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Spatiotemporal analysis of *montado* land cover dynamics in southern Portugal: the influence of anthropogenic and natural disturbances

J. T. Marques · N. Guiomar · R. Machado · T. Pinto-Correia

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Abstract The *montado* is a traditional agroforestry system in Portugal that combines cork or holm oak trees with pastures and crops. It provides multiple ecosystems services and supports rural livelihoods. However, in recent decades, the *montado* has faced several threats that have caused its decline and degradation. Here, we analyse the recent changes in *montado* cover—between 2006 and 2018—and assess the main drivers and processes of change. We used a 2006 *montado* cover map as a baseline and overlayed it with aerial photographs of 2018, examining the *montado* areas for land use shifts by installation of intensive crops, wildfire occurrences or tree plantations. Our results show that the *montado* covered 1,189,390 hectares (ha) in 2018, and that there was a decrease of the *montado* area from 2006 by 31,312 ha (95% CI 29,706–32,943 ha), declining at an annual loss of 2609 ha (0.21% year^{-1}; 95% CI 0.201–0.223% year^{-1}). Although this is a slower rate compared to an early analysis, the impact of large-scale events (record burned areas) and infrastructure (large dam) likely explains it. The *montado* area shifts were mainly caused by wildfires (70%), the opening or broadening of clearings due to tree mortality (18%) and the new installations of intensive crops (olive or almond groves and irrigated cereals—8.4%). Most of the analysed quadrats (60%) exhibited one category of loss in *montado* patches: perforation, loss of area, fragmentation or decrease in the number of patches; but fragmentation was the type of dynamic with higher value of area loss. The perforation specific analysis revealed that this phenomenon of the early phase of decline is prevalent throughout the *montado* land cover. The main process identified was tree mortality linked to pathogens, pests, and inadequate management, while wildfires and the establishment of intensive agricultural practices were ranked second and third, respectively. Despite the efforts to slow the decline of the *montado*, we have observed

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J. T. Marques (✉) · N. Guiomar · R. Machado · T. Pinto-Correia
MED Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Institute for Advanced Studies and Research, Universidade de Évora, Évora, Portugal
e-mail: jtiagom@uevora.pt

N. Guiomar
e-mail: nunogui@uevora.pt

R. Machado
e-mail: rdpm@uevora.pt

T. Pinto-Correia
e-mail: mtpc@uevora.pt

T. Pinto-Correia
MED Mediterranean Institute for Agriculture, Environment and Development & CHANGE Global Change and Sustainability Institute, Departamento de Paisagem Ambiente e Ordenamento, Escola de Ciências e Tecnologia, Universidade de Évora, Évora, Portugal

its continuing transformation into smaller, more fragmented and less connected *montado* patches. These resulting patches are considerably less resilient to the pressures they are facing. In a scenario of the continuation of the decline and loss pressures, the evolving transformation will continue and may even accelerate.

Keywords Landscape dynamics · Montado decline · Spatial distribution · Clearing

Introduction

The *montado in Portugal* and the *dehesa* in Spain are the preponderant silvo-pastoral systems in southern Iberian Peninsula; these are distinct farming systems in the European context, typified by their multifunctionality that integrates agriculture, forestry and livestock raising activities (Fonseca et al. 2019; Pinto-Correia et al. 2011). The *montado* has an open canopy woodland structure of cork or holm oaks, with natural or cultivated pastures and scattered small shrubs in the understory (Godinho et al. 2016c), which forms an heterogeneous and complex landscape supporting economic activities, high biodiversity and cultural values (Ferraz-de-Oliveira et al. 2016; Pinto-Correia et al. 2011). The *montado* most important products are cork, wood and meat. Due to its heterogeneous vertical and horizontal structure and its extensive use, the *montado* also provides a wide range of ecosystem services, as biodiversity, water infiltration, carbon storage, and supports activities such as hunting, bee keeping and mushroom picking. This led to the classification as a High Nature Value Farming system, by the European Environmental Agency (Paracchini et al. 2008; Pinto-Correia et al. 2018).

Regardless of its importance, several pressures are threatening the *montado* (Acácio et al. 2021; Arosa et al. 2017; Pinto-Correia et al. 2019; Sevillano et al. 2017): the intensification of agricultural practices such as mechanical shrub cleaning with deep ploughing, high livestock grazing pressure, localized prevalence of tree diseases and pests, shrubland encroachment in the most marginal conditions, increasing frequency and severity of droughts and soil degradation. The complexity of managing *montado* areas is also increasing by decision-making conflicts resulting from different stakeholder perspectives and governance strategies (Pinto-Correia et al. 2019; Pinto-Correia and Azeda 2017). Several policy instruments influence the management and activities in the *montado* (Fatahi et al. 2026). However, they have top-down character and single purpose focus (Plieninger et al. 2021) and thus, fail to consider its multi-functional role. As a consequence, they can contribute to the lack of sustainability of numerous *montado*s in the medium-term (Pinto-Correia and Azeda 2017). Therefore, the monitoring of the system essential to correctly inform public policies, design effective landscape management plans, foster restoration initiatives and conservation strategies. Tracking the changes occurring in the landscape, and specifically the *montado* progress or decline (trends and rates) is also instrumental to assess the effectiveness of ongoing policies and environmental laws that directly or indirectly affect this valuable system.

The area covered with *montado* in Portugal has been assessed to cover a large area of 1.2 million hectares (ha) in 2006, according to Godinho et al. (2016d). However, the authors also revealed a reduction at an annual rate of 5624 ha from 1990 to 2006. A literature review shows also a corresponding decline registered at local case study level (*e. g.* Plieninger 2006; Plieninger and Schaar 2008), where fine scale variations are detected (Acácio et al. 2021; Costa et al. 2010; van Doorn and Pinto-Correia 2007). Several of the factors mentioned above have shown to have a significant relationship with this decline, in particular intensification of grazing and replacement of sheep by cattle. Since 2006, a few significant factors have shifted that may influence this declining trend: (1) the legislation to protect the *montado* areas has been strengthened—in 2004 a new law clarified and reinforced the protection of cork and holm woodlands covering a minimum area of 0.5 hectares (Dec. Lei 155/2004); (2) rapid expansion of irrigated olive and almond groves in former *montado* areas, in between scattered oaks in low density *montado* areas (Morgado et al. 2022; Muñoz-Rojas et al. 2024); and (3) further abandonment of marginal areas (Heider et al. 2021; Romero-Díaz et al. 2024; Suess et al. 2018).

The *montado* has been thoroughly studied in different aspects, from structural ones like genetics (Usié et al. 2023), to more circumstantial ones like pests (Tiberi et al. 2016), soil conditions and water balance, or economic viability (Fragoso et al. 2011), and recently on the policy tools that could support the regeneration of the system (Guimarães et al. 2023; Pinto-Correia et al. 2022a). A strong research focus has been put on biodiversity, management and long-term sustainability (Acácio et al. 2010; Arosa et al. 2017; Chozas et al. 2022; Godinho and Rabaça 2011; Pinto-Correia et al. 2018; Plieninger et al. 2021; Simonson et al. 2018). However, the study of the *montado* spatial variation has not continued so far. Such an assessment is crucial to properly monitor the overall *montado* condition, evaluate possible causes of decline or regeneration, anticipate trends, and consequently design solutions in particular public policy interventions at the national level. It is essential to track the variations in its amount and spatial distribution through reliable mapping procedures, which identify the dynamics of the *montado* even within *montado* areas and patches. Due to the categories used in the currently available official land use/ landcover maps (COS and Corine Land cover) even a thorough analysis cannot show the fine grain dynamics that are happening in the *montado* areas.

Remote sensing data (i.e. satellite images, aerial photographs) is highly suited for the regional assessments of land use change (Acácio et al. 2021; Allen et al. 2018; Carreiras et al. 2006). From the available datasets, aerial photographs offer significant advantages for mapping changes in the *montado* over large areas (e. g. Sevillano et al. 2017). These advantages stem from the high spatial resolution and detailed landscape information that they provide, allowing for comprehensive analysis of landscape features and changes across scales.

Aerial photographs can also support a variety of analytical techniques (Gennaretti et al. 2011; Wentz et al. 2006), including human interpretation, object-oriented segmentation and automated methods such as neural network analysis. These techniques can be tailored to specific research needs, enhancing the versatility of aerial photographs for different types of landscape analysis and at different spatial scales (Acácio et al. 2021; Morais et al. 2023). On the other hand, the interpretation of aerial photographs requires expertise and can be time-consuming, particularly when dealing with historical images that may have varying quality and coverage. Despite these challenges, they enable detailed mapping of land-cover baselines and long-term changes, providing a valuable tool for the quantification of the change from one land-cover to another (Plieninger and Schaar 2008).

Therefore, the objectives of the work we show in this paper are to (i) apply a detailed spatial analysis to the *montado* area to reveal the spatial dynamics which the official registers and other national level assessments based on existing land cover maps, do not consider; (ii) conduct a comprehensive mapping of the *montado* land cover as in 2018 and evaluate the changes observed between 2006 and 2018 and, (iii) assess the spatial distribution of these changes, differentiating the types of dynamics identified, either gain and loss categories. As referred above, the last spatial assessment of the *montado* was for the period up to 2006. As for 2018, it was the last year of available aerial photographs covering the full extension of the *montado* in Portugal. These three objectives can be summarized into two main research questions:

How have the spatial extent and distribution of the montado in Portugal changed between 2006 and 2018 based on a detailed land cover analysis? and What spatial dynamics (gains, losses, and patterns of change) characterize the *montado* landscape over this period?

Materials and methods

Study area

The study area comprised the region of southern Portugal, which is predominantly covered by cork oak and holm oak *montado* (Godinho et al. 2016d; Pinto-Correia 1993; Pinto-Correia et al. 2011). This large region is mainly located south of the Tagus River, except for most of the southwestern and southern coastal areas (Fig. 1).

The *montado* area is based on the biogeographic boundaries drawn by Costa et al. (1998), which integrate the information of vegetation (phytogeography), geomorphology, soil and bioclimate (Fig. 1). The often-poor soils of *montado* originate from palaeozoic siliceous bedrock.

Data collection and *montado* map production

The *montado* baseline map of 2006 was sourced from the information published by Godinho et al. (2016d). This map has a minimum mapping unit of 25 hectares and combined data from several data sources at different spatial scales: Corine Land Cover (scale

Fig. 1 Study area—*montado* cover in southern Portugal. Map projection—ETRS89—TM06

1:100,000), national land cover map (scale 1:25,000), Portuguese Forest Inventory (year 2005) and in a few specific areas, human interpretation of high resolution orthophotos (year 2005). For further details on the integration of these different data and the resulting map see Godinho et al. (2016d).

To obtain the *montado* cover map of 2018, we screened all the areas identified as *montado* in the baseline map (year 2006) and visually interpreted the overlayed aerial photos of 2018 (pixel size 25 cm, available at DGT (https://cartografia.dgterritorio.gov.pt/wms/ortos2018?service=wms&request=getcapabilities), using QGIS 3.28—Firenze (QGIS.org, 2022). We collected data for the *montado* change analysis by recording if the land use of each *montado* patch remained unchanged or shifted between the two time points, 2006 and 2018 (Fig. 2A). In the case of land use shift in only part of the patch, the perimeter of the remaining patch was re-drawn and updated to the 2018 new boundary thus, excluding the lost *montado* areas (Fig. 2B). So, when changes affected only part of a patch, the altered area was delineated and assigned to the corresponding land-use category. However, in patches where multiple, spatially distinct changes occurred, each sub-area was delineated and classified according to its specific land-use category shift. This patch-based and within-patch delineation approach enabled a more precise quantification of land-use change by capturing fine-scale spatial heterogeneity. Moreover, by explicitly separating unchanged and shifting sub-areas within patches, we aimed to avoid double counting of changed areas. As a consequence, we also avoided the use of priority hierarchy in a *montado* patch subject to several non-overlapping land use change processes, a common issue in land-change studies when spatial units are treated as homogeneous (Olofsson et al. 2014).

Land use changes that converted *montado* patches to other uses were categorized as installation of intensive crops, wildfires, building of medium and small dams or plantations of trees. The visual cues used to differentiate each of these land use categories were as follows: 1—Intensive or permanent crops—regular patches (rectangular or circular) with even spacing of vegetation and irrigation lines, included olive orchards, vineyards, central irrigation; 2—Clearing in the *montado*—distinctly open areas without tree cover in 2018 but that had tree cover in 2006; 3—Wildfire—presence of burnt vegetation, either trees, shrubs or grasses; the limits of these areas were cross referenced with the Portuguese wildfire data base available from ICNF. We considered wildfires between 2006 and 2018 with burnt area equal or larger than 100 hectares, (*e. g.* Bermudez et al. 2009, Ganteaume and Barbero 2019). 4 -Tree plantation (Pine, *Eucalyptus* spp.)—even spacing of the trees lines following the terrain contour, stone pines show rounded tree crowns whereas Eucalyptus trees show pointed shape tree crowns and the plantations have a very high tree density, covering almost all plot area; 5—Dams—small and medium size earth barrier dams; 6—Buildings—houses and farm buildings; 7—Scrubland—loss of tree cover while the undergrowth remained; 8—Solar plants—extensive area covered with solar panels. The ambiguous cases were resolved by consensus with more experienced co-authors. We also identified new areas of *montado*, mainly from the mature plantations of cork and holm oaks. To aid in the screening and photointerpretation of larger patches of *montado*, we used an auxiliary squared grid (100 m) to avoid image overlap in the analysis.

Uncertainty analysis of land-use change

To assess the uncertainty land-use maps for 2006 and 2018 produced by visual interpretation of aerial photographs we employed a bootstrap analysis. Although photo-interpretation typically yields accurate delineation of land-use classes, spatially structured data of this kind can violate the assumption of pixel independence, as land uses occur in contiguous patches where neighbouring pixels are likely autocorrelated. Treating pixels as independent observations in such contexts leads to underestimation of uncertainty in area estimates and change statistics (Legendre 1993; Dormann et al. 2007; Olofsson et al. 2014). Thus, to account for spatial autocorrelation, we quantified uncertainty in *montado* area differences between the two dates using a spatial block bootstrap approach (Lahiri 2013). This method also enabled us to assess the robustness of the observed land-use changes by generating an empirical distribution of area change estimates under spatial resampling, without imposing parametric assumptions about the error structure of the maps.

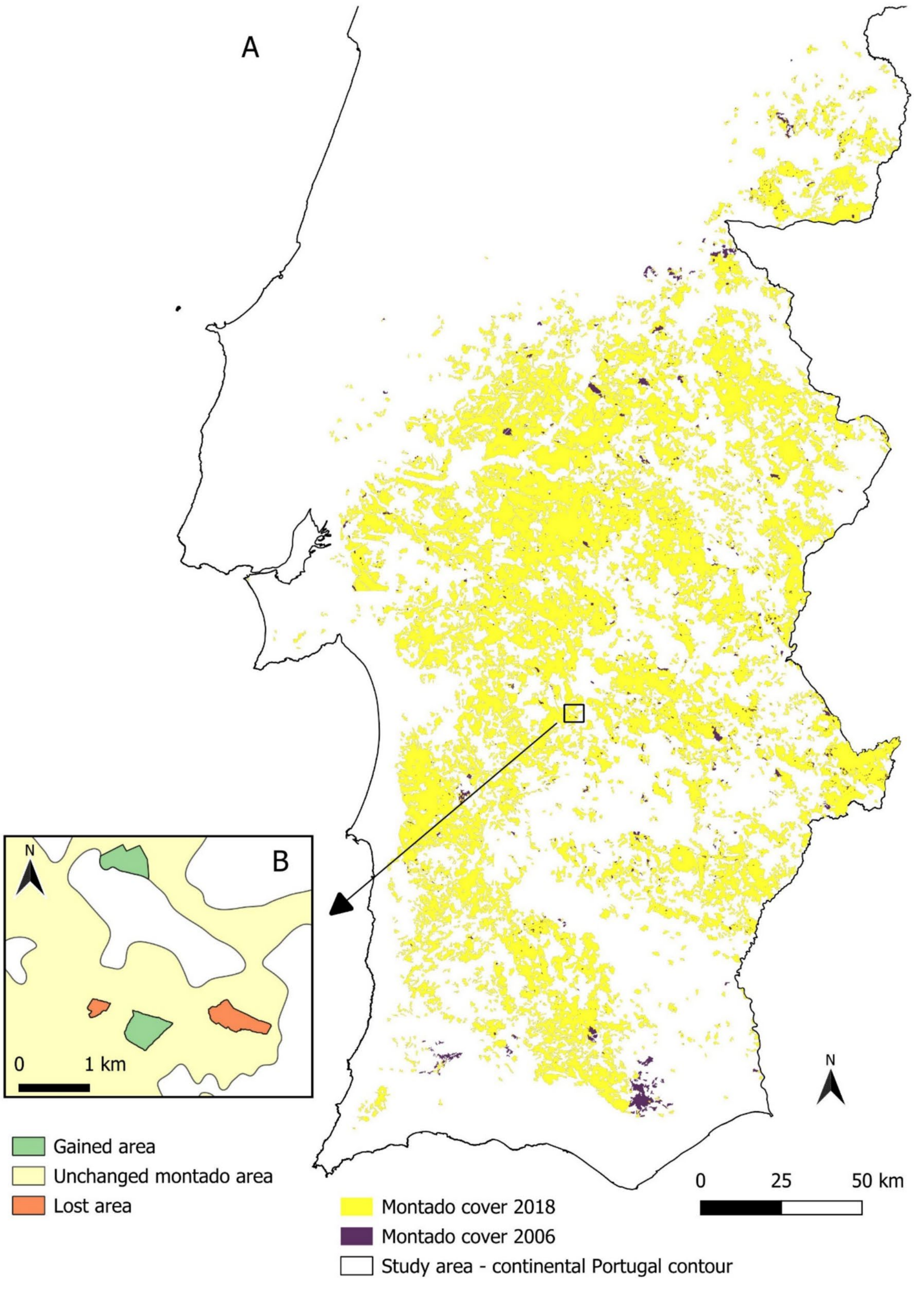
Initially, we rasterized both *montado* land cover maps, 2006 and 2018, to a pixel size of 20 m and partitioned the study area into contiguous squared blocks of 1 km, which were resampled with replacement to produce bootstrap replicates of the landscape (Efron and Tibshirani 1994). For each replicate, randomly sampled blocks were reassembled to form a representation of the study area, from which the total area of *montado* was recalculated for each year. Pairwise differences in *montado* area between 2006 and 2018 were then computed across all replicates, resulting in an empirical distribution of land-use change estimates. Blocks were set to 1 km × 1 km — substantially larger than the 20 m raster resolution, yet small enough to capture local landscape heterogeneity and to provide large number of resampling units across the study area. Selecting block sizes that exceed the range of spatial autocorrelation reduces bias in uncertainty estimates derived from spatially structured data (Lahiri 2013). A total of 10,000 bootstrap iterations were performed, and the resulting empirical distributions were used to derive 95% confidence intervals for the observed differences in the area of *montado* between 2006 and 2018. All analyses were conducted in R (version 4.5.2) using the packages terra, dplyr, and tidyr. The R code is available as supplementary material.

Montado dynamics assessment

Spatial patterns of land transformation are useful not only to diagnose and understand past changes in the landscapes but also to predict future alterations. Given the functional and temporal continuity among the different types of dynamic it is possible to infer (or at least exert informed speculation) about the future, assuming the trend will continue. For example, if two close patches are increasing in size, it is expected that they will merge into a single patch in the future.

A comparison between the two *montado* maps, that by themselves represent discrete snapshots, adds a temporal dimension which provides additional analytical and interpretative value. We used the LDT4QGIS (Paixão and Machado 2023) to conduct this analysis, applying the LDT method developed by Machado et al. (2018). The tool LDT4QGIS compares binary layers or shapefiles of two time points and calculates the Types of Dynamics (ToD) that occurred in the time span between them. The different ToD categories result from the combination of the variation of two metrics—land use area and number of patches (NP)—and therefore can be strictly related to area amount (gain or loss), strictly geometric (fragmentation or aggregation) or, more often, reflect both (fragmentation due to area loss, etc.). The analysis was conducted between two time points (*montado* cover shapefiles of 2006 and 2018) and using 5 km UTM quadrats as analytical units (AU) for a detailed mapping of the changes (option "Districts provided by user"). All patches smaller than 5000 square meters were discarded from the analysis to avoid spurious and/or meaningless polygons resulting from geoprocessing operations. Additionally, the area differences (variations from 2006 to 2018) smaller than 1 ha in a 5 km UTM square, were re-classified as ToD A—No change. For the sake of an effective comparison with the map built by (Godinho et al. 2016d), the procedure was reproduced using 10 km UTM quadrats as AU (see maps in the Supplementary Material). The QGIS Version used for this analysis was 3.34.10-Prizren.

According to Forman (1995b), the transformation of a land type, or habitat in a decreasing trend (i.e., losing area), by natural or human causes, is a sequence of five spatial processes: perforation, dissection, fragmentation, shrinkage and attrition (or


A
B
N
0
1 km
N
0
25
50 km
Gained area
Unchanged montado area
Lost area
Montado cover 2018
Montado cover 2006
Study area - continental Portugal contour

◂**Fig. 2** **A** *Montado* cover in 2006 and 2018. **B** Inset shows the the *montado* change analysis performed. Map projection—ETRS89—TM06

disappearance). These processes overlap in time but peak in different phases of the overall change. Perforation—the process of making holes in a habitat or a land type (Forman 1995a) -, and dissection—subdividing of an area using lines, usually peak at the start of the transformation process. Fragmentation—breaking the patch into smaller, uneven patches—and shrinkage—eduction of patch size—are more frequent in the middle phase, and attrition or disappearance of patches, peaks near the end of the land transformation (Forman 1995b). Thus, by identifying the main spatial process or type of dynamic acting in an area, it is possible to determine which phase of the land transformation that area is subject to, making the analytic procedure more robust and more likely to produce concrete and actionable outputs.

Perforation analysis

The land transformation pattern "perforation" is particularly relevant in the early stage of habitat loss. Whether due to natural causes (*e.g.* storms, blowdown clearings or tree death) or provoked by human activities (*e.g.* logging), once the habitat or land type is perforated, succeeding area losses have a higher probability of producing fragmentation. Because the process of *montado* degradation and area loss often involves concentrated tree mortality, resulting in the formation and enlargement of clearings in the *montado* patches (Godinho 2016b; Pinto-Correia et al. 2019), we separately calculated the total area and land use transitions associated to these perforations. We performed this specific analysis using the script Perforation.py from the LDT4QGIS tool (Paixão and Machado 2023).

Results

Montado cover of 2018

We estimate that the *montado* of 2018 covered 1,189,390 hectares (ha) in southern Portugal (number of patches = 1707; mean patch size = 679 ha) (available from Marques et al. 2025). Compared to the earlier estimate of 1,220,702 ha of 2006, according to Godinho et al. (2016d), this indicates that between 2006 and 2018 there was a reduction of the *montado* area by 31,312 ha (95% confidence interval: 29,706–32,943 hectares). Thus, the area annual loss of *montado* is approximately 2610 ha (2609.3 hectares/year), which amounts to an annual percent loss rate of 0.21% (95% CI 0.201–0.223% per year). Our mapping also shows that the loss of *montado* coverage is widespread and extends to large areas of southern Portugal (Fig. 2A). The areas of *montado* loss are almost continuous and more numerous in the eastern regions of the study area (central and northern Alentejo).

The *montado* area shifts were mainly caused by wildfires (approximately 70%), the opening or enlargement of clearings due to tree mortality or cuts (18%) and the installation of intensive crops such as, olive or almond groves and irrigated cereals (8.4%) (Table 1). Tree plantations (*Eucaliptus* spp. and pine trees), medium or small dams, and buildings contributed to a combined *montado* loss value lower than 3.5%.

Types of dynamics in the *montado*

The areas of *montado* loss are almost continuous and more numerous in the eastern regions of the study area (central and northern Alentejo). The southern region shows a contrasting pattern: there are large areas that showed no change, but, on the other hand, many *montado* areas experienced dynamics of loss of *montado* patches, fragmentation of the patches or the reduction of patch area (Fig. 3). In fact, in the southernmost region there are two large areas where we observed patch disappearance or number of patch decrement by loss (dynamic H). Categories of gain dynamics were only identified in a few and scattered quadrats in the study region however, in two regions in central and northern Alentejo there was an increase in the number of patches by gain (dynamic F).

The type of dynamic of the *montado* areas assessed in UTM 5 km squares is shown in Fig. 4. A very high number of the quadrats had no change in the *montado* cover or these changes were less than 1 ha (ToD A; n = 558), whereas in a few areas (n = 13 quadrats), there was an increase on the number of patches of *montado* (ToD F) or aggregation by gain, only in 1 quadrat (ToD G). It is noteworthy that we observed

Table 1 Distribution of the shifts in *montado* coverage and losses between 2006 and 2018

Land use/process	Area loss (ha)	Coverage loss (%)
Wildfire	21,981.0	70.2
Opening/clearing	5636.2	18.0
Intensive/permanent crops	2630.2	8.4
Tree plantation (Pine, Eucalyp.)	688.9	2.2
Dams	156.6	0.5
Buildings	125.3	0.4
Scrubland	62.6	0.2
Solar plants	31.3	0.1
Total	31,312.1	100

types of dynamics related to loss of *montado* coverage in almost 60% of the quadrats. Specifically, in 276 squares there was a decrease of the patch size (ToD E), and in 410 quadrats this loss occurred with patch perforation (ToD E1) The two remaining categories of the decline dynamics of *montado*, fragmentation by loss (ToD I) and the reduction of the number of patches by loss (ToD H), were observed in 126 and 35 quadrats, respectively.

Going beyond the quadrat analysis numbers and considering the areas involved, we observed that the fragmentation by loss was the dynamic that contributed most to the decrease in *montado* cover, accounting for approximately 54% of the *montado* area lost (ToD I, Fig. 5). It was followed by perforation (E1, 21.9%), loss of patch area (ToD E, 14.5%) and a reduction in the number of patches associated to area loss (ToD H, 12.3%). The dynamics related to the increase in *montado* coverage—gain, increase in the number of patches or aggregation of patches by gain—accounted for very low area percentage changes, only 2.4% of the *montado* shifts.

Perforations in the montado

We observed that perforations are common and widespread across the *montado* distribution area (Fig. 3). This early phase of transformation usually leads to further degradation and loss, requires tracking and close monitoring to correctly anticipate near future occurrences. The large contiguous regions showing perforation are in the eastern and central Alentejo. The transition areas for this dynamic are different from south to the central and northern regions. In the south, many areas with perforation are in the vicinity of areas with no change or where *montado* is absent. In contrast, in the central and eastern regions, perforations are interspersed within the *montado* areas that also show loss of patch area thus, indicating that these are critical areas of decline where multiple decline dynamics are at play, resulting in very large areas of *montado* loss.

The perforations in the *montado* were mostly due to changes to or induced by similar processes that occurred in the overall loss of *montado* cover (Table 2). The highest value was due to clearings in *montado* patches (approximately 67% of area loss in perforations) but, the impact of wildfires was also marked, accounting for approximately 19% of the perforation area. The installation of intensive/permanent crops resulted in the conversion of more than 8% of the perforation total area.

Discussion

This study follows on previous research that track the *montado* cover and its transformation in the recent decades (e.g. Acácio et al. 2017, 2021; Costa et al. 2009, 2010, 2011; Godinho et al. 2016d; Plieninger 2006). Our results reveal that the *montado* area continues the ongoing process of decrease; we observed a decrease of over 31,000 hectares between 2006 and 2018, which results in an annual area loss of 2600 ha or 0.21% year^{-1}. This annual rate is comparable to the range of *montado* loss values reported by other authors for previous periods, 0.16–0.22% year^{-1} for cork oaks and 0.26% year^{-1} for holm oaks (Costa et al. 2011) and 0.04–0.27% year^{-1} (Plieninger 2006). Nevertheless, there is a noticeable difference between the values we recorded between 2006 and 2018, and the *montado* annual loss of 5670 ha (0.43% year^{-1}) reported for the same study region between 1990 and 2006, according to Godinho et al. (2016d).

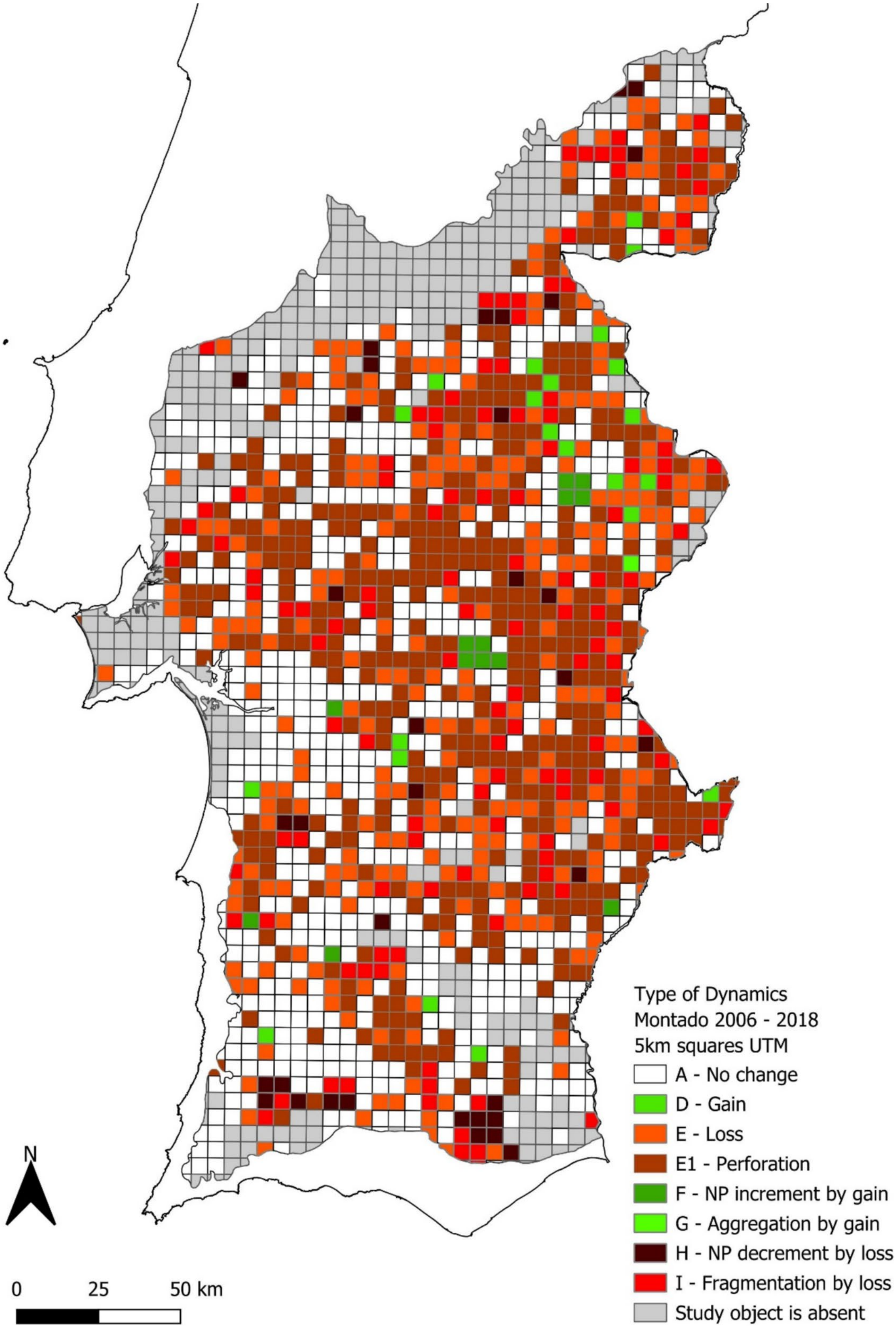
This marked decrease in the rate of loss is likely the result of multiple, complex, non-exclusive and interconnected factors. We propose four factors to explain this rate decrease, three contributing in an integrated fashion to the reported higher value of *montado* loss between 1990 and 2006 compared to recent times, and one factor that probably is linked to the decreasing value observed between 2006 and 2018. First, we consider a potential overestimation effect of the process in the previous time interval (1990–2006) due to the lower quality of the information available at the time, satellite images and CORINE Land Cover maps, compared to the higher spatial resolution and overall image quality of the aerial photographs used in this study. The aerial photographs enable a finer-scale analysis, which is particularly needed in the uneven tree cover *montado* patches and fuzzy boundaries of the *montado* areas (Acácio et al. 2021; Costa et al. 2010; van Doorn and Pinto-Correia 2007). Second, the higher impact of the tree cutting to build large infrastructures between 1990 and 2006, namely the Alqueva dam project, which closed the flood gates in 2002. This large dam affected more than 25,000 hectares by tree cutting and shrub clearing in the flooded area alone but, its main impact occurred before our analysis time frame. The infrastructure project also integrated another large dam (Pedrógão), several smaller dams and an extensive network of canals. Also, during the previous period of analysis, the motorway from Lisbon to Spain was built, crossing large *montado* areas along its route. Third, while in our results the wildfires were identified as the major factor for *montado* loss (Table 1), the previous wildfire seasons of 2003 to 2005 yielded much higher and record areas of *montado* areas affected. In fact, between 1990 and 2006 there were over 48,000 ha of burnt area in the Algarve hills (Moreira et al. 2009; Silva and Catry 2006), while we observed a total of 22,500 ha loss of *montado* due to wildfire from 2006 until 2018, a value corresponding to less than 46% of the previous time period. More than the largest burned area, these fire seasons were characterized by large and extreme fires (Guiomar et al. 2015; Silva and Catry 2006). Conversely, we consider that there was a marked change in the *montado* protection laws between the two time periods: the legislation protecting the cork and holm oaks was strengthened in 2004 (Law 155/2004), providing clearer definitions and aspects of its application. We argue that the stricter law has probably yielded better results since, however, the impact and effectiveness of policy measures are often difficult to evaluate.

Overall *montado* dynamics and associated drivers

The most predominant loss in the *montado* occurred in burned areas, while the second and third was attributed to openings and clearcuts, and to the installation of intensive permanent crops, respectively (Table 1). Overall, these three categories of landscape changes accounted for more than 96% of the *montado* loss (Table 1).

The effect of large wildfires—burnt area larger than 100 hectares -, regardless of their human or “natural” origin, is inherently a stochastic disturbance, characterized by random variation in timing, intensity (or severity), and spatial extent of the affected landscape (e. g. Fernández-Guisuraga et al. 2023). These characteristics likely have contributed to the unexpectedly severe impact that we found of the wildfires on the *montado*. Agroforestry or silvopastoral land use systems, such as *montados* and *dehesas*, are considered land use alternatives to reduce fire hazard at landscape scale (Bergmeier et al. 2021; Damianidis et al. 2021; Wolpert et al. 2022), given the vertical discontinuity between surface fuels and canopy fuels promoted by livestock grazing or annual crop production. The dominant trees species of *montados*, cork and holm oaks, developed several fire-resistant traits, such as thick bark (cork) and basal or epicormic resprouting ability of burned trees (Pausas 2015; Pausas and Keeley 2017). However, the effect of the landscape (or the spatial distribution of vegetation fuels) on fire behaviour diminishes as fire-weather conditions worsen (Cruz et al. 2022). In fact, the 2003 and 2004 wildfires occurred under extreme weather conditions (Trigo et al. 2006), thereby affecting land use systems that are less susceptible to fire, such as *montados*.

Our results show that a continuing and widespread loss of *montado* cover is occurring at a large spatial extent. Several authors have reported this trend and related it to the increasing vulnerability to climate and management factors. Camilo-Alves et al. (2017) indicate a declining trend in the *montado* resilience to drought, driven by distinct physiological mechanisms responsible for either tree chronic decline or sudden death. Additionally, there are several contributing factors, which include overgrazing, soil compaction, a reduction in understory complexity, altered fire regimes, and the abandonment of traditional management practices (*e. g.* Godinho et al. 2016d). These processes compromise not only individual tree vitality but also broader system functions such as nutrient cycling, microclimate regulation, and regeneration dynamics (Bugalho et al. 2011) and may contribute to


Type of Dynamics
Montado 2006 - 2018
5km squares UTM
A - No change
D - Gain
E - Loss
E1 - Perforation
F - NP increment by gain
G - Aggregation by gain
H - NP decrement by loss
I - Fragmentation by loss
Study object is absent
N
0
25
50 km

◂**Fig. 3** Type of change dynamics of *montado* area between 2006 and 2018 in 5 km squares (UTM). Perforation (E1) is widespread in the *montado* areas. *Montado* cover change values < 1 ha were reclassified to A—No Change. NP – Number of Patches. Map projection ETRS89 – TM06

the long-term degradation process (Joffre et al. 1988; Plieninger et al. 2021).

The decline of the *montado* is particularly evidenced by the expanding presence and spatial distribution of clearings across the landscape. Once scattered and relatively contained, these open areas have grown in extent and now form a fragmented mosaic that disrupts the continuity of the woodland canopy (Godinho et al. 2016b). The clearings in the *montado* have been described from the early research focused on the decline of this agro-silvo pastoral system (Plieninger 2006). The clearings develop because of a decrease in tree cover that often is spatially concentrated coupled with a lack of tree regeneration. While cork and holm oak decline in vitality and death is caused by several factors: poor management of the grazing intensity, pests and diseases, low soil health and impacts of soil ploughing on tree roots (Acácio et al. 2021; Plieninger et al. 2021), these factors can also negatively impact the survival of treelets in the *montado*. Moreover, the harsher local soil conditions and less shaded areas in the tree and shrub clearings can decrease the survival of seedlings (Godinho et al. 2016a) thus, hindering the tree re-colonization of the clearings. At the same time, less trees (or less vegetation in general) means lower soil protection, which increases erosion, and once the negative feedback loop is in place, it is much harder to restore the ecosystem's balance. Most of the abovementioned factors derive or are influenced by the increasing aridity. Aridity expresses the relationship between precipitation and evapotranspiration (acting as a proxy for temperature) and, among other consequences, is directly relatable to drought events. Droughts are a "ramp"-type disturbance (Nimmo et al. 2015) that build up gradually, putting the system under pressure, until a rain event comes that is strong enough to provoke a relaxation in the disturbance that allow for at least a partial recovery. But other hidden effects can be at play besides the obvious immediate negative effect of droughts on the vegetation. According to Ramos et al. (2015), long-term normal precipitation can be more important for phenology and productivity than concurrent precipitation, due to memory effect in the response of vegetation to climate—phenology may not follow promptly sudden changes (*e.g.* changes in precipitation patterns). The same study suggests that *montado* maintenance can become constrained bellow 600–650 mm which can be particularly alarming since cork and holm oak distribution in Portugal greatly match the semi-arid zone that covers the southern part of the country.

Our results also reveal that the installation of annual crops in *montado* areas is a localized process and that accounted for a comparatively small area of loss. However, we registered locally the crop cultivation intensification identified long ago (Pinto-Correia 1993). Indeed, conversion to annual crop farming has been pointed out as pressures—one of the five top pressures on *montado/dehesa* reference state as a result of land management actions—in a recent review of 128 studies (see Plieninger et al. 2021). We also observed a low overall value of *montado* area converted to buildings, dams, shrubland and solar farms. However, due to the ongoing societal demand for decarbonization of the economy, the area dedicated to solar farms in the more marginal farmland as the one dedicated to silvo-pastoral systems is under growth already and will undoubtedly increase more in the future.

Spatial patterns of the *montado* transformation

While the analysis of type of dynamic of *montado* has been reported before for a smaller study area (Machado et al. 2018), we have extended this assessment to the overall *montado* area of occurrence in southern Portugal. This assessment of the spatial transformation dynamic of the *montado* provides information on which phase of the landscape transformation the system is: early, middle or final phase (Forman 1995b). By analysing the spatial distribution of each dynamic, from either loss or gain, we also identified which regions are in the initial phase or have progressed further in the transformation of the *montado*. Our results show that the most frequent types of dynamics were related to loss: perforation, patch area loss and patch fragmentation by loss. Also, fragmentation by loss was the dynamic related to the higher percentage of area lost. Therefore, the *montado* shows signs of the first stage of the land transformation across the

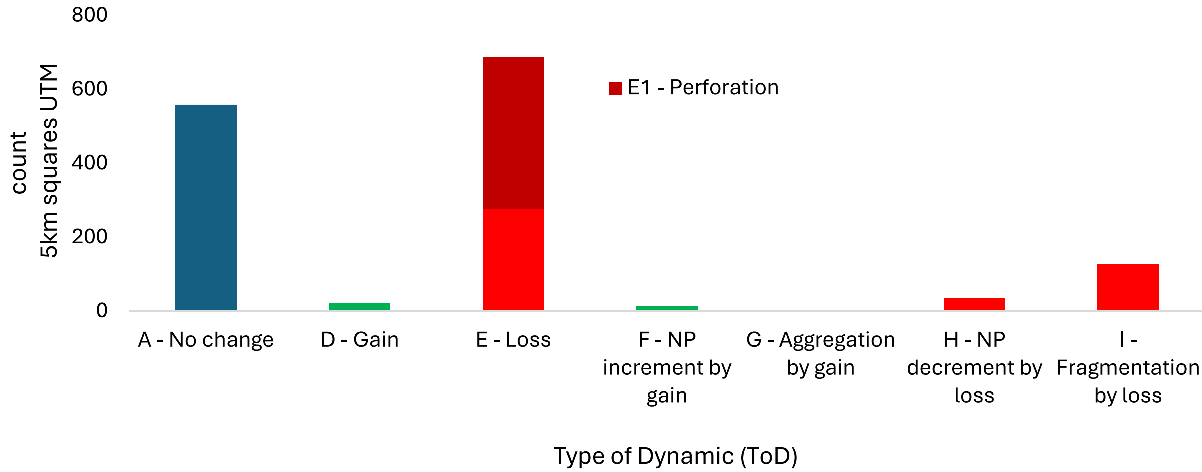


Fig. 4 Type of dynamic of *montado* between 2006 and 2018, summarized as number of 5 km UTM squares

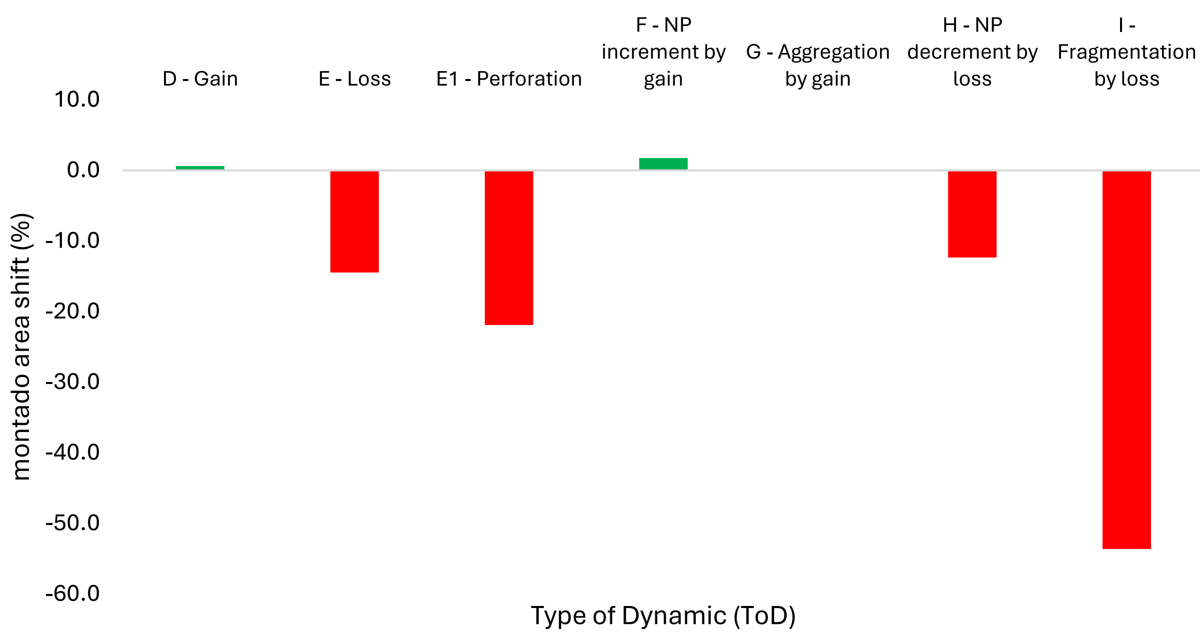


Fig. 5 *Montado* area shifts (%) between 2006 and 2018 in southern Portugal. Area values were obtained from LDT4 except the perforation, which was computed using perforation.py script (see Materials and Methods)

whole coverage, *i.e.* widespread perforation (Forman 1995a) but, the high area value of patch fragmentation also shows a progressing middle phase of the land transformation. Finally, we observed a few areas with concentration of loss of *montado* patches in the southernmost regions of the hills of Algarve and in the northern part of the study region. The transformation of these regions is particularly concerning given our minimum mapping unit of 25 hectares; a decrease in the number of land-use patches typically signals the final phase of landscape transformation. (Forman 1995a). Therefore, we believe that the system *montado* is near the limits of its sustainability in these marginal regions.

Table 2 Land uses observed in 2018 from perforations in *montado* areas of 2006

Land use/process	*Montado* area loss (ha)	Perforation relative loss (%)
Opening/clearing	4246.73	66.96
Wildfire	1200.29	18.93
Intensive/permanent crops	546.79	8.62
Tree plantations	241.67	3.81
Buildings	42.84	0.68
Dams	28.70	0.45
Solar plant	25.66	0.40
Scrubland	9.46	0.15
Total	6342.15	100

The importance of perforations

Although the importance of perforations in the degradation of the *montado* has been evaluated before (Plieninger 2006), this was the first assessment of its role and impact at the broader scale. This may be a challenging spatial dynamic to track and monitor because of the scattered trees characteristic of the *montado*, the slow change caused by clusters of dead standing trees, and the enlargement of the small clearings. As mentioned above, the perforation of the *montado* is one of the early phases of the landscape transformation process. These perforations tend to persist or increase their size also because the tree regeneration is lower in open areas (Plieninger et al. 2010), probably because of degradation of soil health due to soil erosion, the higher soil temperature and less favourable micrometeorological conditions (Godinho et al. 2016a). By analysing the perforation features we can have a much better understanding of what are the changes and drivers of the initial phase of the *montado* loss. Although there is a considerable overlap in the ranking between the processes and changes of the perforations and those of the overall change of the *montado*, in the perforations the higher impact category was openings or clearings. Thus, it is likely that the impact of soil conditions, mobilization and health, the high grazing load and the diseases and pests contributes decisively for most of the initial phase of transformation. It has been described that the management activities in the *montado*s are strongly linked to their condition (Machado et al. 2018; Pinto-Correia and Azeda 2017; Plieninger 2006; Plieninger et al. 2021). Our results concur with this point of view and the management focused on tackling the *montado* loss drivers can reverse the decline of this system; several of these management factors are acting on the initial phase of the decline and on the subsequent phases (Pinto-Correia et al. 2022b). We argue that this analysis can support and assist in the public policies aiming to maintain and recover the *montado*.

Despite the advantages of the high spatial resolution (25 cm) of the aerial imagery used in the assessment of *montado* cover changes here presented, our results can be subject to two important sources of uncertainty or biases. The process of visual interpretation introduces observer-dependent bias, influenced by individual experience and assessment (Olofsson et al. 2014). Although the visual interpretation was mainly performed by a single observer (JTM), differences in the interpretation of visual cues may affect the comparability of the results with other reports in the literature. To reduce the impact of this potential bias, there was a discussion and consensus process with more experienced co-authors, when ambiguous or doubtful areas were categorized. Secondly, temporal comparisons are sensitive to inconsistencies arising from variations in image characteristics, such as resolution and acquisition conditions. As we referred above, there are differences between the image data sources in quality or acquisition timing that supported the *montado* cover maps of 2006 and 2018. Therefore, apparent changes in vegetation structure may not correspond to land use modifications but instead reflect methodological artefacts. This limitation may be more frequent when marking out the precise patches' limits. Consequently, these limitations must be carefully considered when interpreting temporal patterns of *montado* degradation based on multi-date remote sensing imagery.

Going beyond the diagnosis, and trying to unveil future possibilities, it is relevant to consider that, assuming the current trend will continue (*montado* area loss) the dynamic E—Loss, and especially E1—Perforation, are predecessors of I—fragmentation by loss, and H—number of patches decrement by loss. Despite the values associated with this system in terms of ecosystem services provided, and isolated essays from concerned producers to halt the decay (*e. g*. Guimarães et al. 2023), we have observed its continuing transformation into smaller, more fragmented and less connected *montado* patches. These resulting patches are considerably less resilient to the pressures they are facing (Machado et al. 2020). In a scenario of the continuation of the decline and pressures, exacerbated by the ongoing climate change, the evolving transformation will continue and may even accelerate.

Concluding remarks

This study provides a thorough spatially explicit, system-wide assessment of *montado* transformation dynamics across its full range in southern Portugal, building on and extending prior localized analyses. By integrating quantitative land cover change data with a spatial typology of transformation phases, our research offers a deeper understanding of where the *montado* stands within a broader degradation trajectory, enabling to identify all the details of a frequently and continuously unseen process of decay. Importantly, it identifies perforation as an early but critical signal of systemic decline, demonstrating how localized disturbances like wildfires interact with slow, cumulative pressures such as fragmentation and land-use change. This approach not only clarifies the current state of the *montado* but also improves our ability to anticipate and manage future risks to this vulnerable socio-ecological system.

Our findings confirm the continued decline of the *montado*, though at a slower rate than in previous decades. Wildfire remains a driver of instant loss, revealing a growing system vulnerability, while gradual clearing formation contributes to widespread fragmentation. Spatial patterns show all phases of landscape transformation, with critical thresholds nearing in marginal regions. Perforations, as early signs of decline, signal continued fragmentation and reduced resilience if current trends persist.

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Author Contribution N. G., T.P–C. and J.T.M. conceived the research, J.T.M, R.M. and N. G. analysed the data. R.M. provided software. J.T.M., R.M. and N. G. wrote the main manuscript text. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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