Is Portugal's forest transition going up in smoke?

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ABSTRACT

The turnarounds from decrease to expansion in forest areas that took place during the last century have been examined through the lens of forest transition theory (FTT). Among temperate and Mediterranean European countries that have seen an expansion of forest cover, Portugal stands out as the only case in which this trend has recently been reverted. In this study, we explicitly map and document the forest transition (FT) in the country over the period 1907–2006, and investigate when and where forest transition happened *de facto*, and which were the land use transition pathways that resulted from the shrublands, agriculture, and forest interplay dynamics. After thematic and geometric harmonization of land cover maps from 1907, 1955, 1970, 1990, and 2006, a cluster analysis established four typologies, and a transition matrix was constructed to assess land cover dynamics. We found that up to 1955, FT occurred simultaneously with agricultural expansion, as shrubland areas diminished. Afterwards, with the retraction of agricultural area and the consequential decoupling of forest management from local actors, FT gained momentum and expanded up to the 1990s. While during the first half of the 20th century, forest expansion followed the "Scarcity" and "State Policy" pathways fostered by local socio-ecological feedback loops, throughout the second half of the century forest transition was driven by exogenous socio-economic forces, following "Economic Development" and "Globalization" pathways. We show how, despite these forces, FT can be derailed by endogenous factors such as wildfires, which limited and in some areas even reverted the afforestation process, initiating a deforestation phase. Since the necessary conditions for FT (technology shift, urbanization, agriculture retraction and public afforestation programs) were available in mainland Portugal, we advance the hypothesis that critical wildfire risk governance deficits may have been responsible for arresting FT. Considering the critical role of forests and other wooded areas in supporting climate change mitigation and sustainable development, our work provides useful evidence and insights for public decision makers on previously unaddressed dimensions of FTT.

1. Introduction

Conserving resilient forests is one of the development goals of the United Nations (UN, 2015) due to their role in providing multiple ecosystem and societal services (Miura et al., 2015; Ninan and Inoue, 2013; Simončič et al., 2015; Vizzarri et al., 2015), as well as in mitigating climate change (IPCC, 2014; Pan et al., 2011; Millar et al., 2007). Understanding the relative contribution of different drivers to land use change is critical to address the abovementioned challenges (e.g. Hersperger and Bürgi, 2009; Jepsen et al., 2015; van Vliet et al., 2015). Europe, for instance, experienced a process of anthropogenic deforestation since the mid-Holocene, but in the last two centuries inverted its deforestation pathway (Kaplan et al., 2009; Williams, 2000). Mather (1992) designated this turnaround from decrease to

expansion in the forest area of a region as "forest transition" (FT), and Mather and Needle (1998) have sought to explain it with the Forest Transition Theory (FTT), in which urbanization and industrialization processes first lead to a deforestation phase, and then rural depopulation, land abandonment, and the concentration of agricultural activities on fertile soils create the conditions that allow forests to recover.

Mather's seminal work (Mather, 1992) was followed by national studies dealing with forest transitions in Denmark, France, Switzerland, Scotland, Asia (Mather, 1998, 2001, 2004, 2007) and Portugal (Mather and Pereira, 2006). Studying the post–FT process in the eastern United States, Drummond and Loveland (2010) and Jeon et al. (2014) have documented a new decline in forest area due to urban sprawl. FFT has framed several studies unveiling the drivers of land use process dynamics at global scale (e.g. Rudel et al., 2005; Baptista and Rudel,

2006; Pfaff and Walker, 2010; Meyfroidt and Lambin, 2011), as well as studies analyzing afforestation and deforestation phases in different biotas (e.g. Rudel et al., 2010; Bae et al., 2012; Oduro et al., 2015), and their teleconnections in a globalized world (Meyfroidt et al., 2010). Barbier et al. (2010); Barbier and Tesfaw (2015) have concluded that in low to moderate income countries governance issues had a relevant role in explaining the timing and magnitude of FTs.

1.1. Forest transition pathways

Complexity and non-trivial interdependencies between several drivers set the challenging stage of land-cover change. FT processes differ among countries and time periods, with population dynamics and poverty alone not being among its major causes, as people's responses to economic opportunities are mediated by institutional factors (Lambin et al., 2001). Moreover, globalization of commodities, capital and people amplified teleconnection effects upon local land use changes (Meyfroidt et al., 2010; Lambin and Meyfroidt, 2011). A complex set of factors is implicated (Mather, 1992; Rudel et al., 2005), with land use transitions operating through endogenous forces and exogenous socio-economic mechanisms, according to Lambin and Meyfroidt (2010), who considered two kinds of drivers: 1) *mostly endogenous forces*, due to negative socio-ecological feedbacks that prompt actions towards afforestation and conservation, as local stakeholders perceive a decline in previously available goods and services; and 2) *mostly exogenous forces*, due to socio-economic dynamics unrelated to local land cover changes, such as markets, globalization, innovation, and supranational afforestation and conservation policies. They also concluded that, in the former, landowner awareness was of utmost importance to stop inadequate land use practices, while in the latter, the exogenous drivers might require investment to allow perceived opportunities to be captured.

Detailing the mechanisms underlying FT, Oduro et al. (2015) summarized the pathways previously proposed by Rudel et al. (2005) and Lambin and Meyfroidt (2010) in five FT types: 1) *Economic development pathway*, related to rural exodus to urban and industrialized areas due to labour shortage, fostering land abandonment and therefore allowing forest regrowth (e.g. Aide et al., 1995; Bowen et al., 2007; Prévosto et al., 2011; Klooster, 2003; Mather and Pereira, 2006; Rudel et al., 2005); 2) *Forest scarcity pathway*, where private or public agents value or anticipate a valuation of goods and services provided by forests and support afforestation programs, or enforce laws to protect woodlands, promoting the increase of forest area (e.g. Frayer et al., 2014; Holmgren et al., 1994; Singh et al., 2017); 3) *Globalization pathway*, related to the exposure of open economies to international markets, international conventions and agreements, and socio-political pressure from environmentalist organizations, fostering investments in afforestation for commodities and protection of forest areas (e.g. Hecht et al., 2006; Li et al., 2015); 4) *State forest policy pathway*, where forest expansion is conducted for strategic national goals, such as poverty alleviation, society modernization, land control, and greening of the economy (e.g. Bae et al., 2012; Mather, 2007); and 5) *Smallholder, tree-based land use intensification pathway*, which is associated with tree-planting for restoration purposes, ecological diversification and resilience of small-scale rural communities (e.g. Blay et al., 2008; Singh et al., 2017).

1.2. Forest transition and wildfires

The statistics that reveal the extent of the impact of wildfires on forest area were not yet available when Mather and Pereira (2006) analyzed the role of fire in the Portuguese FT, but they proposed the hypothesis that fires were jeopardizing private and public afforestation efforts. According to IFN (2013), FAO (2015), and Uva (2015), this forest expansion reversal trend is being documented since 1995 and appears to be a consequence of extensive vegetation burning (e.g. Moreira et al., 2001; Silva et al., 2011; Jones et al., 2011). The role of

fire as a driver of land cover change, as land abandonment and afforestation increased fuel loads, has also been discussed by Rego (1992), Fernandes et al. (2014), Pausas and Fernández-Muñoz (2012) and Oliveira et al. (2012).

1.3. Portugal as a case study in the western world

According to FAO (2015), Portuguese total forest cover declined at about 0.3% yr^{-1} since 1990. Being part of the group of higher income countries, whose forest area increased at 0.05% yr^{-1} during the same period (Keenan et al., 2015), Portugal features an unexpected trend, as Kauppi et al. (2006) also suggest. Mather and Pereira (2006, p. 259) considered that Portugal "presents a spectacular example of operation of forest (area) transition", as it was greater and faster than in several other European countries. Through historical analysis of land use and demographic data at national level, they documented the increase in forest area between 1875 and 2000 from about 7% to near 40% of the country's mainland area. In addition to this expansion, during that period forest management goals changed from meeting local agrarian needs to global industrial wood commodity markets. More recently, forest management is also being challenged to satisfy both industrial procurement and a growing demand for environmental services. This paradigm shift also embodies a FT (Mather and Pereira, 2006), framed as a globalization FT pathway (Rudel et al., 2005).

1.4. Aim and scope

Our aim is to expand upon Mather and Pereira (2006) and perform an in-depth, spatially explicit analysis of FT in Portugal during the last 100 years. Without using *a priori* historical narratives or demographic transition, which have been criticized by Robbins and Fraser (2003) and Perz (2007), we use FTT as a framework to anchor the discussion of results from land use transition pathway analysis. We formulate the hypothesis that FT described at national level may mask the existence of sub-national transition dynamics, regional drivers and pathways that ultimately substantiate the national-level process. We thus ask where and when did forest areas expand and contract. Similarly to other authors who have linked forest land cover evolution with wildfire and its risk management strategies (Badia et al., 2002; Seijo and Gray, 2012; Moreira et al., 2011), we discuss our results unveiling the role that fire and its mismanagement may have had to arrest a sustainable FT, and showing that although its necessary endogenous and exogenous conditions were present, they were not sufficient to ensure the expected forest area change process.

2. Study area

The study was conducted in mainland Portugal, at the municipal level (LAU 1–Local Administrative Units) (Fig. 1). With the majority of its ~10 million inhabitants living in densely urbanized coastal areas, forest, shrublands and pastures occupy ~67% of the country (ICNF, 2013), while agricultural areas cover another ~24%. Portugal is an open economy, integrated in the European Union, and with most of its workforce employed in the tertiary sector. The country has a Mediterranean climate, with dry, warm summers in the northern half, and dry, hot summers in the southern half. Maritime pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) plantations cover broad areas of rugged terrain in the northern part of Portugal, while the woodlands of the undulating southern plains are dominated by evergreen oak woodlands (*Quercus suber* and *Quercus rotundifolia*) of diverse density in a mosaic with croplands.
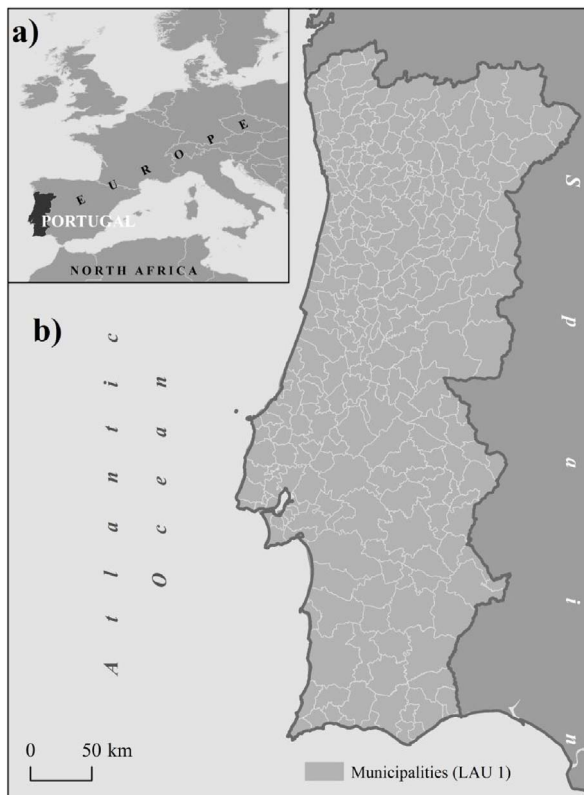
Fig. 1. Portugal in the context of southern Europe (a) and the boundaries of its 278 municipalities (b) (Official Administrative Map of Portugal 2015).

3. Data and methods

3.1. Forest maps: data sources and thematic homogenization

We used land cover maps from five different dates to assess forest dynamics in Portugal since the beginning of the 20th century. After an extensive review of the maps available for that period, documenting the major land uses (agriculture, forest, shrublands, urban areas, and bare surfaces and water bodies) and thus candidate to supporting the reconstruction of land cover dynamics, we selected five sources of information at national level: the Agriculture and Forest Map of 1910, at the scale 1:500,000, with final fieldwork done in 1907 (Radich and Alves, 2000), the reference year used herein; the Agriculture and Forest Map, published in three sheets (1960, 1964, and 1965) at the scale 1:250,000, with fieldwork mostly carried out between 1950 and 1955, with subsequent updates up until 1960 (Daveau, 1995); the first National Forest Inventory of 1970 (fieldwork carried out from 1965 to 1982) and the CORINE Land Cover maps of 1990 (updated version from 1986/87 satellite images) and 2006, at the scale 1:100,000 (Caetano et al., 2005, 2009a,b; Painho and Caetano, 2006). Because equivalent, but not similar, definitions of land cover and mapping techniques were used in each map, we carried out a thematic and geometric harmonization process, detailed below.

To match the definitions of forest from the five different maps, and due to known differences between the dominant species and their function at landscape level, especially in Mediterranean land use systems, we divided the wooded areas in two classes: "forest stands" (hereafter forests) and "evergreen oak woodland" (hereafter oak woodlands).

Oak woodlands represent the typical agroforestry systems of the southwestern Iberian Peninsula (*montados* in Portugal, *dehesas* in Spain), and can be characterized by their multi-functionality, comprising areas with dominance of evergreen oaks in the tree layer (mainly cork and holm oaks), and an understory formed by annual crops,

pastures, or shrub cover (Pinto-Correia et al., 2011). They are well defined in the oldest map (1907), the only one to explicitly use the term *montado* (additionally distinguishing between cork oak and holm oak woodlands). Given the differences in the criteria used to define these areas between the 1955 and 1990/2006 data sources, we used the datasets of Guiomar et al. (2015) and Godinho et al. (2016), who identified and addressed these limitations. The data produced by Godinho et al. (2016) are also based on CORINE Land Cover and ancillary data to map oak woodlands in 1990 and 2006. Guiomar et al. (2015) also used the Agricultural and Forest Map, together with maps of cork and holm oak distribution at the 1:250,000 scale, to map the boundaries of these multiple-use oak woodlands in 1955. Considering the abovementioned characteristics, we aggregated patches classified as cork oak and holm oak in the 1970 data source to obtain the oak woodlands for this reference year.

In both the 1907 and 1955 maps, forest areas are represented by a single land cover class. In the case of the 1970 map, forest areas result from the aggregation of evergreen and deciduous forest types, excepting oak woodlands. For the 1990 and 2006 maps (based on CORINE Land Cover), they were obtained from the spatial aggregation of the three main forest land cover classes (311–broad-leaved forest, 312–coniferous forest, and 313–Mixed forest). According to Nery (2007) and Guiomar et al. (2009), "transitional woodland/shrub" (CORINE Land Cover class 324) represents forest degradation, regeneration, and recolonization, or transitional stages related to forest management operations (e.g. clearcutting), without loss of identity as forest area. To classify those areas as forests or shrublands in 1990 and 2006, two land cover change maps were created (1990–2000 and 2006–2012) using the available CORINE Land Cover datasets. The areas classified as "transitional woodland/shrub" in 1990 and in 2006, and as forests (land cover classes 311, 312 and 313) in 2000 and 2012 respectively, were also considered forests. Areas that remained in the "transitional woodland/shrub" class between the earlier and later dates were classified as shrublands.

Agricultural and shrubland areas for the 1990 and 2006 maps were also taken from CORINE Land Cover maps. While agricultural areas result, for all reference years, from the aggregation of more detailed classes present in each reference map, the definition of shrublands had to ensure thematic consistency. In the 1907 and 1955 reference year maps, shrublands are aggregated with other land cover classes, in a broad class of "uncultivated areas". This land cover class includes rock outcrops, sand beaches and dunes, and water bodies, in addition to shrublands. Thus, and assuming the temporal stability of the non-vegetated land cover types, we used the CORINE Land Cover 1990 classes 331 (beaches, dunes, sands) and 332 (bare rock) to disaggregate the "uncultivated areas" of 1907 and 1955. The process was similar for water bodies, but we had to take into account the year of construction of each dam to use only those that had been built up to the date of each reference year. Built-up or artificial areas were not considered in our analysis given the complexity of evaluating transitions related to urban sprawl. Thus, the "artificial surfaces" identified in CORINE Land Cover 2006 were used to mask out these areas from the older maps.

This set of operations produced, for each reference year, a five-class land cover map (agriculture, shrublands, forests, oak woodlands, and bare surface) with a minimum mapping unit of 25 ha.

3.2. Cluster analysis and transition matrix

The percentages of forests and oak woodlands for each of the five periods (1907, 1955, 1970, 1990 and 2006) were calculated at municipal level. Ten out of 278 municipalities were excluded from further analysis, as they had less than 5% of forest or oak woodland cover area throughout the whole period or had become mostly urban municipalities, such Lisboa, Oeiras, and Porto. A hierarchical cluster analysis (HCA) was performed on this dataset to group municipalities according to their land cover trajectories, using Ward's method (Ward,
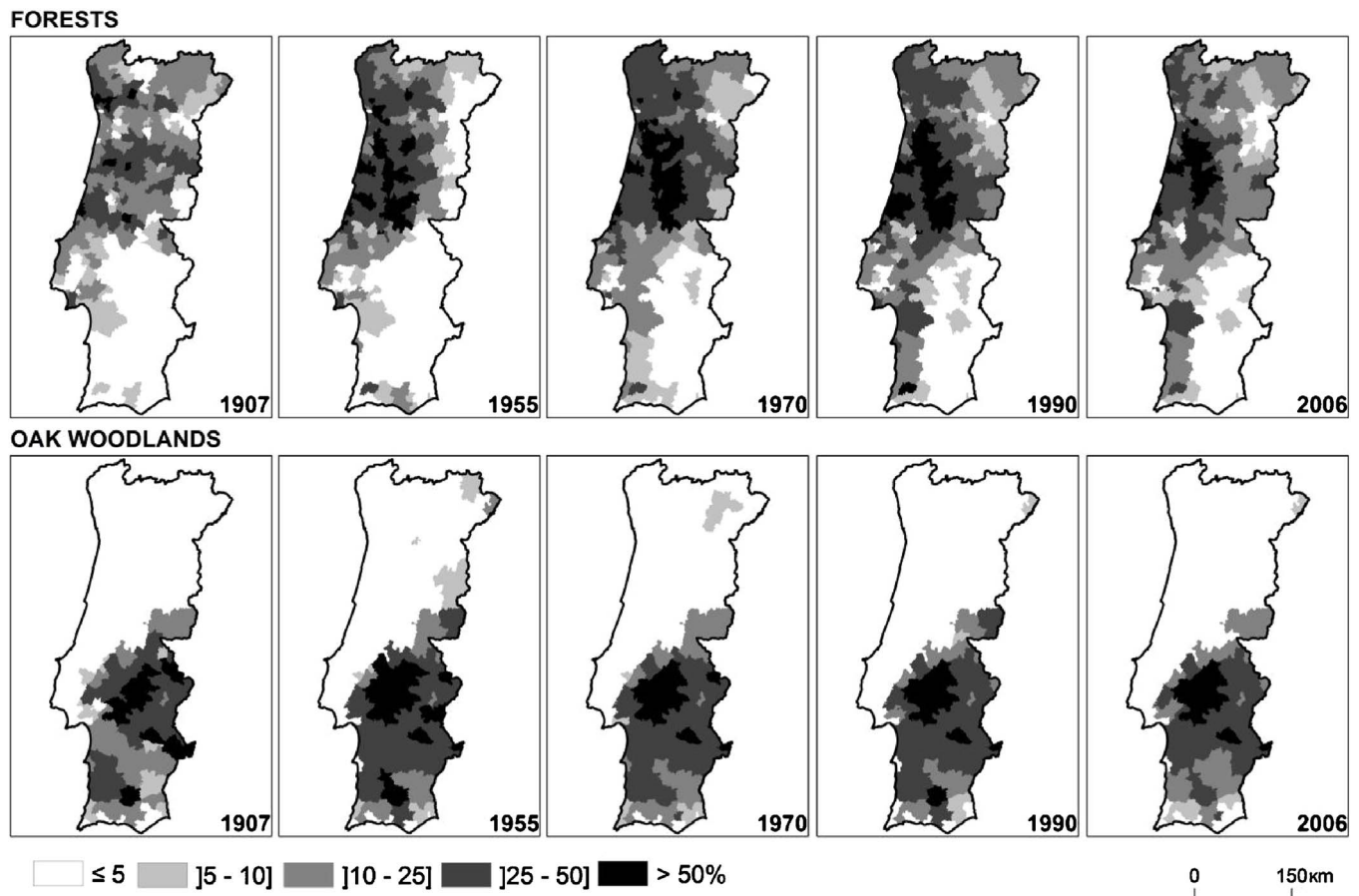
FORESTS

OAK WOODLANDS

Fig. 2. Dynamics of the percentage (at municipal level) of forest (a) and oak woodland (b) covers between 1907 and 2006.

1963) and the Euclidean distance metric. Connectivity (Handl et al., 2005), Dunn index (Dunn, 1974) and silhouette width (Rousseeuw, 1987) were used to evaluate the results of the cluster analysis and to select the number of clusters. While Dunn index and silhouette width are non-linear combinations of compactness (cluster homogeneity) and separation (distance between cluster centroids), connectivity measures the extent to which neighboring observations share the same cluster (Handl et al., 2005; Brock et al., 2008). To select the number of clusters, Dunn index and silhouette width should be maximized, while connectivity should be minimized (Brock et al., 2008). All analyses were performed using R 3.1.3 software (R Development Core and Team, 2015), through the native R functions for clustering, as well as the *clValid* and *NbClust* packages (Brock et al., 2008; Charrad et al., 2014). Box plots (McGill et al., 1978) were then used to compare the means and ranges of the proportions of forests and oak woodlands between clusters.

For each cluster, and considering the major land cover classes (agriculture, shrublands, forests, oak woodlands, and bare surface), four transition matrices were calculated for the periods 1907–1955, 1955–1970, 1970–1990 and 1990–2006 using the cross tabulation function of IDRISI Selva (Eastman, 2012). Prior to this calculation, a vector-raster conversion was performed for each land cover map, with a 250 m cell size. The generated datasets were used to calculate the annual rate of land cover change in each period, for each cluster and each municipality.

3.3. Forest transition drivers

To identify drivers of forest transition, we collected data on burnt area, population censuses, sheep and goat censuses and data on afforestation area. To analyze the role of fire, we used the fire perimeter

atlas from 1975 to 2006 described by Oliveira et al. (2012). Population data from 1911 to 2006 were obtained from national censuses (Santos, 2016; Pordata, 2015). Sheep and goat densities were determined using the dataset of Santos (2016). From this dataset we discarded cattle livestock, which are not restricted to extensive grazing. Data on funds spent in public afforestation programs and incentives are from Carvalho and Morais (1996), CESE (1996), Mendes and Dias (2002) and ISA (2005). Private afforestation efforts for 1907–1955 and 1955–1970 were estimated as the difference between total wooded area and public afforestation expenditures, neglecting losses due to biotic and abiotic disturbances. Because wildfire losses after 1970 are very significant, we were unable to calculate private expenditures for 1970–1990 and 1990–2006. Land cover trajectories for each cluster were interpreted taking into account milestones in Portuguese forest and agricultural history, and classified according to the FT pathways proposed by Rudel et al. (2005) and Lambin and Meyfroidt (2010).

4. Results

Here, we provide a spatially explicit description of the temporal trajectories of wooded area change in Portugal, and organize them as a set of geographically coherent clusters.

4.1. The evolution of wooded areas: forests and oak woodlands (1907–2006)

In 1907 wooded areas covered only about 27% of the country area, with oak woodlands accounting for 14%, and forests for the remaining 13%. Agriculture and shrublands dominated the landscape, occupying more than 2/3 of Portugal's mainland. One hundred years later, wooded areas covered 32%, with 14% of oak woodlands, and 18% of

Table 1
Values of connectivity, Dunn index and silhouette width to select the number of clusters.

Number of clusters	Connectivity	Dunn index	Silhouette width
4	31.51	0.08	0.37
5	34.35	0.08	0.35
6	51.16	0.08	0.34

forests. Observing five time steps, we found that maximum woody vegetation cover (37%) was recorded in 1990, when forests peaked at 22% and oak woodlands were at 15%, declining from their maximum of 18% in 1955.

When examining the geography of those changes at municipal level, expressed as percentages of areas occupied by forests (Fig. 2a) and oak woodlands (Fig. 2b), we observe that in the North and in the Southwest of Portugal, the forest cover increased up to the 1990s and then decreased, while in the South oak woodlands reached their peak area in the middle 1950s and then declined.

4.2. Where and when did woody vegetation areas expand?

The dendrogram generated by the hierarchical cluster analysis is available as **supplementarymaterial** and the indicators supporting the selection of the number of clusters are summarized in Table 1. Since the Dunn index is constant and the four clusters case features the highest silhouette width and lowest connectivity values, it was considered the best choice.

Fig. 3 shows the distribution of forests and oak woodlands between 1907 and 2006 for each of the four clusters. Each cluster aggregates municipalities that displayed similar land cover change processes.

Fig. 4 shows the spatial distribution of the four clusters, highlighting the different regional patterns for forest and oak woodland areas change. Detailed information for each municipality can be found in the **supplementarymaterial.**

Cluster 1 represents 99 municipalities (Fig. 4) that had an average 24% of wooded cover in 1907 and expanded during more than 65 years, reaching an average of 32% cover in 1970 (Fig. 3). Afterwards, they underwent a deforestation phase of similar magnitude, but concentrated in 2/3 of the time previously required for the forest area expansion process, with the forest and oak woodland areas shrinking to an average of about 26% in 2006.

Cluster 2 represents 53 municipalities that had an average of 28% forest cover in 1907 and twice that area 83 years later. Forest areas expanded from 28% to 51% between 1907 and 1955. In the following period (1955–1970) forests stalled, regaining its momentum subsequently (1970–1990) to reach an average area of 56%, but finally decreasing to under 48%.

Cluster 3 includes 57 municipalities, where oak woodlands expanded on average from 32% to 43% of the cluster area up to 1955. Afterwards, their area retreated and forests expanded until 1990, while oak woodlands ceased to decline. After one hundred years, oak woodlands covered just 2% more area than in 1907, while forests grew from 4% to 8% of the cluster area.

Cluster 4 has 59 municipalities, where wooded areas represent about 10% of the area. They featured, on average, a deforestation trend between 1907 and 2006, affecting both forests and oak woodlands. After an initial decrease, forest cover expanded between 1955 and 1970, but decreased again in the final period of analysis. Oak woodland areas increased from 1907 to 1970, but contracted afterwards.

Fig. 5 illustrates the temporal dynamics of wooded areas for each cluster, considering the sum of forest and oak woodland areas divided by the total area of the cluster. Expressing different proportions of cluster cover, all clusters exhibited a downward concave trajectory. Clusters 2 and 3 illustrate the fastest forest cover expansion up to 1990, although cluster 3 exhibited from 1955 to 1970 a substantial contrac-

tion of woody vegetation, while it remained stable in cluster 2. Cluster 1 has overall lower forest and oak woodland cover and a downward concave trajectory, with the highest values occurring between 1970 and 1990. Finally, cluster 4 has the lowest woody vegetation cover which decreased throughout the study period, with a small peak in 1970.

4.3. Forest transitions and pathways

The matrix of net transitions between the three major land cover types is shown in Fig. 6, and the rate of change for each land cover type is given in Table 2. Both summarize land use dynamics and were used to typify the land use change pathways summarized in Table 5.

1907 to 1955: Wooded areas expanded in all clusters in tandem with agriculture, except in cluster 2, where the former retreated. We found that this simultaneous growth occurred at a rate of 0.6% yr^{-1}, but was faster in cluster 2 (1.6% yr^{-1}) due to the conversion of agricultural areas to forest. About 1814 kha of shrublands (-1.3% yr^{-1}) were converted to wooded areas (780 kha, including 430 kha of oak woodlands) and agriculture (1055 kha). In cluster 3, shrublands decreased sharply at 1.9% yr^{-1}, while agriculture expanded at 1.3% yr^{-1} and oak woodlands grew at 0.7% yr^{-1}.

1955 to 1970: Wooded areas retreated 11 kha, as forests expanded 240 kha (1.0% yr^{-1}) but oak woodlands lost 251 kha. Except for cluster 2, where forest area remained constant and agriculture grew, areas occupied by agriculture declined 286 kha (-0.4% yr^{-1}), while shrublands grew 270 kha, notably in clusters 3 and 4, expanding respectively at 14.4 and 3.9% yr^{-1}. Remarkably, in cluster 3 oak woodlands lost 222 kha to agriculture, forests and shrublands.

1970 to 1990: Forests expanded by 217 kha and oak woodlands decreased 43 kha, namely in clusters 1 and 4. Forest expansion reached a 5.0% yr^{-1} rate in cluster 3 and retreated 1.0% in cluster 4. Total decline in agriculture areas amounted to 308 kha, leading towards expansions of forests and shrublands in all clusters except cluster 1. In all clusters, but especially in 1 and 2,288 kha of forest cover were converted to shrublands, as forest area expanded 217 kha. In this period, wildfires affected more than 1,535 kha of area in clusters 1, 2 and 4, where the average annual percent burnt area was 1.7%, 1.8% and 1.6% yr^{-1}, respectively.

1990-2006: Wooded cover retreated by 400 kha (309 kha of forest and 91 kha of oak woodlands), notwithstanding strong public support towards afforestation, that reached 324 kha in that period (Table 4). Agriculture lost a total of 50 kha to shrublands and gained 24 kha from wooded areas. Farmed area decreased in all clusters, except for cluster 3 (see Table 4). Fires burnt more than 2,201 kha converting various land covers to shrublands, which increased 450 kha.

Table 3 shows that fires were relevant in all clusters, except #3. Cluster 1 had the highest fire density, the highest annualized burnt area growth rate in the period 1990–2006, and also the highest proportion of burnt area (2/3).

Table 3 also includes data on the population, and shows that between 1907 and 2006 the total population density more than doubled in cluster 4 and almost doubled in cluster 1, while it had only a small increase in cluster 3. If we consider the rural population density (2006) and assume that in 1907 most of the areas were rural, we can observe that it was reduced in half in cluster 3, had a small retraction in clusters 1 and 4, and increased in cluster 2.

Still in Table 3, the available farmed area statistics (1989–2009) show a reduction of farmed area twice faster in cluster 2 than in clusters 1 and cluster 4, while for cluster 3 an increase of 0.3% yr^{-1} is observed. Regarding the data for sheep and goats, which closes Table 3, in clusters 1 and 4 they were half as abundant in 2006 as in 1911/20, while their density decreased by a factor of 3 in cluster 2 and remained stable in cluster 3.
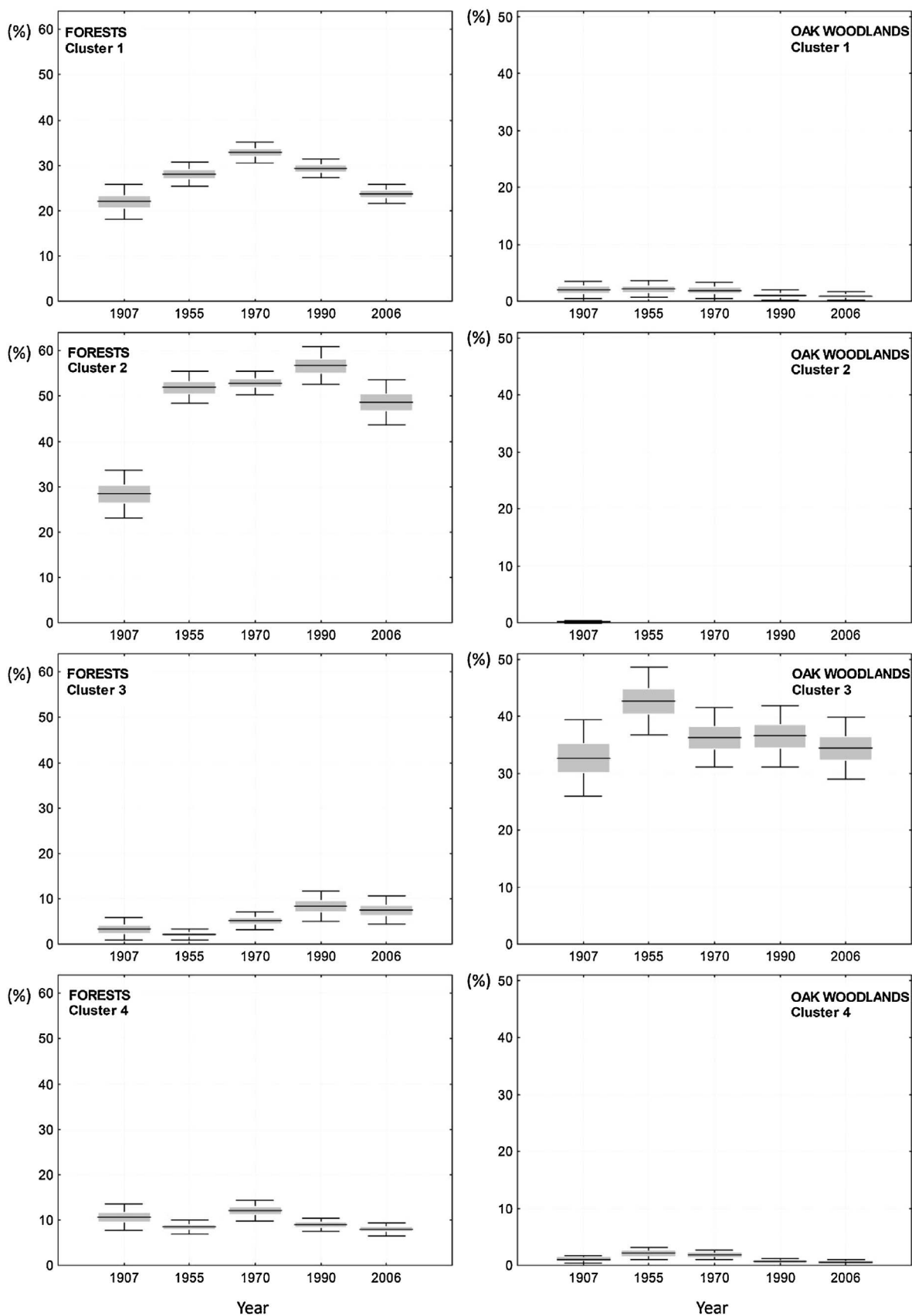
Fig. 3. Boxplots representing the distribution of the mean values (mean ± standard error, mean ± 0.99 confidence interval) of the percentage of forests and oak woodlands at the municipal level in each cluster.
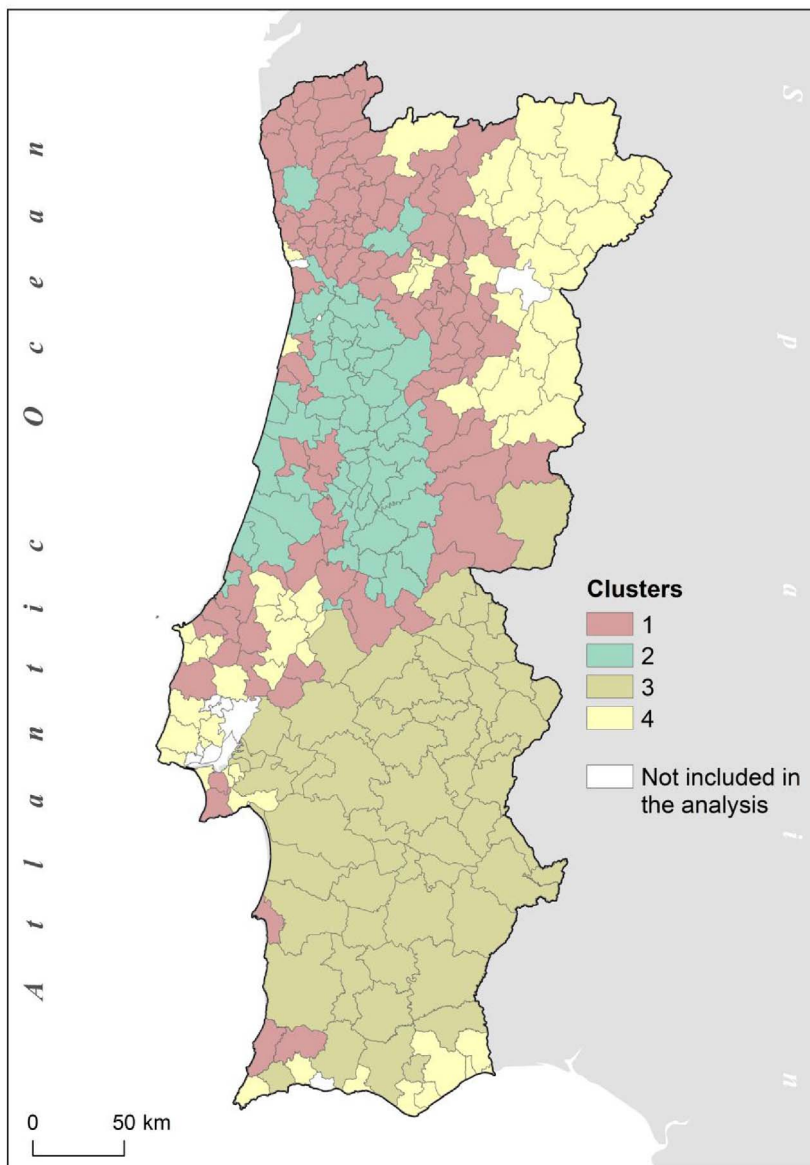
Fig. 4. Spatial distribution of four Forest Transition clusters, with municipality boundaries overlaid.
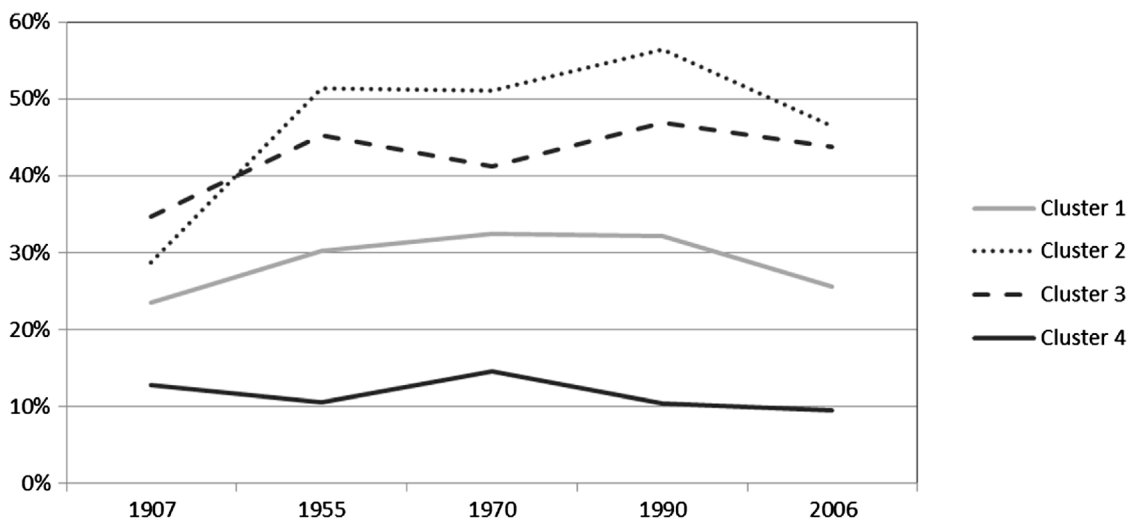

Fig. 5. Forest and oak woodland extent as a proportion of each cluster area (X-axis not to scale).
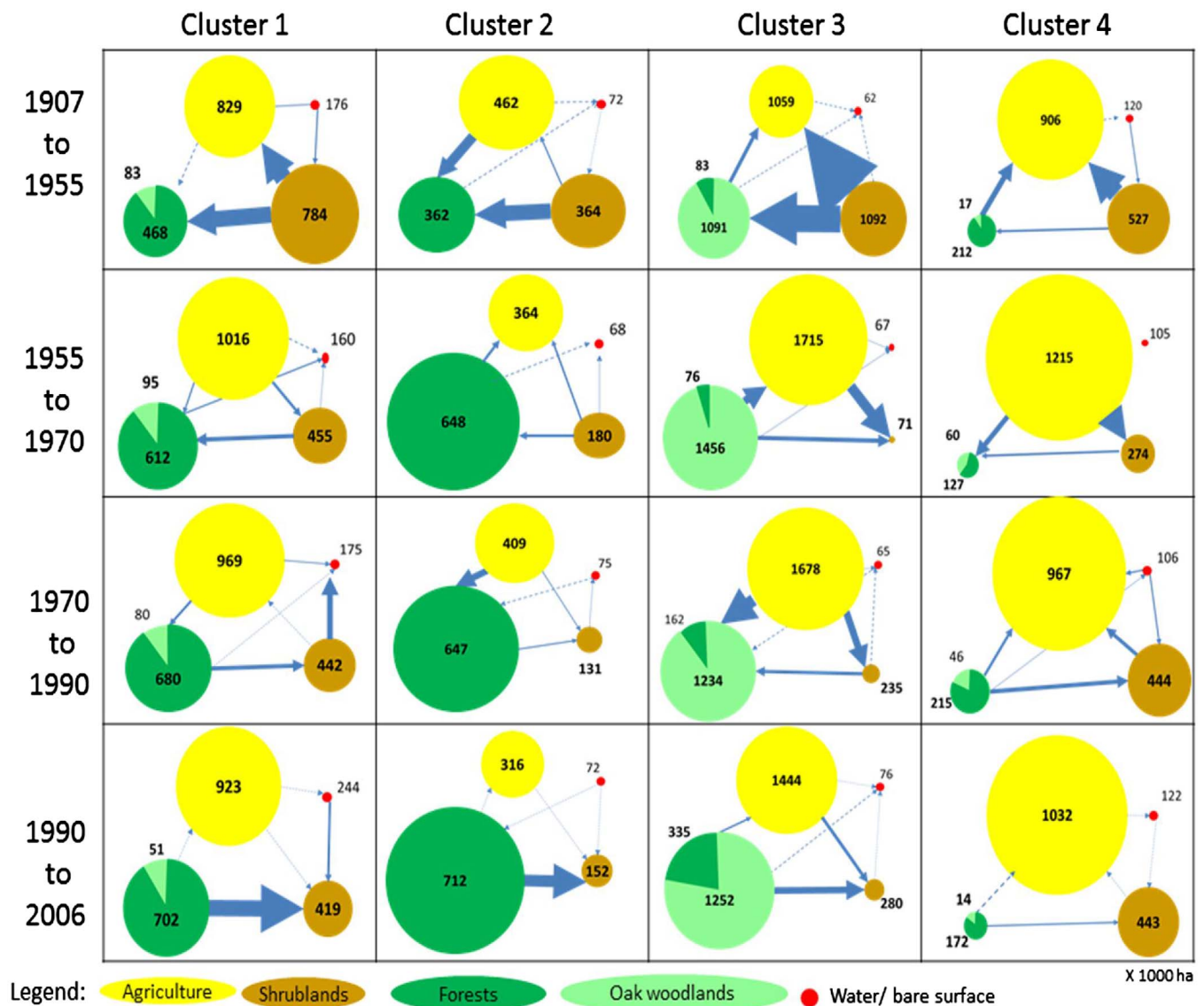
Fig. 6. Land cover transition matrix (size of circle is proportional to % of cluster area and arrow width is proportional to transferred area).

5. Discussion

Our results show that wooded areas grew from 1907 to 2006, confirming the national FT process previously analyzed by Mather and Pereira (2006). We clustered municipalities with similar land cover change trajectories and found that, depending on the cluster considered, maximum wooded area was attained either in 1970 or in 1990, and decreased afterwards. Forest expansion occurred simultaneously with agricultural area growth between 1907 and 1955, as shrublands area decreased. In a second phase, from 1955 to 1990, forests kept expanding, as agricultural areas and oak woodlands retreated. After 1990, croplands and wooded areas reverted to shrublands. Our findings confirm an originality of the Portuguese FT, in comparison with other processes (Mather, 2001, 2007; Rudel et al., 2005), first pointed out by Mather and Pereira (2006): for decades, forests expanded in tandem with agricultural area, and also with population. Although the forest expansion rate was higher later, when the agricultural area started to decrease between 1955 and 1990, the forest area subsequently contracted, again in tandem with croplands.

Our results indicate that from 1907–1955, agricultural area expansion may have contributed to the reduction of about 100 kha of forest areas in clusters 3 and 4 and, to a lesser extent, to the conversion of forests to oak woodlands. In this period, population increased (national population censuses in Table 3) and interventionist agricultural policies (Caldas, 1991) supported traditional small-scale farming, mostly in the areas corresponding to clusters 1 and 2, and promoted the expansion of cereal crops and vineyards, mostly in clusters 3 and 4. Local farmers fostered the expansion and protection of wooded areas, as they produced understory biomass (used to improve soil fertility), firewood, timber, resin, cork, or as a domestic multiuse raw material. Based on Mendes and Dias (2002) data, we estimate that private landowners afforested more than 561 kha (Table 4) of pine stands in northern Portugal (clusters 1 and 2) and evergreen oaks in the agroforestry land use systems of southern Portugal (cluster 3). The need for energy, and industrial and social development policies, were behind the public afforestation program (Estevão, 1983) and forest regulation (Radich and Alves, 2000). From 1907–1955, the Portuguese Forest Service afforested 199 kha of coastal sand dunes and mountain areas (Carvalho and Morais, 1996; CESE, 1996; Mendes and Dias, 2002 and ISA (2050); summarized in Table 4), notably in clusters 1 and 2. Given the endogenous needs of agricultural areas for goods and services provided by wooded areas and industrial demand for timber and cork, which drove the private and public afforestation effort from 1907 to 1955, we argue that forest expansion followed the *Forest scarcity* and *Public forest*

Table 2
Annual rate of land cover change in each period, for each cluster.

	Annual rate (% yr^{-1})	Country	Cluster 1	Cluster 2	Cluster 3	Cluster 4
1907–1955	Forests	+0.6	+0.6	+1.6	−0.1	−0.8
	Oak	+0.7	+0.3	+0.8	+0.7	+5.2
	woodlands	+0.6	+0.4	−0.4	+1.3	+0.7
	Agriculture	−1.3	−0.9	−1.0	−1.9	−1.0
	Shrublands	−0.1	−0.2	−0.1	+0.2	−0.2
	Water/Bare surface					
1955–1970	Forests	+1.0	+0.7	=	+7.0	+4.3
	Oak	−1.0	−0.9	−2.8	−1.0	−1.5
	woodlands	−0.4	−0.3	+0.8	−0.1	−1.3
	Agriculture	+1.7	−0.2	−1.7	+14.4	+3.9
	Shrublands	+0.5	+0.4	+1.0	+0.8	+0.2
	Water/Bare surface					
1970–1990	Forests	+0.6	+0.2	+0.5	+5.0	−1.0
	Oak	−0.2	−1.8	−4.3	+0.1	−3.3
	woodlands	−0.4	−0.2	−1.1	−0.7	+0.3
	Agriculture	+0.2	−0.2	+0.8	+0.9	=
	Shrublands	+1.0	+2.1	−0.1	=	+0.5
	Water/Bare surface					
1990–2006	Forests	−0.9	−1.2	−1.0	−0.4	−0.5
	Oak	−0.4	−0.9	=	−0.4	−1.1
	woodlands	+0.0	=	=	−0.1	=
	Agriculture	+2.0	+2.5	+5.0	+2.4	+0.3
	Shrublands	=	−0.6	−0.3	+1.2	−0.2
	Water/Bare surface					

Table 3
Cluster information for total burnt area (1975–2006), fire density, total population density, rural population density (people living in locations with less than 2000 inhabitants), sheep and goat density. Burnt areas for 1975–2006 were calculated with data from Oliveira et al. (2012) Population records from 1911 to 2011 were obtained from national censuses (Santos, 2016; Pordata, 2015). Sheep and goat densities were determined using the dataset of Santos (2016).

	Units	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Fire profile					
Burnt area (1975–2006)	kha	1556	791	360	978
Burnt area/cluster total area	%	66	63	11	55
Burnt area (x two or more)	%	79	66	23	74
Burnt area (x three or more)	km^{-2}	11.0	7.4	0.5	4.7
Fire density					
Annual burnt rate (1989–1975)	%yr^{-1}	+1.7	+1.8	+0.2	+1.6
Annual burnt rate (2006–1990)		+2.6	+2.3	+0.5	+1.9
Population					
1911/1920	Population density (PD)	km^{-2}	88	82	22	59
1907–1955	PD (1960–1911)	%yr^{-1}	+0.9	+0.7	+0.7	−1.0
1955–1970	PD total (1970–1960)		−0.2	−0.2	−1.7	+0.3
	PD rural[a,b]		0.0	=	−1.2	−0.3
1970–1990	PD (1991–1970)		+0.8	+0.5	−0.1	+1.7
	PD rural[c]		−0.4	−0.3	−0.5	−0.4
1990–2006	PD (2006–1991)		+0.5	0.5	+0.3	+0.3
	PD rural[d]		−1.1	−0.6	−0.8	−1.0
2006	PD[e]	km^{-2}	155	127	25	130
	PD rural[e]		79	85	12	46
Agro-statistics					
1989–2009	Farmed area	%yr^{-1}	−1.2	−2.1	+0.3	−1.1
Sheep and Goats					
1911/1920	Sheep/goats	km^{-2}	65	65	54	68
1907–1955	Sheep/goats (1955–1920)	%yr^{-1}	−0.5	−0.6	−0.2	−0.8
1955–1970	Sheep/goats		−2.3	−2.2	+0.6	- 2.0
1970–1990	Sheep/goats		+0.3	− 0.8	−0.1	+1.3
1990–2006	Sheep/goats		−0.5	−1.5	−0.2	−0.4
2006	Sheep/goats	km^{-2}	31	19	56	36

[a] Total population living in villages with less than 2000 inhabitants. In 1960, the rural population density was (km−2) 103, 97, 20, and 58, respectively, for clusters 1–4. In 1981 it was 104, 97, 15, and 55, respectively, for clusters 1–4.
[b] Difference between values for 1981 and 1960.
[c] Difference between the mean of the 2001 and 1981 values, and the mean of the 1981 and 1960 values.
[d] Difference between the value for 2006 and the mean of the 2001 and 1981 values.
[e] Mean of the values for 2011 and 2001.

policy pathways.

From 1955–1970, shrinking of agricultural land and public afforestation programs boosted the necessary conditions for forest area expansion, which occurred at a rate 1% yr^{-1} higher than in the previous period, in line with FTT. These land use dynamics occurred as the Portuguese society and economy faced major changes, during the 1960s (Barreto, 2005), mechanization and fertilizers were introduced in the cereal plains of the South (Baptista, 1993), and industrialization and urbanization promoted economic growth (Lains, 2003). Portugal's economy opened up to wider markets as Portugal joined the European Free Trade Agreement (EFTA), rural exodus to various European countries and Portugal's coastal cities (see Table 3) made rural labour scarce, and inflation raised agriculture production costs, undermining its profitability, which later led to land abandonment (Amaral, 1994; Baptista, 1994) or extensive grazing. Notably, in cluster 3, the number of sheep and goat increased in this period (see Table 3), possibly reflecting a shift towards extensive agriculture. As the public afforestation effort, which had started in 1938 and represented 2/3 of forest expansion (Table 4), was coming to an end, a program for afforestation of low productivity cereal croplands was launched (Radich and Alves, 2000). Thus, from the above, large private landowners in the southern part of the country (cluster 3) had a relevant role in forest expansion, as they sought alternative income sources for their available land, formerly under agricultural or agro-forestry systems. Establishment of pine sawmills and resin industries in the North and four eucalypt pulp mills in the center and South of the country may have increased the earnings prospects of landowners, fostering investment in pine and eucalypt plantations. Forest management goals shifted towards an industrial perspective, as forests became uncoupled from local land use dynamics, and exogenous demand for industrial goods increased. We found that during this period forest expansion followed three different pathways: *Forest scarcity, Economic development* and *State forest policy*.

From 1970–1990 agricultural areas kept declining and wooded areas expanded. In this period socio-economic changes were even more dramatic with an urbanized life style being adopted by the majority of

the population (Barreto, 2005), as global and regional drivers triggered a decline of agriculture (Pinto et al., 1984; Baptista, 2010). Within the forest sector, three more pulp mills were built (two for pine and one for eucalypt), resin prices dropped (Mendes and Dias, 2002), a network of protected areas was established and green movements emerged (Mansinho and Schmidt, 1994; Figueiredo et al., 2001). FT drivers were now exogenous, as international demand for wood fiber supported a Portuguese World Bank Forest project (pine and eucalypt plantations) and other national and European afforestation public incentives (*Economic development*), and environmental awareness emerged in urban population (*Globalization*).

After 1990, we found a reversal in wooded and shrubland areas expansion. Our results suggest that fire has played a major role in the conversion of forest cover to shrublands (Table 3), namely in cluster 1, where 53% of the total burnt area (1975–2006) has burnt three times. As documented by IFN (2013), for the region corresponding to cluster

Table 4

Forest area change by period of analysis. Data for public direct and indirect afforestation effort adapted from Carvalho and Morais (1996, CESE (1996), Mendes and Dias (2002) and ISA (2005).

	1907–1955	1955–1970	1970–1990	1990–2006	100 yr total
	x 1000 ha				
Wooded area change	**760**	**−11**	**173**	**−400**	**522**
Forests	340	240	216	−309	487
Oak woodlands	420	−251	−43	−91	35
Public direct and indirect afforestation effort	199	152	251	324	926
Private afforestation	562	87	–	–	–

Bold values are total value from (forest + Oak woodlands).

2, since 1990 there has been a shift in forest composition, from maritime pine stands to eucalypt, namely in the westernmost municipalities of the central and northern parts of the cluster. This shift may explain the resilience of FT in cluster 2, which has retained a high forest area (> 40%), in spite of a fire incidence similar to cluster 1. In Fig. 7, we illustrate the frequency of total burnt area in 1975–2006 superimposed in each cluster, observing lower fire incidence in cluster 3. Notably, we found that farmed area decreased in all clusters except cluster 3, as Common Agriculture Policy drove farmers first to set aside traditional croplands, and later to concentrate on farming of niche products (wine, vegetables, milk, beef, and olive oil) and extensive cattle (Avillez, 2015).

With an increase in fire frequency or severity, the extent of change from forest or oak woodland to shrubland areas is likely to increase (Silva et al., 2011). Although it is very common to find in the scientific literature that most of the Mediterranean forest species are well-adapted to fire, it must be highlighted that "plants are not adapted to fire *per se* but to fire regimes" (Keeley et al., 2011). Thus, post-fire response of plants and vegetation communities can be different following changes in fire regime. Despite the high post-fire resilience of maritime pine (*Pinus pinaster*), seedling densities can decrease if the following fire occurs before the reproductive maturity (Fernandes and Rigolot, 2007), facing an immaturity risk due to high fire frequency (in the sense of Keeley et al., 1999), or if affected by high severity fires (Maia et al., 2012). Increase in fire frequency and fire severity also constrains post-fire survival and regeneration of cork oaks (*Quercus suber*; Díaz-Delgado et al., 2002; Catry et al., 2009a; Moreira et al., 2009; Schaffhauser et al., 2011). Transitions from cork oak to persistent shrublands have in addition related with the cumulative effect of disturbances, such as fire followed by drought (Acácio et al., 2009),

or following large fires (Guiomar et al., 2015). Although eucalypt is a fire-resilient species, forest plantations are also vulnerable to fire, as fire-induced steam mortality is inversely correlated with tree diameter and post-fire tree mortality and top-kill increase with fire severity (Catry et al., 2013). A lower rate of post-fire conversion from eucalypt to shrublands highlighted by Fernandes and Guiomar (2017) is explained by the active role of forest owners in maintaining these high economic value forest stands.

Using the national forest inventory from 2005/2006 and Markov chain models, Rego et al. (2013) acknowledged the role of wildfire as a key driver to decrease timber availability, but admitted the possibility of a reversal, if annual fire incidence were reduced. Using a small county in Catalonia (Spain) as case study, Marull et al. (2015) examined 160 years of land cover change and criticized the alleged opportunity for ecosystem recovery in face of land abandonment, as FT can homogenize landscape and reduce biodiversity. Although these authors did not posit the wildfire threat, Badia et al. (2002), associated the decline of the traditional mosaic to unmanaged high fuel load landscapes that fueled large fire events in central Catalonia. For Galicia, in northwestern Spain, Corbelle-Rico et al. (2015) considered farmland abandonment a consequence of Spain's accession to the European Union, and identified a reduction in shrubland area and an increase in forest cover, between 1956 and 2005.

Although afforestation programs did not fully compensate for the extensive annual burnt area after 1970 (Table 3 and Fig. 7), they appear to have minimized the magnitude of the reversal in southern forest and oak woodlands (Table 2).

Considering the land use change trajectories documented above and the extent of wooded area change in each cluster between 1907 and 2006, we named the forest transitions of clusters 1–4 as *Failed*, *Endangered*, *Slow* and *Non-existent*, respectively.

No land use change analyses for other fire-prone regions of the world document a FT reversal of this magnitude. For example, in Galicia (Seijo and Gray, 2012) and Catalonia (Badia et al., 2002; Marrul et al., 2015), which also experienced rural land abandonment and publicly-subsidized afforestation, wildfire incidence is lower than in Portugal (Turco et al., 2016), and forest statistics show solid forest expansion trends in Spain, France, Italy, Greece, Turkey and Morocco (FAO, 2015).

Further research may reveal reasons behind this policy failure. We hypothesize that necessary conditions fostered the conversion of land covers towards forest but sufficient conditions to mitigate wildfire risk were not in place, such as risk governance deficits (IRGC, 2009). If agricultural land abandonment apparently led to an old-field vegetation succession, with an early shrubland stage followed by naturally regenerated forest, forest expansion policies ought to have invested earlier in programs to manage the natural regeneration process, combined with extensive fuel management to promote fire-smart landscapes (Fernandes, 2013).

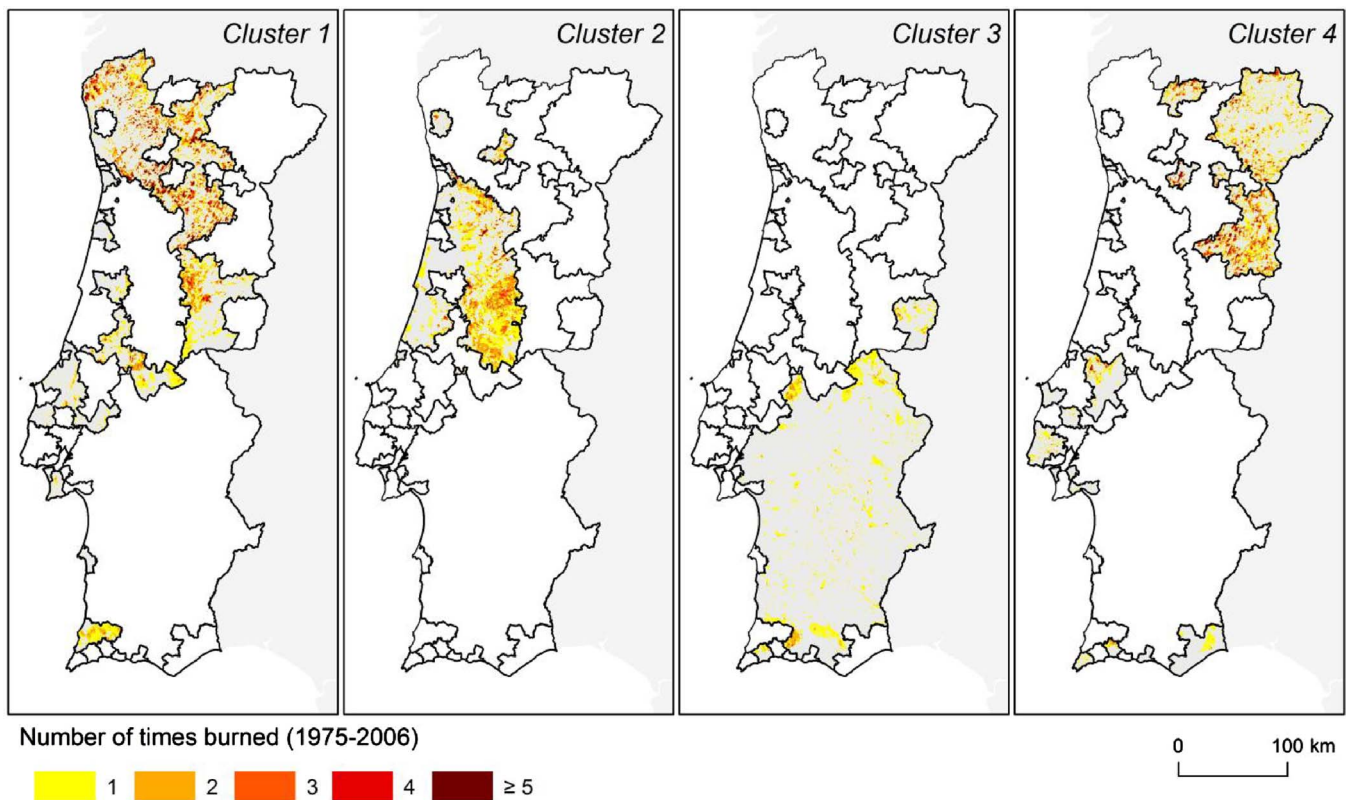Drummond and Loveland (2010) first documented how FT dy-

Table 5

Forest transition paths suggested for each cluster by period. Adapted from Rudel et al. (2005), Lambin and Meyfroidt (2010), Oduro et al. (2015) and Bae et al. (2012).

	Country level	Cluster 1 *Failed transition*	Cluster 2 *Endangered transition*	Cluster 3 *Slow transition*	Cluster 4 *Non existent*
Wooded area expansion from 1907 to 2006	23%	8%	62%	27%	−26%
1907–1955	• Endogenous drivers, due to socio-ecological feedback loops	• State forest policy • Forest scarcity		• Forest scarcity	
1955–1970	• Mostly exogenous forces, due to socio-economic dynamics	• Forest scarcity • State forest policy • Economic development			
1970–1990		• Forest scarcity			
1990–2006		• State forest policy • Economic development • Globalization			

Fig. 7. Wildfire frequency (1975–2006) overlaid on the four Forest Transition clusters.

namics ended in the eastern United States due to urban sprawl. As people left rural landscapes, rewilding of forest cover and land abandonment has been suggested as an opportunity for nature conservation (Navarro and Pereira, 2012), but in the Portuguese landscapes, lack of active management and suppression driven wildfire policies promote fuel accumulation (Collins et al., 2013) and bigger and recurrent fires set an important disturbance, jeopardizing forest and conservation goals.

Wildland fire dynamics and causes, including their social and economic drivers, vary across the clusters, and raise different challenges for fire risk management. Fire frequency expressed by the fire return interval, exhibits regional variability (Oliveira et al., 2012) due to fuel accumulation rate, spatial distribution of wildfire ignitions, land cover, slope and extreme meteorological events (Pereira et al., 2006; Verde and Zêzere, 2010). Most ignitions are located in densely populated areas (Catry et al., 2009b; Pereira et al., 2011), and 85% of all ignitions occur at the urban-rural interface, with 98% located less than 2 km from the nearest roads (Catry et al., 2009b). Moreover, the distribution of wildfire ignitions shows high spatial autocorrelation, since 46% of ignitions are concentrated within just 10% of Portugal mainland (Fernandes et al., 2017). In contrast, the largest burned areas are found in more sparsely populated areas and unbroken forest landscapes (Fernandes et al., 2016). According to ICNF (2014), negligent use of fire (accidents with machinery) and lightning are responsible for the few fires that occur in cluster 3, while for clusters 1 and 2 wildfire ignitions are related with intentional use of fire (pastoral and agricultural burns, arson). Additional research is needed to explore relations between drivers of fire ignitions and FT clusters, as a social manifestation of the relationships of local populations with forest landscapes, and to support the design of appropriate instruments and strategies for risk prevention and mitigation, exploring opportunities to reduce ignition probability, and to identify critical areas for fuel management. Non-trivial effects of socio-economic drivers on the landscape must be well understood, so that proper wildfire policies may be enacted, and climate change challenges ahead can be better addressed (Pausas and Keeley, 2014).

6. Conclusions

In this work we explicitly map and document the Portuguese FT over a period of 100 years, starting in 1907. After thematic and geometric harmonization of land cover maps from 1907, 1955, 1970, 1990, and 2006, we identify four types of land use transition pathways, using cluster analysis. In mainland Portugal, since 1907, hundreds of thousands of hectares of shrublands were converted to wooded areas up to 1990. Since then, and in particular for clusters 1 and 2 (in the North), we found a dramatic decreased in forest areas toward shrublands. Up to the 1960s, FT occurred simultaneously with population growth and agricultural expansion, as extensive uncultivated areas covered by shrublands were converted to satisfy human needs. Afterwards, with the abandonment of agriculture in marginally productive lands, and with stimuli from global commodity markets and public afforestation programs, FT gained momentum and expanded until about 1990. We posit that the pattern of agricultural land abandonment was different in the North (clusters 1 and 2) and South (cluster 3). While in the large size tenure lands of the South (cluster 3) farmers shifted their income sources to extensive grazing and subsidized farming kept the landscape mosaic with low fuel loads, in the North (clusters 1 and 2), land abandonment led to unbroken landscapes with heavy fuel loads highly exposed to fire. In here, we show that FT dynamics can be derailed by endogenous local factors, namely wildfires, despite the presence of necessary conditions that foster forest expansion, such as exogenous socio-economic and ecological drivers. Our work provides evidence and insights on conditions not foreseen in FTT, useful for public decision making relating to management of rural landscapes, forest and wildfire policies for climate mitigation, and sustainable development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2017.04.046.

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