013), there is a relationship between the soil surface texture and the subsurface soil properties. The soils developed on sandstone outcrops at the top of the hillslopes are shallow, with a sandy texture (Regosols) and very low soil water holding capacity. Following the hillslopes, the soils are developed over the marls, and the soil depths vary with the slope, with a maximum on the alluvial plain in the bottom part of the area. The textures are generally more than 40% clay (Clayic, Calcic Cambisols or Vertisols), and the soil water holding capacity is not restrictive for classic rainfed crops.

Arable land (annual and perennial crops) accounts for 75% of the study area (Table 1), while natural and seminatural areas account for one-fifth. Within these areas, seminatural vegetation mainly covers the steepest slopes of the hillsides and the edges of the wadis. Urban areas (villages and scattered settlements) and roads or tracks cover the rest of the area (4%).

As described in Mekki et al. (2018a), agricultural systems are mainly based on rainfed mixed farming and livestock. Annual crop areas cover 67% of the study area. As in other rainfed agricultural systems in North Africa (Latiri et al., 2010), cereal production (mainly wheat) is a key activity of the Lebna agricultural system. However, Lebna's climate increases the diversity of crops, and thus, annual crops also include fodder crops (mainly barley, oats and triticale), food legumes (mainly fava beans and chickpeas) and spices (mainly coriander). Perennial crops (mainly olive trees) cover 8% of the total area of the study area. Wheat is mainly rotated with legumes or spices to capture the benefits of nitrogen fixation (in the case of legumes) and/or to control pests or weeds. However, forage crops may sometimes replace legume or spice crops in biennial succession. Livestock husbandry includes cattle, sheep and goat breeding. Livestock feeding relies on forage production, the grazing of natural vegetation and crop residues, and the use of external feed supplements.

A multitude of cultivation areas of various sizes and shapes, separated from each other by other land use classes, characterizes the cultivated landscape. These cultivation areas are larger in size in the plain than in the hilly zone (Fig. 1). A cultivation area corresponds to a mosaic of very small fields (0.5 ha on average) that often belong to different farmers due to farmland fragmentation. Most fields are unfenced and are not adjacent to roads or tracks. Due to the small farm sizes (most are less than 10 ha), most farmers have little equipment and outsource mechanized operations to agricultural contractors. Mechanized operations mainly involve soil preparation for all crops, the sowing of wheat and the harvesting of fodder and wheat.

Farmland fragmentation influences the allocation of crops to fields by farmers (Mekki et al., 2018a). When farmers' fields are dispersed because of farmland fragmentation, farmers implement, together with some of their neighbours, collective successions of crops that permit the management of the following common constraints: a lack of roads or tracks for accessing fields, the grazing of crop residues after harvesting by farmers' herds, and limited access to agricultural contractors. The absence of roads available to access fields in the middle of other fields

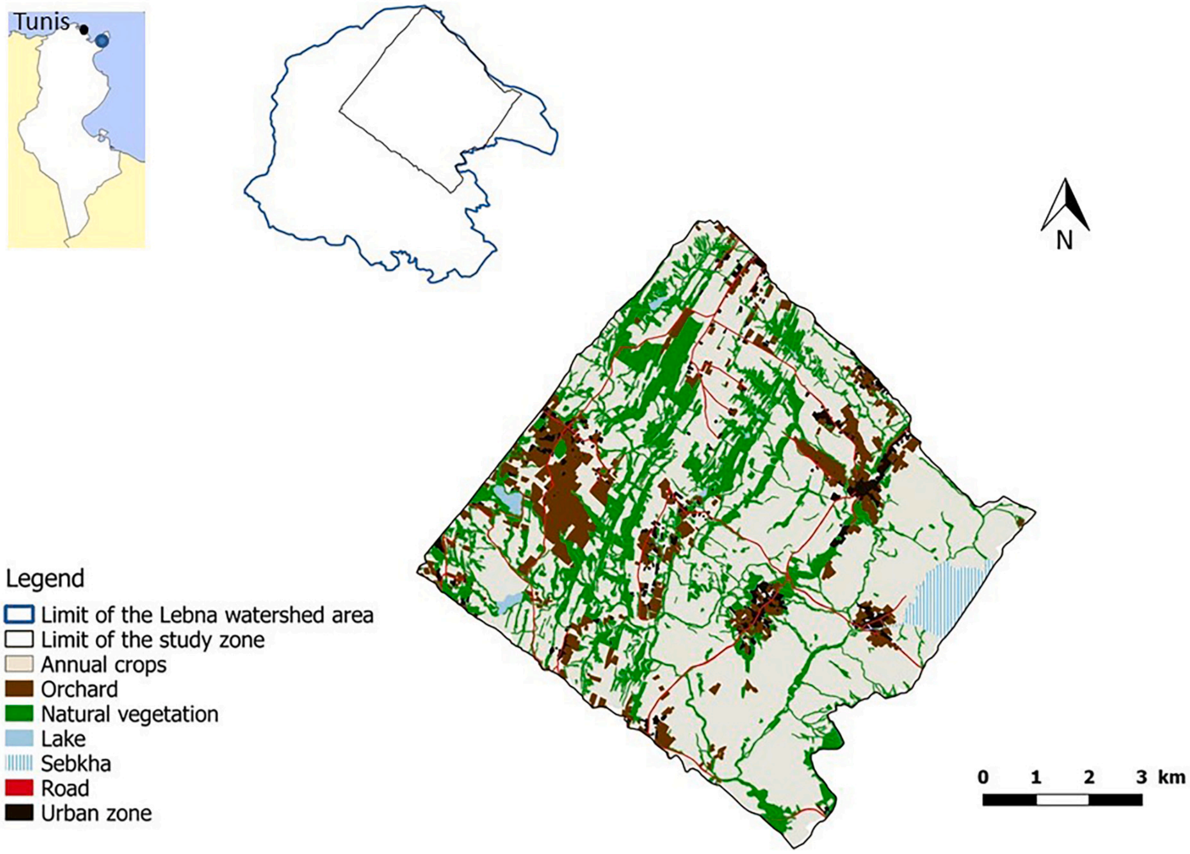

Fig. 1. Location of the study area and the distribution of land use classes within the area. The land use classes were manually classified and digitized at a fine spatial resolution from a Spot image dated 03/21/2016 and a Google Earth image dated 05/24/2016. The map includes features with dimensions over 10–15 m. Narrow secondary roads or tracks, paths and narrow strips of natural vegetation are not considered.

Table 1
Cover of land use classes in the study area. Percentages are relative to the total area of the study zone.

Land use type	Land use class	Cover (%)
Natural and seminatural areas	Sebkha, artificial lakes, wadis	3
	Forests, shrubs, herbaceous pastures, outcrops of sandstone	18
Sealed manmade areas	Roads, tracks, urban areas	4
Rainfed mixed farming	Annual crops	67
	Orchards	8

makes it impossible to use a tractor for mechanized operations if the adjacent fields are already sown or are not yet harvested. As shown in Fig. 2, from early February to mid-July, the green grazing of barley or the grazing of crop residues after harvesting a field is only allowed for the herd of the farmer who cultivates the field. When the herd is large or insufficiently controlled, crop damage may occur in adjacent fields that are not yet harvested. After the harvesting of all crops, a field is open to free grazing by all herds. Finally, it is not always easy to secure timely access to agricultural contractors when fields are small and scattered because some agricultural contractors are more willing to work in grouped fields to limit their movements from one field to another. The grouping of fields managed in the same manner makes it possible to address these constraints. The landscape subsequently depicts groups of adjacent fields with the same type of crops or the same succession of crop types.

The spatiotemporal distribution of crops in the landscape is a major concern in the study area to obtain better soil and water management in the context of global change. The Lebna watershed is subject to soil erosion and subsequent reservoir siltation (IAO, 2002; Gaubi et al., 2016). In some parts of the area, the diffuse erosion rate, which results from agricultural practices that determine the presence of vegetation cover during the rainy season, is four times higher than the concentrated erosion rate (Ben Slimane et al., 2013, 2016). Regarding water management, there is a need to ensure that both the needs for water for rainfed crops within the area and for the storage of water for irrigated agriculture developed downstream of the Lebna watershed are met. Mekki et al. (2018b) have shown that evapotranspiration is the predominant factor influencing soil moisture dynamics in this area and that evapotranspiration differs significantly depending on the crops, cropping practices, soil properties and climatic conditions. Consequently, they assumed that it is possible to control the amount of green water and, in part, runoff and downstream water yield by adopting appropriate agricultural practices, including the spatiotemporal distribution of crops.

2.2. *Overview of the methodological strategy*

To evaluate any possible impact of farmers' collective successions on the distribution of crop successions within the landscape, we assessed the statistical significance of the sizes of clusters of adjacent fields with the same type or subtype of crop succession. A cluster included at least two adjacent fields. We defined a field as an agricultural plot managed by a single farmer with a single annual crop. We assumed that in the study area, any three-year crop sequence was an indicator of a type or subtype of crop succession. Expert classification rules were used to define different types and subtypes of crop succession based on the crop sequences corresponding to the 2015–2016, 2016–2017 and 2017–2018 cropping cycles.

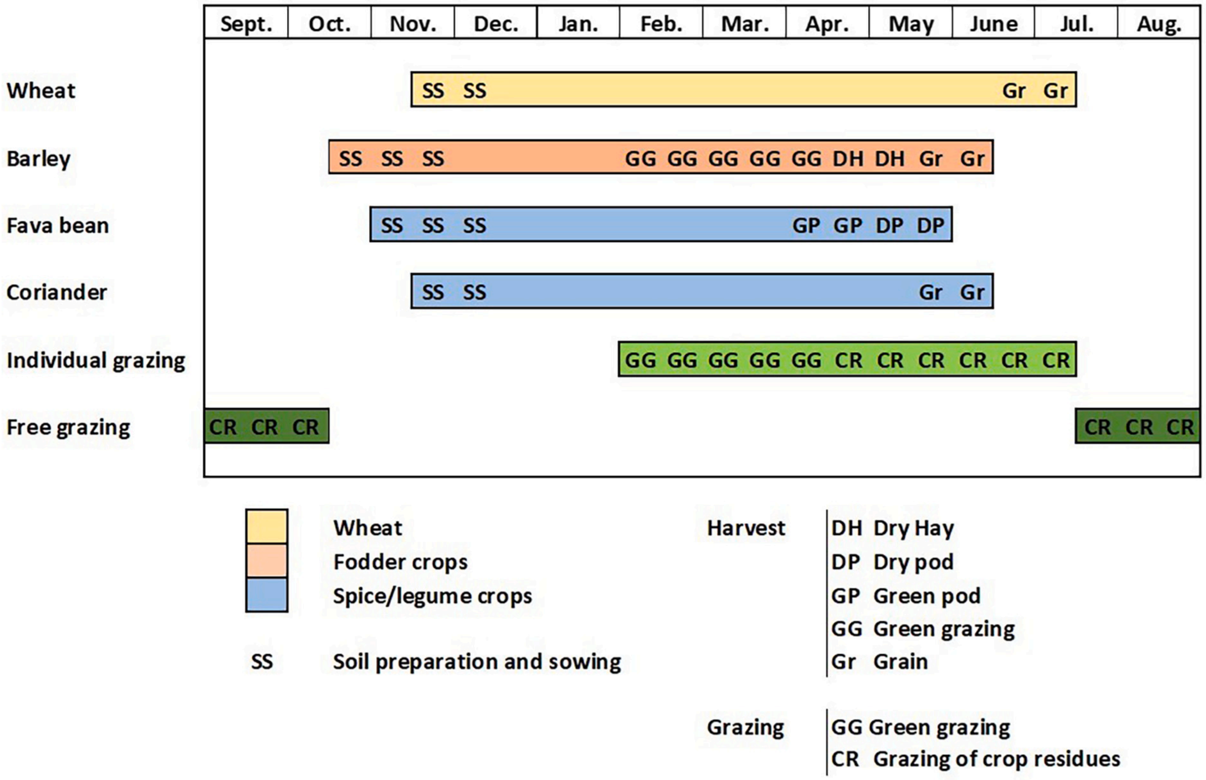

Fig. 2. Timeline of the main activities.

The methodological strategy included the following two steps: (i) the identification of clusters of fields and (ii) the evaluation of the statistical significance of the number of fields in each cluster based on a spatial permutation test. To develop and implement the test, we considered the number of fields in a cluster to be an indicator of collective crop succession when this number was significantly higher than it would have been in the case of a crop succession distribution based on the determinants of the location of individual crop successions.

The required georeferenced data were acquired by using existing data and classifying Spot® images (Fig. 3). The data were collected from the following three nested support units: an agricultural field, a cluster and a cultivation area, as shown in Fig. 4. A cultivation area corresponds

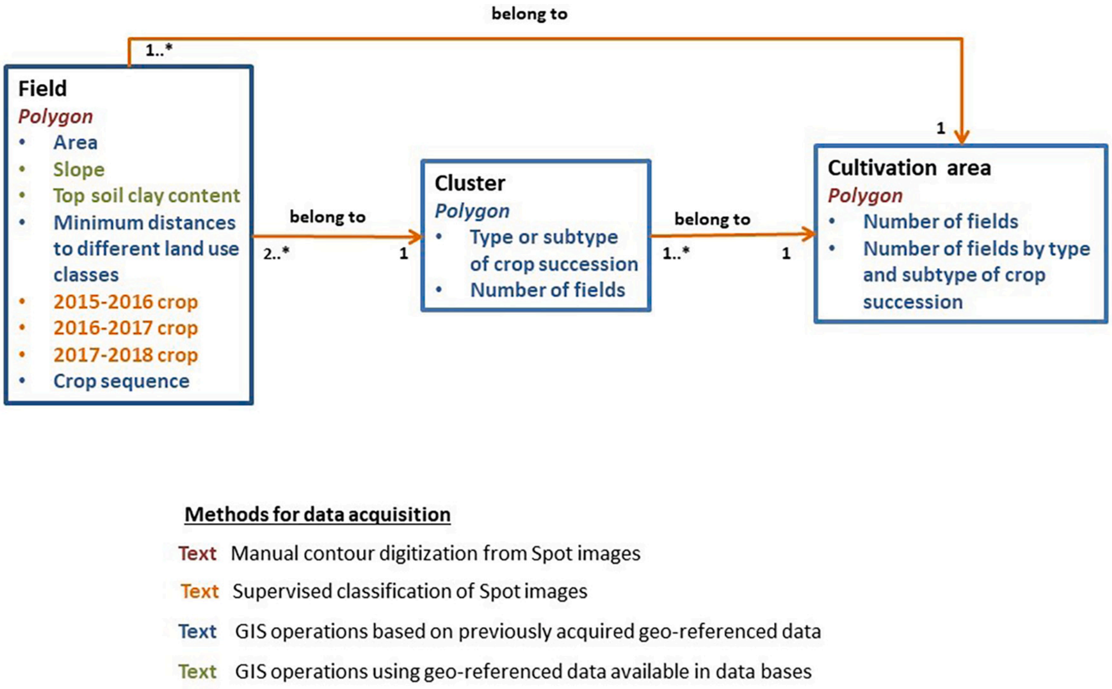

Fig. 3. Support units, acquired data and methods for their acquisition. The database is described here with a unified modelling language (UML) class diagram.

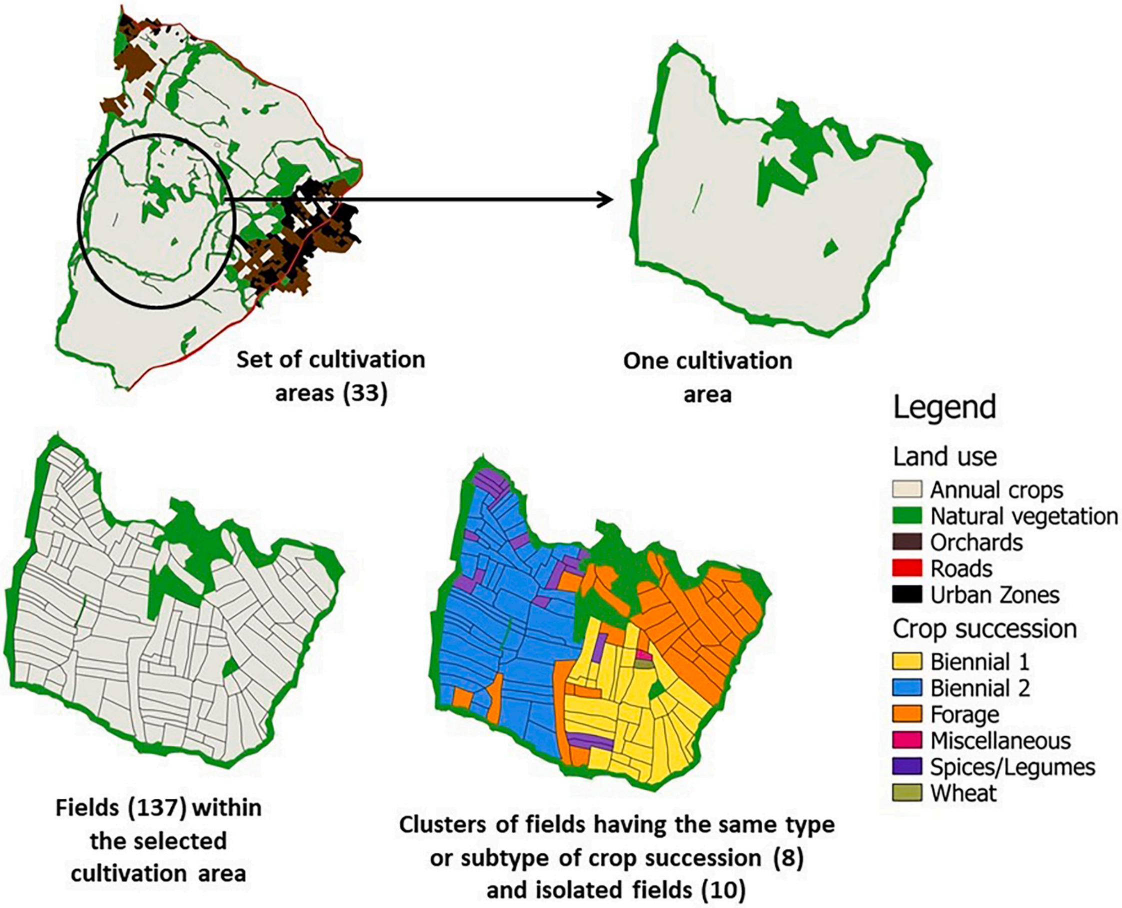

Fig. 4. Spatial structure used in the study.

to a continuous area of annual crops separated from any other cultivation area by the presence of other land use classes. It usually includes several fields, each of which may belong to a cluster of fields with the same type or subtype of crop succession.

2.3. *Geo-database*

2.3.1. *Data collected at the crop field and cultivation area levels*

As shown in Fig. 3, the data acquired at the field level were (1) a polygon representing the field, (2) the cultivation area to which it belonged, (3) the area of the polygon, (4) the average slope, (4) the average soil surface clay content, (5) the minimum distances to each land use class, (5) the dominant crop type for each of the three years of our study, and (6) the resulting crop sequence.

Databases providing access to field boundaries do not exist in many countries, including in North Africa. Methods for automatically detecting field boundaries from satellite images are still under development (e.g., Persello et al., 2019; Watkins and Van Niekerk, 2019). Therefore, we opted for manual digitization based on high-resolution satellite images. Field contours were manually digitized in Quantum GIS from Spot® panchromatic images (1.5 m resolution) dated 21/03/2016 and 16/04/2016. We did not consider a possible change in the contours by regrouping or dividing the fields from one year to the next, except in the case of the fields characterized by a large area in 2016 (1% of the fields). For these larger fields, the predictions of the crops sown in 2016, 2017 and 2018 (see below) clearly indicated subdivisions created between 2016 and 2017 or between 2017 and 2018. The polygons included in the database for these fields were those corresponding to subplots with the same crop sequence (150 subplots in total). A total of 9150 polygons were digitized. The field sizes ranged from 0.02 ha to 13 ha. The average field size was 0.5 ha, while the median was 0.32 ha.

The average slopes were calculated from the Spot® 2015 digital elevation model (20 m resolution). The soil surface clay contents (30 m resolution) were taken from a map by Ciampalini et al. (2012). This map was obtained by using a cokriging procedure based on surface clay content estimates for bare soil surfaces derived from a Vis-NIR hyperspectral image (Gomez et al., 2012). The minimum distances to each land use class were obtained from the map of land use classes presented in Fig. 1. For each land use class and field, the minimum distance calculated is the minimum distance between the edge of the field and the edge of the areas of that land use class.

Data on the crops present in the fields were obtained by the supervised classification of Spot® image series. For each annual cycle, the classification was carried out in four successive steps. As the first step, a georeferenced database of the crops present in a sample of fields during the growing season was built through field observations. Depending on the cycle considered, this database covered 1300 to 1500 fields and 1000 to 1200 ha. The observed fields were distributed among the three existing types of crops (wheat, forage crops, and spices and legume food crops) and among the hilly area and the plain. In the second step, a model for predicting crop types from the spectral data of multispectral images was constructed at pixel resolution (6 m resolution). This model was constructed by applying a random forest algorithm (Pelletier et al., 2016) to crop data from a sample of calibration fields and to spectral data from those fields. The spectral data were derived from a time series of multispectral Spot® images. The calibration sample consisted of a subset of the observed fields (one-quarter to one-fifth of the fields). Depending on the year, three to six images taken from between the end of February to mid-June were used. In the third step, the model was applied over the entire study area to predict the crop types present at pixel resolution. The most frequently predicted crop type based on the pixel population within the polygon representing a field was then assigned to the field. In the final step, we assessed the rate of well-predicted fields using a sample of validation fields consisting of the observed fields not selected for calibration. The average prediction rate was 82%. Wheat had the best average prediction rate (84%), and spices/crop legumes had the worst prediction rate (80%).

The polygons for the 440 cultivation areas in the study area were extracted from the land use class map shown in Fig. 1. The observed number of fields in a cultivation area ranged from 1 to 849 plots. The average was 21 fields.

2.3.2. *Crop sequence classification and identification of clusters of fields*

The three-year crop sequences resulting from crop prediction were classified into five types (biennial, forage crop, wheat, spice/legume and miscellaneous) and two subtypes (biennial 1 and biennial 2) of crop succession according to expert classification rules (Fig. 5). First, sequences characterized by the alternation of a wheat crop and spice/legume or forage crop were classified as biennial successions. Second, we distinguished two subtypes of biennial successions according to the position of wheat within the sequence. In doing so, we assumed that wheat was the pivot crop in a biennial crop succession and that farmers relied on this crop to synchronize their biennial successions in adjacent fields. Sequences with wheat grown in years 1 and 3 were classified as biennial 1. Sequences with wheat grown in year 2 were classified as biennial 2. Third, sequences that were not classified as biennial successions were classified as forage crop successions, wheat successions or spice/legume successions depending on the dominant crop type in the sequence. Finally, the remaining sequences were classified as miscellaneous successions.

Clusters of adjacent fields with the same succession type or subtype were identified on the basis of this classification.

2.4. *Assessment of the statistical significance of cluster sizes*

2.4.1. *Identifying the determinants of the locations of individual crop successions*

We assumed that field characteristics drive the locations of individual crop successions. The statistical identification of such location determinants was conducted based on a tree classification algorithm (CART) (Breiman et al., 1984). The CART algorithm relies on a recursive partitioning process of the multidimensional space defined by a set of explanatory variables for hypercube areas that are as homogeneous as possible regarding the variable being explained. In our case, the qualitative variable to be explained was the type of succession allocated to a field. Since we recognized that the position of wheat in a biennial succession is not related to the field characteristics, we did not consider differentiating the biennial type into two subtypes. The explanatory variables tested were (1) the physical characteristics of the field (area, slope and soil surface clay content) and (2) the environment of the field (minimum distances to each land use class).

A classification tree is characterized by several splits whose nodes depend on homogeneity measures (the Gini index in our case) and determines a set of logical if-then conditions linking the variable to be explained to the explanatory variables. The classification process starts at the root node, which encompasses the entire dataset (all the fields in the study area in our case), and ends at the terminal nodes (also called “leaves”). Each leaf is assigned the majority class and a probability vector for each class of the variable to be explained.

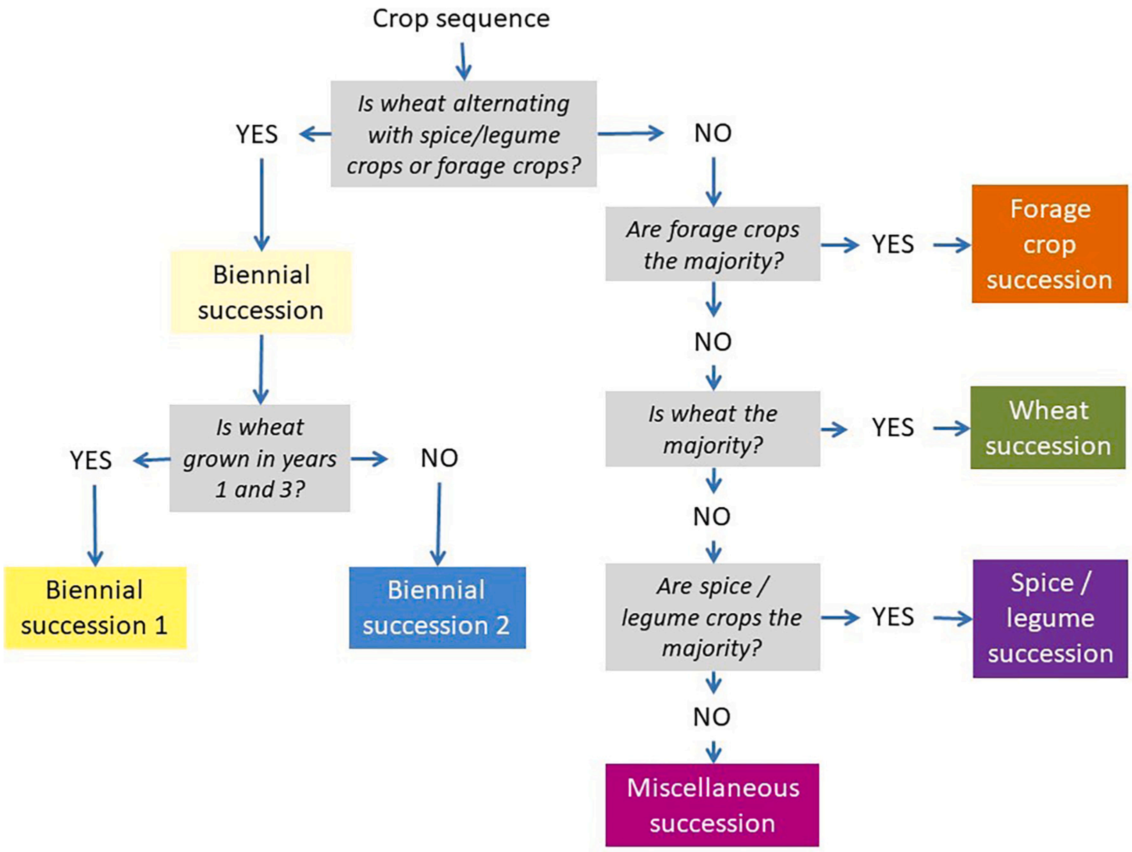

Fig. 5. Rules for the classification of crop sequences into crop succession types. The rule “at least two years out of three with a given crop” defines the majority presence of this crop in the observed sequence.

2.4.2. *Testing the statistical significance of the sizes of clusters of succession types*

The statistical significance of the observed succession cluster sizes was determined using a self-developed testing methodology with a null hypothesis that incorporates the spatial randomness of the succession types and subtypes at the field level. Our methodology was based on the spatial randomness conditional simulation method from Besag (1974). Its purpose was to apply random simulations on an irregular lattice of fields instead of a regular grid and to perform them by spatial permutations with respect to the observed conditional empirical distribution of succession types and subtypes. The test indicates whether a given size of a cluster of fields is the result of a hazard based on previously defined determinants for the allocation of succession types to fields. Under the null hypothesis, clusters of significant size are then those with a probability of less than 0.05 of being only the result of the determinants of the location of individual crop succession types.

This test is based on the following four steps for each cultivation area: i) Multiple random simulations of succession types in fields are first performed using Bayes' conditional probability (Bayes, 1764) for a given succession type in a field resulting from the global proportion of this type at the cultivation area scale based on the characteristics of the field (i.e., the leaf that the field belongs to in the previous classification tree) and, consequently, the probability of the succession type in the field; ii) for a field with a previously simulated biennial type in i), one of the two biennial subtypes is randomly assigned with a probability corresponding to its overall observed proportion in biennial fields; iii) for each succession type or subtype, an empirical cumulative distribution function (*e.c.d.f*) of the cluster size is computed from the distribution resulting from multiple random simulations; and iv) the probability of the observed cluster size is computed from the *e.c.d.f*. It should be noted that the *e.c.d.f* can be viewed as a cumulative histogram and is used here as an analogue of the repartition function of a random variable from which a probability can be derived. Fig. 6 shows an example of random simulations and the resulting probability of one of the observed cluster sizes occurring in a small cultivation area. To make the figure simpler and more meaningful, simulations were carried out without taking into account the division of the biennial type into two subtypes.

2.5. *Software applications used*

The constitution of the database and the data processing were carried out with R software. The *random forest* library (Liaw and Wiener, 2002) was used for the classification of Spot® images. The *raster* (Hijmans, 2017), *sp* (Pebesma and Bivand, 2005; Bivand et al., 2013) and *maptools* (Bivand and Lewin-Koh, 2018) libraries were used for spatial data extraction. Tests of the statistical significance of cluster sizes were performed by successively using the *sp*, *spdep* (Bivand and Piras, 2015) and *maptools* libraries for spatial vector data (polygons) processing and the *igraph* library (Csardi and Nepusz, 2006) for cluster identification and characterization from spatial vector data. Cluster identification results from the contiguous field list were obtained with the *spdep* library using the “queen” rule of contiguity (a single shared boundary point meets the contiguity condition for fields) and a null snap distance.

3. Results

3.1. *Diversity of crop succession types*

Twenty-seven crop sequences representing all possible combinations of the three types of crops over the three years were observed and classified into five types of succession (Table 2). The results show that the forage-dominant type and the biennial type were dominant. The forage-dominant type was present in 43% of the fields, representing 33.6% of the total area with annual crops. Fifty-nine percent of the fields (2351 out of 3969 fields) of this type were characterized by forage monoculture, while forage was grown in the remaining fields in two out of the three years. Biennial subtypes 1 and 2 were present in 36% of the fields (42.2% of the area). In 62% of these cases (2049 fields out of

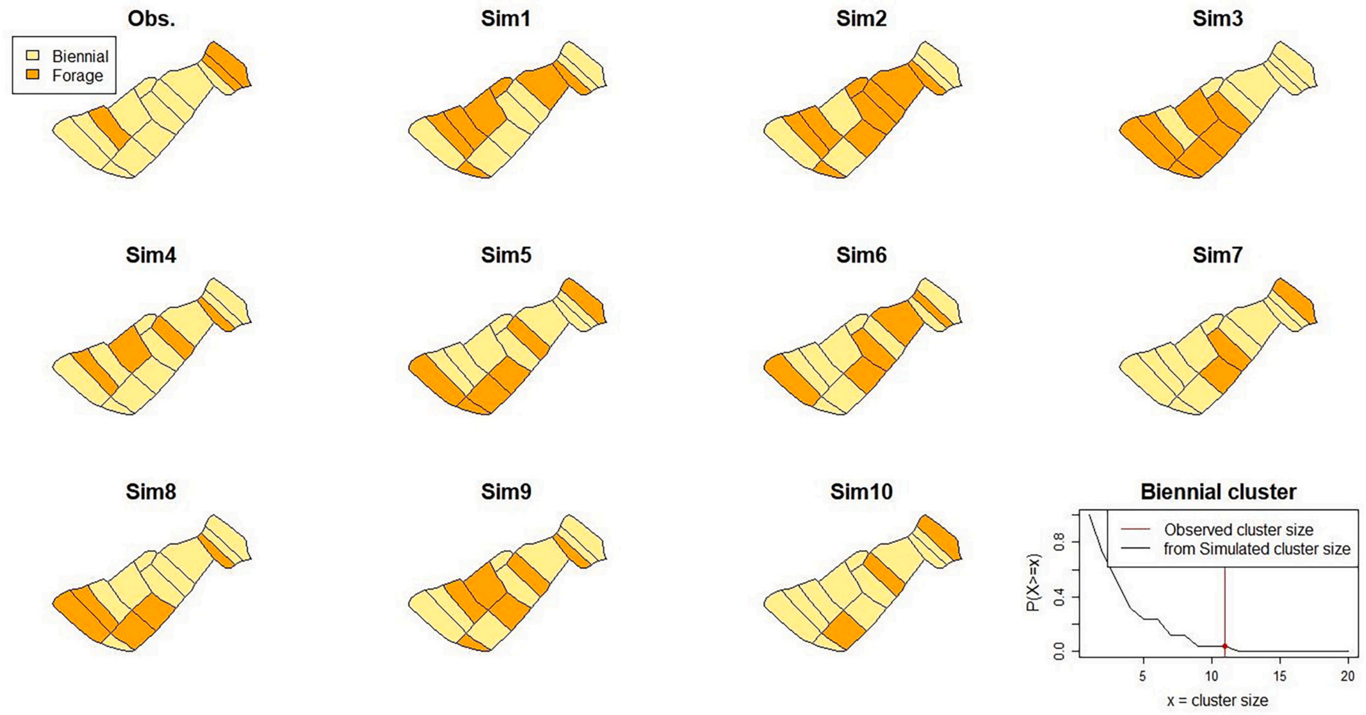

Fig. 6. Comparison of observed and randomly simulated succession types for a cultivation area containing 14 fields. The observed cluster of biennial successions, called the “biennial cluster”, contains 11 fields. After 10 simulations, the probability of obtaining a biennial cluster containing at least 11 fields from simulation is 0.1 (a biennial cluster of size 11 is simulated in Sim 7). Obs.: Observed clusters, Sim1 to Sim10: Simulated clusters for each of the 10 simulations, Biennial cluster: Probability of obtaining a biennial cluster size ≥ x.

Table 2
Distribution of the 27 observed sequences among succession types and subtypes. The crop types within the sequences are wheat (W), spice or legume (S/L), and forage (F).

Observed sequence	Number of fields per sequence	Succession type or sub- type	Number of fields per succession type or subtype	% of the total number of fields	Total area per succession type or subtype (ha)	% of the total area
W-S/L-W	997					
W-F-W	394	Biennial 1	1391	15.2	904.3	20.0
S/L-W-S/L	1052					
F-W-S/L	184					
S/L-W-F	335					
F-W-F	320	Biennial 2	1891	20.7	1000.5	22.2
F-F-F	2351					
F-F-W	208					
F- F- S/L	350					
W-F-F	327					
S/L-F-F	385					
F-S/L-F	348	Forage crop	3969	43.4	1513.5	33.6
W-W-W	87					
W-W-F	89					
W-W-S/L	117					
F-W-W	54					
S/L-W-W	145	Wheat	492	5.4	475.8	10.6
S/L-S/L-S/L	154					
S/L-S/L-F	111					
S/L-S/L-W	78					
F-S/L-S/L	134					
W-S/L-S/L	57					
S/L-F-S/L	339	Spice/legume	873	9.5	324.8	7.2
F-S/L-W	200					
W-F-S/L	90					
S/L-F-W	174					
W-S/L-F	70	Miscellaneous	534	5.8	289.5	6.4

3282), the observed sequence was an archetypal sequence (alternation of a wheat crop and a spice or legume crop). The remaining three succession types accounted for a total of 20.7% of the fields (24.2% of the area). Spice/legume-dominant successions were present in 10% of the fields. Wheat-dominant and miscellaneous successions were found in equivalent proportions (5% to 6% of the fields).

3.2. *Observed distribution of cluster sizes*

As shown in Table 3, 80.7% of the 9150 fields in the study zone belonged to clusters of fields with the same type or subtype of crop succession. The other fields, called isolated fields, were not adjacent to fields having the same type of succession. The total number of clusters was 1249, 31% and 41.7% of which belonged to biennial sequences and forage successions, respectively. The other three types of successions represented 27.3% of the total number of clusters. A total of 90% of all clusters had a maximum of ten adjacent fields, and only 10% included more than 10 fields. However, the former accounted for only 41.8% of the total number of fields in the study area, while the latter accounted for 38.8%. The largest clusters were biennial or forage succession clusters. The maximum number of fields in a cluster was 87 for biennial succession clusters and 96 for forage succession clusters. The maximum numbers of fields in a cluster were only 11, 23 and 5 for the spice/legume, wheat and miscellaneous successions, respectively. The largest clusters in terms of the number of fields are among the clusters with the largest areas, except for the clusters with miscellaneous successions.

3.3. *Determinants of individual crop succession locations*

The classification tree (Fig. 7) clearly shows that the probability of a crop succession type being found in a field was related to the land-use environment (minimum distance to urban areas) and the soil properties (soil surface clay content) of the field. These two variables explained 53% of the observed variability in crop successions. Slope did not appear to be a significant variable in explaining the distribution of crop successions. The tree is interpreted as follows. When the minimum distance to urban areas was less than 267 m, forage crop successions were the most likely observed ($p = 0.6$). When the minimum distance was greater than 267 m, the choice of crop succession depended on the soil surface clay content. The most likely successions belonged to the forage type for

Table 3
Distribution of clusters and fields by succession type and cluster size. Cluster size is expressed as the number of fields. Bien1: Biennial 1, Bien2: Biennial 2. The two numbers shown in square brackets indicate the cluster size class; the first number is the minimum number of adjacent fields, while the second is the maximum number.

Type of succession	Number of fields	% of isolated fields	% of fields belonging to clusters	Number of clusters	% of total number of clusters	% of clusters by cluster size class		% of fields by cluster size class		Characteristics of the largest cluster			
										By the number of fields		By area	
						[2,10]	[11,100]	[2,10]	[11,100]	Number of fields	Area (ha)	Number of fields	Area (ha)
Bien1	1391	12.7	87.3	172	13.8	87.2	12.8	38.2	49.1	84	39.7	79	65.8
Bien2	1891	12.1	87.9	215	17.2	85.6	14.4	35.5	52.4	87	37.4	84	40.5
Forage	3969	12.2	87.8	521	41.7	87.3	12.7	42.6	45.3	96	25.0	70	35.9
Wheat	492	35.6	64.4	84	6.7	95.2	4.8	52.4	12.0	23	37.2	23	37.2
Spic/Leg	873	45.7	54.3	162	13.0	98.8	1.2	51.8	2.5	11	7.6	11	7.6
Miscell	534	57.5	42.5	95	7.6	100.0	0.0	42.5	0.0	5	1.1	2	6.8
All types	9150	19.3	80.7	1249	100.0	90.0	10.0	41.8	38.8	96	25.0	79	65.8

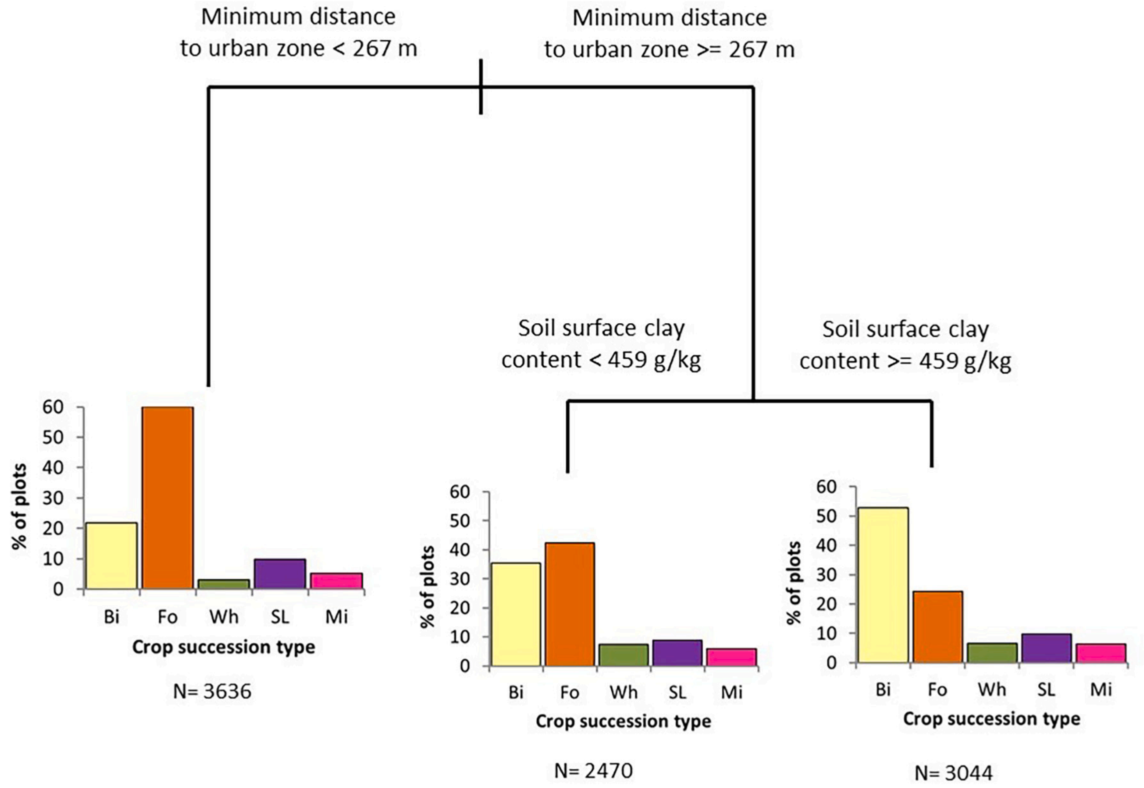

Fig. 7. Presentation of the selected classification tree. The tree links the values of two explanatory variables to a probability distribution of the succession types. Bi: Biennial succession, Fo: Forage succession, Wh: Wheat succession, SL: Spices/legumes succession, Mi: Miscellaneous succession, N: Total number of fields in the leaf.

a soil surface clay content below 459 g/kg ($p = 0.42$) and to the biennial type above that value ($p = 0.53$). In all the leaves, the probability of each of the three minority succession types (spices/legumes, wheat and miscellaneous sequences) was less than or equal to 0.1.

The tree results were driven by the importance of biennial and forage successions in the study area. Consequently, the tree did not appear to be relevant to explaining the locations of successions other than biennial and forage types, and we focused the analysis of the statistical significance of cluster sizes on biennial and forage succession clusters.

3.4. *Statistical significance levels of biennial and forage succession cluster sizes*

Among the 908 biennial and forage succession clusters, only 204 were significant, i.e., 22.5% (Table 4). These significant clusters represented 3505 fields, i.e., 48.3% of the fields with biennial or forage successions and 38.3% of the total number of annual crop fields in the study area. These fields covered 1588 ha, i.e., 46.5% of the total area with biennial or forage successions and 35.2% of the total area with annual crops in the study area. As shown in Table 4, the significant clusters were very unevenly distributed between biennial and forage successions. Biennial and forage successions represented 68.1% and 31.9% of the significant clusters, 62.7% and 37.3% of the fields in those clusters, and 73.4% and 26.6% of the total area in those clusters, respectively.

Clusters of biennial or forage successions could be significant with two fields (Fig. 8), but significant clusters clearly tended to be larger than nonsignificant clusters. Clusters of biennial 1 or biennial 2 successions were always significant above six and eight fields, respectively. Above these thresholds, the probability of clusters of adjacent fields carrying the same synchronized succession without being the result of a collective succession was therefore very low. These clusters of more than six and eight fields represented a total of 90 clusters, i.e., 64.7% of the significant biennial succession clusters, and 1917 fields, i.e., 89.7% of the significant biennial cluster fields. Whether the smaller clusters were significant depended on the respective local distributions of the different successions and field characteristics. In the case of forage succession clusters, the size threshold above which all clusters were significant was much higher (63 fields). Only six clusters representing 441 fields were included in this case, i.e., 9.2% and 33.7% of the significant forage clusters and their fields, respectively. There were many nonsignificant cluster sizes because it was possible to simulate clusters of the same size by applying the statistically defined determinants of the individual crop succession locations.

As shown in Fig. 9, the significant clusters were distributed throughout the study area. However, there was a higher concentration

Table 4

Distribution of the statistical significance levels of cluster sizes by the type of succession. NS: Non-significant, S: Significant, All levels: Significant and non-significant clusters, Bien1: Biennial 1, Bien2: Biennial 2.

Level of significance of cluster size	% of clusters by type of succession			Total number of clusters	% of fields by type of succession			Total number of fields	% of area by type of succession			Total area (ha)
	Bien1	Bien2	Forage		Bien1	Bien2	Forage		Bien1	Bien2	Forage	
NS	15.2	20.0	64.8	704	9.7	14.1	76.2	2857	16.3	16.5	67.1	1317
S	31.9	36.3	31.9	204	26.8	35.9	37.3	3505	33.8	39.6	26.6	1588
All levels	18.9	23.7	57.4	908	19.1	26.1	54.8	6362	25.9	29.1	45.0	2905

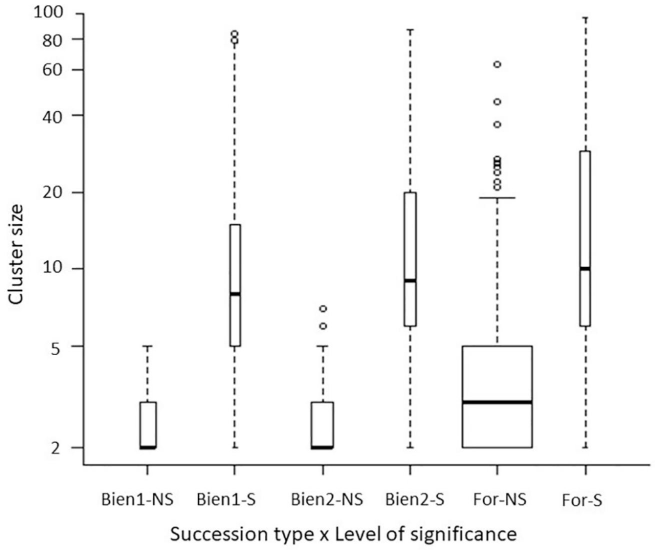

Fig. 8. Boxplots of cluster sizes by the type of succession and level of significance of clusters (logarithm scale). The cluster size is expressed by the number of fields. The horizontal lines within the boxes represent the median values. The respective widths of the boxes are proportional to the ratio between the number of clusters in the mode and the total number of biennial or forage succession clusters. Bien1-NS: nonsignificant clusters of biennial 1 successions, Bien1-S: significant clusters of biennial 1 successions, Bien2-NS: nonsignificant clusters of biennial 2 successions, Bien2-S: significant clusters of biennial 2 successions, For-NS: nonsignificant clusters of forage successions, For-S: significant clusters of forage successions.

of large significant clusters of biennial 1 and 2 successions in the plain area, which is characterized by larger cultivation area sizes.

4. Discussion

4.1. Individual and collective crop successions

In this study, we used the spatiotemporal pattern of the landscape as an indicator of collective crop successions. The pattern was characterized using land use time series at field resolution and described through the sizes of clusters of adjacent fields having the same type of crop succession. Five types of succession were observed. The biennial type and the forage-dominant type were predominant. We showed that 80.7% of the fields in the study zone belonged to clusters including two to 96 adjacent fields. Using a specific spatial permutation test, we were able to distinguish between individual and collective successions to explain the observed distribution of the sizes of the clusters of biennial and forage-dominant successions.

The search for statistical relationships between the presence of a type of crop succession in a field and the characteristics of that field and its land-use environment made it possible to characterise determinants for assigning individual crop successions to fields. The results showed that forage successions were preferentially located close to settlements (grouped in villages or scattered) or in fields with low clay content soils, while biennial successions were preferentially located far from habitation in fields with clay-rich soils. The preferences of farmers for the cultivation of forage close to villages or isolated farmsteads have been observed in other livestock farming contexts, such as in France (e.g., Deffontaines et al., 1995; Le Ber and Benoit, 1998), Morocco (Lazarev, 2014) and Tunisia (Ibidhi et al., 2017). This location preference can be explained by the need to keep grazing or fodder areas and stables near each other. In the case of the study area, this preference could also be

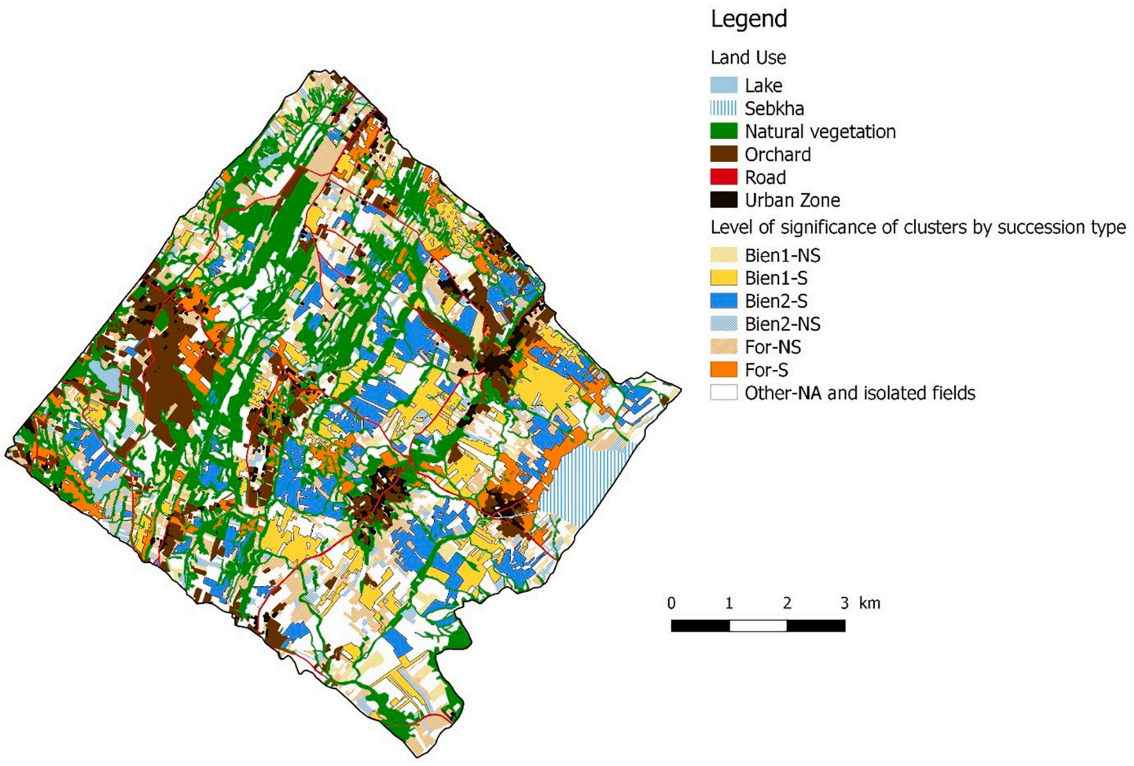

Fig. 9. Spatial distribution of the significance levels of the biennial and forage clusters. Bien1-NS: nonsignificant clusters of biennial 1 successions, Bien1-S: significant clusters of biennial 1 successions, Bien2-NS: nonsignificant clusters of biennial 2 successions, Bien2-S: significant clusters of biennial 2 successions, For-NS: nonsignificant clusters of forage successions, For—S: significant clusters of forage successions, Other-NA: clusters of other successions whose significance has not been assessed.

explained by the fact that most of the villages are located on sandstone outcrops with shallow, sandy-textured soils and low water availability. Far from the settlements, the dominant location factor is the soil. Clay-rich soils are considered to be the best soils both by farmers in the region (Sethom, 1977) and by agronomists (Mekki et al., 2018b), and they are preferentially reserved for the most demanding crops grown in biennial successions. Indeed, as stated by Mekki et al. (2018b), wheat exhibits better development in clay loam soil, and this observation is probably due to the larger soil moisture supply during its most active growing period. Forage crops accept lower mean soil moisture linked to a sandy soil texture with a lower water retention capacity.

When determinants of individual crop succession locations could not explain the sizes of the observed clusters, we considered the possibility of collective crop succession. We assumed that collective successions potentially explained the significant sizes of 204 clusters of biennial or forage successions. These significant clusters represented 38.3% of the fields and 35.2% of the area with annual crops in the study area. Large clusters of biennial synchronized successions were systematically explained by the existence of collective successions. While the characteristics of fields may explain the locations of biennial successions, the results clearly show that the synchronization of crop successions among several adjacent fields was within the scope of collective succession. Conversely, collective successions were not always relevant to explaining the existence of large forage clusters.

These results are consistent with observations by Mekki et al. (2018a). These authors described three main constraints justifying collective successions in the Lebna watershed context, which is characterized by high farmland fragmentation and field dispersion. As explained in the Study area section, these constraints are as follows: (i) the lack of access paths to fields for mechanized operations or harvest transport, (ii) the risk of damage to crops still in place by animals or herds grazing on crop residues, and (iii) the difficulty of obtaining access to agricultural contractors. Such constraints are not strictly the same as those mentioned in the literature describing the older open field systems of agriculture that have been used in Europe, the Middle East and North Africa (see the introduction section). However, they particularly justify the clustering of wheat fields, which is a key crop for most farmers because of a state guarantee of marketing that limits the variability of income relative to the variability of yields (Chebbi, 2018) and because it is the last crop harvested. Consequently, these constraints explain the synchronization of biennial successions between adjacent fields on the basis of the wheat crop.

According to the farmers that were informally interviewed during our field observations, the clusters of biennial synchronized successions result from shared knowledge of the areas to be cultivated with wheat in a given year rather than from consultations between farmers. A cluster of wheat fields in year n may be subdivided into subclusters of different crops in year n + 1 and then formed again in year n + 2 due to the possible alternation of wheat with a legume, spice or forage crop in a biennial succession. The interviewed farmers pointed to the disappearance of the consultation structures that existed in the past for annual crop choices. Consequently, most of the observed clusters of significant size are probably the result of the application of a social norm (Demeulenaere, 2003) rather than a result of the implementation of collective rules. Collective rules are the product of an explicit agreement brought about by an authority and involving sanctions when they are not followed, which is not the case for social norms (Crawford and Orstrom, 1995). Here, the norm is to respect the type of crop to be sown in a given year in a given area. Farmers conform to this approach, as it helps them manage the common constraints mentioned above.

The convoluted forms of many clusters of significant size (Fig. 9) show that the norm is not strictly followed. Some farmers may choose not to make the same choice as their neighbours when the their field locations make it possible. For example, a field that is easily accessible because it is located close to a road makes it possible to choose a crop that is harvested earlier than the crop sown in adjacent fields. If adjacent fields do not have access to roads, the reverse is not possible.

4.2. Performance and limits of the methods used

In this study, we took the precaution of assessing the potential determinants of the location of individual crop successions to limit the risks of overestimating the number of clusters potentially linked to collective succession. Nevertheless, the main limitations of our approach should be mentioned.

The first limitation concerns the uncertainty related to crop predictions errors made by remote sensing. However, as the spatial structure of the classification errors was random, we considered the errors to have little influence on the results.

A second limitation concerns possible errors made in assigning a three-year crop sequence to a type of succession, as we were not sure if the sequence pattern would be the same over time. Based on farmers' views of their practices and our expertise regarding crop succession diversity, we assumed the misclassification rate to be low for the biennial and forage succession types even in the case of the “biennial 2” subtype for which we were not certain whether the fields concerned grew wheat in 2019. In the case of the minority crop sequences, it is possible that the assignment of a succession type (the wheat, spice/legume or miscellaneous type) from the observed sequences was incorrect and that the actual crop successions were based on flexible combinations of crop sequences over time. In particular, the dominant presence of spices or legumes in a succession is very unlikely over a long period of time because of the vital need to break pest and disease cycles. As we did not consider these successions for the analysis of the statistical significance of cluster sizes, possible misclassifications do not affect our results.

A third limitation concerns the risks of underestimating the real sizes of clusters. Underestimation may be related to edge effects when observed clusters extend beyond the study area boundaries. However, this is mostly related to the way clusters were defined. We considered a cluster to be a set of adjacent fields forming a continuous surface of the same type of crop succession. Two neighbouring clusters of fields having the same type of succession will be classified into two separate clusters if the clusters are not joined. It is not possible to know whether these two clusters are part of the same cluster from the point of view of farmers with fields in the area of interest.

A fourth limitation is related to the identification of the determinant of the individual crop succession location. The classification tree was constructed by mobilizing suitable data available at field resolution that could explain these successions from the point of view of agronomic theory. In doing so, we did not consider variables known to be potential determinants because they were not available, such as the distance from the farm's headquarters. We also considered the determinants to be homogeneous throughout the study area, which may be a simplification of reality. Moreover, the classification tree only highlighted the dominant determinants. There may be determinants for locating individual crop successions that are not statistically detectable but that could explain some clusters. For example, this may be the case for forage successions located on the edge of the Lebna sebkha. High soil salinity in this area may account for individual choices to grow resistant forage crops.

Another limitation is that it is not easy to distinguish between an individual decision and a decision resulting from social norms (Anderson and Dunning, 2014). Growing fodder near the sebkha may also be the result of a local norm related to particular constraints and opportunities, including agglomeration benefits that apply to the farmers in the zone. The sebkha is known to be a valued grazing area for herders who live nearby. Sowing fodder in the fields close to the sebkha allows the herders to increase their grazing area in this zone. Nonherders not following the norm might experience damage to crops not yet harvested when herds pass by. To avoid or limit the risks, they rent out their fields to herders, or they grow early-harvest forage as a cash crop.

Finally, a last limitation concerns the agricultural field. By assuming that the field contours are stationary, we took the risk of artificially increasing or decreasing the number of fields in each cluster. In addition, there are no available data to link the fields in the study area to the territories of the farms. Some farmers may have several adjacent fields with the same type of crop succession even in areas where farm fields are extremely dispersed, as observed by Mekki et al. (2018a) during their field surveys. Therefore, two adjacent fields may be cultivated by the same farmer. This uncertainty raises the question of the interpretation of the significance of the sizes of small clusters.

Despite these limitations, we have a unique dataset that allows spatial compensation of local errors and ensures the significance of the observed trends.

4.3. Research perspectives

The limitations in crop and crop succession prediction and field mapping are expected to be overcome in the future with the increasing availability of satellite imagery with finer temporal and/or spatial resolutions and improved algorithms for crop prediction and field contour detection from these satellite images. However, future research is needed to overcome most of the other abovementioned limitations. Three areas for improvement are proposed. The first is to validate our results with farmers, with particular emphasis on (i) the determinants of the individual crop succession locations described statistically and (ii) the link made between a statistically significant cluster size and the existence of a collective succession. The second concerns the analysis of the organization of collective successions by farmers to better understand how collective successions are defined and implemented and how much flexibility farmers have in choosing their own crops and crop successions. The third concerns the analysis of the role of structural landscape elements (roads, tracks, wadis, natural vegetation, etc.) in the spatial arrangement of clusters. For example, further studies could focus on identifying (1) the elements that systematically act as barriers between clusters (e.g., wide and/or deep wadis), justifying their current delimitation, and (2) those that, on the contrary, do not act as barriers (e.g., narrow strips of herbaceous natural vegetation) and could therefore make redefining the contours of clusters possible by integrating these elements within larger clusters.

5. Conclusion

In this study, we characterized the spatial arrangement of crop successions from a land use time series. We used the spatial arrangement of the main crop successions into clusters of adjacent fields with the same crop succession type as a potential indicator of collective successions. In addition, we developed a spatial permutation test to perform the evaluation. The results show that collective successions are mainly comprised of synchronized biennial successions and are secondarily comprised of forage-dominant successions. These collective successions have a significant impact on the distribution of crops in the landscape, as they involve approximately 40% of the fields and area of the study area. They address common constraints that apply to groups of farmers cultivating adjacent fields.

These results indicate that for some regions of the world, to improve our understanding of the drivers of crop allocation at the landscape level, it is not sufficient to only address drivers of crop allocations at the field and farm levels, it is also necessary to account for the collective context in which farmers operate. In the Lebna watershed, any scenarios aiming at modifying the current distribution of crops in the landscape for better soil and water management and any public and/or agricultural policies supporting these scenarios must take into account the coexistence of individual and collective decisions made regarding crop allocation in fields and the respective determinants of these decisions. For example, any public or agricultural policy favouring the spatial alternation of crops at the landscape level to reduce erosion may face difficulties due to farmers' organizational collective constraints linked to the dispersion of agricultural land.

It is therefore very important to be able to assess the diversity and spatial importance of collective successions when the presence of such successions is reported. The use of land use time series and the spatial permutation test that we developed allow for the mapping of the likely presence of such successions at the landscape scale. Such a map could make it possible to identify the groups of farmers behind field clusters and to rely on those groups to define and promote sustainable landscape management practices adapted to the constraints of farmers. In general, this approach is a tool for considering the issue of collective successions and the constraints they face for defining sustainable land use scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anderson, J.E., Dunning, D., 2014. Behavioral norms: variants and their identification. Soc. Personal. Psychol. Compass 8 (12), 721–738. https://doi.org/10.1111/spc3.12146.

Baudry, J., Burel, F., Aviron, S., Martin, M., Ouin, A., Pain, G., Thenail, C., 2003. Temporal variability of connectivity in agricultural landscapes: do farming activities help? Landsc. Ecol. 18, 303–314. https://doi.org/10.1023/A:1024465200284.

Bayes, T., 1764. An essay toward solving a problem in the doctrine of chances. Philos. Trans. R. Soc. Lond. 53, 370–418.

Ben Slimane, A., Raclot, D., Evrard, O., Sanaa, M., Lefevre, I., Ahmadi, M., Tounsi, M., Rumpel, C., Ben Mammou, A., Le Bissonnais, Y., 2013. Fingerprinting sediment sources in the outlet reservoir of a hilly cultivated catchment in Tunisia. J. Soils Sediments 13, 801–815. https://doi.org/10.1007/s11368-012-0642-6.

Ben Slimane, A., Raclot, D., Evrard, O., Sanaa, M., Lefevre, I., Le Bissonnais, Y., 2016. Relative contribution of rill/interrill and gully/channel erosion to small reservoir siltation in Mediterranean environments. Land Degrad. Dev. 27, 785–797. https://doi.org/10.1002/ldr.2387.

Benoît, M., Rizzo, D., Marraccini, E., Moonen, A.C., Galli, M., Lardon, S., Rapey, H., Thenail, C., Bonari, E., 2012. Landscape agronomy: a new field for addressing agricultural landscape dynamics. Landsc. Ecol. 27, 1385–1394. https://doi.org/10.1007/s10980-012-9802-8.

Besag, J., 1974. Spatial interaction and the statistical analysis of lattice systems. J. R. Stat. Soc. Ser. B Methodol. 36 (2), 192–225.

Bivand, R., Lewin-Koh, N., 2018. maptools: Tools for Reading and Handling Spatial Objects. R package version 0.9-3. https://CRAN.R-project.org/package=maptools.

Bivand, R.S., Piras, G., 2015. Comparing implementations of estimation methods for spatial econometrics. J. Stat. Softw. 63 (18), 1–36. http://www.jstatsoft.org/v63/i18/.

Bivand, R.S., Pebesma, E., Gomez-Rubio, V., 2013. Applied Spatial Data Analysis with R, Second edition. Springer, New York, p. 405.

Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and Regression Tree. Chapman and Hall, London, p. 358.

Calvo-Iglesias, M.S., Fra-Paleo, U., Diaz-Varela, R.A., 2009. Changes in farming system and population as drivers of land cover and landscape dynamics: the case of enclosed and semi-openfield systems in northern Galicia (Spain). Landsc. Urban Plan. 90, 168–177. https://doi.org/10.1016/j.landurbplan.2008.10.025.

Caput, J., 1956. La formation des paysages agraires béarnais. Observations et problèmes. Revue géographique des Pyrénées et du Sud-Ouest 27, pp. 219–242.

Castellazzi, M.S., Matthews, J., Angevin, F., Sausse, C., Wood, G.A., Burgess, P.J., Brown, I., Conrad, K.F., Perry, J.N., 2010. Simulation scenarios of spatio-temporal arrangement of crops at the landscape scale. Environ. Model. Softw. 25, 1881–1889. https://doi.org/10.1016/j.envsoft.2010.04.006.

Chebbi, H.E., 2018. Évaluation du système de soutien au secteur agricole en Tunisie. Rapport de recherche CIHEAM-IAMM, p. 122.

Ciampalini, R., Lagacherie, P., Monestiez, P., Walker, E., Gomez, C., 2012. Co-kriging of soil properties with Vis-NIR hyperspectral covariates in the Cap Bon region (Tunisia). In: Minasny. Malone & McBratney (Eds). In: Digital Soil Assessments and Beyond. Taylor & Francis Group, London, pp. 393–398.

Colin, F., Moussa, R., Louchart, X., 2012. Impact of the spatial arrangement of land management practices on surface runoff for small catchments. Hydrol. Process. 26, 255–271. https://doi.org/10.1002/hyp.8199.

Crawford, S.E.E., Orstrom, E., 1995. A grammar of institutions. Am. Polit. Sci. Rev. 89 (3), 582–600.

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJ. Complex Syst. 1695. http://igraph.org.

de Planhol, X., 1956. Les ententes intervillageoises d'assolement. Bull. Assoc. Géograph. Français 255–256, 39–40. https://doi.org/10.3406/bagf.1956.7505.

Deffontaines, J.P., Thenail, C., Baudry, J., 1995. Agricultural systems and landscape patterns: how can we build a relationship? Landsc. Urban Plan. 31, 3–10.

Demeulenaere, P., 2003. Les normes sociales entre accords et désaccords, Paris. Presses universitaires de France, p. 304.

Dury, J., Garcia, F., Reynaud, R., Bergez, J.-E., 2013. Cropping-plan decision-making on irrigated crop farms: a spatio-temporal analysis. Eur. J. Agron. 50, 1–10. https://doi.org/10.1016/j.eja.2013.04.008.

Ekasingh, B., Ngamsomsuke, K., 2009. Searching for simplified farmers' crop choice models for integrated watershed management in Thailand: a data mining approach. Environ. Model. Softw. 24, 1373–1380. https://doi.org/10.1016/j.envsoft.2009.02.015.

Fahrig, F., Baudry, J., Brotons, L., Burel, F., Crist, T.O., Fuller, R.J., Sirami, C., Siriwardena, G.M., Martin, J.-L., 2011. Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. Ecol. Lett. 14, 101–112. https://doi.org/10.1111/j.1461-0248.2010.01559.x.

Fay, G., 1979. L'évolution d'une paysannerie montagnarde : les Jbalas Sud-Rifains. Méditerranée 35 (1–2), 81–91. https://doi.org/10.3406/medit.1979.1901.

Gaubi, I., Chaabani, A., Ben Mammou, A., Hamza, M.H., 2016. A GIS-based soil erosion prediction using the revised universal soil loss equation (RUSLE) (Lebna watershed, cap bon, Tunisia). Nat. Hazards 86, 219–239.

Gomez, C., Lagacherie, P., Bacha, S., 2012. Using Vis-NIR hyperspectral data to map topsoil properties over bare soils in the cap bon region, Tunisia. In: Minasmy, B., Malone, B.P., McBratney, A.B. (Eds.), Digital Soil Assessments and beyond: Proceedings of the 5th Global Workshop on Digital Soil Mapping. CRC Press, London, pp. 387–392.

Hijmans, R.J., 2017. raster: Geographic Data Analysis and Modeling. R package version 2.6-7. https://CRAN.R-project.org/package=raster.

IAO, 2002. Land resources of the Oued Lebna catchment (Tunisia). In: 20th Course Professional Master: Remote Sensing and Natural Resources Evaluation. Florence, Italie, Istituto Agronomico per l'Oltremare, p. 132.

Ibidhi, R., Hoekstra, A.Y., Gerbens-Leenese, P.W., Chouchanec, H., 2017. Water, land and carbon footprints of sheep and chicken meat produced in Tunisia under different farming systems. Ecol. Indic. 77, 304–313. https://doi.org/10.1016/j.ecolind.2017.02.022.

Jiang, F., Drohan, P.J., Cibin, R., Preisendanz, H.E., White, C.M., Veith, T.L., 2021. Reallocating crop rotation patterns improves water quality and maintains crop yield. Agric. Syst. 187, 103015. https://doi.org/10.1016/j.agsy.2020.103015.

Joannon, A., Souchère, V., Martin, P., Papy, F., 2006. Reducing runoff by managing crop location at the catchment level considering agronomic constraints at farm level. Land Degrad. Dev. 17, 467–478. https://doi.org/10.1002/ldr.714.

Joannon, A., Bro, E., Thenail, C., Baudry, J., 2008. Crop patterns and habitat preferences of the grey partridge farmland bird. Agron. Sustain. Dev. 28, 379–387. https://doi.org/10.1051/agro:2008011.

Kark, R., Grossman, D., 2003. The communal (musha') village of the Middle East and North Africa. In: Leimgruber, W., Majoral, R., Lee, C.W. (Eds.), Policies and Strategies in Marginal Regions. Ashgate Publishing Ltd, Aldershot, UK, pp. 223–236.

Lagacherie, P., Sneep, A.-R., Gomez, C., Bacha, S., Coulouma, G., Hamrouni, M.H., Mekki, I., 2013. Combining Vis–NIR hyperspectral imagery and legacy measured soil profiles to map subsurface soil properties in a Mediterranean area (Cap-Bon, Tunisia). Geoderma 209–210, 168–176. https://doi.org/10.1016/j.geoderma.2013.06.005.

Latiri, K., Lhomme, J.P., Annabi, M., Setter, T.L., 2010. Wheat production in Tunisia: Progress, inter-annual variability and relation to rainfall. Eur. J. Agron. 33, 33–42. https://doi.org/10.1016/j.eja.2010.02.004.

Lazarev, G., 2005. La gestion participative des terroirs de montagne au Maroc, condition d'une maîtrise de la "production d'eau". Critique économique 15, 141–154.

Lazarev, G., 2014. Les structures agraires au Maroc. In: Une Mise En Perspective Historique. Université Mohammed V-Agdal. Publication de la Faculté des Lettres et des Sciences Humaines, Rabat, Essais et Études, 62, p. 422.

Lazrak, E.G., Mari, J.-F., Benoît, M., 2010. Landscape regularity modelling for environmental challenges in agriculture. Landsc. Ecol. 25, 169–183. https://doi.org/10.1007/s10980-009-9399-8.

Le Ber, F., Benoit, M., 1998. Modelling the spatial organization of land use in a farming territory. Example of a village in the Plateau Lorrain. Agronomie. EDP Sci. 18 (2), 103–115.

Leturcq, S., 2014. La macro analyse des structures agraires à l'épreuve de la micro-analyse d'un terroir. Contraintes communautaires et individualisme agraire dans un finage beauceron (XVII-XXe s.). Les petits cahiers d'Anatole 14, 1–20.

Liaw, A., Wiener, M., 2002. Classification and Regression by randomForest. R News 2 (3), 18–22. https://CRAN.R-project.org/doc/Rnews/.

Mari, J.-F., El Ghali Lazrak, E.G., Benoît, M., 2013. Time space stochastic modelling of agricultural landscapes for environmental issues. Environ. Model. Softw. 46, 219–227. https://doi.org/10.1016/j.envsoft.2013.03.014.

Martinez-Casasnovas, J.A., Martin-Montero, A., Casterad, M.A., 2005. Mapping multi-year cropping patterns in small irrigation districts from time-series analysis of Landsat TM images. Eur. J. Agron. 23, 159–169. https://doi.org/10.1016/j.eja.2004.11.004.

Mekki, I., Bailly, J.S., Jacob, F., Chebbi, H., Ajmi, T., Blanca, Y., Zairi, A., Biarnès, A., 2018a. Impact of farmland fragmentation on rainfed crop allocation in Mediterranean landscapes: a case study of the Lebna watershed in cap bon. Tunisia. Land Use Policy 75, 772–783. https://doi.org/10.1016/j.landusepol.2018.04.004.

Mekki, I., Zitouna-Chebbi, R., Jacob, F., Ben, Mechlia N., Prévot, L., Albergel, J., Voltz, M., 2018b. Impact of land use on soil water content in a hilly rainfed agrosystem: a case study in the cap bon peninsula in Tunisia. AGROFOR Int. J. 3, 64–75. https://doi.org/10.7251/AGRENG1801064M.

Meynier, A., 1958. Les Paysages Agraires. Armand Colin, Paris, p. 199.

Pebesma, E.J., Bivand, R.S., 2005. Classes and methods for spatial data in R. R News 5 (2), 9–13. https://CRAN.R-project.org/doc/Rnews/.

Pelletier, C., Valero, S., Inglada, J., Champion, N., Dedieu, G., 2016. Assessing the robustness of random forests to map land cover with high resolution satellite image time series over large areas. Remote Sens. Environ. 187, 156–168. https://doi.org/10.1016/j.rse.2016.10.010.

Peltonen-Sainio, P., Jauhiainen, L., Sorvali, J., 2017. Diversity of high-latitude agricultural landscapes and crop rotations: increased, decreased or back and forth? Agric. Syst. 154, 25–33. https://doi.org/10.1016/j.agsy.2017.02.011.

Peltonen-Sainio, P., Jauhiainen, L., Sorvali, J., Laurila, H., Rajala, A., 2018. Field characteristics driving farm-scale decision-making on land allocation to primary crops in high latitude conditions. Land Use Policy 71, 49–59. https://doi.org/10.1016/j.landusepol.2017.11.040.

Persello, C., Tolpekin, V.A., Bergado, J.R., de By, R.A., 2019. Delineation of agricultural fields in smallholder farms from satellite images using fully convolutional networks and combinatorial grouping. Remote Sens. Environ. 231, 111253. https://doi.org/10.1016/j.rse.2019.111253.

Ren, J., Campbell, J.B., Shao, Y., 2016. Spatial and temporal dimensions of agricultural land use changes, 2001–2012, east-Central Iowa. Agric. Syst. 148 (2016), 149–158. https://doi.org/10.1016/j.agsy.2016.07.007.

Renes, H., 2010. Grain lands. The landscape of open fields in a European perspective. Landsc. Hist. 31, 37–70. https://doi.org/10.1080/01433768.2010.10594621.

Rizzo, D., Marraccini, E., Lardon, S., Rapey, H., Debolini, M., Benoît, M., Thenail, C., 2013. Farming systems designing landscapes: land management units at the interface between agronomy and geography. Dan. J. Geogr. 113, 71–86. https://doi.org/10.1080/00167223.2013.849391.

Sabir, M., Herivaux, C., Guillot, F., Bouaziz, A., 2019. Dynamique agraire et dynamique paysagère dans le bassin versant du Tleta, Rif Occidental (Maroc). Rev. Mar. Sci. Agron. Vét. 7 (2), 323–332.

Schaller, N., Lazrak, G., Martin, P., Mari, J.-F., Aubry, C., Benoît, M., 2012. Combining farmer decision rules and landscape stochastic regularities for landscape modelling. Landsc. Ecol. 27, 433–446. https://doi.org/10.1007/s10980-011-9691-2.

Scheiner, C., Martin, E.A., 2020. Spatiotemporal changes in landscape crop composition differently affect density and seasonal variability of pests, parasitoids and biological pest control in cabbage. Agric. Ecosyst. Environ. 301 https://doi.org/10.1016/j.agee.2020.107051.

Sethom, H., 1977. Les Fellah de la presqu'île du Cap Bon (Tunisie). Université de Tunis, Etude de géographie sociale régionale. Faculté des lettres et sciences humaines de Tunis, p. 371.

Sorel, L., Viaud, V., Duran, P., Walter, C., 2010. Modeling spatiotemporal crop allocation patterns by a stochastic decision tree method considering agronomic driving factors. Agric. Syst. 103, 647–655. https://doi.org/10.1016/j.agsy.2010.08.003.

Steinmann, H.-H., Dobers, E.S., 2013. Spatio-temporal analysis of crop rotations and crop sequence patterns in northern Germany: potential implications on plant health and crop protection. J. Plant Dis. Protect. 120, 85–94. https://doi.org/10.1007/BF03356458.

Thenail, C., Joannon, A., Capitaine, M., Souchère, V., Mignolet, C., Schermann, N., Di Pietro, F., Pons, Y., Gaucherel, C., Viaud, V., Baudry, J., 2009. The contribution of crop-rotation organization in farms to crop-mosaic patterning at local landscape scales. Agric. Ecosyst. Environ. 131, 207–219. https://doi.org/10.1016/j.agee.2009.01.015.

Viaud, V., Monod, H., Lavigne, C., Angevin, F., Adamczyk, K., 2008. Spatial sensitivity of maize gene-flow to landscape pattern: a simulation approach. Landsc. Ecol. 23, 1067–1079. https://doi.org/10.1007/s10980-008-9264-1.

Watkins, B., Van Niekerk, A., 2019. Automating field boundary delineation with multi-temporal sentinel-2imagery. Comput. Electron. Agric. 105078 https://doi.org/10.1016/j.compag.2019.105078.

Watteaux, M., 2005. Sous le bocage, le parcellaire. Etudes rurales [en ligne] 175–176. http://etudesruralesrevues.org/8023.

Wohlfahrt, J., Colin, F., Assaghir, Z., Bockstaller, C., 2010. Assessing impact of spatial arrangements of agricultural practices on pesticide runoff: an approach based on regression trees inferred on a database numerically simulated with a physically based model. Ecol. Indic. 10, 826–839. https://doi.org/10.1016/j.ecolind.2010.01.004.

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. Comput. Electron. Agric. 102, 51–63. https://doi.org/10.1016/j.compag.2014.01.010.