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# Modeling drivers of farming system trajectories in Mediterranean peri-urban regions: two case studies in Avignon (France) and Pisa (Italy)

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**Keywords**

Intensification; extensification; farm typology; spatial autocorrelation; *Spatial Autoregressive Probit*

## 1. Introduction

In the last decades, land use and land cover changes and the ongoing dynamics in terms of land management have been threatening farming systems, affecting a viable food production and regulation services (Overmars et al., 2014). The Mediterranean region is particularly vulnerable in terms of land use and land cover changes due to its biophysical and climatic conditions (Bouma et al., 1998; Ruiz et al., 2020). For instance, the important share of hilly and mountain areas has led to an important abandonment of elevated agricultural areas since World War II (McDonald et al., 2000), summer droughts have contributed to repeated fires (Turco et al., 2017) and consequent land use changes in burnt areas (Parente et al., 2018), and the large coastal areas have favored tourism development and massive coastal urbanization (Robert et al., 2019). Mediterranean farming systems are characterized by a high degree of heterogeneity in terms of their composition and fragmentation in terms of their distribution, which make complex their analysis and the understanding of the dynamics' underlined drivers (Malek and Verburg, 2018). Urban sprawl, as well as intensification on productive agricultural land and abandonment of traditional/extensive production systems are among the most relevant ongoing dynamics in the Mediterranean (Debolini et al., 2018; Serra et al., 2008; Van Vliet et al., 2015). In general, the observed agricultural changes can be grouped in four main trajectories, identified in various theoretical framework (Debolini et al., 2018; Plieninger et al., 2016; van Vliet et al., 2015): intensification vs extensification and diversification vs specialization. These farming system trajectories reflect the two gradients of biotechnical functioning and relationships with socio-economic contexts that Therond et al., (2017) considered as the factors for classifying the key-models of agriculture.

In most cases, these dynamics are identified through land use and land cover change analysis (e.g. Bajocco et al., 2012; Delattre et al., 2020; Kefalas et al., 2019; Marraccini et al., 2015), whereas land use management and spatially-explicit information about agricultural and farming practices are seldom considered, even though they are relevant to understand the actual impact on ecosystem services, instead of the potential one (Rizzo et al., 2019; Temme and Verburg, 2011). Moreover, there are still some gaps of knowledge on how divergent development trajectories act on the same areas (Debolini et al., 2018). In particular, most of the existing literature is based on homogeneous areas in terms of farming systems, such as arable lands, whereas few studies analyze regional and territorial case studies on more complex or heterogeneous agricultural systems e.g., polycultural systems or periurban farming systems (Ruiz-Martinez et al., 2015).

Farming system dynamics on the surroundings of urban areas may take different trends based on different acting drivers. Some recent studies compared the processes ongoing on Athens (Greece) and Rome (Italy) (Salvati et al., 2014) or the case study of Barcelona (Spain) (Serra et al., 2008), which are strongly influenced by their demographic and economic characteristics. Cropland abandonment may occur in areas with high urban pressure, where there is a strong competition between agricultural and urban lands (Geniaux et al., 2011; Serra et al., 2014; Casanova-Enault et al., 2021) and these dynamics can affect traditional production systems that have shaped Mediterranean landscapes (Martínez-Fernández et al., 2013). Moreover, most fertile and productive areas can be subject to a process of intensification, such as coastal or alluvial planes in proximity of cities (Parcerisas et al., 2012; Ruiz-Martinez et al., 2020; Scheromm and Soulard, 2018). At the same time, the proximity to the city and thus to the consumers can facilitate the implementation of different sustainable practices, such as shortening the food supply chains, engaging in organic farming and even sustainable intensifying farming systems to maintain local food production (Scorsino and Debolini, 2020; Weiltin, 2019; Sanz Sanz et al., 2018).

The existing literature on drivers of land use and land cover changes is mostly based on modelling approaches for testing drivers' relation with the underlined dynamics (Veldkamp, 2009; Verburg et al., 2002). Drivers are usually classified in five groups: political and institutional, economic, socio-cultural, technological and geographical/environmental (Debolini et al., 2018; Plieninger et al., 2016; van Vliet et al., 2015), based on the assumption that the cultural and socio-economic factors interact with the biophysical ones influencing the farmers' decision-making process (Benoit et al., 2012; Chopin et al., 2015). Most of the spatial statistical models attempt to explicitly identify the drivers of land cover changes using multiple logistic regression models (Chopin et al., 2015; Serneels and Lambin, 2001). In such approaches, feedbacks from farming management and dynamics at local scale are seldom considered (Verburg et al., 2015), while spill-over effects from neighboring areas are neglected (Qiu et al., 2015). In the context of farming system dynamics, the spillover effect could be defined as the response of a farmer to changes made by other farmers. Nonetheless, the heterogeneous agricultural and production landscape typical of the Mediterranean makes it difficult to assess to which other farmers choices one farmer is reacting to, since different factors can determine the direction of the spillover, namely spatial proximity, the affinity of farming typology or a combination of both factors. In this work we test the hypothesis that spatial spillover alone can improve the understanding of farming system dynamics.

Our analysis is based on a multi-temporal approach using existing European databases: The Land Parcel Identification Systems (LPIS) and the agricultural census at individual farm level on the cadastral parcels, which are used as elementary spatial statistical units. The LPIS is a pan-EU database that provides very detailed and accurate information as well as a mandatory adequate update cycle of the dataset thus highly suitable for multi-temporal and spatially-explicit analysis (Bertaglia et al., 2016). It has been often proposed as support to improve the spatial management of agriculture and the environment and as a fundamental tool to distribute and monitor area-based subsidies (Rizzo et al., 2017). Barbottin et al. (2018) have used the French LPIS as a tool to highlight farm area dynamics, and Marraccini et al. (2020) mobilized LPIS as a support for the design of innovative crop rotations.

Our paper proposes a methodology to analyze farming systems' trajectories and their explanatory factors as proxies of underlined drivers, through a novel statistical modelling approach. In particular, we aimed to answer the following research questions: 1) what divergent trajectories can be observed on the land systems? 2) What drives these trajectories? The possible underlying drivers are represented through proxies in terms of a set of explanatory variables in the spatial model. This approximation, from drivers to proximate variables, is used on most of the land use change modeling approaches, even though it could mask the real understanding of casualties and it implies to do some assumptions in this sense (Veldkamp and Lambin, 2001; Serneels and Lambin, 2001; Mottet et al., 2006; Chopin et al., 2015; Viedma et al., 2017).

The two urban regions analyzed differ for their agricultural context (extensive arable vs specialized crops oriented), but they are illustrative of typical Mediterranean farming systems in urbanized areas. In order to provide a faithful representation of the underlining agricultural trajectories, we characterize the landscape through a farm typology combining on-farm land use and its management using different drivers (e.g. population density, irrigation, agricultural yields). We estimate the contribution of different explanatory variables to the probability of change at the farm level using a Spatial Autoregressive Probit model. This model has the advantage explicitly considering a spatial autocorrelation term of the dependent variable that can be used to estimate spatial spill-over effects (Martinetti and Geniaux, 2017).

## 2. Case-studies

We considered two case studies in medium-sized towns within the Mediterranean region: the peri-urban areas of Pisa (Northwestern coast of Italy) and Avignon (Southeastern France). The two urban regions share common demographic trends but their land cover and use dynamics are different, especially for agricultural areas (Marraccini et al., 2015). The urban region of Pisa is a dispersed urban area of around 500 $km^2$, representing six municipalities located in the coastal plain of the Arno River (*Area Pisana*) and in the hilly area known as Monte Pisano. The average rainfall ranges between 800 mm near the coast to 1100 mm in Monte Pisano and the average annual temperature is around 15°C. Soils are mainly sandy and clay in the coastal area, with siltier loams in the Northern part, which is characterized by several water management issues connected to land reclamation (Pistocchi et al., 2012; Silvestri et al., 2017). Along the coastal area of Pisa lies the regional natural park of *Migliarino San Rossore Massaciuccoli* that also includes agricultural areas (Silvestri et al., 2012). Agricultural land uses are mostly characterized by arable land (winter wheat, maize) in its plain part and permanent crops (olive groves) in the hilly part (Filippini et al., 2018). Like other Mediterranean coastal areas, urbanization and tourism have a strong impact on agriculture, affecting local farming systems with a strong decrease in the number and surface of livestock and vegetable farms (Lardon et al., 2017).

The peri-urban region of Avignon includes a dispersed urban area of 337 $km^2$, representing 17 municipalities. The urban center has an average density of 323 inhabitants/$km^2$ compared with an average of 820 inhabitants/$km^2$ for other urban centers in France. This region is characterized by a specialized agriculture mainly dedicated to fruit production, which represents 32% of the total utilized agricultural area (UAA). Unlike Pisa, the area of Avignon represents an example of Mediterranean landscape undergoing strong polarization of land use, with intensification focusing on the most profitable areas and cultures, and abandonment on the less productive systems (Scorsino and Debolini, 2020). Such Mediterranean areas are characterized by agricultural systems leading to conflicts in terms of ES provision and regulation, such as water supply and biodiversity. The main characteristics of the two-study area are represented on Fig.1.

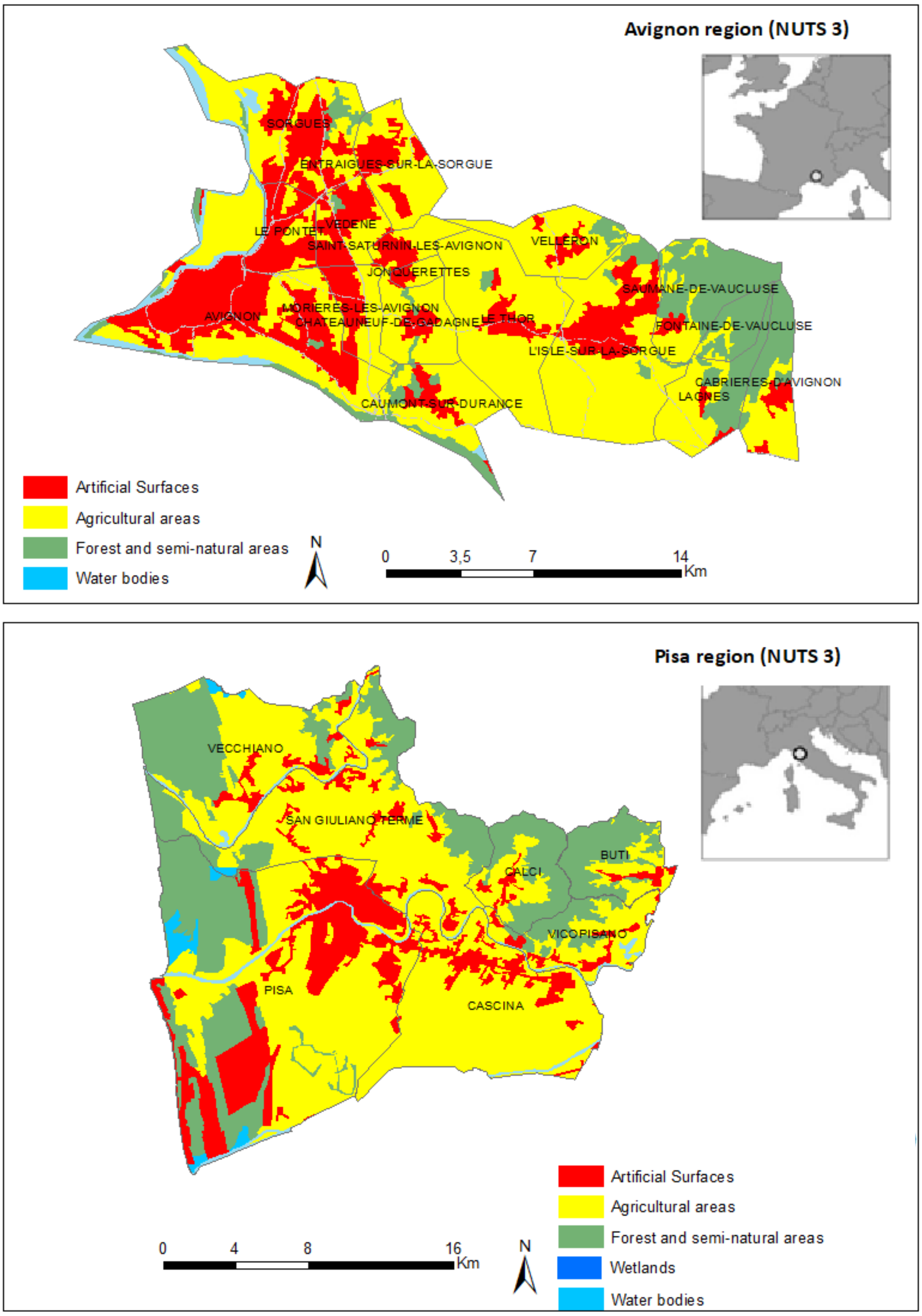


Fig.1: Location of the two cases study and land cover (CLC 2018 — Copernicus Land Monitoring Service)

## 3. Materials and methods

The overall methodology is organized in five steps, resumed in Fig. 2, and is based on the characterization of the farming systems of an area in a given time span (for Pisa in the years 2007 and 2015, for Avignon in 2000 and 2010), then of their trajectories and finally on the identification of the main drivers underlying such trajectories. First, we built the two different databases in the two regions, using as main data the Land Parcel

Identification System (LPIS) for the case study of Pisa, and the individual data of the agricultural census database (Ministère De L'Agriculture (SSP), 2013, 2012) for the case of Avignon. Then, we classify the main farming systems in the two regions, obtaining in each case a typology for the two different years (Fig. 2). Through the analysis of the transition matrix, we obtained the main farming system changes, and these changes were assessed to identify similar or different trajectories. Finally, we tested a series of possible explanatory variables to evaluate their contribution to the trajectories. In the following paragraph we describe in detail each phase of the methodology.

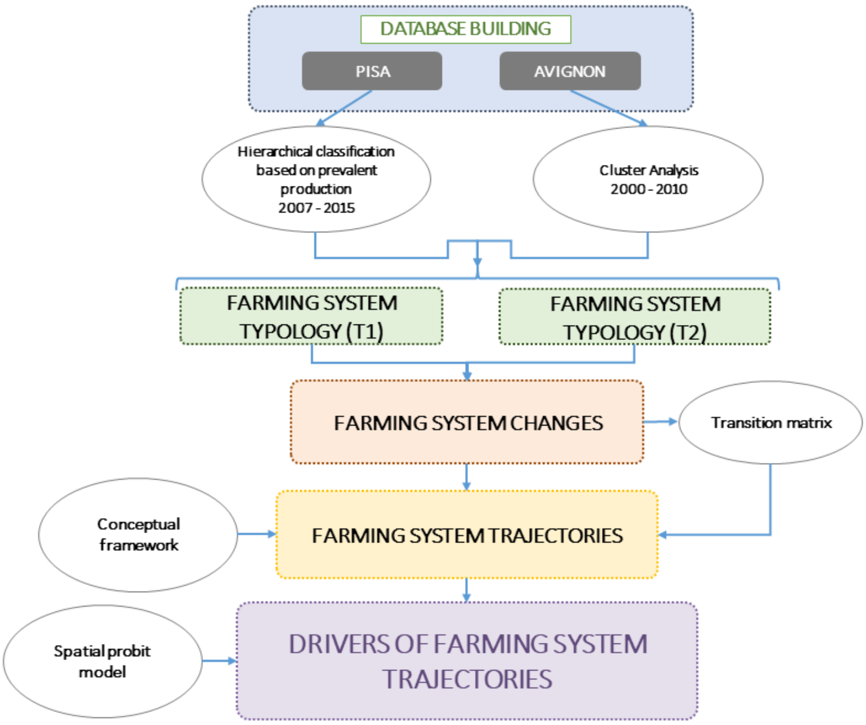


Fig.2: Scheme of the overall methodology.

### 3.1 Database building

In order to characterize farming system typology and their trajectories, we use the farm as the spatial statistical unit of the study. In terms of temporal scale, because of the limitations due to the data availability, we assess the changes between 2007 and 2015 for the case study of Pisa and between 2000 and 2010 for the case study of Avignon. In fact, we used two different sources of information for the two cases: for the case study of Pisa, the farming system and drivers' characterization were developed coupling data from the Land Parcel Identification System (LPIS) database at farm level with relevant information such as elevation, rainfall, proximity to urban areas, organic production, age and gender of the farmer. LPIS allows to identify the main crop sequence types in the study area for a short-term period (from 2007 to 2015), in a similar way to what was proposed by Chopin et al. (2015) but it does not give information about farming practices and few information is given on the farm structure, mainly the usable agricultural area and of the total farm area. This has not been considered a bias, since a previous survey-based and non-systematic farming system typology built in the same area by Filippini et al. (2018) showed the importance of the crop allocation choices and structural variables instead of the farming practices. The complementary data were compiled from existing geographical databases and agricultural census at municipal scale.

For the case study of Avignon, the information was obtained from the French agricultural census at the farm level for a period of 10 years (2000-2010). It is particularly interesting because it gives comprehensive and detailed information about the usable agricultural area (e.g. percentage of the different crops, land use), structure (e.g. farm size and farmland), crop management (e.g. irrigation, machineries, organic or conventional farming) and other socio-economic information (e.g. profitability, commercialization). The detailed description of the typology obtained for the two case studies of Pisa (2007 and 2015) and Avignon (2000 and 2010) are in Appendix 1 and Appendix 2.

### 3.2 Identification of farming system changes and trajectories

We assessed farming system changes between the two years analyzed comparing the different farming system distributions through the transition matrix. Then, we classified the changes based on the proposed conceptual framework (Fig.3), in order to understand the underline trajectories.

In particular, in order to identify the main trajectories, we aggregated different type of changes on some groups (Tab. 1), namely intensification, extensification, diversification and specialization, according to Feranec et al. (2010). This aggregation was based on the conceptual framework shown on Figure 3, obtained coupling the existing bibliography about farming system trajectories (Debolini et al., 2018; Plieninger et al., 2016; van Vliet et al., 2015) and the recent classification of key-models of agriculture (Therond et al., 2017): the intensification and specialization processes being understood as those related to the increase of the production whereas diversification and extensification led to less production and even abandonment.

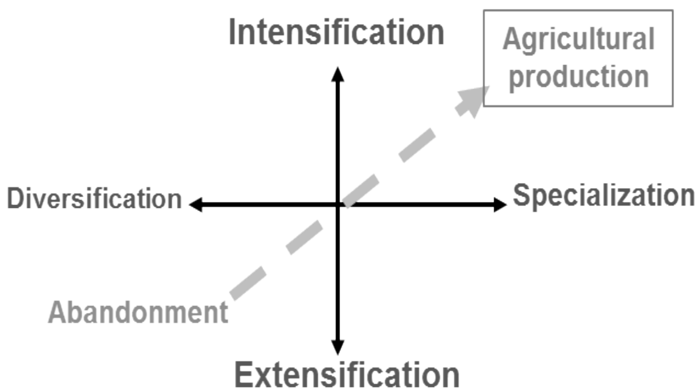


Fig. 3: Conceptual framework for farming systems trajectories definition

Table 1: Definition of the observed farming system trajectories

| | It is defined as the… | Examples of observed changes |
|---|---|---|
| INTENSIFICATION | Increasing production per unit area through more intensive use of inputs (e.g. fertilizers, pesticides, irrigation) or an increase in the farm surface of more intensive managed crops. | • Extensive arable land -> intensive arable land<br>• Meadows – pastures or forest -> arable land.<br>• Arable land (cereal crops) -> arable land (industrial crops)<br>• Increasing of inputs (irrigation, fertilization) |
| EXTENSIFICATION | Increasing production by extending the area under cultivation while maintaining or reducing aggregate input levels per unit area or an increase in the fam surface of more extensive managed crops. | • Vineyards, orchards & berry plantations -> arable land or grasslands<br>• Arable land -> grasslands.<br>• Intensive arable land -> extensive arable land |
| DIVERSIFICATION | Increasing the number of species cultivated in the farm or by increasing the part of the crops in the on-farm land use | • Toward high-value cash crops (mixed cropping systems with vegetable crops)<br>• Arable land (cereal crops) arable land (mixed cereal, industrial, vegetable crops) |
| SPECIALISATION | Decreasing on the number of species cultivated on the farm or more specialized management methods or increasing the land use in a higher-value crop. | • Non-labelled -> labelled vineyards<br>• Table grapes -> vineyards<br>• Permanent crops -> vineyards, orchards & berry plantations |

Given the different data sources, the two case studies showed different ways of identifying farming system trajectories. In Pisa, the agricultural dynamics are defined by changes in the on-farm land use, based on the agronomic rule of the correspondence between crop sequence and crop spatial allocation (Castellazzi, 2008; Doré, 2012; Chopin et al., 2015). For instance, arable systems shifting from winter cereal-based land uses (more than 50% of winter wheat in the crop sequence) to industrial crops-based (more than 50% of industrial crops in the crop sequence) are considered to show an intensification trend as their land use allocation at the farm level has changed. On the other hand, in the case study of Avignon, other intensification trends have been identified, such as those deriving exclusively from a change in the crop management (e.g. increase on fertilization, pest or water use for irrigation). Results about farming system trajectories were spatially represented, and we test if there is spatial dependency between the observed trajectories via the join count test: it is present, so we need to account for that in the model that links drivers to trajectories to avoid inconsistent estimation.

### 3.3 Drivers assessment through spatial statistic modelling

In order to understand the most important drivers acting on farming systems dynamics, we tested four classes of explanatory variables: accessibility or geographic factors, such as distance to urban areas or to the main roads; bio-physical factors, such as soil characteristics and climate conditions; socio-economic factors, such as population density and farm characteristics, such as the farmer age.

The model was applied to both case-studies, but the different conditions and results about farming system trajectories (see Section 4.2) on the two case studies induced to apply the model in two different ways. In particular, in the Pisa region, we identified two main sub-regions in terms of farming systems and associated dynamics: the plain area and the hilly one. The former was characterized by a mostly intensification process on the cereals-livestock arable lands, whereas in the latter farming systems were mostly characterized by permanent crops and in particular olive groves, almost stable during the analyzed period. For this reason, we run the model just on the plain area, in order to identify the factors acting on the intensification process of cereal livestock farming systems compared to the stable farms on the same area (i.e. intensification vs stability). On the case study of Avignon, we identified two contrasted trajectories: on one side an intensification of farming systems mainly due to the farm specialization and on the other side the extensification and the progressive abandonment of the more traditional farming systems, and so we tested the explanatory variables playing on the intensification trajectories vs extensification ones (i.e. intensification vs extensification). To do that, we regressed a binary choice variable related to the type of trajectory assessed as a dependent variable against a set of explanatory variables using a spatially explicit model (Probit model) with spatial autocorrelation in the dependent variable a.k.a. SAR probit, (Martinetti and Geniaux, 2017) in order to account for the spatial dependence of the dependent variable and avoid inconsistent and inefficient estimators (McMille, 1992). The model takes the following form:

$$y=\rho Wy+\beta X+\epsilon$$

Where y represents the binary dependent variable, X a matrix of covariates, β a set of regression parameters and ϵ a vector of normal iid disturbances with zero mean and unit variance. The $n \times n$ matrix W (n is the size of the sample) is the spatial weight matrix that contains the information about the spatial distribution proximity of the observations (here we considered a k-nearest neighbor scheme), while $\rho \in [-1,1]$ is the spatial autocorrelation coefficient determining the strength and the direction of the spatial autocorrelation. Here we used the row-standardized matrix of the first k=5 nearest neighbors for Avignon and k=10 nearest neighbors for Pisa. We used different values for the two cases study because we tested different K-values of k until we got the minimum error. All the analysis was conducted in R package ProbitSpatial (Martinetti & Geniaux, 2021). In the probit spatial statistical model, we introduced all explanatory variables and then we analyzed which factor contribute significantly to the explanation of farming system changes. The descriptive statistics of the variables included in the empirical model are in supplementary materials (Appendix 3).

# 4. Results

## 4.1 Farming system typology and changes

The farming system typologies obtained are summarized in Tab. 2. In Pisa, we distinguished thirteen classes of farming systems, based on the main farm production, whereas in Avignon, we obtained nine. The detailed description of the obtained typologies and their changes are reported on Supplementary materials (Appendix 1 and Appendix 2). In both case studies, the most stable during the considered time interval are related to vegetables, cereals, permanent crops, nursery and table grapes, while vineyard systems tend to increase together with livestock farming at the expense of mixed extensive farming systems.

Table 2: Farming system types obtained for the two case studies and their amount at T0 in terms of number of farms

| Farmig systems' types (Pisa) | Main characteristics of each type | Number of farms in 2007 |
|---|---|---|
| Olive-groves | >30% UAA Olive | 243 |
| Vineyards | >20% UAA Vineyards | 6 |
| Fruits | >30% UAA Fruits | 1 |
| Nursery | >30% UAA Nursery crops | 3 |
| Vegetables | >30% UAA Vegetable crops | 13 |
| Cereal | >70% UAA Cereals | 54 |
| Legume | >70% UAA Legumes | 7 |
| Industrial | >70% UAA Industrial crops | 2 |
| Cereal & Legume | >70% UAA Cereal & Legume crops | 66 |
| Cereal & Industrial | >70% UAA Cereal & Industrial crops | 86 |
| Legume & Industrial | >70% UAA Legume & Industrial crops | 6 |
| Set-aside | >50% UAA Set-aside | 12 |
| Mixed-crops | Several crop types within farm (e.g >20% vineyards and >30% vegetables) | 21 |

| Farmig systems' types (Avignon) | Main characteristics of each type | Number of farms in 2000 |
|---|---|---|
| Pasture | Farming systems dedicated to small-scale livestock farming | 3 |
| Vegetables | Vegetables systems extend a small proportion of cultivated area | 88 |
| Cereals | Conventional cereal farms with medium level of mineral & herbicide use and tillage | 88 |
| Permanent crops-medium intensity | Irrigated permanent farms-medium intensity | 47 |
| Nursery | Nursery farming systems are few and small farms | 17 |
| Vineyards | Specialized vineyards systems with quality vineyards, average size, and medium yielding | 5 |
| Table grapes | Table grapes production, with average size and medium yielding. | 115 |
| Cereal-Vineyards | Mixed-farming systems dedicated to vineyards and cereal production | 4 |
| Permanent crops - high intensity | Irrigated permanent highly intensive with average size. | 107 |

The peri-urban area of Pisa is mainly characterized by cereal-industrial farming systems representing around 50% of the total UUA in 2007 and 56,3% in 2015. Mixed cereal-legumes are the most affected farming systems towards cereal-industrial (6,5%) and legumes-industrial systems (2%). In the same way, mixed-crops tended to change towards cereal-industrial (4,65%). The farming system changes are mainly located on the plain part of the area, whereas on the hilly part the olive growing system is rather stable.

In the region of Avignon, we observed an increase in irrigation as well as increasing labor inputs and yields. Analyzing the shift between the two years observed and comparing the different farming system distributions, we assessed farming system changes, as shown on Fig.4.

The most relevant changes were from table grapes to specialized vineyards (11%), mixed vineyards, and cereals systems (18%), and from cereals systems and permanent crops with high intensity to mixed crops of vineyards and cereals systems (22% and 16%). Moreover, more transitions resulted from permanent crops with low intensity to those with higher intensity (around 13%). Fig. 4 shows the main farming system changes on the two case studies.

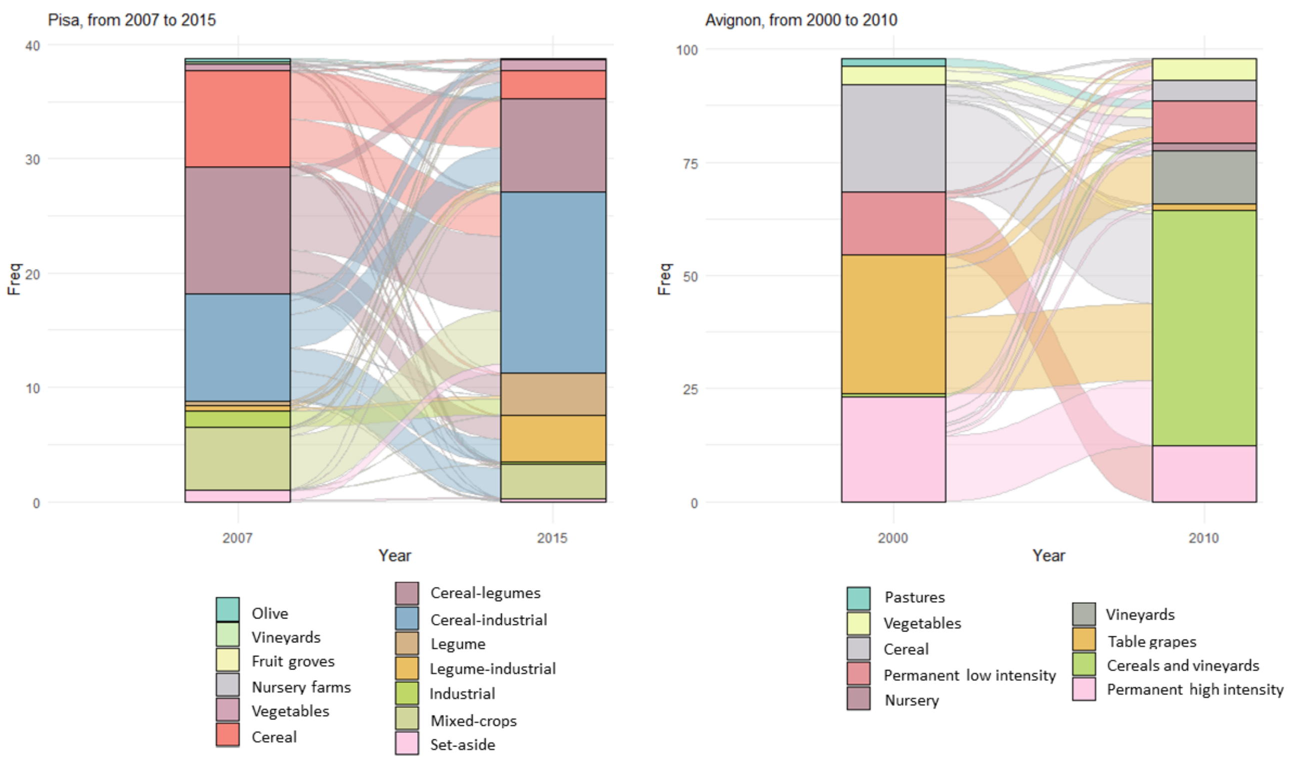


Figure 4: Farming system changes on the two-study area of Avignon and Pisa.

## 4.2 Farming system trajectories

The farming system changes observed have been classified in terms of corresponding trajectories applying the conceptual framework explained on §3.2. The results are shown on Tab.3. In Pisa, the most relevant trajectory is intensification/specialization, whereas extensification is concentrated more on the hilly part of the area. In Avignon, the results are very different, as we observe different trajectories and also located in similar areas.

Tab.3: Farming system trajectories observed on the two case studies

| Case study | Trajectory | Farming system change | Surface % |
|---|---|---|---|
| Pisa | Intensification | Mixed-crops -> Cereal-industrial | 5 |
| | | Cereal-industrial -> legume-industrial | 2 |
| | Specialization | Mixed cereal-legumes -> cereal-industrial | 6.5 |
| | | Mixed cereal-legumes -> legume-industrial | 2 |
| | | Mixed cereal-legumes -> Legumes | 2 |
| | Diversification | Cereal-industrial ->Mixed-crops | 2.5 |
| | Extensification | Cereal-industrial -> Cereal-Legumes | 3 |
| | | Cereal -> Cereal-Legumes | 4 |
| Avignon | Specialization | Table grapes -> Specialized vineyards | 11 |
| | Diversification | Cereals systems -> Vineyards and cereals systems | 20 |
| | | Permanent crops -> Vineyards and cereals systems | 14.5 |
| | | Table grapes -> Cereal&Vineyard | 17 |
| | | Permanent high intensity -> Vegetables | 3 |
| | Intensification | Permanent low intensity -> Permanent high intensity | 12 |
| | | Pastures -> Permanent low intensity | 2 |
| | | Vegetables -> Permanent low intensity | 2 |
| | | Cereal -> Permanent low intensity | 2 |
| | Extensification | Permanent high intensity -> Cereal | 2.5 |

Join count test measures the presence of spatial dependence between observed farming system trajectories, and it has been observed to be more clustered in the region of Pisa (p-value<0.01) than Avignon (p-value<0.1). This is due to the different spatial structure of the agricultural lands on the two case studies. The peri-urban area of Pisa can be split on two sub-areas: the plain area, where cereal and annual crops are dominant and quite homogeneous within the zone, and the hilly area characterized by olive grows, which are stable over time. In this sense, the farming systems are spatially clustered, explaining the high degree of spatial dependence for the case of Pisa. The case study of Avignon has a different spatial structure: there is a bigger diversity of farming systems and they are less clustered within the whole landscape, explaining the lower value of spatial dependence. Moreover, for the case study of Avignon, considering the database we exploited, we could estimate also changes in terms of practices and not only in terms of production typology.

### 4.3 Drivers of farming system trajectories

We use the spatial probit model to avoid biases in the analysis of drivers due to spatial autocorrelation effects. It suggests that changes in the level of a single observation will have an impact on the expected probability of the event being analyzed in both own- and neighboring area. As suggested LeSage et al. (2011) and LeSage and Pace (2009), the interpretation of the coefficients is done through the marginal effects in farming change as consequence of changes in the explicative variables at same location (direct effect), on the surrounding observations (indirect) as well as the total effect. The effect would depend on spatial proximity of farm i to j, captured by the spatial weight matrix W as well as the strength of spatial autocorrelation coefficient measured by the parameter ρ (rh0). To better understand the coefficient meaning, we will consider the example of the effect of the variable ‘Utilised agricultural area (UAA)’ for the case study of Pisa. There, the average direct effect amounts to $-4.6*10^{-3}$, the average indirect effect to $1.2*10^{-4}$, and the average total effect to $-4.5*10^{-3}$. These values can be interpreted as follows: an increase of one unit in the UAA of any farmer i, leads to an average decrease of $4.6*10^{-3}$ on the probability of change in that same farm i (average direct effect); an increase of one unit in the UAA of any farmer i leads to an average increase of $1.2*10^{-4}$ in the probability of change of neighboring farms (average indirect effect). It has to be noticed that this scalar average measure cumulates over the spatial spill-overs of all other observations and it is usually greater in magnitude for nearby observations, gradually fading away for observations farther apart. The sum of average direct and indirect effects represents the cumulative total effect of a unitary change in the variable ‘UAA’ of one single observation.

Likewise, Tab.4 reports direct, indirect and total effects based on the estimated coefficients for the case study of Pisa. The elevation remains statistically significant, meaning that also for a generally plain area it is a factor driving the observed changes. On the one hand, we obtained significant signs for the factors related to soil quality (silt, high available water capacity and the organic matter). The silty soil and the quantity of organic matter exert a positive direct effect on the probability of intensification in that farm. However, the available water capacity leads to an average decrease on the probability of change in that same farm. On the other hand, factors related to both land use configuration (fragmentation) and the monoculture practices were statistically significant for intensification, i.e. fields and crops number as well as the cultivated area.

The results for the case of Avignon are reported on Tab.5. The most significant drivers reveal different scenarios on the farming system dynamics towards intensification: on the one hand, they are related to the urban influence; and on the other hand, to the farming practices and management. A greater distance to urban areas with lower values of population density, leads to the increase on the probability of extensification in a given farm. However, the increase of accessibility to the roads lead to more intensification. Farming practices related to irrigation and work units, both statistically significant, leads to the increase on the probability of intensification dynamics by the presence of permanent crops characterized by a high management intensity. The increase of the agricultural yields is leading to the decrease on the probability of changes corresponding to permanent crops with lower intensity management as well as vegetables. On the other hand, there are dynamics of specialization by the presence of vineyards, orchards & berry plantations in flood plain where availability water capacity is higher.

Table 4: Statistical modelling of drivers for the plain of Pisa area. Database of 259 farms. UAA means Usable Agricultural Area, more details on each variable in Appendix 3. Regression coefficients of the SAR probit model. *** if p-value<0.001; ** if p-value <0.01; * if p-value <0.05.

| | Coefficient | Direct effect | Indirect effect | Total effect |
|---|---|---|---|---|
| **(Intercept)** | -7.40e-01 | | | |
| **Protected area** | 4.36e+00 | 1.40e+00 | -3.64e-02 | 1.37e+00 |
| **Rainfall** | 2.48e-03 | 8.02e-04 | -2.07e-05 | 7.81e-04 |
| **Elevation** | -8.22e-02*** | -2.65e-02 | 6.85e-04 | -2.58e-02 |
| **Insolation** | -5.94e-08 | -1.91e-08 | 4.96e-10 | -1.86e-08 |
| **Gender of farmer** | 2.73e-01 | 8.80e-02 | -2.27e-03 | 8.57e-02 |
| **Age36-55** | 7.46e-01 | 2.40e-01 | -6.22e-03 | 2.34e-01 |
| **Age>55** | 4.62e-01 | 1.49e-01 | -3.85e-03 | 1.45e-01 |
| **Location** | -9.29e-02 | -2.99e-02 | 7.75e-04 | -2.91e-02 |
| **Distance from urban center** | 7.45e-03 | 2.40e-03 | -6.21e-05 | 2.34e-03 |
| **Distance from main roads** | 7.42e-02 | 2.39e-02 | -6.19e-04 | 2.33e-02 |
| **UAA** | -1.44e-02** | -4.66e-03 | 1.20e-04 | -4.54e-03 |
| **Number of cultivated crops** | -1.19e-01* | -3.84e-02 | 9.94e-04 | -3.74e-02 |
| **Number of fields** | 9.10e-03* | 2.93e-03 | -7.59e-05 | 2.85e-03 |
| **Amount of clay on soil** | 3.53e-02 | 1.13e-02 | -2.94e-04 | 1.10e-02 |
| **Amount of sand** | 2.45e-02 | 7.90e-03 | -2.04e-04 | 7.70e-03 |
| **Amount of silt** | 1.26e-01*** | 4.07e-02 | -1.05e-03 | 3.97e-02 |
| **Available water capacity** | -3.76e-02*** | -1.21e-02 | 3.13e-04 | -1.18e-02 |
| **Organic farming** | 6.05e-01 | 1.95e-01 | -5.05e-03 | 1.90e-01 |
| **Amount of organic matter on soil** | 1.52e-01*** | 4.92e-02 | -1.27e-03 | 4.79e-02 |
| **Flooding risk** | 1.56e-01 | 5.06e-02 | -1.30e-03 | 4.93e-02 |
| **Distance from river** | 3.31e-02 | 1.06e-02 | -2.76e-04 | 1.04e-02 |
| **Distance from water bodies** | -2.76e-01* | -8.92e-02 | 2.30e-03 | -8.69e-02 |
| **rho** | -2.64e-02 | | | |

Table 5: Statistical modelling of drivers for Avignon Area. Database of 85 farms. UAA means Usable Agricultural Area, more details on each variable in Appendix 3. Regression coefficients of the SAR probit model. *** if p-value<0.001; ** if p-value <0.01; * if p-value <0.05.

| | Coefficient | Direct effect | Indirect effect | Total effect |
|---|---|---|---|---|
| **(Intercept)** | 3.81e+03 | | | |
| **Elevation** | 2.12*** | 8.56e-11 | -5.45e-11 | 3.11e-11 |
| **Urban density** | -3.24*** | -1.30e-10 | 8.33e-11 | -4.75e-11 |
| **Population** | 1.12 | 4.53e-11 | -2.89e-11 | 1.65e-11 |
| **Distance from Avignon** | 2.17 | 8.77e-11 | -5.59e-11 | 3.19e-11 |
| **Distance from urban area** | 1.08e+02*** | 4.39e-09 | -2.79e-09 | 1.59e-09 |
| **Distance from the main roads** | -7.17e+01*** | -2.89e-09 | 1.84e-09 | -1.05e-09 |
| **Age of the farmer 36-55** | -1.21e+02*** | -4.88e-09 | 3.10e-09 | -1.77e-09 |
| **Age of the farmer >55** | -1.11e+02 | -4.49e-09 | 2.86e-09 | -1.63e-09 |
| **Age of the farm 36-55** | 9.85 | 3.97e-10 | -2.53e-10 | 1.44e-10 |
| **Farm activity: short food supply chain** | -5.45 | -2.19e-10 | 1.39e-10 | -7.98e-11 |
| **Surface on organic farming** | -1.39e+01 | -5.62e-10 | 3.57e-10 | -2.04e-10 |
| **Irrigated surfaces** | 2.93*** | 1.18e-10 | -7.51e-11 | 4.29e-11 |
| **UAA** | -8.11e-01 | -3.26e-11 | 2.08e-11 | -1.18e-11 |

| | | | | |
|---|---|---|---|---|
| **Work units** | 1.85e-02*** | 7.45e-13 | -4.74e-13 | 2.71e-13 |
| **Yield** | -1.81e-04*** | -7.31e-15 | 4.65e-15 | -2.65e-15 |
| **Available water capacity** | -2.75 | -1.10e-10 | 7.05e-11 | -4.02e-11 |
| **Insolation** | -7.01e-03 | -2.86e-13 | 1.82e-13 | -1.04e-13 |
| **Cadastral value** | -6.44e-03*** | -2.59e-13 | 1.65e-13 | -9.43e-14 |
| **Water resource management** | 1.22e+02*** | 4.94e-09 | -3.15e-09 | 1.80e-09 |
| **Distance from water bodies** | -1.11e-02*** | -4.47e-13 | 2.85e-13 | -1.62e-13 |
| **Water channels** | -8.16e+01*** | -3.29e-09 | 2.09e-09 | -1.19e-09 |
| **Protected area** | -1.11e+01 | -4.47e-10 | 2.85e-10 | -1.62e-10 |
| **Rho** | -8.22e-01*** | | | |

# 5 Discussion

## 5.1 Methodological discussion

This paper presents an innovative modelling approach to analyze farming system trajectories and their drivers. The proposed method was tested on two Mediterranean peri-urban areas, particularly complex in terms of farming system structure and dynamics: the area of Pisa (Italy) and Avignon (France). In particular, we started from an assessment of farming system changes and then we used a methodological framework obtained by existing bibliography to understand the main trajectories. Finally, we applied a spatial modelling approach to analyze the possible explanatory variables of these trajectories. Classifying observed changes in terms of their meaning for management and trade-offs allowed to better investigate the processes underlying the ongoing dynamics. In particular, this analysis can be considered as based on the land system approach, wherein a landscape is represented not only by its land use and land cover, but also by its structure and management (Verburg et al., 2015). In this sense, intensification and extensification trajectories give deeper insight for a global modeling analysis (Duvernoy, 2000; Ellis and Ramankutty, 2008; Letourneau et al., 2012).

For the last part of the analysis, i.e. the study of the relationships between farmers' changes in agricultural practices and a list of explanatory variables, we chosen to implement a spatial probit model. The advantage compared to other binary regression models, such as a standard logit model, is that it accounts for the spatial dependence of the dependent variables, that has been observed and measured in both case studies through a join-count test. Hence, to prevent inconsistent and inefficient parameter estimation, the choice of the spatial probit model seemed natural. On the other hand, interpreting the way in which changes in the explanatory variables impact the probability of a farmer's change in agricultural practices for a SAR Probit model is not straightforward and requires some care. The two main reasons are, firstly, that Probit models use a non-linear function to link the set of covariates to the dependent variable (normal distribution). Secondly, the presence of spatial autocorrelation of the dependent variable implies that changes in the value of one explanatory variable at one single location can affect all remaining observations (spatial spill over). There, marginal effects for the SAR Probit model are the key to infer the real effects of a change in explanatory variables on the probability of change in the agricultural practices of farmers, rather than the estimated regression coefficients.

However, under this scenario, marginal effects can differ from one observation to another and their true value can only be fully understood by looking at the complete matrices of cross derivatives. To account for the combined effects of a non-linear link function and for potential spatial spill-over effects, we hence adopted the methodology proposed by (LeSage et al., 2011; LeSage and Pace, 2009). They suggest using average measure for the direct, indirect and total effects of the model in order to display the general trend and to improve the interpretation of the results.

**5.2 Drivers of farming system trajectories**

In the case study of Pisa, the main farming system dynamics was intensification on the plain area, whereas the other parts of the case study presented a stability in terms of farm organization. In agreement with these results, the study of Silvestri et al. (2012) found on this area farming changes towards intensification in summer and winter cereals, fodder crops and length of crops rotation. In terms of farm management, over the last decades, farms divided their fields into smaller ones (Ruiz-Martinez et al., 2020). Nevertheless, in terms of urban sprawl, the proximity to urban areas is not the main drivers of the dynamics. The results of the drivers modelling show that these trajectories in Pisa are mainly related to agro-pedoclimatic conditions. In particular, soil characteristics are important determinants of the distribution of arable land: silty soils and organic matter have positive direct effects towards intensification. However, the high available water capacity decreases on the probability of change, and this is probably due to the fact that it is not a limiting factor for that farming systems. In general, these results are concordant with the literature about Mediterranean coastal plains, where we observe an intensification on the most fertile plains together with an abandonment of the less rentable productions because of the urbanization (Caraveli, 2000; Debolini et al., 2018). In this sense, the agro-pedoclimatic conditions which determine soil fertility seem to drive the farmers' choices on intensifying their productions. This was observed also by (van der Sluis et al., 2016), who found intensification process across Europe mainly located in areas with good farming conditions. Moreover, the prevalence of professional than hobby farmers is a key factor for them, and this is the case also in Pisa urban region, where permanent crops are diffused mainly among hobby farmers. In this sense, we observed the UAA as a relevant factor in driving intensification processes.

In Avignon, the circumstances are quite different because both the different agricultural dynamics and the distribution of the observed dynamics. The diversification to high-value crops such as horticulture is encouraged in these areas, because farmers have less pressure on land compared with traditional crops. Based on intensification processes, irrigation practices and the labor input (work units) are the most relevant factors. In this sense, specialization dynamics take place by the presence of vineyards, orchards and berry plantations in flood plain. Another important factor is the proximity to urban areas. Despite the significance of urban factors in Avignon, intensification processes are more likely to occur away from urban areas although close to good road infrastructure. The conditions of marketing (good road infrastructure) and favorable production (availability of irrigation water during warm periods, adequate temperatures in winter, deep soils) increase on the probability of intensification (Sanz Sanz et al., 2017). It is noted that this kind of agriculture create an environmental function around the urban systems. However, due to the lack of land guarantee (and its dependence on aid, in some cases), it offers little resistance to the effective progression of urbanization (Geniaux and Napoléone, 2005).

Comparing the two case studies, we can observe that in the Pisa region environmental and agronomic factors are more relevant to understand the intensification processes, whereas in Avignon socio-economic and geographical variables are the most relevant. This could be related also to the modeling results. In fact, according to the model, the results reflected a stronger spatial dependence in the case study of Avignon. Apparently, the plain of Pisa would show a more heterogeneous system in terms of intensification whereas in Avignon these changes occur on particular areas, thus, in a less clustered way. This could be due to the different spatial configuration of the two areas and the main existing farming systems. In fact, the Pisa region present a main urban center, so it can be considered as mono-centric, whereas the Avignon urban area is more scattered, with different important urban centers distributed all around the study area, in a poly-centric configuration (Zambon et al., 2017). This could also explain why the distance from the main urban area of Avignon is not a relevant explaining factor for intensification, whereas the distance from the nearest urban area play a relevant role. In terms of farming systems, Pisa is mainly characterized by mixed cereals-livestock farming, which are more likely to be influenced from agro-pedoclimatic conditions, as observed by (Pacheco de Castro Flores Ribeiro et al., 2021).

## 6. Conclusions

Our results provide new evidence supporting the hypothesis that peri-urban farming systems trajectories are influenced by different factors based on their spatial configuration and the characteristics of their farming systems. In general, peri-urban regions cannot be defined just in terms of their distance to city center and urbanization processes. Although it has been clearly identified the urban sprawl that characterizes the medium-sized regions, this factor is not relevant on farming systems trajectories on the region of Pisa, where structural agro-pedoclimatic variables are more significant on the probability of intensification. The region of Avignon reveals different aspects: the good road infrastructure and favorable production (availability of irrigation water during warm periods, adequate temperatures in winter, deep soils) increase the probability of farming system intensification in areas where the marked and the access conditions can be more favorable. In general, on the case of Avignon, socio-economic factors explain in a more significative way the different existing dynamics of intensification and extensification. This analysis can give important insight to develop specific policy measures to orient ongoing farming system trajectories and maintain productive systems in Mediterranean peri-urban areas.

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**CRediT authorship contribution statement**

**Irune Ruiz-Martinez:** Formal analysis, Investigation, Data Curation, Writing - Original Draft; **Davide Martinetti:** Methodology, Software, Writing - Review & Editing; **Elisa Marraccini:** Conceptualization, Supervision, Writing - Review & Editing, Project administration; **Marta Debolini:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

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