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Full Length Article

Double cropping in North Mediterranean cereal systems: farm size prevails over irrigation as adoption driver

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ABSTRACT

Double cropping (DC) is a promising strategy for cropping systems, diversification, and intensification. While it is widely adopted in tropical regions, its feasibility in temperate and Mediterranean areas depends largely on the length of the growing season. Climate change may further enhance thermal suitability of these regions for DC, although future water availability may decrease. However, large-scale assessments of DC adoption across diverse cropping systems in Mediterranean contexts remain limited. This study addresses this gap by systematically analysing DC patterns in the Friuli Venezia Giulia region using Land Parcel Identification System data from 2019 to 2023. It also evaluates three potential drivers associated to DC adoption: farm size, irrigation availability, and soil available water content (AWC) as farm size may influence DC as smaller farms seek to offset fixed costs and yield variability; irrigation can mitigate summer drought; and higher AWC may support DC, especially under rainfed conditions. Moreover, several drivers of adoption at the field and farm levels were tested through a binary logistic regression. A total of 122 winter/summer DC combinations were identified for the first time in the region, though only 12 types accounted for 91% of the DC surface. The most common system combined winter cereals (barley or wheat) with soybean. Contrary to expectations, small and medium-sized farms adopted DC less frequently than large farms, although they used it more intensively when implemented. Contrary to expectations, irrigation availability was negatively associated with DC adoption, likely owing to sufficient summer rainfall in the region. Consistently, areas with higher AWC showed lower DC adoption. Overall, DC is well integrated in northeastern Italy, where it represents a potential source for diversification, but also it appears to be an intensification strategy adopted primarily by larger, arable-oriented conventional farms. While DC adoption is largely supported for now by favourable rainfall patterns, climate change may constrain DC viability, particularly in rainfed systems.

1. Introduction

Climate change poses significant challenges to agricultural productivity and sustainability, particularly in temperate regions where shifts in temperature and precipitation regimes are altering crop growth conditions (Farah et al., 2025). Increasing the resilience of agroecosystems is therefore essential to ensure long-term food security and environmental stability (El Chami et al., 2020). One of the most promising approaches to enhance resilience is the implementation of crop diversification measures, which improve ecological stability (Arndt and Helming, 2025), resource use efficiency (El Chami et al., 2020), and adaptive capacity to climatic variability (Li et al., 2019). Such measures aim to reduce vulnerability to climatic shocks while maintaining or even improving productivity and profitability (Sridhar et al., 2025). At the same time, the agricultural sector increasingly requires a better understanding of territorial dynamics to identify the diversification practices adapted to each region and system. In particular, regional patterns of crop distribution and farm management allow the tailoring of crop diversification practices to a particular territory, finding the most effective options considering both agronomic (e.g. pedoclimatic conditions, crop rotations), and socioeconomic aspects (e.g. food supply chains). However, diversification measures at the landscape level are poorly addressed in the literature (Arndt and Helming, 2025). In this context, the growing availability of spatially-explicit data offers valuable opportunities to improve our understanding of farmland dynamics, which is fundamental to designing adaptive and sustainable agricultural

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strategies.

Crop rotation, cover cropping, cultivar mixtures, intercropping, and double cropping are the most common diversification strategies in arable systems (Hufnagel et al., 2020). These practices contribute to soil fertility enhancement (Raseduzzaman and Jensen, 2017), pest, and disease diminution (Altieri, 1999), weed control (Liebman and Dyck, 1993), improved resource allocation across seasons (Tilman et al., 2002), and higher cropping intensity; thus supporting the transition toward more sustainable agricultural systems. Among these practices, double cropping (DC) represents a form of intensification like intercropping. Double Cropping consists of sowing and harvesting two crops in the same field within a single year, but in contrast to intercropping without overlapping their crop cycles (Kawasaki, 2019). Double Cropping has been promoted to increase total biomass yield and nutrient use efficiency without expanding cropland, thereby reducing the negative environmental impacts associated with agricultural intensification (Heggenstaller et al., 2008; Ranck et al., 2020). In South America, DC allows a more efficient use of land, machinery, and labour, potentially enhancing economic resilience for farmers (Silva, 2012; Moura and Goldsmith, 2020). Nevertheless, DC also presents several agronomic and environmental challenges due to the intensification of land use, which could affect soil quality if not well managed (e.g. decrease soil organic carbon). Moreover, DC increases water demand and may face limitations such as insufficient thermal time accumulation, harvest constraints, or drought stress, particularly under rainfed conditions (Liu et al., 2019; Lamichhane et al., 2023). For these reasons, DC is traditionally typical of tropical and subtropical regions, where temperature and water availability support multiple cropping cycles (Waha et al., 2020; Dou et al., 2023). The Mediterranean basin, characterized by dry summers and irregular rainfall distribution, has only recently been considered for potential DC systems, mostly for forage, biomass or biofuel production (Su et al., 2025; Sessa et al., 2026), or even for food crops in areas where irrigation is possible (Zugusti-Lopez et al., 2024). However, Mediterranean areas are mostly rainfed (Zhu et al., 2025). The limited irrigation availability and the highly fragmented farms characterizing Mediterranean farmland, leads to an irregularity of irrigation availability at farm level. This makes it necessary to consider crops water needs at the farm level.

Despite the recognized benefits of crop diversification, the extent and adoption of DC in Mediterranean Europe remain poorly characterized. A comprehensive understanding of where and under what conditions DC can be implemented effectively is crucial to support sustainable agricultural development. As temperate regions continue to warm under climate change, the lengthening of the growing season and increased thermal time accumulation may open new opportunities for DC adoption (Porter, 2005; Zhao et al., 2017; Gammans et al., 2025). Studies have shown that in Southern Europe, DC of wheat followed by maize is feasible under current conditions and could offset climate-induced declines in caloric productivity (Su et al., 2025). Yet, most of the existing literature focuses on field trials testing agronomic feasibility, or on research conducted in tropical and subtropical regions, while few studies investigate the extent of DC and the drivers of DC adoption in the global North and particularly in the Mediterranean (Marković et al., 2025).

Methods to characterize DC at the regional or national level commonly involve the use of remote sensing, which allows monitoring the cycle of tillage, growth, and harvest of multiple crops in a year. Rufin et al. (2019) using Landsat time series were able to quantify double-cropped surface in Turkey as 8.5% of the annual croplands. Waha et al. (2020) using national or subnational dataset coupled with crop calendars were able to estimate that at a global level, the area under multiple cropping systems covers 12% of cropland and has potential to increase world food security. In other cases, double cropping is a part of the data from national censuses and can easily be quantified, even though those data are not spatially-explicit but aggregated at municipality or county levels (Xu et al., 2021). An interesting but still unexplored source of data at least in the European Union is the Land Parcel Identification System (LPIS) yearly reporting spatially-explicit data declared by farmers on their land use and practices (Sagris and Devos, 2008). To the best of our knowledge, no research has yet exploited this data to map double cropping. The advantages of LPIS with respect to remote sensed data are not only the possibility to map DC but also to identify its intensity at the farm level, intended as the amount of DC on the total cropped farmland.

The adoption of double or multiple cropping in literature was identified to be related to different factors: first climatic ones such as length of the growing season or rainfall patterns (Gammans et al., 2025) but also those related to the profitability of double cropping (Feng et al., 2017). Most of these studies are conducted in the Global South and the US, and drivers in Mediterranean Europe remain largely unexplored. Only Pitchers et al. (2023) investigated the constraints for DC in Southern France as perceived by farmers, highlighting as main constraints work organization, available water for irrigation, available machines in case of relay cropping, difficult weed control, and lower efficiency to provide other services than cover crops. Particularly, from on-farm experiments, the same authors showed that irrigation is the main practice securing the harvest of the second crop.

This research has two aims. The first aim is to detect and describe DC patterns at a regional level in Mediterranean Europe using LPIS-derived parcel records. As DC is a very little-studied practice in Mediterranean areas, information on DC patterns at regional level will improve our understanding of the relevance of this crop diversification and intensification practice. The second aim is to detect factors associated with DC adoption to better understand the potential for DC development at the regional level. Building on the literature review, local expert knowledge, and six preliminary interviews with farmers, we formulated a set of hypotheses to be tested. These hypotheses are intended to identify the structural, environmental, and management factors that may explain the presence of DC in farms and fields across the region.

- Farm size hypothesis: DC is expected to be more common in small and medium-small farms, which tend to be more exposed to climate risks (e.g., drought, floods, or hail) and more sensitive to the need to increase cropped area (Islam et al., 2024). Therefore, we hypothesize a negative association between farm size and the presence of at least one DC parcel on the farm (DC adoption).
- Irrigation availability hypothesis: DC requires a proper amount of water to complete two crop cycles in the same year. Without irrigation, the success of the second crop is strictly dependent on rainfall, so irrigation availability should increase the success rate and yield stability of DC and consequently its adoption (Pitchers et al., 2023). We then hypothesize that DC adoption is positively associated with the availability of irrigation at the farm level.
- Available water content (AWC) hypothesis. For the same reasons as in the previous case, soils having a higher available water content, irrespectively to their management as irrigated or rainfed, can be considered more suitable for DC adoption. We hypothesized that DC adoption is positively associated with higher AWC classes.

Considering that ongoing climate change could make DC feasible in new areas of Europe (Pitchers et al., 2023, Su et al., 2025), improving our understanding of the environmental, farm, and field drivers of DC adoption can provide valuable insights for future studies on DC suitability and intensification under changing climatic conditions.

2. Materials and methods

2.1. The case study of Friuli Venezia Giulia region

The study area is the Friuli Venezia Giulia (FVG) region, located in northeastern Italy, at the northern edge of the Adriatic Sea, bordering Austria (north) and Slovenia (east). Friuli Venezia Giulia belongs to the

Mediterranean North in the climatic stratification of Europe (Metzger et al., 2005), aggregating most of the Mediterranean areas and excluding drier areas not suitable for DC. Friuli Venezia Giulia is characterized by an average annual rainfall of 1510 mm (ARPA FVG, 2023), of which approximately 613 mm occurs between June and August, ensuring relatively favourable water availability during the summer season. The average annual temperature is around 13 °C. Soils are heterogeneous (ERSA FVG, 2006). From north to south, after the alpine area there are shallow soils with low AWC in the hilly region, deeper soils with high content in gravel in the high plain and the deepest and fertile soils of the region in the low plain, close to the Adriatic Sea. A spring line separates the two areas as it happens all over the Po river valley (Martelli and Granati, 2006). Agricultural systems are characterized by small-scale farming as half of farms are smaller than 5 ha, 40% are between 5 and 50 ha, and only 6% of the farms are bigger than 50 ha. These bigger farms cover half of the total usable agricultural area (UAA) as reported by FVG (2025). Cropping systems in FVG are mainly based on summer crops, particularly maize and soybean, grown in rotation with winter cereals, such as wheat and barley. Overall, these biophysical conditions make FVG a potentially suitable region for DC systems. In fact, DC is already practiced in FVG and well-integrated in regional cropping systems as highlighted by the study of Virili et al. (unpublished) concerning DC in soybean-based systems. The combination of these biophysical characteristics, along with the increasing attention to diversification practices for climate change adaptation, make FVG an illustrative case to explore DC extent and adoption in the Mediterranean North areas.

2.2. Overall method

To investigate the spatial distribution of DC and the factors of DC adoption, we used the land parcel identification system (LPIS) database, which provides spatially-explicit and yearly updated data on the crop distribution as declared by farmers (Sagris and Devos, 2008). In this database, DC is not explicitly reported but farmers have the capability to declare different crops several times in the same parcel within the same year. In Italy, LPIS is managed by AGEA (Agenzia per le Erogazioni in Agricoltura) in most of the regions (including FVG until 2022), whereas in other regions it is managed independently by regional authorities. Starting from 2023 declaring the second crop became mandatory, whereas before 2023 it was voluntary. In both cases (before and after 2023), in the FVG LPIS database some parcels are "duplicated" as the same parcel is present several times with different declarations of a crop. These duplicated parcels may correspond to real double crop combinations or mistakes due to erroneous updates by the farmer. It can happen that the old version remains in the database generating false DC with unrealistic crop declarations for the same year (e.g.: two summer crops like soybean and sorghum for the same parcel). In these cases, it is impossible to define which of the two, or more crops, was cultivated. These cases were removed from our database. All other situations of two crops on the same parcel in the same cultivation year were kept and considered as possible DC. The six on-farm interviews conducted to gather information to formulate hypothesis on possible DC drivers, were also used to test the accuracy of the DC identification method, the reliability of the observed crop combination, and to collect additional information on DC management practices. More detailed information about the methodology is provided in Section 2.3.

Starting from this knowledge, to identify DC we developed three steps of identification, cleaning, and validation of DC parcels (Fig. 1). After that, we combined the generated database with information included in LPIS (e.g.: irrigation availability) and other ancillary data (e.g.: soil AWC databases) to test factors affecting DC distribution across the region at the farm and field levels.

2.3. Methodology to find DC

Five annual LPIS layers (2019–2023) of the FVG region were obtained from AGEA and OPR (Organismo Pagatore Regionale, translated in English Regional Payment Agency). Each parcel reports an anonymized farm code, a parcel ID, the surface area, the crop code and crop

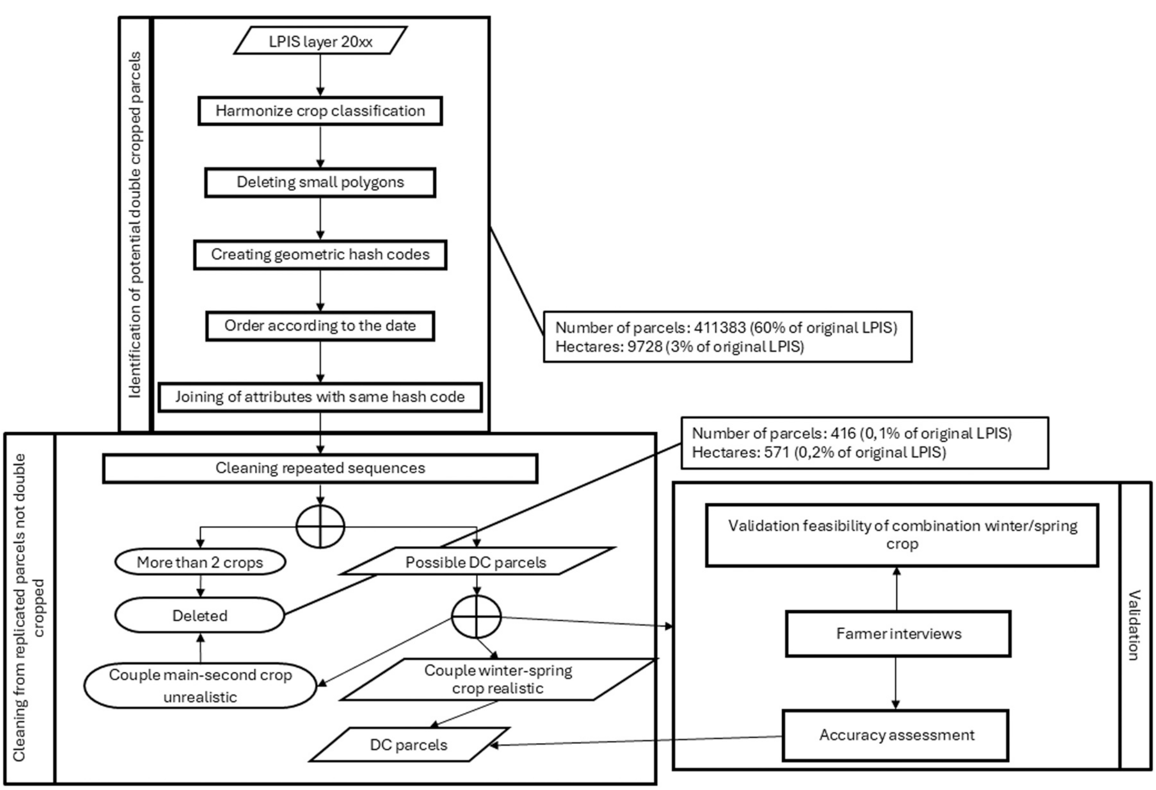

Fig. 1. Methodology to find double cropped parcels from a LPIS layer.

use with 5 numbers, the start and the end of validity of the land cover declared on that parcel, irrigation availability, and other information on the farm management such as of the parcel under organic, soil conservation, or labelled low-input production. Among the five years, 2023 represents the most complete dataset because it became mandatory to declare the second crop. Double Cropping areas from 2019 to 2022 are likely underestimated as DC declaration was voluntary. This makes any interannual comparison based on absolute areas almost impossible. However, local experts (farmers, policy-makers, advisors) considered that the overall relative frequency of DC sequences remains comparable over the years because they saw no factors that may cause under- or overestimation of DC frequencies. Consequently, a qualitative comparison in terms of relative abundance of DC types (association of first and second crops) is still meaningful.

To prepare the LPIS database for a multiple year analysis, several data harmonization steps were performed (Fig. 1). Firstly, crop and crop use codes in the original LPIS changed from one year to another. For example, over the five-year study period, maize was represented by 22 different codes in the original classification (supplementary Material S1). In contrast, the harmonized classification developed to facilitate multi-year analyses reduced these to two codes, distinguishing grain maize from silage maize (supplementary Material S2). So, to make the comparison among years easier, we standardized crop codes across years, reducing them from 3745 original combinations of crop and crop use codes to 544 unique codes. Then, as in the 2023 database 686,329 parcels were present, most of them having very small size, we removed very small parcels to avoid potential methodological biases and make further elaboration easier without losing representativity. We consulted local experts (farmers, policy-makers, and advisors) who stated that parcels smaller than 1000 m^2 are hardly used for productive agriculture in FVG, eliminating approximately half of the parcels but less than 3% of the total agricultural area. This size threshold was also used by Levavasseur et al. (2016) and Marraccini et al. (2020) in managing LPIS data in France. To increase the reliability of this step, land use of the deleted small parcels was analysed showing that 73% of the deleted surface was used for non-productive purposes, e.g. buildings, field margins, or ditches and channels. The next step was to reduce all replicated parcels to one parcel reporting the information of all the copies. So, we created a unique alphanumeric sequence (hash code) for each geometry (parcel). Then, the script sorted the parcels by the starting date and combined all the information of the different parcels with the same hash code. The output no longer contained duplicated geometries. However, overlapping parcels with different IDs were still present, representing either identical crops (e.g., soybean/soybean) or incompatible crop cycles (e.g., maize/soybean or maize/soybean/wheat).

Both cases occur when the farmer changes the declared crop adding a new parcel rather than modifying the existing one. In the first case (soybean/soybean), where the crop did not change, we consider it a single cropped parcel, while in the second case (two summer crops or more than 2 crops) we discard that parcel as we are not able to identify the crop. There was also a third case that could lead to false positives, when farmers change their mind from a winter crop to a summer one, for example because of difficult winter sowing. In this case, even though the two crops were reliable, as we could not distinguish if it was a choice or an error in the declaration, we used the starting and the end dates of the two crops to check the temporal reliability. The unreliable cases of false DC accounted for 401 fields excluded and 0.2% of the LPIS surface. The final output of this cleaning step was composed of 3 layers without duplicated parcels: 1) all the DC parcels considered reliable (two crops at least, no doubts on the crop succession between the two crops, no spatial overlapping); 2) the UAA, excluding non-productive land, woods, or buildings; 3) the arable land, excluding orchards or home gardens.

To validate the LPIS-based DC identification process and collect qualitative data on the factors associated with DC adoption, a survey was conducted in six farms covering 347 ha of arable land (0.2% of regional arable land) accounting 73.3 ha of DC in 2023 (0.3% of DC surface) in the FVG region (supplementary material S3). The farms were identified through a snowball approach by considering the farm land use (either arable crops-based or permanent crops-based (orchards) with a part of arable crops) and the distribution in the FVG region. The two aspects to validate were the reliability of the methodology (an identified DC corresponds to a real cropped DC in a farm) and the feasibility of first /second crop combinations detected (the sequence of the crop couple corresponds to the real sequence of a given farm, the combinations removed are reported in supplementary material S4). For each farm, we checked all the parcels declared in 2023 to confirm the location and crop combination of DC and full season (SC) crops. The questionnaire was designed accordingly. The results of the parcel validation are shown in supplementary material S5. Moreover, we asked information on the farm characteristics, cropping systems, crop location, and DC management practices in the year 2023. The interviews were also used to refine the hypotheses to be tested for DC adoption drivers. No personal data was collected and consent for data elaboration was given to the authors.

2.4. Factors affecting DC adoption

Based on the literature review and the preliminary interviews, three main factors were identified as potentially influencing DC adoption in FVG: farm size, irrigation, and soil available water content (AWC).

- Farm size hypothesis: we hypothesized that small farms are more willing to adopt DC than bigger farms as a strategy of land intensification. To test the hypothesis, we compared the farm size from the LPIS database in terms of Usable Agricultural Area (UAA) and the farms having at least one DC parcel (adopter) vs the farms not having DC parcels (non-adopters). Based on the UAA distribution in FVG, three levels of farm size were considered and compared to DC adopters/non adopters: small farms having a surface of less of 5 ha, medium-sized farms between 5 and 50 ha, large farms having a UAA of more than 50 ha. In a second step, as several adopters had more than one DC parcel, we calculated the DC intensity, expressed as the ratio between DC surface and arable land at the farm level. We also associated the DC intensity with the three levels of farm size.
- Irrigation availability hypothesis: we hypothesized that farms having DC have a higher irrigation availability due to the higher amount of water needed for growing two crops. Moreover, considering the same crop e.g. maize, the amount of water needed is higher in double cropping due to a shift of the crop cycle in the summer. In the LPIS data there is information about irrigation availability for each parcel. When checking the reliability of this information with the land reclamation consortia, 99% of the fields where irrigation is available are irrigated (data not shown) so we can assume that parcels where irrigation is available are actually irrigated. Starting from this variable, we assessed the share of irrigated area for each crop type relative to the total irrigated area, considering both SC and DC. Moreover, for each summer crop, we calculated the ratio of irrigated and rainfed areas in SC or DC. We compared the irrigated and rainfed areas for the summer crops mostly involved in the most common DC types.
- Available water content (AWC) hypothesis: we hypothesized that DC area is higher where AWC is higher due to higher water needs of summer crops in DC. In irrigated fields this effect can be hidden by irrigation, so we expect to have a clearer relation in rainfed fields rather than in irrigated ones. Starting from the 5 classes of AWC defined in the regional map (ERSA FVG, 2006) going from <50 mm (very low) to >200 mm (very high), we aggregated the lowest and highest classes to obtain 3 AWC classes that were used in the analysis (low class, <100 mm; average class between 100 mm and 150 mm; high class >150 mm). We made the aggregation considering that, in terms of crop management there are no differences between "very low (<50 mm)" and "low (50–100 mm)", as well for high

(150–200 mm) and very high (>250 mm) classes. The AWC map was intersected with LPIS arable crop parcels, and each parcel was assigned an AWC value computed as the area-weighted average of the soil units occurring within the parcel.

2.5. Statistical analysis

Three different statistical analyses were made. First, we analysed the spatial autocorrelation of the DC and SC parcels to understand if there was a spatial clustering or these parcels were randomly distributed in the region using global and local Moran's autocorrelation indices (I and LISA respectively) (Moran, 1950; Koutsos et al., 2021). For that we constructed a spatial weights matrix using the K-nearest neighbours' algorithm (K=8) to prevent topological isolation caused by landscape fragmentation (such as rivers and canals). The spatial operations were implemented via a custom Python script utilizing the "GeoPandas" and "PySAL" ecosystems. The Global Moran's I significance was validated through a non-parametric permutation test with 999 random simulations. Results were considered clustered with a Moran's I equal to one or unclustered with an index close to zero. Then, we used LISA to map and classify the parcels in 4 classes. High-High class (hotspot) identifies statistically significant areas where DC parcels are near to other DC parcels. The Low-Low class (coldspot) identifies those areas where SC parcels are near to other SC parcels. The High-Low class identifies spatial outliers where DC parcels are isolated and surrounded by a neighbourhood dominated by SC parcels, while the Low-High class delineates areas where SC parcels are enveloped by neighbouring parcels characterized by high DC intensity.

Second, for each hypothesis we tested the significance of the different factors through a chi-square test of goodness-of-fit as we have nominal variables (our classes of farm size, irrigation and AWC) and we want to see if the number of observations in each category fits a theoretical expectation. The statistical analysis was performed in RStudio (2026.01.0 + 392) using the "dplyr", "ggplot2", "grid", "pwr" packages. For the theoretical expectations, we proceed as follows for the three hypothesis: 1) farm size: we accounted for the total number of farms of the three DC intensity classes of less than 40%; between 40% and 70%; more than 70% (0.15: 0.65: 0.20); 2) irrigation availability: in this case we used the distribution of irrigated vs rainfed arable surface (0.44: 0.56); 3) AWC: in this case we used the distribution of the three classes of AWC in the arable land (low 0.41: medium 0.14: high 45).

Third, we evaluated the drivers of DC adoption at both the farm and field (parcel) levels using a binary logistic regression model, implemented as Generalized Linear Models (GLMs) with a binomial error distribution and a logit link function. In both analytical levels (farm and field), the dependent variable was a binary index "DC adoption" (1 for adopters, 0 for non-adopters). At the farm level, the predictors used were total UAA (ha) and the respective ratio of arable crops, irrigation availability, low AWC class, high AWC class, organic farming, and soil conservation farming. At the field level, the explanatory variables were the field area (m^2), the ratio of summer crops in the last 5 years, the irrigation availability, the previously defined AWC classes, if the field was under no till management, organic management, and the geographic position relative to the spring line (top or bottom). To account for the nested structure of the field level data and potential intra-farm correlation, standard errors for the parcel level model were clustered at the farm level. Both models were estimated within the RStudio environment using the packages "glm", "sandwich", "lmtest", and "margins".

3. Results

3.1. General results about DC in arable cropping system

Arable crops of FVG regions are mainly summer crops with soybean and maize accounting for 29 and 26% of the arable land respectively in 2023. Winter cereals represented on the other side 20% of the arable land. While winter cereals and soybean increased their surface in the considered time span (2019–2023), maize decreased constantly (Fig. 2) when considering both full season cropping and DC.

Double Cropping represented 14% of the arable land in 2023 and resulted in a total of 122 different DC combinations. Twelve of them individually accounted for more than 1% of the total DC area, covering 91% of total DC area. The most frequent winter/summer crop sequences are represented by barley or soft wheat in combination with soybean, which represents 66% of the total DC area (Table 1). The same winter cereals in combination with maize are less frequent, representing less than 10% of the total DC area. In that case, 84% of the DC maize area is used for silage. Other DC specific to livestock farms (fodder grass coupled to maize or soybean) have a limited area, covering 3% of the DC area.

From 2019 to 2023, we were able to assess only the relative changes among DC types, as the declaration of DC was voluntary between 2019 and 2022. The 2023 data are considered reliable because DC declaration became mandatory. Therefore, although the 2019–2022 data may not represent the complete extent of DC adoption, the distribution and relative abundance of DC types during this period can still be considered representative of DC uses in the region.

Fig. 3 shows that the soybean-based DC types represent a larger relative share in the later years of the dataset, whereas the maize-based DC types show a decrease in the same years, consistently with the increase of the total crop surface in the region. Other minor types like sorghum-based DC remained stable.

Double Cropping visually appeared poorly clustered (Fig. 4). We validated the visual assessment through the Global Moran's Index showing a small clustering effect (I = 0.1967, Z-value = 95.7922, p-value = 0.001). The local index of spatial autocorrelation (LISA) of DC highlighted that the 96.4% of the arable surface has not significant autocorrelation (supplementary material S6); there are not significant coldspot; finally, the hotspots of DC are spread all over the region, covering 0.8% of arable land.

3.2. Factors associated to DC adoption in the FVG region

3.2.1. Farm size

Fig. 5 illustrates the adoption of DC in at least one parcel versus SC across different farm sizes (Fig. 5a), and the distribution of DC intensity in the farm size (Fig. 5b). The ratio between farms in DC and SC is very low in small farms (0.07) and medium-sized farms (0.34), whereas in large farms this ratio is beyond one (1.16). On the other hand, it is possible to notice in Fig. 5b that small farms having DC are few, and that most of the small farms practicing DC have a DC intensity of more than 40%. On the contrary, big farms tend to have a smaller DC intensity, as most of these farms have a DC intensity of less than 40%. Finally, medium-sized farms showed the highest number of DC, mainly characterized by low DC intensity, similarly to what happened in large farms. It appears that the bigger DC intensity classes (> 40%) is decreasing in percent of the farm size class from 73% in the small farms, 34% in the medium-sized farms, 19% in the big farms. For each of the three classes of arable land represented in Fig. 5, we found a significant difference from the general distribution of the three DC intensities (FS <5 ha: χ^2 = 229.92, df = 2, p-value < 2,2e−16; 5 <FS <40: χ^2 = 3323,9, df = 2, p-value < 2,2e−16; FS > 50: χ^2 = 1720,5, df = 2, p-value < 2,2e−16;). When observing the DC area for each of the classes of arable land, we observe that small farms (FS < 5) have a very low amount of hectares in DC whereas medium sized (FS between 5 and 50 ha) and large farms (FS > 50 ha) group most of the DC area (FS < 5 = 11682,7 ha; 5 < FS < 50 = 56184,8 ha; FS > 50 = 43618,4 ha). In the cases of medium-sized and large farms, the DC intensity is lower (DC < 40%) than in small-sized farms.

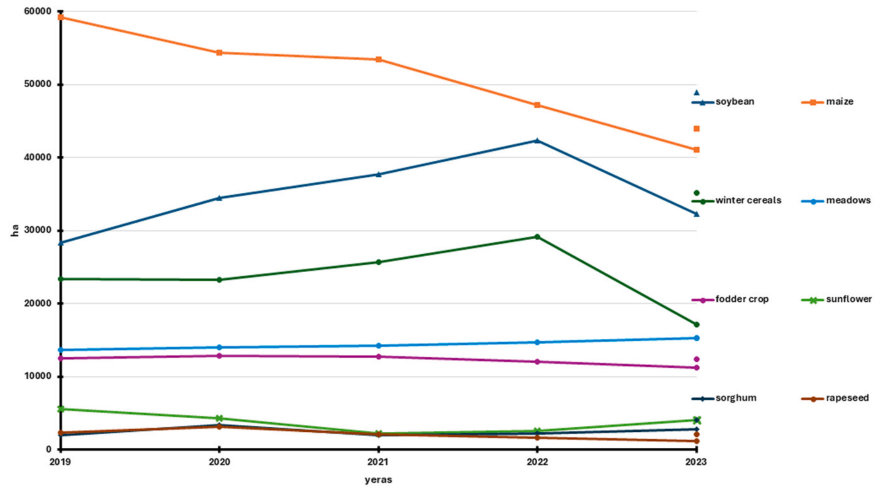

Fig. 2. Arable crops dynamics in FVG region during the considered time span (2019–2023). Winter cereals (wheat, barley, and triticale) and fodder crops including clover are grouped. The single points in 2023 represent the sum of the crop in full season and DC. Crops with less than 1% of the arable land area are not included. Source: own elaboration on regional LPIS data (2019–2023).

Table 1
Main double cropping (DC) combinations in Friuli Venezia Giulia region in 2023. In “mainly for silage”, yes means that more than 70% of the summer crop is used for silage. Source: own elaboration on regional LPIS, 2023.

	ha	% on DC	% on arable land	Mainly for silage
Barley/Soybean	8132	38.2%	5%	No
Soft wheat/Soybean	6008	28.2%	4%	No
Barley/Maize	1049	4.9%	1%	Yes
Rapeseed/Soybean	981	4.6%	1%	No
Soft wheat/Maize	728	3.4%	1%	Yes
Triticale/Soybean	603	2.8%	0.4%	No
Soft wheat/Sorghum	452	2.1%	0.3%	Yes
Triticale/Maize	389	1.8%	0.3%	Yes
Fodder grass crop/ Maize	308	1.4%	0.2%	Yes
Ryegrass/Soybean	256	1.2%	0.2%	No
Fodder grass crop/ Soybean	246	1.2%	0.2%	No
Barley/Sorghum	241	1.1%	0.2%	Yes
Other DC (<1% of DC area)	1887	8.9%	1%	Not relevant
Total	21,280	100%	14%	

3.2.2. Irrigation

Whereas in SC the agricultural area with available irrigation covered 43,000 ha and rainfed agricultural area accounted for 37,221 ha, in DC these areas were 9640 ha and 8960 ha, respectively. These values indicate a similar DC/SC ratio for irrigated areas (0.22) and rainfed areas (0.24). To provide a descriptive overview of these patterns, we further investigated the patterns by summer crop type. The main full season irrigated crops in the region are maize (27,040 ha) and soybean (13,449 ha), which are also the main irrigated DC as shown in Fig. 6. On the contrary, the less common summer crops in DC are sunflower and sorghum. When comparing SC and DC per crop, it is possible to notice that the ratio of rainfed areas is always lower in DC than in SC (Fig. 6), with a maximum difference in the case of maize. We can also observe that soybean, sunflower, and sorghum present a similar pattern in terms of ratio between rainfed and irrigated areas, whereas maize shows the higher amount of irrigated areas in DC with respect to SC. Descriptive chi-square test confirmed that each summer crop represented in Fig. 6 showed a significantly different distribution than the average between the rainfed and irrigated areas as a SC or DC (soybean: $\chi^2 = 3579{,}2$, df = 3, p-values < 2,2e−16; maize: $\chi^2 = 16{,}571$, df = 3, p-values < 2,2e−16; sunflower: $\chi^2 = 1119{,}9$, df = 3, p-values < 2,2e−16; sorghum: $\chi^2 = 158{,}2$, df = 3, p-values < 2,2e−16).

3.2.3. Soil available water content

To complement the spatial analysis with a descriptive breakdown, the summer crops considered have a similar pattern within each AWC class in rainfed and irrigated areas respectively. In rainfed conditions, the amount of soybean and maize DC decreases with the increase of AWC (Fig. 7) and soybean represents more than half of the surface in the three classes of AWC. In irrigated conditions, maize has at least half of the surface in the three classes of AWC. In soybean, the amount of DC is higher in low AWC (9%) rather than in average or high AWC (2 and 6% respectively), as occurs for sorghum (8, 2 and 4%). In rainfed conditions, descriptive chi-square tests confirmed that the distribution of SC and DC in each AWC class is significantly different to the average distribution of rainfed summer crops for each AWC class (Low AWC: $\chi^2 = 1807{,}2$, df = 3, p-values < 2,2e−16; Average AWC: $\chi^2 = 312{,}24$, df = 3, p-values < 2,2e−16; High AWC: $\chi^2 = 1799{,}2$, df = 3, p-values < 2,2e−16).

3.2.4. DC adoption at farm and field levels

Table 2 and supplementary Materials S7 present the main results of the factors of DC adoption at the farm and field levels. The farm level analysis shows for log-UAA a positive and highly significant impact on DC adoption ($\beta = 0.922$; $p < 0.001$). Specifically, the odds of adopting DC increase by a factor of 2.51 for each unit increase in log-UAA (OR = 2.515), which corresponds to an increase in the net probability of adoption by approximately 10.9 percentage points (AME = 0.109). The two land-use indices exhibit contrasting and statistically significant effects. A higher proportion of arable crops (Arable_crops_ratio) represents the strongest positive driver in the model ($\beta = 3.078$; $p < 0.001$; OR = 21.72). The average marginal effect confirms this, with a full transition toward arable land increasing DC probability by 36.5 percentage points (AME = 0.365). Conversely, the increased presence of forage (Forage_crops_ratio) acts as a significant deterrent ($\beta = -1.496$, $p < 0.001$), decreasing the probability of adoption of DC (AME = −0.177). Unexpectedly, the available irrigated ratio (Irrigated_ratio) displays a slight negative correlation with DC adoption ($\beta = -0.142$, $p = 0.045$; OR = 0.867), reducing the probability of farms to adopt DC (AME = −0.017). Regarding soil quality, a low AWC (Low_AWC_ratio) significantly increases the likelihood of adoption ($\beta = 0.722$, $p < 0.001$; OR = 2.059; AME = 0.086), whereas a high AWC (High_AWC_ratio) exhibits a negative effect ($\beta = -0.225$, $p = 0.037$; AME = −0.027). Organic management (Organic_ratio) drastically reduces the probability of double cropping ($\beta = -1.292$, $p < 0.001$; OR = 0.275). Holding other

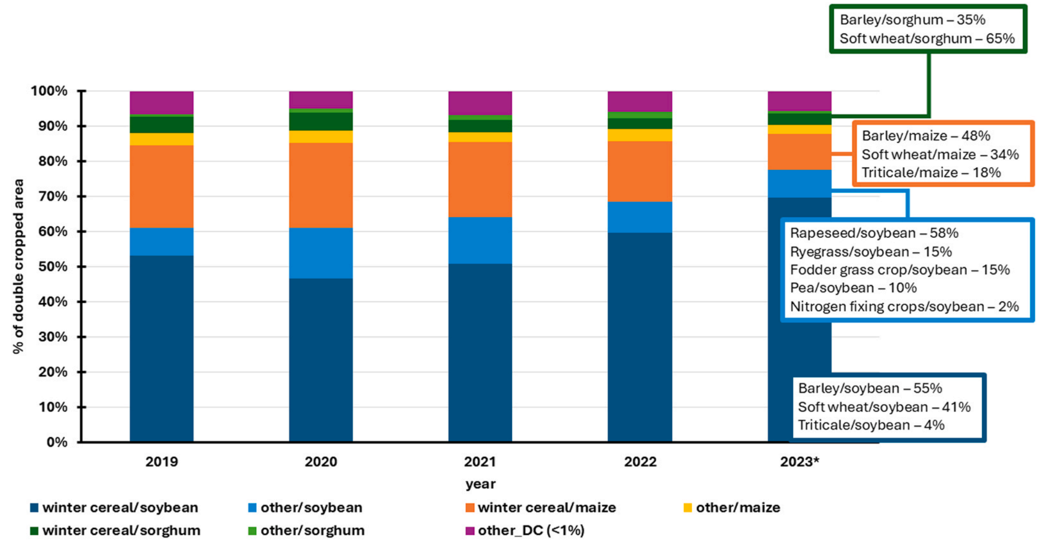

Fig. 3. Main double cropping (DC) types in FVG region (2019–2023) and their ratios on the total DC surface. Other/soybean/maize/sorghum indicates another winter crop instead than winter cereal (e.g.: rapeseed or winter pea). OTHER_DC (<1%) groups DC combinations covering less than 1% of total DC area. Source: own elaboration on regional LPIS data (2019–2023). *From 2023 it was mandatory to declare all crops, whereas it was voluntary until 2022. Therefore, 2023 is the only reliable year in term of amount of DC, while 2019–2022 DC are underestimated. On the contrary, for DC types, the relative proportion is considered reliable also in the 2019–2022 time span.

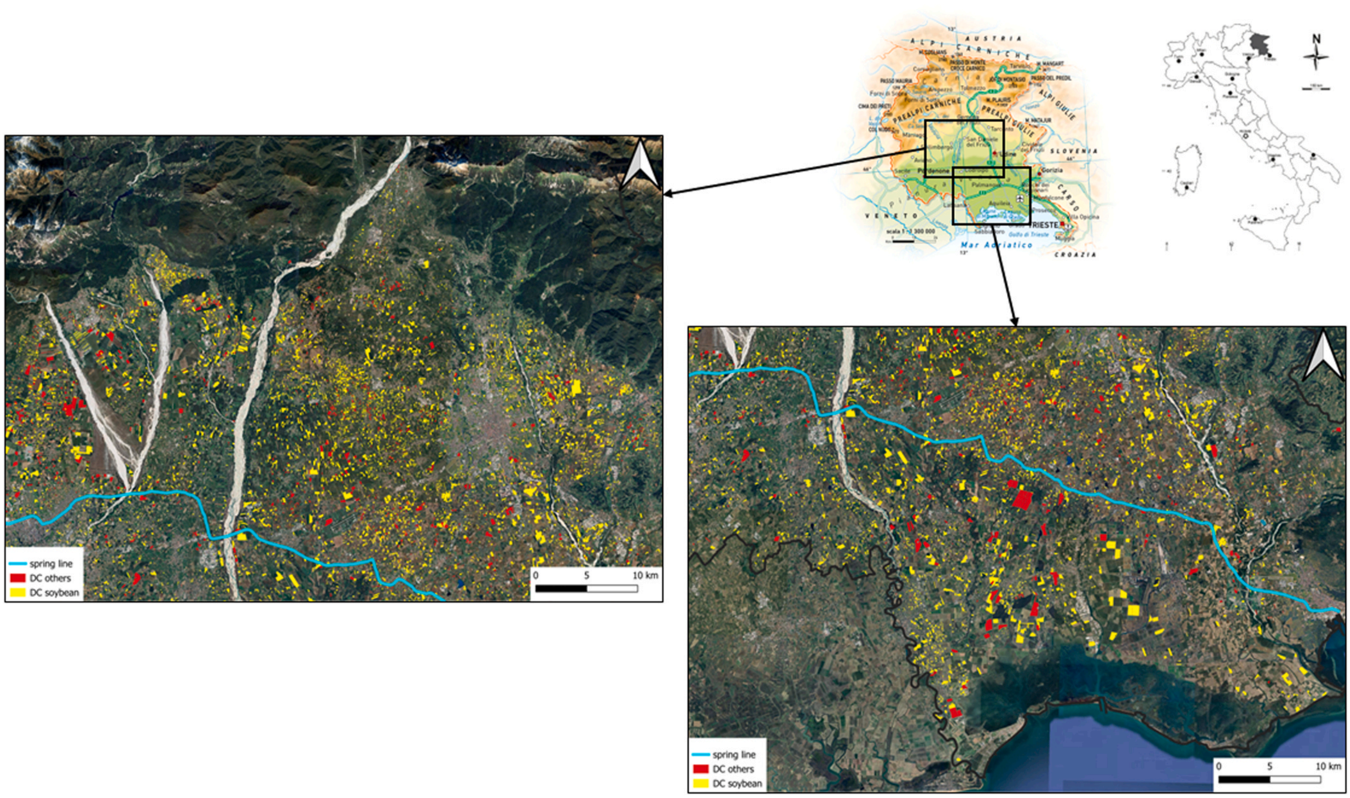

Fig. 4. High plain (a) and low plain (b) captions, scale 1:200,000. In yellow double cropped (DC) fields with soybean as second crop, in red double cropping (DC) with other second crops. In blue, the spring line.

factors constant, organic farms have a 15.3 percentage point lower probability of adoption (AME = −0.153) compared to conventional ones. The conservation practice of no-till (No_till_ratio), while displaying a positive trend (β = 0.346, OR = 1.413, AME = 0.041), does not reach statistical significance (p = 0.123).

At the field level, the size of the field (log_area) exerts a positive and highly significant impact on DC adoption (β = 0.205, $p < 0.001$). For each unit increase in the logarithm of the field area, the odds of adoption increase by a factor of 1.23 (OR = 1.228), which translates into a 2.4 percentage point increase in the net marginal probability of adoption (AME = 0.024). The presence of irrigation availability (Irrigation_availability) shows a slight negative correlation with DC (β = −0.129, p = 0.039, OR = 0.879), marginally decreasing adoption probability by 1.5 percentage points (AME = −0.015). Interestingly, the location in

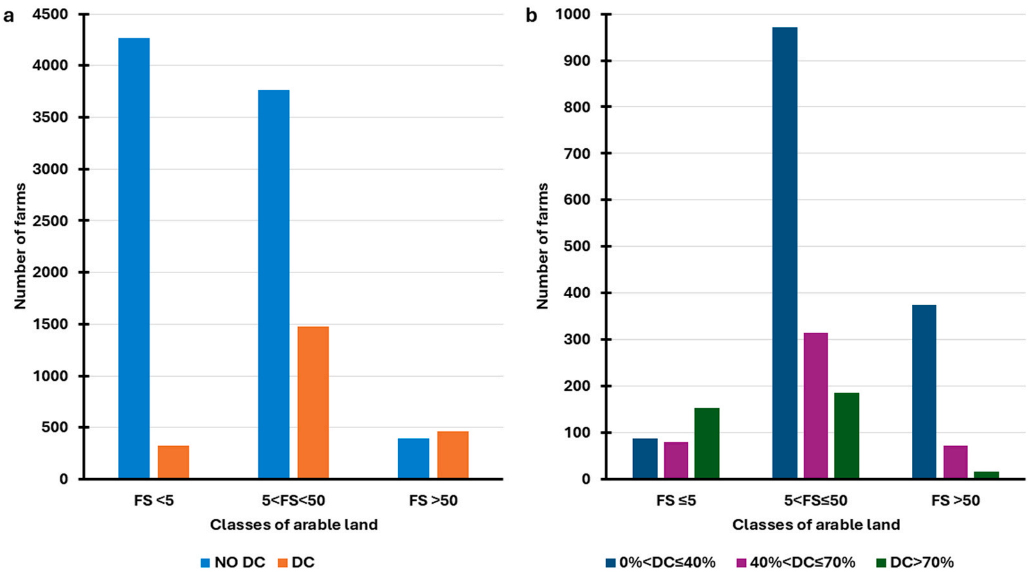

Fig. 5. Number of farms adopting DC on at least one side and not adopting DC across farm size (FS) classes (FS: <5 ha, >5 ha and <50 ha, >50 ha) (a) and number of farms practicing double cropping divided for FS and double cropping (DC) intensity (<40%, >40% and <70%, >70% of the arable land) in Friuli Venezia Giulia region in 2023 (b). The distribution of farms using DC is significantly different ($p < 0.001$) from the expected distribution of farms in each farm class size in the region. Source: own elaboration on regional LPIS, 2023.

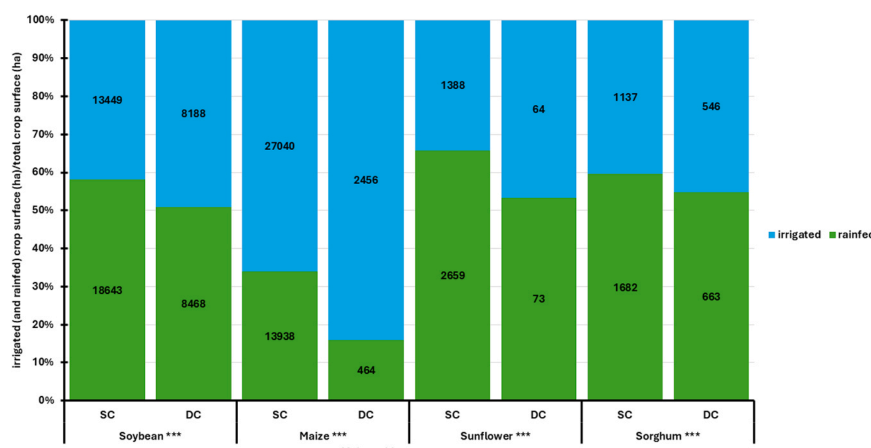

Fig. 6. Portion in irrigated and rainfed condition (ha), in full season cropping (SC) and double cropping (DC) of the main arable crops. The distribution of the area in the 4 categories is significantly different ($p < 0.001$) to the average distribution of crops in the region. Source: own elaboration on regional LPIS, 2023.

respect to the spring line (North/South) acts as a highly significant deterrent ($\beta = -0.263$, $p = 0.001$), decreasing the net probability of finding a DC parcel by 2.9 percentage points (AME = −0.029) compared to fields located to the North of this hydrogeological feature. Low available water capacity (AWC_Low) significantly favours adoption ($\beta = 0.357$, $p < 0.001$, OR = 1.430, AME = 0.044), while high water retention (AWC_High) decreases the probability by 1.6 percentage points ($\beta = -0.153$, $p = 0.041$, AME = −0.016).

4. Discussion

4.1. DC adoption in Friuli Venezia Giulia (Italy), a North Mediterranean region

This research focused on double cropping (DC), an intensification technique poorly investigated in European and Mediterranean cropping systems. Our results showed that DC is well integrated in FVG cropping systems, where it covered 14% of arable land recorded by the regional LPIS in 2023. Double Cropping is spread all over the region, with a significant but weak regional autocorrelation and only limited local hotspots. It involves the main arable crops of the region, winter cereals with soybean and maize. While 122 DC types of winter/summer crops were identified for the first time in the region, just 12 DC types are the most common, each covering more than 1% of the regional DC surface for a total of 94% of the regional surface interested by DC. The most common DC type is the winter cereal/soybean, which is also the most common DC type in other environments such as the US or southwestern France (Pitchers et al., 2023; Parvej and Holshouser, 2025). Even though several authors (Santos Hansel et al., 2019; Parvej and Holshouser, 2025) highlighted a yield difference between soybean in full-season and in DC, particularly in high-yielding environments, Virili et al. (2024) during a survey with farmers in the FVG region showed that soybean in DC appeals to farmers because of the easier management and the lower irrigation needs than full-season soybean. The relevance of the DC types can be also related to the farm technical-economic orientation. For instance, the most common winter cereal/soybean DC type can be retrieved in diversified arable farms, whereas livestock farms tend to use other DC types such as winter cereals associated with silage maize or

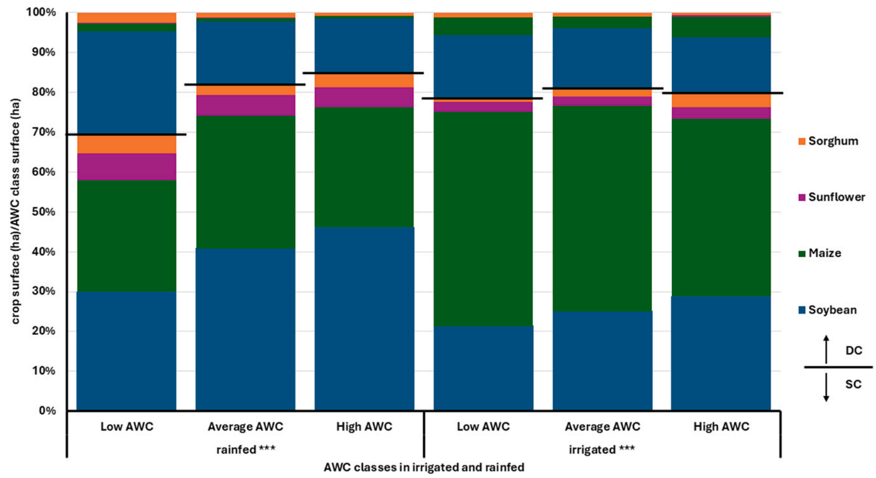

Fig. 7. Differences of crop proportion in the three available water content (AWC) classes in rainfed and irrigated conditions (SC: full season cropping). In rainfed conditions the crop distribution in AWC classes differs significatively ($p < 0.001$) to the regional distribution. Source: own elaboration on regional LPIS, 2023.

Table 2
Logit regression estimation results for DC adoption at the farm and field analytical levels. β represents the estimated log-odds regression coefficient, indicating the direction and strength of the relationship; SE represents the cluster-robust standard error measuring estimation precision; z value denotes the Wald z-statistic evaluated against the standard normal distribution and P(>|z|) indicates the two-tailed significance probability (p-value). p < 0.05*; p < 0.01**;0.001***. For farm level model the variables are: log-UAA indicates the natural logarithm of the farm's total UAA (ha); arable_crops_ratio indicates the percentage of arable crops calculated over the farm UAA; the Irrigated_ratio indicates the percentage of UAA where irrigation is available; low AWC ratio indicates the percentage of the farm's agricultural land in the low AWC class; high AWC ratio indicates the percentage of the farm's agricultural land in the high AWC class; organic ratio indicates the percentage of the farm's UAA managed under organic farming practices; no till ratio indicates the percentage of the farm's UAA managed under conservation agriculture; forage crop ratio indicates the percentage of forage crops calculated over the total farm UAA. While for field level model the variables are: log_area indicates the natural logarithm of the specific agricultural parcel area (m^2); irrigation availability indicates a binary status if the individual parcel has access to irrigation or not; organic management indicates if the individual parcel is managed under organic practices; spring line South indicates if the agricultural parcel is geographically located at south of the spring line or in the north; AWC High indicates if the parcel belongs to a high AWC soil class; AWC Low indicates if the parcel belongs to a high AWC soil class; no till index indicates that the parcel is conducted in conservation tillage (no-till practices); summer crop ratio indicates the historical 5-year proportion of summer crops cultivated on the parcel.

FARM LEVEL	**β**	**SE**	**z value**	**P(>|z|)**
Intercept	−6.04542	0.165076021	−36.62202793	1.28e^{-293}***
log_UAA	0.922079	0.024614643	37.46059822	4.04e^{-307}***
Arable_crops_ratio	3.078303	0.129883699	23.70045366	3.57e^{-124}***
Irrigated_ratio	−0.14242	0.07100338	−2.00578691	0.044878988*
Low_AWC_ratio	0.722086	0.098569221	7.325671692	2.38e^{-13}***
High_AWC_ratio	−0.22541	0.107989838	−2.087314882	0.03685968*
Organic_ratio	−1.29227	0.192909222	−6.698830072	2.10e^{-11}***
No_till_ratio	0.345564	0.224201422	1.541308789	0.123241651
Forage_crop ratio	−1.49587	0.105017109	−14.24404101	4.88e^{-46}***
FIELD LEVEL	**β**	**SE**	**z value**	**Pr(>|z|)**
Intercept	−4.18924	0.190246	−22.0202	1.85e^{-107}***
log_area	0.205292	0.019964	10.28321	8.39e^{-25}***
Irrigation_availability	−0.12899	0.062478	−2.06453	0.038968*
Organic_management	−0.19678	0.2061	−0.95479	0.339685
Spring_line_South	−0.26268	0.079935	−3.28618	0.001016**
AWC High	−0.15263	0.074813	−2.0402	0.041331*
AWC Low	0.357407	0.079309	4.506495	6.59e^{-06} ***
No_till_index	0.734995	0.135504	5.424158	5.82e^{-08} ***
Summer_crop_ratio	1.036478	0.069741	14.86175	5.84e^{-50} ***

sorghum (Fouli et al., 2012). Specialized farms, such as vineyards and orchards, that include arable land generally do not adopt DCs within their cropping systems (supplementary material S8).

4.2. Factors associated to DC adoption

Starting from the DC types, we have tested three factors associated with DC adoption in FVG region: farm size, presence of available irrigation, and the AWC. The results depicted a more complex picture than we expected. First, DC adoption at the farm level was assessed in relation to farm size. We found that, among small and medium-sized farms, the number of farms adopting DC was lower than the number of farms exclusively adopting SC. Conversely, in large farms, the number of DC adopters was slightly higher than those of farms adopting only SC. Moreover, small farms practising DC appeared to have a higher DC intensity than medium and big farms where the DC intensity decreased. From a methodological point of view, the 1000 m^2 filter affected the distribution of farm size (FS) classes by reclassifying 332 borderline medium-sized farms into the <5 ha category. However, because the DC/SC ratio remained below 1 in both small and medium-sized farms and exceeded 1 only in large farms, this reclassification is unlikely to have influenced the overall results. The results on the farm size suggest that small farms have a greater tendency to increase cropping intensity, only a limited proportion of small farms adopt DC (7%), although those that do generally apply them intensively (DC intensity >70%). Conversely, DC adoption is more widespread among larger farms (31%), but with lower intensity levels (DC intensity <40%). When comparing several adoption factors, the positive effect of both farm size (log_UAA) and field size (log_area) suggests that scale is an important driver of double-cropping adoption. At the farm level, larger farms were substantially more likely to adopt DC, with the odds increasing by a factor of 2.5 for each unit increase in log-UAA. A possible explanation of this result may be that DC requires more operations than full season cropping, and despite the need to increase the surface, the availability of machines for the proper tills can be a limiting factor. While bigger farms more often have the machineries and organization required, at the same time the need to intensify is less pressing. This could explain why there are more farms practicing DC in large farms and why they practice it less intensively than smaller farms. In the literature, there are contrasting results about the role of farm size in DC adoption. Most of the studies refer to the Global South where multiple cropping is more common than in Global North. Phetcharat et al. (2017), found that larger farms are more inclined to allocate land to multiple cropping than small farms in Thailand. This was also the case in the work of Haileyesus and Mekuriaw (2021) that observed that the adopters of wheat-chickpea double cropping are significantly larger than non-adopters. On the other hand, Shapiro et al. (1992), studying wheat–soybean DC systems in the US Midwest, highlighted that this DC combination did not appear to be scale-dependent across the range of farm sizes considered in their study. This can suggest that the link between farm size and DC can be context dependent. Second, we showed that irrigation availability appears to be associated with crop choice, particularly maize, which is more often grown as a full-season crop. The results suggest that soybean is the alternative to maize for the fields where irrigation is not available, and in comparison soybean appeared to be more suitable for DC. Thus, irrigation availability, which favours maize that is more likely cropped as a full season crop, may indirectly discourage DC practice. This is probably due to the rainfall pattern of the region where in the summer period (June to August), more than 100 mm per month is still available (ARPA FVG, 2023). So, the results on irrigation availability suggest that at least for soybean, sunflower, and sorghum, the water amount for summer crops in DC can be almost fully provided by rainfall. On the contrary, in southwest of France (Pitchers et al., 2023) irrigation is considered fundamental for both soybean and sunflower in DC. This result has also been found by Calatrava et al. (2025), who underlined that in Aragon (Spain) multiple cropping was considered a suitable diversification alternative only in irrigated cereals. This contrasting role of available irrigation in the uptake of DC may find its explanation in the amount of summer rainfall being higher in FVG than in Nouvelle Aquitaine or Aragon. While in the US climate change is expected to have a positive effect on the yield and acreage of double cropped soybean mainly due to the increase of the frost free season (Gammans et al., 2025), in the FVG, where the rainfall patterns may change, this would be a concern for local stakeholders for all types of summer crop based DC systems. Finally, the results on AWC seems to enhance this explanation, as we showed a lower portion of the DC area in high AWC classes to be independent of irrigation availability. A possible explanation is that farmers try to maximize the profitability of what they have. So, in soils with a better AWC it would be more profitable to find a full season crop rather than a double cropped alternative. The logistic regression results show that, for both low and high AWC classes, the effects are stronger at the farm than at the field level. Although this difference partly reflects the distinct spatial scales of analysis, it suggests that farm-level management conditions have a greater influence on DC adoption than the soil characteristics of individual fields. Thus, the likelihood of DC occurring on a low or high-AWC parcel appears to be more closely related to overall farm management than to the soil quality of the individual parcel.

The results of the binary logistic regression analyses at both the farm and field levels were consistent with the tested hypotheses. At the farm level, the analysis also provided additional insights, indicating that large conventional farms specializing in arable crops seems to be more likely to adopt DC than smaller farms or those oriented toward organic production, or forage crops. Given that organic farms and those implementing soil conservation practices frequently rely on crop diversification to enhance resilience and manage pests (Barbieri et al., 2017; Adeux et al., 2022), these findings suggest that, in the Friuli Venezia Giulia (FVG) region, diversification strategies may differ from DC. Specifically, farmers may preferentially adopt alternative practices, such as extending crop rotations or implementing intercropping systems.

4.3. Limitations of this study

The present study detected double cropping using LPIS, leveraging the specific characteristics of the Italian database. The results demonstrate the potential of LPIS as a valuable data source for capturing different aspects of crop diversification at regional level, as previously shown by several authors, such as Leteinturier et al. (2006), Stein and Steinmann (2018), or Reumaux et al. (2023). Those authors used LPIS to model crop sequences or crop rotations in a given area, in this case it is the first time that DC is detected by LPIS. This was favoured by the structure of LPIS that allowed this identification, but it is unknown if the methodology can be adapted to other LPIS structures. For instance, in the case of French LPIS, only full season crops are declared by farmers (Levavasseur et al., 2016). Usually, for studies at regional or territorial levels centred on crop diversification, Sentinel images are analysed (Dobrinić et al., 2021) because of LPIS limits for territorial analysis. These limits are related to the structure of the database, changing among the EU members. So, in any case it is possible to assess crop sequences or diversification, but DC or intercropping depends on the declarations allowed in the LPIS structure. The internal characteristics of the LPIS limit its use, such as the use of changing codes across years requiring a time-consuming dataset cleaning or changing the rules for crop declarations that allowed only partial analysis in the 2019–2022 time span. This calls for the integration of LPIS analysis with other data such as remote sensing (David et al., 2021) to test the reliability of the analysis. Moreover, as LPIS is based on farmers' declarations, farmers' interviews can support a deeper understanding of on-farm decision making in DC adoption.

5. Conclusions

In this study, we developed and applied a methodology for identifying and monitoring double cropping (DC) in Northeastern Italy using LPIS. The approach provides a first framework for tracking DC adoption from 2023 onwards, enabling future assessments of its temporal dynamics and role within crop rotations. Due to the favourable climatic conditions of the Friuli Venezia Giulia region, DC is well integrated in local cropping systems, occupying 14% of the arable land in 2023 and is broadly distributed across the region, showing only weak spatial autocorrelation and a few localized hotspots. Although 122 different DC combinations were identified during the 2019–2023 period, winter cereals (wheat or barley) followed by soybean dominated the system, representing 66% of the DC area in 2023.

Three factors associated with DC adoption were investigated, the farm size, the availability of irrigation, and the available water content (AWC). The farm size was associated with both likelihood and intensity of adoption. Medium and large farms appeared more likely to implement DC, whereas smaller farms tended to allocate a larger share of their cultivated area to DC when adopting the practice. This pattern may reflect differences in machinery availability, economies of scale, or reliance on contract services. Irrigation availability and higher AWC were more frequently devoted to full-season crops, particularly maize, whereas DC was more commonly associated with soybean and soils characterized by lower AWC.

Taken together, the results at the field and farm level suggest that double cropping is not merely a response to favourable environmental conditions for small farms. It appears to be an intensification strategy adopted by larger, arable-oriented conventional farms of the region and preferentially implemented on specific fields characterized by operational advantages due to large size and particular soil conditions. The negative effects of irrigation and high AWC may indicate that there are more important drivers of adoption than resource availability alone. This analyses reveals that adoption decision-making operates at multiple scales, with structural farm characteristics shaping the decision to adopt, and local biophysical conditions determining where the practice can be implemented. From a broader perspective, the widespread adoption of DC in FVG demonstrates the capacity of local farming systems to exploit long growing seasons and favourable summer rainfall. However, projected increases in the frequency and severity of spring and summer droughts may alter the agronomic and economic viability of these systems, potentially increasing their dependence on irrigation and affecting their contribution to cropping system diversification.

Future studies may investigate DC adoption in different farming systems, such as alternative and conventional systems, or livestock and arable farms. Moreover, further research can focus on the crop rotations where DC are involved, to understand if DC can be considered itself a diversification practice by the introduction of different summer crops than the other full season crops in the rotation, or an intensification practice to increase the annual surface of summer crops, as the results at the farm level seem to suggest. The method developed to study DC is to the best of our knowledge implementable over all Italian regions where CAP payments are managed by AGEA due to the LPIS structure, even though further validation on datasets from other Italian regions and from dataset of FVG after 2023 are needed to make stronger the methodology. The use of this method in other countries may be determined by the local LPIS structures and farm declarations.

CRediT authorship contribution statement

Antonio Bruno: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Philippe Martin:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Elisa Marraccini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used AI-assisted technologies to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given her role as member of the editorial board and co-guest editor of the Special Issue "Designing multi-actor farming practices for agrifood system transitions", Elisa Marraccini had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they 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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijagro.2026.100113.

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