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ORIGINAL ARTICLE

Trajectories and drivers signalling the end of agricultural abandonment in Trás-os-Montes, Portugal

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Abstract
Agricultural abandonment has given rise to novel landscape dynamics worldwide. This paper investigates abandonment and post-abandonment dynamics in continental Portugal as a hotspot of landscape change. We mapped the spatial patterns and drivers of recent (1995–2018) land use changes in a remote mountainous region as post-abandonment trajectories, based on detailed land use/land cover data made available by the Portuguese government. We showed that 'Revegetation' trajectories, indicative of agricultural abandonment, were still widespread between 1995 and 2007. However, between 2007 and 2018, the landscape was much more stable with 'Return to agriculture' as the dominant change trajectory. To understand what drives landscape changes after abandonment, we explored the influence of a wide range of potential biogeophysical and socio-economic drivers on the observed trajectories. We contrasted different landscape outcomes in binary logistic regression models with the potential underlying drivers as independent variables. The regressions revealed that the most significant determinants of these alternating dynamics are existing land use, climate, slope, protection regime and accessibility. The results of the regressions are at times counterintuitive and give important indications of the changing spatio-temporal scales at which these variables exert influence on the landscape outcomes. However, the regression models' limited accuracies highlight the need for deeper investigation of the socio-economic and historic context of the observed changes. Improved understanding of the (drivers of) alternative dynamics following agricultural abandonment can help inform policy decisions regarding agriculture and cultural landscape preservation.

Keywords Land use change · Post-abandonment trajectories · Drivers · Afforestation · Recultivation

Introduction

Agricultural land abandonment is a dominant landscape change process in rural areas all over the world (Cramer et al. 2008). It is caused by a complex interaction of factors that can be split into two broad categories: environmental and socio-economic (Rey Benayas et al. 2007; Terres et al. 2015; Lasanta et al. 2017). The first includes drivers determining the suitability of land, such as climate, topography and soil characteristics (Plieninger et al. 2016). The second covers a wide range of human-induced factors, such as demographics, market dynamics, policies, tenure systems, technological advancements and cultural and historical aspects (van Vliet et al. 2015; Plieninger et al. 2016). Agricultural abandonment gained momentum in rural Europe in the 1950s (Anguiano et al. 2008; Keenleyside and Tucker 2010) and has particularly affected remote and mountainous areas (MacDonald et al. 2000; Estel et al. 2015; Lasanta et al. 2017). Continental

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Portugal is considered a hotspot of land use change in Europe (Caetano et al. 2005; Feranec et al. 2010; Kuemmerle et al. 2016), with coastal areas urbanising rapidly, while inland agricultural areas were abandoned at high rates (Alves et al. 2022). The study of land abandonment in the Portuguese interior has been focused on the landscape impacts, such as wildfire frequency and severity (Azevedo et al. 2011; Silva et al. 2011; Pereira et al. 2013; Sil et al. 2019), soil erosion and land degradation (Nunes et al. 2010, 2011; Sil et al. 2016; Ramos et al. 2017) and biodiversity changes (Godinho et al. 2011; Honrado et al. 2017), as well as on cultural and identity preservation (van der Zanden et al. 2018; Quintas-Soriano et al. 2022).

Just a few studies have investigated the driving forces behind landscape changes in Portugal (Van Doorn and Bakker 2007; Diogo and Koomen 2012; Meneses et al. 2017). In other European regions, the causes of land abandonment have been extensively researched, but the determinants of what drives landscape changes *after* abandonment are only recently receiving more attention (Munroe et al. 2013; Fayet et al. 2022a). These are mostly European case studies focused on specific post-abandonment trajectories such as recultivation (Estel et al. 2015; Smaliychuk et al. 2016; Dara et al. 2018; Pazúr et al. 2020; Corbelle-Rico et al. 2022) or vegetation succession (Poyatos et al. 2003; Weissgerber et al. 2023). Understanding the drivers of post-abandonment landscape change gains importance when forecasting future landscape changes and their accompanying processes and outcomes. For example, it is estimated that 50% of abandoned cropland globally will be recultivated within 30 years (Crawford et al. 2022), which limits their appropriateness for alternative purposes, such as carbon sequestration and storage (Schulp et al. 2008; Novara et al. 2017; Bell et al. 2020), biodiversity conservation (Daskalova and Kamp 2023) and rewilding or restoration (Navarro and Pereira 2012; García-Ruiz et al. 2020).

Within Europe, several EU policy and funding initiatives have directly or indirectly addressed agricultural land abandonment (Delattre et al. 2020; Zavalloni et al. 2021; Fayet et al. 2022a; Dimopoulos et al. 2023). In addition, national level policies such as conservation based on protected areas have for decades been promoting the maintenance of landscape dynamics in (pre)historically human-managed areas that are important for natural heritage conservation. This is particularly relevant in countries like Portugal, where some of the most valuable areas for nature conservation are simultaneously cultural landscapes, privately owned and subject to individual (or collective in the case of commons) management decisions (Frazão-Moreira and Martins 2023). While these policy measures counterbalance global market pressures and other megatrends, they do not include strategies addressing possible post-abandonment trajectories (Fayet et al. 2022a).

In this study, we applied a post-abandonment perspective to describe the landscape changes that are emerging in Terras de Trás-os-Montes (TTM), a remote, mountainous region in the northeastern interior of Portugal, valued for its biodiversity and cultural landscapes (ICNF 2023). TTM has experienced high rates of depopulation and agricultural land abandonment since the 1960s, which is projected to continue, according to previous research (Keenleyside and Tucker 2010; Levers et al. 2018b; Perpiña Castillo et al. 2021; Debonne et al. 2022). Studying landscape change in this area can provide essential insight into how trends, rates and patterns impact natural and cultural values and improve directions for land management and policy making that are also relevant for other regions facing similar challenges. Our objectives were to (i) quantify and spatially represent land use change processes in this region as post-abandonment trajectories, and to (ii) identify underlying drivers of these trajectories, in general and for each particular trajectory, and assess their respective effects over time.

Methods

Study area

TTM is an administrative region (Fig. 1) that covers an undulating, mostly Mediterranean landscape of 5544 km^2 on the Iberian Massif, with altitudes reaching nearly 1500 m in the higher mountains (Aguiar and Vila-Viçosa 2017; Pereira and Pereira 2020). The total area under cultivation in TTM peaked to about 70% in the 1960s (Nunes 2002) but had reduced to 44% by 1995 and 42% by 2018 (DGT 2023a). Population numbers also peaked to well over 200,000 inhabitants in the 1960s (INE 1962) before decreasing to 107,000 in the most recent census (INE 2022a). Climate change poses new risks to the region, namely drought and desertification, which negatively affects already low agricultural yields, as well as severe wildfires (Pereira et al. 2013; Sil et al. 2016; Debonne et al. 2022). TTM has a long tradition of extensive forestry and farming in different forms, including Pyrenean oak coppices, grazed orchards (Castro 2009), cork oak systems and humid or naturally irrigated permanent pastures (*lameiros*) (Pires et al. 1994). The region has four protected areas, three Natural Parks and one Protected Landscape, in addition to several Natura 2000 network sites and regional ecological corridors (ICNF 2023). The entire region has also been included in the UNESCO Meseta Ibérica Biosphere Reserve established in 2015 (Meseta Iberica Território | Reserva Biosfera Meseta Iberica n.d.).

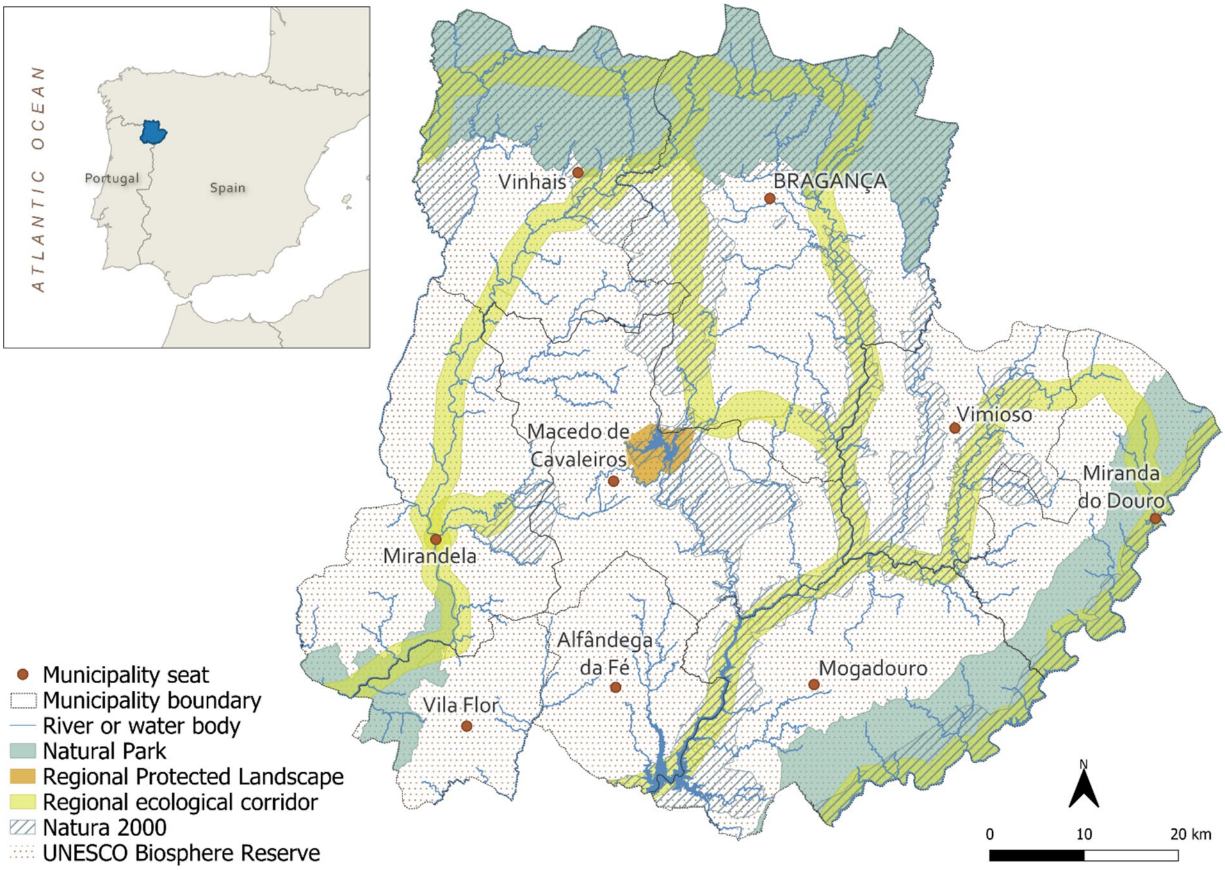

Fig. 1 Study area TTM and its location on the Iberian Peninsula. The various protection regimes highlight the region's importance for natural heritage conservation (ICNF 2023)

Data and analysis

Land use change

We based our analysis on the official Portuguese Land Cover & Land Use Maps (COS), a hierarchical classification system which currently distinguishes 83 classes (DGT 2022). The COS time series has been published for the years 1995, 2007, 2010, 2015 and 2018. COS maps are produced through the visual interpretation of 50 cm orthophotos (except for the 2018 version which is based on 25 cm orthophotos) and manual mapping in a vectorial data model. COS data are stated to be verified in the field and report a thematic accuracy of at least 85%. The minimum mapping unit is 1 ha and the minimum mapping width is 20 m, resulting in a scale of 1:25,000 (DGT 2022). A shortcoming of COS is that small land plots (< 1 ha) may be overlooked despite being very common in Portugal. Adjoining land plots may have the same land use, but this is not always the case.

We used the start and end points of the available time series for our analysis (1995 and 2018) and added 2007 as a middle point to create two study periods with a near-equal time span. We rasterized the available COS maps to a resolution of 5 m/pixel to capture the highest level of detail presented in the vector data. For the first part of the analysis, we reclassified the applicable land use/land cover (LULC) classes defined in COS to five broad categories: urbanised, agriculture, natural forest, forestry plantation, shrubland and water body (Feranec et al. 2010; Fayet et al. 2022b). We did not distinguish between different types of agriculture as the boundaries between systems are often fuzzy in this region. For instance, an olive or chestnut grove may also be used for grazing, or specific systems such as the abovementioned *lameiros*, which are used for grazing or hay cropping as well as fodder and firewood, are identified in COS as semi-natural systems rather than grasslands. Details on the reclassification process are available in Table S1 of the Supplementary Materials. To gain insight in the spatial distribution of the various LULC categories, we subsequently mapped each LULC category in area proportion per parish using official administrative data (DGT 2023b).

Trajectory analysis

The transitions among the six LULC categories were combined in a change matrix, allowing them to be assigned into four groups according to what Fayet et al. (2022b) call ‘directions of post-abandonment landscape change’: Managed revegetation, Spontaneous revegetation, Return to agriculture and Urbanisation (Fig. 2). This classification permits to focus more on the change processes rather than on the specific landscape outcomes, thereby bypassing regional differences or specificities. We reclassified the transitions in LULC categories between two moments in the time series, allowing us to quantify and map each trajectory. ‘Spontaneous revegetation’ encompasses all trajectories of natural vegetation succession after previous land uses have been abandoned, including, for example, transitions from agriculture to shrubland and from shrubland to natural forest. ‘Managed revegetation’ covered active afforestation trajectories leading to single species plantations. ‘Return to agriculture’ was any transitions from shrubland, natural or plantation forest to agriculture. Finally, ‘Urbanisation’ applied to all trajectories of urban transformation including infrastructure development such as roads. A detailed conceptual description of (post-)abandonment trajectories is provided by Fayet et al. (2022b). We further added ‘Water buffering’, an impactful trajectory resulting from the construction of dams and reservoirs, which was left out of our subsequent analyses as it involves decision-making mechanisms on a completely different scale. We then mapped the main trajectories in area proportion for each parish of TTM, to visualise the spatial patterns of landscape change across the region as expressed at local scales (Plieninger et al. 2016), which enabled us to profile localities according to the degree to which a specific trajectory occurred.

Analysis of underlying drivers

We used logistic regression to gain insight into the underlying drivers of landscape change (Overmars et al. 2007; Lakes et al. 2009; Lin et al. 2011; Müller et al. 2013). Logistic regression estimates a coefficient for each independent variable which allows to assess the significance and direction of influence (positive or negative) on the binary dependent variable (Corbelle-Rico et al. 2012). The most common trajectories we observed were tested as dependent variables in four different logistic regressions (referred to as ‘change regressions’ by Hatna and Bakker 2011). Each change regression compares a possible trajectory outcome (1) against a contrasting trajectory or landscape outcome (0) to assess the influence of a selection of independent variables in the observed outcome (Table 1). A combined (spontaneous and managed) ‘Revegetation’ trajectory was contrasted against ‘Staying in agriculture’ (regression R1) to assess drivers associated with agricultural abandonment, while ‘Managed revegetation’ was contrasted against ‘Spontaneous revegetation’ (regression R2) to understand differences between the two types of revegetation. ‘Return to agriculture’ was tested against ‘Staying vegetated’ (regression R3) to assess which drivers influence recultivation. We also contrasted ‘Return to agriculture’ against ‘Managed revegetation’ as they are both active land management trajectories (regression R4). ‘Urbanisation’ trajectories were not considered in the analysis because of their limited occurrence in this sparsely populated rural region.

To build each change regression model, a binary raster map was created for the dependent variable, whereby all pixels on a specific trajectory were marked as 1, and the pixels on the contrasting trajectory or outcome were marked as 0 (all other pixels were assigned NoData values). The independent variables are potential underlying biogeophysical

Land use / Land Cover (t)	Land use / Land Cover (t+1)					
LULC category	Urbanised	Agriculture	Forest (natural)	Shrubland	Plantation (forestry)
Urbanised	*No change*	*Unlikely*	*Unlikely*	*Unlikely*	*Unlikely*
Agriculture	Urbanisation	*No change*	Natural succession	Natural succession	Afforestation
Forest (natural)	Urbanisation	Recultivation	*No change*	Deforestation	Afforestation
Shrubland	Urbanisation	Recultivation	Forest transition	*No change*	Afforestation
Plantation (forestry)	Urbanisation	Recultivation	Natural succession	Deforestation	*No change*
Direction of landscape change	**Urbanisation**	**Return to agriculture**	**Spontaneous revegetation**		**Managed revegetation**

Fig. 2 The land use/land cover matrix and associated change trajectories at the beginning (t) and end (t + 1) of each study period. Transitions between LULC categories produce specific change trajectories, which in turn determine the direction in which the landscape continues to evolve. Adapted from Fayet et al. (2022b)

Table 1 Change regressions tested for trajectories observed between 1995 and 2007 (a) and between 2007 and 2018 (b). Each change regression was calculated from an equal number of sampled pixels of areas marked as 1 and as 0

Change regression		Sample size	Areas with trajectories marked 1	Areas with trajectories / landscape outcome marked 0
R1	a. 1995–2007	2000	Revegetation (all types)	Staying in agriculture
	b. 2007–2018	1140		
R2	a. 1995–2007	2000	Managed revegetation	Spontaneous revegetation
	b. 2007–2018	424		
R3	a. 1995–2007	2000	Return to agriculture	Staying in vegetation
	b. 2007–2018	2000		
R4	a. 1995–2007	2000	Managed revegetation	Return to agriculture
	b. 2007–2018	424		

and socio-economic factors driving LULC change (Table 2). We purposefully used a wide range of variables rather than a clean selection to test for the influence of these factors on the observed landscape changes, which may have shifted over time. The variables were selected based on their role in landscape change according to published research on drivers of land use change and abandonment (Rey Benayas et al. 2007; van Vliet et al. 2015; Plieninger et al. 2016; Lasanta

Table 2 Description of independent variables, and their source data, tested as potential spatial drivers in each of the four change regressions

Independent variable	Unit	Original data resolution	Reference year	Data source
Biogeophysical variables				
Climate: annual ombrothermic index (Io)	unitless	111 m	1960–1990	Monteiro-Henriques et al. 2016
Soil type: *leptosol*, *cambisol*, *alisol*, *fluvisol*, *luvisol*, *anthrosol*	categorical	1 km	1991	COBA 1991
Soil cation exchange capacity	$cmol_c\ kg^{-1}$	1 km	various	Ramos et al. 2017
Soil organic carbon	%	1 km	various	Ramos et al. 2017
Soil pH	unitless	1 km	various	Ramos et al. 2017
Soil silt content	%	1 km	various	Ramos et al. 2017
Slope	degrees	25 m	2000	Gonçalves and Pinhal n.d.
Aspect (deviation from South)	degrees	25 m	2000	Gonçalves and Pinhal n.d.
Socio-economic variables				
Proportion of agriculture	%	Parish	1995/2007	DGT 2023b
Area under agriculture in 4×4 km neighbourhood of each cell	pixels	20 m min. mapping width	1995/2007	DGT 2023b
Area under (Re-)vegetation in 4×4 km neighbourhood of each cell	pixels	20 m min. mapping width	1995/2007	DGT 2023b
Protection priority: *high (1)*, *medium (2)*, *general (3)*	categorical	n/a	2021	Iglesias et al. 2022
Cost distance to nearest settlement	unitless	n/a	2023	Geofabrik GmbH 2023 + DGT 2023b
Cost distance to nearest municipality seat	unitless	n/a	2023	Geofabrik GmbH 2023 + DGT 2023b
Cost distance to nearest highway entry	unitless	n/a	2023	Geofabrik GmbH 2023 + DGT 2023b
Population density (mean across two census results)	$individuals/km^2$	Parish	2001–2011/2011–2021	INE 2022a, b
Population rate of change	unitless	Parish	2001–2011/2011–2021	INE 2022a, b
Mean farmer age	years	Parish	2009/2019	INE 2022b
Relative value of farm output in proportion to the regional mean	%	Parish	2009/2019	INE 2022b
Livestock density	units/100 ha	Parish	2009/2019	INE 2022b
Farm density	units/100 ha	Parish	2009/2019	INE 2022b

et al. 2017; Levers et al. 2018b; Pazúr et al. 2020; Subedi et al. 2022). All variable raster layers were, when necessary, interpolated and reprojected to achieve the same extent and pixel size (5 × 5 m).

Biogeophysical factors include climate, soil type and chemical and physical characteristics, slope and aspect (Table 2). Climate was represented by the variable annual ombrothermic index based on the World Bioclimatic Classification by Rivas-Martínez (Monteiro-Henriques et al. 2016). Higher values of this index indicate colder/wetter conditions associated with higher altitudes and low values warmer/drier conditions. Even though the source data for the annual ombrothermic index are older (1960–1990), we assumed that the climate patterns produced in this map are still valid, as they are strongly influenced by altitude and continentality. Soil type is a categorical variable that includes seven classes: leptosols, cambisols, alisols, fluvisols, luvisols, anthrosols and a general urban class (COBA 1991). Topsoil properties were obtained from the Portuguese INFOSOLO database (Ramos et al. 2017) and include soil cation exchange capacity, organic carbon content and pH to assess soil fertility, as well as silt content for soil texture. Slope and Aspect were derived from the SRTM digital elevation model (Earth Science Data Systems N 2023) , made available in a reprojected dataset for Portugal by CIIMAR (Gonçalves and Pinhal n.d.). Aspect was reclassified as Deviation from South, resulting in a deviation from 0 (full southern exposure) to 180 (full northern exposure).

Several socio-economic factors were also added, including existing land use in the area, protection regime, distance costs, population and farm metrics. Existing land use was based on COS data at the start of each study period. 'Area of agriculture' and 'Area of revegetation' were calculated in a 4 × 4 km neighbourhood around each cell using the focal sum function. 'Area proportion of Agriculture per parish' was also included as an alternative variable to address the effect of the presence (or absence) of agriculture at an intermediate spatial scale. Three levels of protection were defined according to the conservation priorities of the UNESCO Meseta Ibérica Biosphere Reserve zoning scheme: low (3) refers to 'Transition areas', medium (2) to 'Buffer zones' and high (1) to 'Core areas' (Iglesias et al. 2022). It should be noted that agricultural activities are permitted, even stimulated, in all protected areas to maintain cultural landscape structures. To assess remoteness and accessibility, three distance cost metrics were calculated in QGIS using the Accumulated Cost tool: (1) to nearest settlement, (2) to nearest municipality seat, i.e. urban area with schools and services, and (3) to nearest highway entry ramp. The friction layer was derived from OpenStreetMap (Geofabrik GmbH 2023) to reflect the different classes of road infrastructure. A very high cost or friction was assigned to any area without road or track access for vehicles, with a reducing cost as the ease and speed of travel increases, i.e. lowest friction was attributed to highways. We did not include elevation and slope in calculating friction because this is already reflected in other independent variables. Locations of settlements and municipality seats were derived from the 2018 Built-Up Areas Map (DGT 2023b). Locations of highway entries were obtained from current OpenStreetMap for the 2007–2018 period, and manually adapted to create a second map representative of the 1995–2007 situation using COS as a reference.

Population and farm variables at the parish level were based on census data for each study period: population density, population rate of change, mean farmer age, mean value of farm output in proportion to the regional mean value of farm output, number of livestock per 100 ha and number of farms per 100 ha (INE 2022a, b). Each of these variables was spatially represented based on parish vector maps that were subsequently rasterised.

We used the GLM function of the R 'stats' package to fit the logistic regression models (R Core Team and Davies n.d.). From each change regression map, an equal number (max. 2000) of random pixels marked 1 and 0 was sampled for the dependent variable (Table 1). To reduce the risk of spatial autocorrelation, only one pixel was sampled within each patch of occurrence of a trajectory and by ensuring a minimum global sampling distance of at least 100 m. Only within large areas of the same trajectory, multiple samples were possible if these were sampled at a distance of at least 1 km. The sampling procedure was repeated five times for each change regression (three times for more sparsely observed trajectories) to verify the robustness of the regression model. Multicollinearity between independent variables was checked before fitting the regressions, using the Variance Inflation Factor (VIF) function of the 'car' package in R (Fox et al. 2023). Variables with a VIF value greater than 5 were assessed in pairs and only one variable was retained in the model (James et al. 2023). Goodness of fit of the regression models was measured by the area under the ROC curve (AUC). The ROC (receiver operating characteristic curve) indicates the predictive ability of the model, whereby values above 0.9 mean excellent model fit, while any values over 0.7 indicate good fit (Lin et al. 2011).

Results

Landscape change trajectories

We reclassified transitions between LULC categories as landscape change trajectories (Fig. 2). Between 1995 and 2018, 15% of the total land area was on a change trajectory, with the dominant trajectory being 'Spontaneous revegetation' (5.0% or 27,895 ha), followed by 'Managed revegetation' (4.2% or 23,046 ha) and 'Return to agriculture' (2.5%

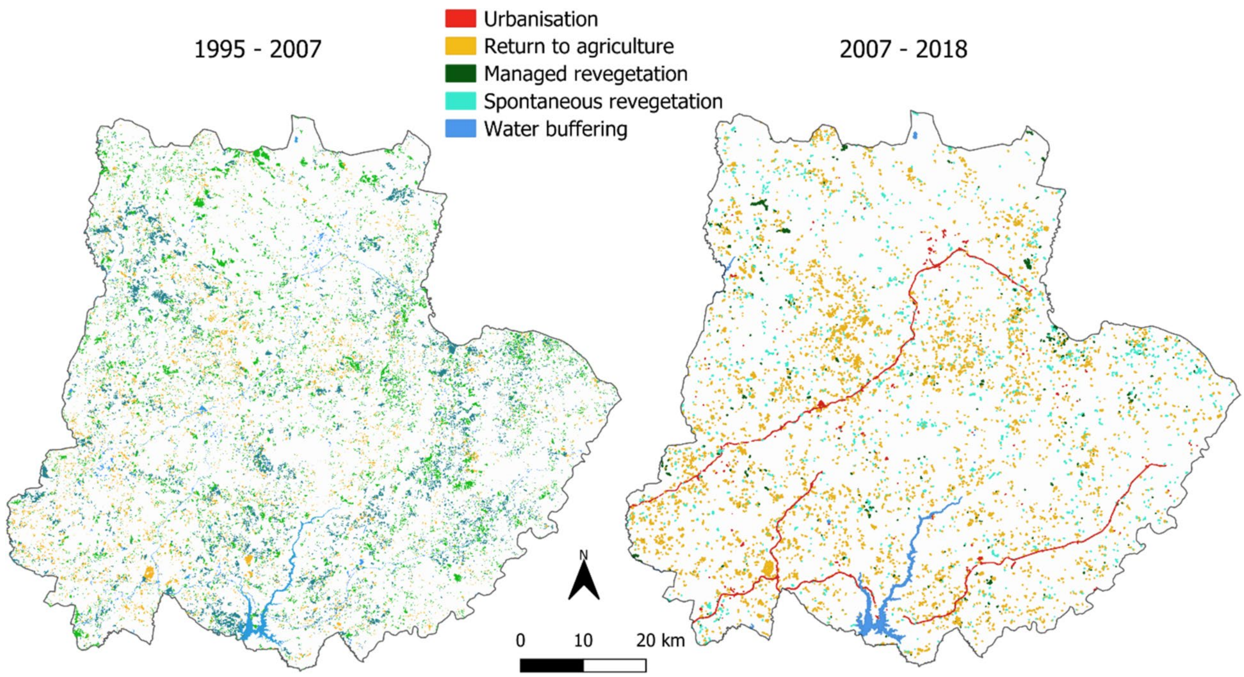

Fig. 3 Spatial distribution of landscape change trajectories in TTM in the 1995–2007 (left) and 2007–2018 (right) study period

or 13,970 ha). However, most of these changes occurred between 1995 and 2007 when 12.8% of the total land area was on a change trajectory compared to just 3.4% in 2007–2018 (Fig. 3). In the first period, the dominant trajectories were 'Spontaneous revegetation' (5.1%) and 'Managed revegetation' (4.0%), followed by 'Return to agriculture' (1.2%). Between 2007 and 2018, the most dominant trajectory was 'Return to agriculture' (1.7%). When assessing the spatial distribution of those trajectories at the local parish scale, we noted that 'Spontaneous revegetation' trajectories were widespread across the entire region between 1995 and 2007, as was 'Managed revegetation', with three groups of parishes having 15% or more of their land area afforested (Fig. 4). More modest 'Return to agriculture' trajectories (5% or less of the total parish area) were also observed, particularly in the southwest. 'Urbanisation' was scattered around parishes associated with cities. Between 2007 and 2018, the landscape in TTM was much more stable, with six parishes showing 'Return to agriculture' trajectories in 5–10% of their total land area and one more than 10%. 'Revegetation' occurred only sporadically, while 'Urbanisation' remained steady, however, this time strongly influenced by road construction linking east of the region to larger cities located to the southwest. Reviewing the original classifications in COS, nearly 88% of all 'Urbanisation' trajectories in the second study period can be attributed to road building, a stark increase of 40% compared to the first study period.

Analysis of drivers

The results of the analysis of underlying drivers using change regressions are presented in Table 3. One representative iteration of each change regression was chosen to provide a comprehensive overview of statistically significant drivers. The results of all regression samples can be consulted in the Supplementary Materials (Tables S2–S5). Variables showed up as significant in some samples and not in others, but we never found any contradictory results between different samples of the same regression. The predictive ability of each model, measured by the Area Under ROC Curve, ranged from poor (<0.60) to good (>0.70), which indicates that variables with valuable information that help explain the observed spatial patterns might still be missing from the models.

Revegetation

'Revegetation' trajectories when tested against 'Staying in agriculture' (R1 in Table 3) revealed that existing agriculture and climate are the drivers that promote the likelihood of 'Revegetation', while slope and protection regime promote 'Staying in agriculture'. Areas with more existing agriculture are more likely to see 'Revegetation', as do areas in climates with a higher annual ombrothermic index. Surprisingly, the influence of slope implies that 'Staying in agriculture' is more likely on steeper slopes. Increasing levels of protection

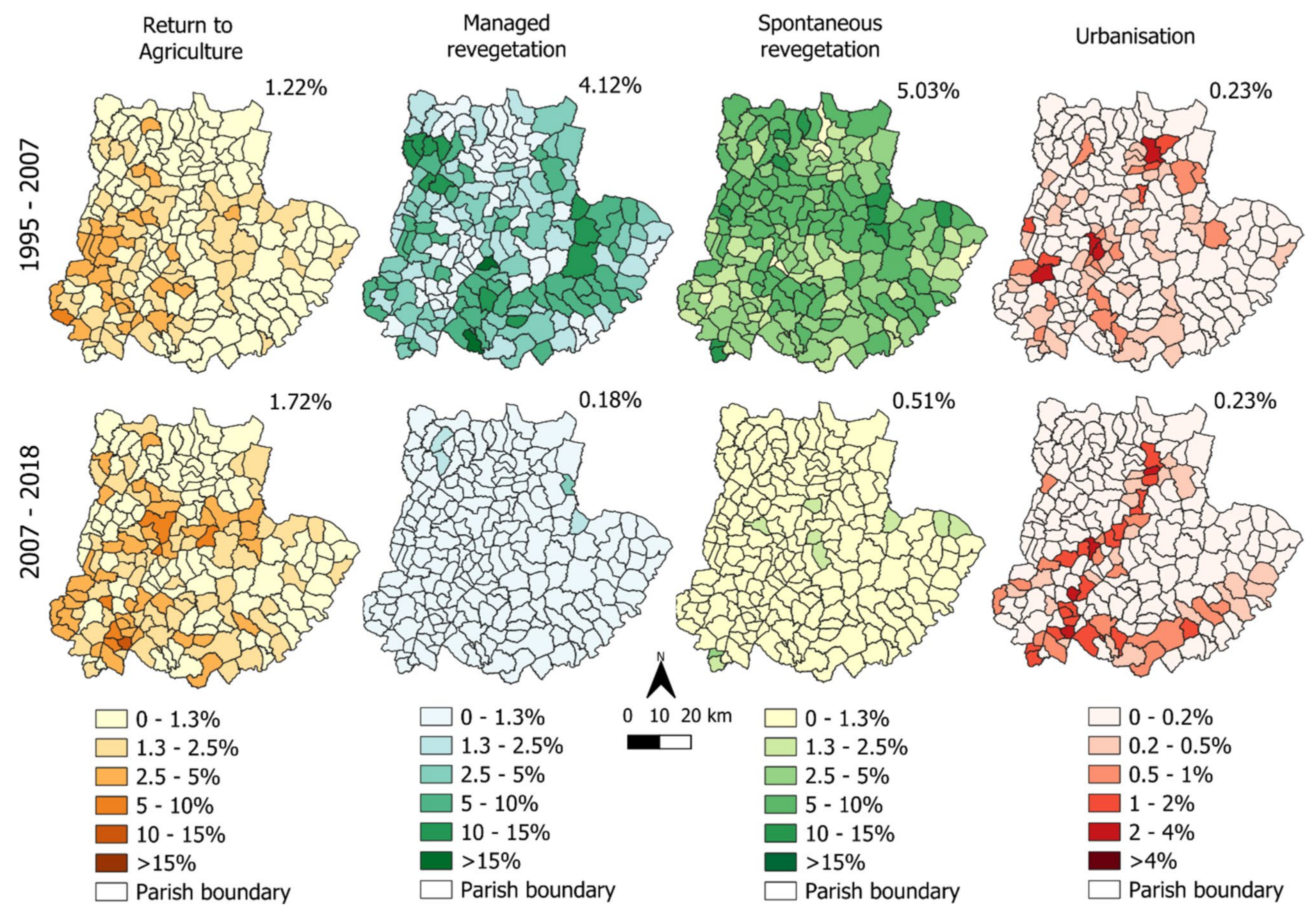

Fig. 4 Spatial patterns of landscape change trajectories in TTM expressed in area proportion per parish in 1995–2007 (upper row) and 2007–2018 (lower row). The percentage in the upper right corner of each map indicates the region-wide total area proportion of the trajectory during that period

also appear to favour 'Staying in agriculture', with the strongest effect showing at the highest level of protection.

There are a few differences between the study periods. The different distance metrics offer some unexpected results that are most apparent in the first study period. 'Staying in agriculture' is more likely in areas that are further removed from the nearest settlement, but 'Revegetation' is more likely in areas further removed from the nearest municipality seat. In the second study period, we observed a stronger influence of demographic variables: areas with a higher population density are more prone to 'Staying in agriculture', while areas with older farmers more likely show 'Revegetation'.

When contrasting the two types of revegetation (R2), the model fit is relatively poor (AUC around 0.60) indicating that location factors can only marginally explain the spatial differences of these two trajectories. 'Managed revegetation' is found with higher likelihood at higher distance cost to the highway, while 'Spontaneous revegetation' is more probable in areas with more existing agriculture, higher levels of protection and climates with higher ombrothermic index. There are additional drivers that are only significant in the first study period when 'Managed revegetation' trajectories were more prevalent. In 1995–2007, 'Managed revegetation' is more probable on cambisols, steeper slopes and areas further removed from the nearest settlement. However, areas that are further away from the nearest municipality seat, as well as areas with older farmers, are more likely to change towards 'Spontaneous revegetation'.

Return to agriculture

We tested 'Return to agriculture' compared to 'Staying vegetated' (R3) and found 'Return to agriculture' more probable in areas with more existing revegetation, highest levels of protection and longer distance to nearest settlements. Probability for 'Staying vegetated' is higher on alisols and luvisols, and in areas with increased distance to highway. High protection 'Core' areas show increased chances for 'Return to agriculture' across both study periods (also in 1995–2007, see the other iterations of regression R3 in Supplementary Materials Table S4), but 'Staying vegetated' is more likely in medium protection 'Buffer' areas in 2007–2018. The

Table 3 Parameter estimates of the four change regressions across both study periods. Parameters were included in this table only when significant

	R1 Revegetation—all types (1) Staying in agriculture (0)				R2 'Managed revegetation' (1) 'Spontaneous revegetation' (0)				R3 'Return to agriculture' (1) Staying vegetated (0)				R4 'Managed revegetation' (1) 'Return to agriculture' (0)			
Independent variables	a. 1995–2007		b. 2007–2018		a. 1995–2007		b. 2007–2018		a. 1995–2007		b. 2007–2018		a. 1995–2007		b. 2007–2018	
Biogeophysical variables																
Climate: annual ombrothermic index	2.24	*	2.102	*	-4.673	***	-2.106	*			3.456	***				
Soil type: *cambisols*	1.65				2.069	*							2.522	*		
alisols									-2.46	*	-3.527	***	4.098	***		
luvisols									-2.028	*						
anthrosols													-2.006	*		
Soil cation exchange capacity									-2.644	**			4.305	***		
Soil organic carbon									2.339	*			-3.409	***		
Soil pH							-2.096	*	2.306	*						
Soil silt content									-2.089	*					-2.702	**
Slope	-3.781	***	-3.125	**					2.659	**			2.067	*	2.535	*
Deviation from South	-2.367	*														
Socio-economic variables																
Existing agriculture in 4×4 km neighbourhood	9.864	***	3.868	***	-2.777	**	-1.88		–		–		-2.211	*	–	
Existing (re-)vegetation in 4×4 km neighbourhood	–		-4.337	***	–		–		11.081	***	9.094	***	–		3.488	***
Protection regime: medium					-2.470	*	-2.566	*			-2.668	**	-2.497	*	-3.251	**
Protection regime: high	-2.922	**	-5.049	***	-3.868	***					1.762					
Distance cost to nearest settlement	-5.373	***			4.437	***			8.129	***	7.867	***	2.573	*		
Distance cost to nearest municipality centre	2.702	**			-2.957	**							-2.966	**		
Distance cost to highway 1995–2007					3.858	***	2.683	**	-3.631	***			9.344	***	2.673	**
Distance cost to highway 2007–2018	–				–				–		-2.87	**	–			
Population density			-2.420	*			1.846									
Mean farmer age			3.002	**	-2.454	*			-2.23	*			2.809	**	3.329	***
Livestock density (cattle, sheep, goats, pigs)											-2.373	*	2.024	*		
Farm density													-2.979	**		
Goodness of fit (Area under ROC curve)	0.6883		0.6466		0.6207		0.5965		0.7086		0.6845		0.6847		0.6434	

Notes: '–' variable was excluded; '***' p < 0.001; '**' p < 0.01; '*' p < 0.05; '.' p < 0.1 (only included if variable is significant in at least one other sample of the same regression)

differences between the two study periods become more pronounced in this regression. In the first study period, there is a clear influence of soil characteristics. 'Return to agriculture' trajectories are more probable on soils with increased pH and organic carbon. 'Staying vegetated' is more probable on soils with higher cation exchange capacity and silt content. Increased mean farmer age increases chances for 'Staying vegetated' in 1995–2007. In the second period, one additional variable that makes 'Return to agriculture' more likely, is climate with higher annual ombrothermic index.

Lastly, we differentiated between 'Managed revegetation' and 'Return to agriculture' (R4). Model fit was not very good (AUC < 0.7), but part of the variance between these two trajectories could still be explained by the location factors. 'Return to agriculture' is more probable in areas with medium protection regime than 'Managed Revegetation'.

The latter is more probable in areas with steeper slopes, greater distance cost to highway and older farmers. In 1995–2007, there are once again additional significant variables. 'Managed revegetation' is more likely in areas with a lower annual ombrothermic index and on alisols than 'Return to agriculture', which is more likely in areas with increased soil organic carbon. Larger distance cost to settlement increases the probability for 'Managed revegetation', while larger distance to the nearest municipality seat makes 'Return to agriculture' more likely. Areas with a greater livestock density are more likely to see 'Managed revegetation' than 'Return to agriculture', but greater farm density and existing agriculture have the opposite effect. In 2007–2018, greater soil silt content improves likelihood for 'Return to agriculture', while more existing (re-)vegetation promotes 'Managed revegetation'. Cost distance to highway is a significant variable for both study periods: increasing costs makes it more likely to see 'Managed revegetation' than 'Return to agriculture'.

Discussion

The distinction between abandonment and post-abandonment landscape trajectories is currently arbitrary and undefined (Fayet et al. 2022b). However, the high spatial and temporal variation in trajectories between the two periods in our case study may help develop such a distinction. Agricultural abandonment is often perceived as a progressive trajectory occurring over long periods of time, strongly affecting areas that are ill-suited for intensification or urbanisation (MacDonald et al. 2000; García-Ruiz and Lana-Renault 2011; Lasanta et al. 2017). More recently, land abandonment in the EU has been spurred by technological developments (mechanisation) and policies such as CAP (MacDonald et al. 2000; Nunes et al. 2010; Feranec et al. 2010; García-Ruiz and Lana-Renault 2011; Lasanta et al. 2017; Dax et al. 2021; Zavalloni et al. 2021). Beyond the EU, abandonment also happened in contexts of rapid socio-economic development and/or political shifts (Grau and Aide 2008; Prishchepov et al. 2013; Subedi et al. 2021; Tan et al. 2021). Since then, recultivation trends have been documented in more favourable areas (Meyfroidt et al. 2016; Smaliychuk et al. 2016; Dara et al. 2018; Pazúr et al. 2020). Our research in TTM revealed strong abandonment trends until the end of the twentieth century, followed by a period of land use stabilisation and even agricultural re-use of previously abandoned lands, which counter projected land use changes for the region (Keenleyside and Tucker 2010; Levers et al. 2018b; Perpiña Castillo et al. 2021; Debonne et al. 2022). This is, however, a very recent shift in the direction of land use change patterns of which the durability and impacts on the landscape are still uncertain.

Socio-economic drivers of (post-)abandonment trajectories

The most notable socio-economic drivers we noted were existing land uses in the surrounding neighbourhood, protection regime and the various accessibility metrics. 'Managed revegetation' was more likely to happen in areas with more vegetation in the first study period, but we noted no other signs of concentration of land use within TTM, a process referred to in many other locations (Tzanopoulos and Vogiatzakis 2011; Stellmes et al. 2013; Levers et al. 2018a) leading to landscape polarisation. Instead, a particular dynamic of 'Revegetation' in areas with agriculture and 'Return to agriculture' in areas with vegetation seems to take place. There could be several possible explanations for these patterns. Much of the TTM landscape is ill-suited for agricultural intensification at scale. Farmers also typically own various smaller plots scattered across an area (Beilin et al. 2014), which may also scatter land use types. Although protection regimes have been found to promote abandonment in Europe (Agnoletti 2014; Schmitz et al. 2021), farmers in TTM seem inclined to continue their activities in within highly protected areas. However, only a qualitative assessment can determine if their current farming approaches are also helpful in maintaining the conservation values of the cultural landscapes in those areas (Fischer et al. 2012; Sarmiento-Mateos et al. 2019). Connectivity with urban centres such as municipality seats, as well as highways that connect to larger cities, gains importance over connectivity with the nearest settlement. Between 1995 and 2018, extensive highway construction has greatly improved accessibility to and within TTM, confirming that connectivity to urban centres and cities has a growing influence on landscape dynamics (Nagendra et al. 2003; Mottet et al. 2006; Nainggolan et al. 2012; Terres et al. 2015). The fact that depopulation continues while land abandonment does not indicates that the influence of demographics may shift in a post-abandonment scenario.

Other demographic aspects such as population density and mean farmer age are more significant as drivers for 'Revegetation' than for 'Return to agriculture' trajectories. As in other EU regions, farming is transforming from a core to a side activity that provides supplemental rather than principal income (Dimopoulos et al. 2023). Data show a 35% increase between 1999 and 2019 in the number of farmers in TTM who have employment outside the farm (INE 2022b). Higher densities of livestock produced a diminished possibility for 'Return to agriculture' and increased 'Managed revegetation', which seems counterintuitive. However, livestock farming requires a daily presence, which is much harder to combine with a separate day job. The number of farm animals in the region has indeed reduced by 28% between 1999 and 2019 (INE 2022a, b), which most likely affects extensive farming systems more than intensive ones (Cocca et al. 2012). Since traditional shepherding practices have historically been instrumental in shaping the landscape structure and biodiversity, the abandonment of this type of farming can strongly alter the landscape and associated biodiversity (Dover et al. 2011; Beilin et al. 2014; Regos et al. 2016; Palacín and Alonso 2018; Maldonado et al. 2019; Quintas-Soriano et al. 2022).

Environmental drivers of (post-)abandonment trajectories

The most significant environmental factors for the observed trajectories were climate and slope. Earlier research found that agriculture usually moves towards lower slopes while steeper slopes are increasingly abandoned (Imai et al. 2023; Müller et al. 2013; Weissgerber et al. 2023; Zhang et al. 2014) to facilitate mechanisation (Arnaez et al. 2011). However, in our change regressions, both 'Return to agriculture' and 'Staying in agriculture' appeared more likely on steeper slopes. To cross-check these results, we calculated the overall mean slope of all agricultural areas in 1995 and 2018, which confirms a modest increase in average slope from 6.91 to 7.00 degrees, still much lower than the average slope of all vegetated areas, which decreased from 13.11 to 11.85 degrees. We can assume that the steepest, most inaccessible slopes have been abandoned much earlier than 1995, and largely remain unchanged (Poyatos et al. 2003; Lasanta et al. 2017). The influence of slope can also vary according to the wider context of landscape organisation (Liang et al. 2020), such as a shift from temporary (cereals) to permanent crops that thrive on (moderately) sloped land, including olive and chestnut (Duarte et al. 2008; Bento and Ribeiro 2020). The total area for annual crops in the region reduced by 46% between 1999 and 2019, while permanent crop areas expanded by 32%, most notably olive and nuts (almond and chestnut) (INE 2022a, b). Climate was a reasonably strong predictive factor for both 'Revegetation' and 'Return to agriculture' trajectories. Locations with a higher ombrothermic index were more likely to experience 'Spontaneous revegetation', but also more likely to see 'Return to agriculture'. In these areas, trade-offs are made between a shorter growing season and a cooler, wetter climate. The average annual ombrothermic index of all areas on a 'Return to agriculture' trajectory increased from 5.09 in the first study period to 5.46 in the second.

While we detected spatial patterns in the landscape changes, these observations can only partly be explained by the socio-economic and environmental factors we included in the regressions. For instance, the influence of policy is undeniable and should be assessed more profoundly (Lambin et al. 2001). The expansion of 'Managed revegetation' in 1995–2007 can be linked to several forestry programmes, including Regulation (EEC) 2080/92 of the European Union's initiative to avoid agricultural surpluses by afforesting agricultural lands, as well as the national Forest Development Plan (1994/99), which had all ended by the start of the second study period (Carvalho Mendes and da Silva Dias 2002). Subsidy programmes such as CAP also appear to play a big role for farmers in TTM. In nearly all parishes, 75–100% of farmers have access to CAP funding, a very high proportion compared to other parts of the country (Viegas et al. 2023). In addition, using finer distinctions between the different LULC categories and a greater variety of associated change trajectories may have improved the precision of the models. Assessing LULC changes at short time intervals in this study enabled us to observe a shift in the landscape trends, which would have gone unnoticed if we had aggregated the data for the entire 1995–2018 period. Extending the temporal scale can be equally useful, considering that land abandonment in Portugal started in the 1960s—late in comparison with other mountainous regions in Europe—following an extended period of protectionism-driven 'artificial agricultural expansion' (Zavalloni et al. 2021) during the *Estado Novo* dictatorship (Carmo and Domingos 2021). The agri-environmental and socio-economic conditions that precede abandonment thus provide essential context for the observed rate and scale of later land use changes. In other words, the incomplete model fits indicate that additional factors co-determine these landscape outcomes, such as the deeper land use history, tenure systems, culture, policy, personal life stories and motivations of landowners.

Conclusions

Some of the general conceptions about land abandonment do not consistently hold in our study region. Agricultural abandonment patterns were prevalent in TTM until the start of the twenty-first century, when the dominant landscape trends became stability and 'Return to agriculture'. Using short temporal scales permits to observe such shifts in landscape trends, which risk being obfuscated in a longer time frame analysis. The mere existence of such a shift may also validate a distinction between abandonment and post-abandonment trajectories, which may respond differently to underlying drivers. Climate, slope, specific policies—including stimulating certain types of agriculture in protected areas—and connectivity with urban areas seem to play a more important role in the landscape dynamics. While land abandonment is often said to lead to polarisation of landscapes, dividing productive and non-productive areas, we found the opposite in TTM. The changing dynamics coincide with changing landscape actors, different crops and new ways—and scales—of using the landscape, of which the (future) impacts on the natural heritage landscapes are still unclear. The fit for most regression models was less than good, indicating that additional variables that can represent the cultural, personal and historic context should be included in the analysis. Whether or not the end of land abandonment in TTM is a (temporary) exception or the first indicator of a possible wider shift, the specific conditions and policy measures that helped generate it will be of great interest to other regions aiming to achieve similar goals.

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Declarations

Conflict of interest The authors declare no competing interests.

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