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Historical changes in biomass carbon stocks in the Mediterranean (Spain, 1860–2010)

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ABSTRACT

Land-use change was the main source of anthropogenic CO_2 emissions until the mid-twentieth century, especially due to deforestation processes. In recent decades, however, CO_2 sequestration is being induced in some countries where forest area is experiencing net increases. Despite the key role of these processes, we hardly dispose of any empirical evidence of historical changes in biomass stocks, especially in the long-term (over 50 years) and in cultivated areas. In this study, we quantify the evolution of the surface area, carbon stocks (C) and C density of living biomass in Spain (50 provinces) between 1860 and 2010. According to our results, the C stock fell from 340.3 Tg C to 254.2 Tg C between 1860 and 1950, to then reach 844.0 Tg C in 2010. Although the stock began to increase much later than in other European countries, annual growth rates were much more significant. A decomposition analysis allowed us to observe that the increase in stock was mainly due to the change in C density (61.2% of the effect), surface area (35.3%) and, to a lesser extent, to the effect of location in more productive areas (5.7%). Woody crops – which were historically managed as agroforestry systems when combined with other crops – stored 15.8% of total stocks during the period studied. They play a particularly important role in areas with a Mediterranean climate because in these provinces, crops such as olive groves, vineyards or oranges have proliferated. The reasons for C stock increases are: the substitution of firewood with fossil fuels; agricultural intensification; and the outsourcing of land use to other countries through agricultural imports.

1. Introduction

Woody areas, particularly forests, have played a crucial role in climate change, both as contributors and mitigators. As carbon sinks, they absorb significant amounts of carbon dioxide (CO_2) through photosynthesis, storing it in living biomass and soil. However, woody areas can also release carbon (C), especially through deforestation processes, contributing to greenhouse gas (GHG) emissions. It is estimated that one-third of global cumulative CO_2 emissions since 1850 are due to land-use and land-use change (LULUC) (Friedlingstein et al., 2022; Jones et al., 2023). However, due to their high C density, the recovery of these types of land can also play a very relevant role in mitigating climate change. Some countries in the world, especially rich countries with a temperate climate, are experiencing a process called 'Forest Transition', which is a continued recovery of their forested area after long periods of deforestation (Rudel et al., 2005; Meyfroidt and Lambin, 2011). Usually, these countries also present an increase in the C density of their forests. In Europe, for example, forest C density rose by 175% between 1950 and 2000 (Ciais et al., 2008; Vilen et al., 2016). The combination of increased forest area and C density is leading to a significant rise in C stocks, thus generating C sinks that help to mitigate climate change. However, at the global level, LULUC (Land Use, Land-Use Change, and Forestry) CO_2 emissions continue to rise, particularly driven by the expansion of agricultural land in regions such as Latin America and Southeast Asia (Pendrill et al., 2019; Hong et al., 2021).

Although our knowledge of the global levels and geography of C stocks is improving, there is still a very high uncertainty regarding their historical evolution (Bastos et al., 2020). Long-term estimations of forest C stocks are usually elaborated following two main procedures. First, drawing on historical records such as national forest inventories (see Liski et al., 2006; Ciais et al., 2008), or aerial photographs (e.g., Asner et al., 2003; Vilà-Cabrera et al., 2017). Nevertheless, these sources are not usually available beyond c. 1920. Second, in the absence of complete

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historical records, through modelling procedures based on variables such as population density, productive capacity or vegetation maps (e.g., Rhemtulla et al., 2009; Kuemmerle et al., 2011; Kaplan et al., 2009; Ellis et al., 2013; Houghton and Nassikas, 2017). Modelling is suitable to provide global, very long-term estimations, and with a high geographical resolution. However, these models are much less dependable than direct observations and can produce unreliable estimates (Erb et al., 2018). While global model-based estimates are expanding, national estimates based on historical records or direct observations are still very limited. Long-term empirical evidence of C stocks based on historical records exists only for very few national case studies, including: Austria (Gingrich et al., 2007, 2016; Niedertscheider et al., 2017), USA, (Kauppi et al., 2006; Magerl et al., 2019), France (Le Noë et al., 2020), or Finland (Myllyntaus and Mattila, 2002; Liski et al., 2006; Kauppi et al., 2010).

This limited literature also has a significant constraint: it only studies the biomass stock of forested areas, without considering the stock of woody crops, which in some countries of the world has a very significant weight (e.g., Infante-Amate et al., 2016; Guo et al., 2014; Infante-Amate and Picado, 2018). In southern Spain, for instance, it is estimated that woody crops such as olive groves, vineyards, and other fruit trees sequester approximately c. 20% of the total C stock and around 50% of the amount of C sequestered by forests (Muñoz-Rojas et al., 2011).

In this article, we aim to analyze the historical evolution of woody C stocks, both forest and cultivated, in the case of Spain from 1860 to the present day. Our estimation is based on a comprehensive compilation of historical records and is presented at the provincial level (50 provinces), allowing us to detect regional patterns of change. Based on this information, we address the following objectives:

1) To quantify and analyse historical changes in woody biomass C stocks.
2) To identify regional patterns of C stock over time and to analyse the impact of location on the stock levels.
3) To assess the role of woody crops as a C sink and whether their expansion has offset forest area losses.
4) To quantify the main drivers of change in biomass stocks, identifying the role of surface area evolution, C density and the spatial location of woody surfaces.

2. Materials and methods

2.1. Boundaries

In this study, we provide an annual estimation of the surface area, C stock, and C density of woody surfaces (both forested and cultivated) in the 50 provinces of Spain between 1860 and 2010 and distinguishing between forested and woody surfaces. The C stock data includes both above and below-ground living biomass, including the trunk, branches, and roots of woody plants (Fig. 1). Although soil organic C may represent more than half of the C stocks in forests, it is the least variable C pool from a historical perspective (Pan et al., 2011).

In the case of forests, we distinguish three types of land use: (1) High forest, generally dominated by conifers and oaks in the Mediterranean climate area dominating most of the country, or by beeches, oaks, and other deciduous trees and also pine and eucalyptus in the temperate climate area in the North of the country, most of them oriented toward timber production. (2) Coppices, dominated by the *Quercus* (oak) genus species, whose main historical usage has been the provision of firewood and other forest products. (3) Open forests, which includes wooded areas with a lower density of trees per hectare, usually of the *Quercus* genus. Open forests generally refer to the '*dehesa*', an agroforestry system whose essential economic use is livestock feeding. It combines scattered trees with grassland and, occasionally, arable crops (Rigueiro-Rodríguez et al., 2009). Following the Spanish forestry statistics criteria, we considered as forested areas those where trees cover more than 20% of the surface. However, in the case of open forests, the limit is 5%. In the case of woody crops we distinguish three main categories: olives, vineyards and other fruit trees. The latter encompasses over 20 types of woody crops, notable among which are almond trees (on average, 35.3% of the surface area in this category over the study period), carob trees (18.1%), and orange trees (13.4%).

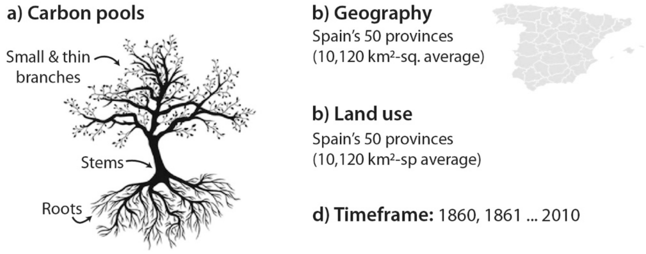

Fig. 1. Synthesis of the study's boundaries: 1. Carbon pools; 2. Geographical framework; 3. Land use categories; 4. Timeframe.

Thus, the C stock(S) for each province *i,* each land use *j,* and in each year *t,* were estimated as follows:

$$S_{ijt} = \sum_{i}^{50} \sum_{j}^{6} A_{ij} \cdot d_{ij}$$

Where A is the occupied land area expressed in hectares and d the C density, i.e., the C per unit of surface area. We followed different methodological strategies according to the historical period and the type of land use, as detailed below.

2.2. Sources and estimation procedure

The information on forest area and C stock is taken directly from Infante-Amate et al. (2022), which provides provincial-level information from 1860. This study estimated C stocks based on historical sources. Firstly, the total forest area was calculated, distinguishing between high forest, coppice, and open forest at the provincial level between 1860 and 2018. To accomplish this, a wide range of historical sources were connected, including Estadísticas de Montes Públicos (Statistics of Public Forests) since the mid-nineteengh century, Anuarios de Estadística Agraria (Agricultural Statistical Yearbooks) from 1929 to the present, the Estadística Forestal Española (Spanish Forest Statistics) since 1941, and the National Forest Inventories, since c. 1965. Subsequently, a C density factor was applied to each forest area based on the aforementioned sources, adjusted historically and spatially. In the case of woody crops, there is no long-term information on C stocks. To estimate it, we calculated the total number of trees and applied C density factors adjusted spatially and historically by tree type. For all crops, information from around 1890 to the present was obtained from the Anuarios de Estadística Agraria (MAPA, 2021a, 2021b) and GEHR (1991). For the year 1858, information was obtained from Gallego (1986). Between 1858 and 1890, information on olive groves was completed with Zambrana (1987) and JCA (1891a), and information on vineyards was obtained from Pan Montojo (1994) and JCA (1891b). For other crops, linear interpolation was used (more information in Tables 1 and 2 in the Supplementary Materials). Planting density data, i.e., trees per hectare, also come from different sources. Since around 1904, the Anuario de Estadística Agraria has offered information (not every year) for most crops. In the early 20th century, several reports from the Junta Consultiva Agronómica (JCA, 1905, 1923) provided information on planting density for most woody crops. For olive groves, the estimation between 1860 and around 1900 comes from Infante-Amate (2014). In the case of vineyards, JCA (1891b) provides planting density information for around 1890. Missing values between two points are estimated by linear interpolation, and when there is no information at the origin point, the first available value is used. Next, we calculated the C density for each tree adjusted by age. To do this, we conducted an extensive literature review on C per plant for olive groves (30 observations), vineyards (49 observations), citrus (17 observations), stone fruits (7 observations), and seed fruits (10 observations). Using this information, we calculated equations to predict the C per plant according to its age (equations in Figure SM1). The C stock is simply estimated by multiplying the density per plant by the number of plants.

2.3. Decomposition analysis

We performed an analysis of additive decomposition following the additive Logarithmic Media Divisia Index (LMDI) proposed by Ang (2005). We quantified the effect of the following variables: change in land use of woody surfaces (*A*); the effect of changes in the location of the surface area*(r)* in each province *i*; and the change in C density *(c)*.

$$S = A\cdot r\cdot c = Area\cdot\frac{Area_i}{Area}\cdot\frac{Carbon_i}{Area_i}$$

This model allows quantifying the effect of the explanatory variables *(A, r,* and *c)* on the explained variable (*S*). The stock variations between two points T and 0 are understood as the sum of the variations of the variables considered in the model.

$$\Delta S_{tot} = S^T - S^0 = \Delta A + \Delta r + \Delta c$$

We conducted three decomposition analyses, one for forest areas, one for cultivated areas and the last for total woody areas.

3. Results

3.1. Land-use change

After centuries of deforestation, the Forest Transition began in Spain as from c. 1950, i.e. forest area began to grow since then, moving from 12.1 Mha to 18.6 Mha between 1950 and 2010. This expansion took place over former crop areas (2.4 Mha) due to the abandonment of agricultural activity, and over old pastures and low productive areas (4.3 Mha) due to active reforestation policies (Iriarte Goñi, 2017; Vadell, 2019).

Different trajectories can be observed depending on the type of forest, underpinning the overall trend. In Fig. 2, we differentiate the evolution of the country's main forest areas. Coppices, the main forest usage, progressively diminished until the 1970 s, and then grew slowly. The *dehesa*, or open forest, was the second largest use in the nineteenth century. The surface area of open forests also declined until the 1980 s. The high forest grew continuously since records began, although this expansion was particularly intense as from the mid-twentieth century due to economic change processes and the various reforestation policies detailed later (see discussion section).

In the case of woody crops (Fig. 2b), a trend of continuous growth can be observed since historical records began until the 1990 s, when they started to stabilise. The surface areas of vineyards and fruit trees, which grew during the twentieth century, have fallen in recent decades. But olive groves, whose surfaces were smaller than that of vineyards in the nineteenth century, have grown relentlessly until today. Today, olive trees are the nation's main woody crop, accounting for 2.6 Mha. In fact, Spain is the country with the largest olive grove surface area in the world (FAOSTAT, 2021).

Forest Transition took place in the mid-twentieth century. Nevertheless, if we consider all wooded areas (see Plieninger et al., 2012; Van Holt et al., 2016), the process was to fast forward at the beginning of the twentieth century, since the expansion of woody crops compensated the shrinkage of the forest surface area during the first half of the 20th Century (Fig. 2c).

Beneath these broad trends, there are discernible patterns at the regional level. Fig. 3 shows the land use of forest areas, woody crop areas and total woody areas. Forest areas have been more extensive in the temperate climate zone in the north of the country, especially since the mid-twentieth century. In these provinces, the climate is more suited to fast-growing species and the orography is less appropriate for agriculture. The concentration of forest areas has, therefore, become more intense. Woody crops, on the other hand, have tended to cluster in the southern and eastern provinces of the country, mainly because their agroclimatic conditions are more conductive to the key crops of the country's agricultural specialisation e.g.: olives vineyards, almond trees and citrus fruits. Consequently, the forest transition narrative differs depending on whether we consider only the forest areas or the entire woodland area.

3.2. Carbon density

The C stock is determined by the woody surface but also by its C density, that is, by the C stored per hectare. Changes in C density have been even greater than surface changes. Over the period under study, the woody area increased by 32% while its density grew by 118%. In forest areas, the C stored per hectare remained relatively stable until the mid-twentieth century at ~20 Mg C ha^{-1}, with a slight but continuous decline until the early twentieth century. This decline was due to thinning or overexploitation. Both factors are the most likely hypotheses for the decrease in forest density. During those decades, the consumption of forest products (firewood and timber as raw materials) increased while the forest area decreased, resulting in increased pressure on the remaining forests, leading to a decrease in density (Iriarte-Goñi, 2013; Infante Amate, Iriarte Goñi, 2017). Additionally, there is no historical evidence of forest pests or climatic changes in Spain during that period that would have caused a decrease in density. Since the early twentieth century, despite the ongoing decline of forest areas, there has been a slight increase in density, caused by the growth of the high forest area,

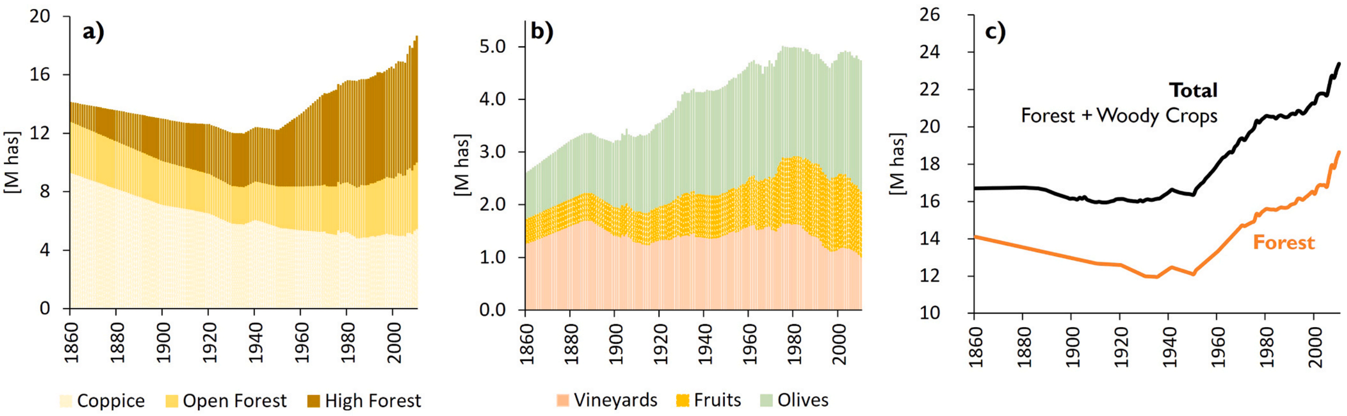

Fig. 2. Woody surface in Spain. (a) Forest area by type. (b) Woody crops surface area by type. (c) Total forest area and woody areas (forest plus cultivated).

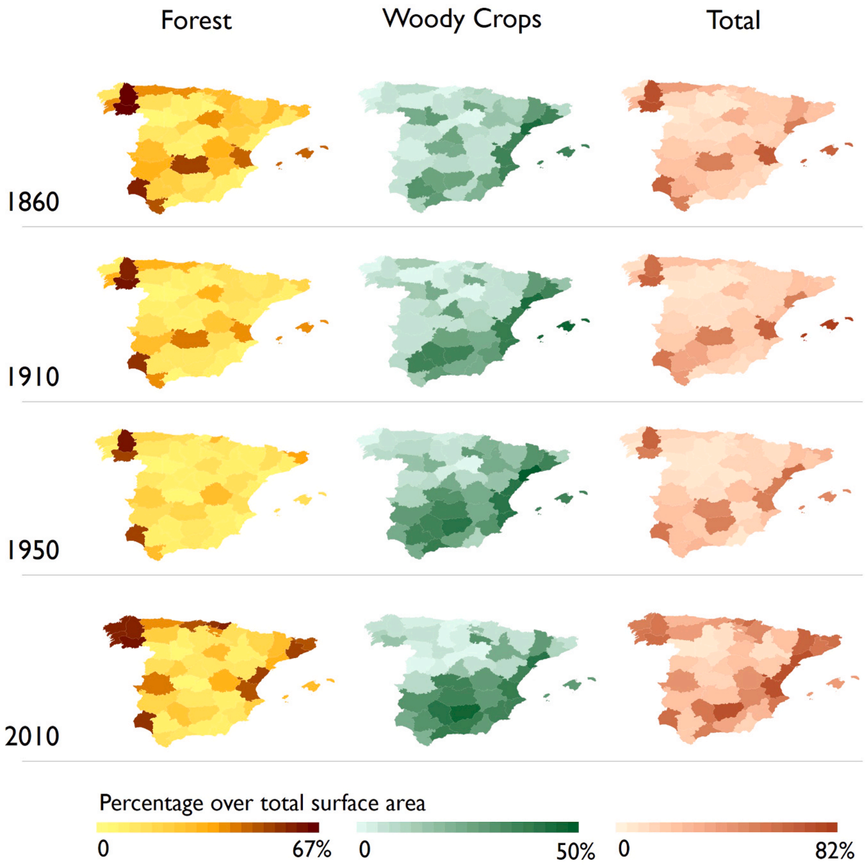

Fig. 3. Forest, woody crops and total woodland area, as percentage of total area.

with a higher density within the forest mix. As from 1950, the density grew rapidly and reached an average of ~40 Mg C ha^{-1} today. The range of provincial values rose considerably: in 1860, the values ranged between 2 and 65 Mg C ha^{-1}, whereas in 2010, they reached between 5 and155 Mg C ha^{-1}.

Woody crops present a similar trend. We found that the density was stable until the mid-twentieth century (at ~12 MgC ha^{-1} yr^{-1}) and then accelerated rapidly until the present day (~21 MgC ha^{-1} yr^{-1} in 2010). This increasing trend can be attributed to two main factors. Firstly, there was a shift in the crop mix, with a greater presence of olive trees which have a higher C density than most other woody crops. Secondly, there was an increase in planting density across all crops. From 1860–2010, the number of trees per hectare rose from 80 to 160 in olive groves, from 1800 to 2800 in vineyards, and from 143 to 344 for other fruit trees on average (see TSM 3 for details). By type of crop, the C density between 1860 and 2010 went from 16 to 24 Mg C ha^{-1} in the case of olive groves, from 5 to 10 Mg C ha^{-1} in the case of vineyards, and from 11 to 19 Mg C ha^{-1} for the rest of the fruit trees (Fig. 4).

Substantial geographical differences in total density (forest and cultivated areas) were also found, which, in addition, have accentuated over time. Fig. 3c illustrates the differences in density of total C among three large geographical areas. The northern region, with an Atlantic climate, presents much higher values than those of the rest of the country: in 1860, the density was 88% higher, and in 1990 it reached 210%. The Mediterranean central provinces presented values that are analogous to the national average throughout the period under study. Conversely, the values of the Mediterranean southern provinces are much lower: between 26% and 43% of the national average over the period studied.

Two factors contribute to the increasing regional differences in C density. First, there is a greater specialization in woody crops in the south and east, which have a lower C density than forest areas. Second, the differences in C density between forest areas and cultivated areas have intensified between the north and south, mainly due to the proliferation of fast-growing species and the increase of tree density. in the Atlantic provinces. As a result, the gap in C density between forest areas and cultivated areas is much smaller in Spain's most arid areas than in those in the north. Furthermore, this regional difference has become more pronounced over time (Fig. 4), indicating that the proliferation of woody crops is better suited to storing C in arid areas.

3.3. *Carbon stocks*

Between 1860 and 2010, the biomass C stock multiplied by 2.5 (Fig. 5). However, this growth has not been constant over time. From 1860–1950, the C stock experienced a decline of 25%, dropping from 340 to 254 Tg C. On the other hand, from 1950 to the end of the study period in 2010, the total stock multiplied by 3.2, reaching its peak at 844 Tg C.

Behind this general trend lie notable divergences among regions and types of land use. Due to the higher relative extension of forest areas and the higher levels of C density, the country's Atlantic areas present a much higher C stock. The Atlantic provinces, which occupy 11% of Spain's total area, have concentrated between 36% (in 1860) and a maximum of 45% (in 1990) of total stock. In these areas, the forest stock has been dominant for most of the period studied. In the Southern and Eastern provinces, on the other hand, the proportion of C stock is much lower than the proportion of the area they occupy in the country. However, despite the relatively small forested area in these provinces, the C stock reaches significant values due to the substantial presence of woody crops. While these provinces account for only 13% of the forest C stock, they store 45% of the C stock in the woodlands. In the Southern and Eastern provinces, woody crops have therefore played a key role, reaching almost 90% of the woodland stock in some of their provinces

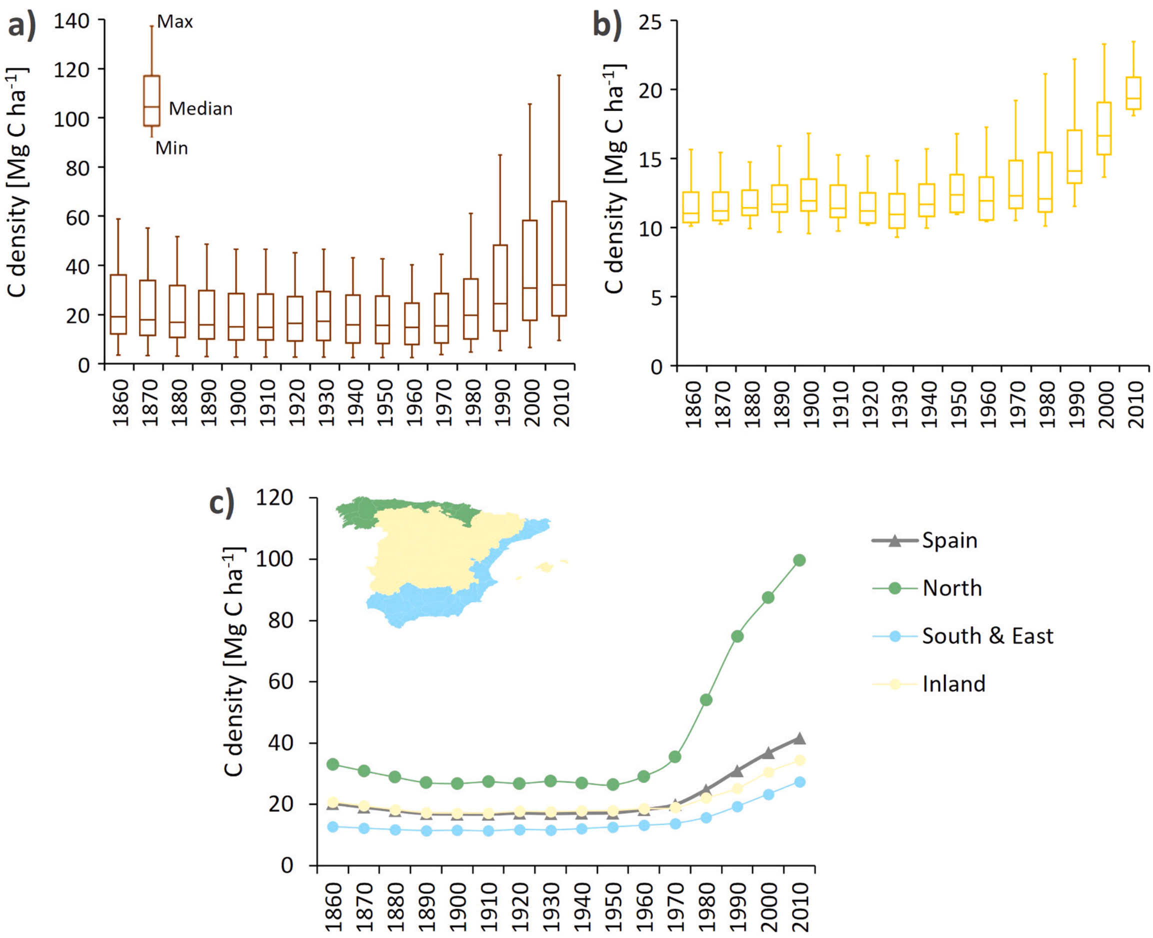

Fig. 4. Variablity in the carbon density per province in forest areas (a) and cultivated areas (b), as well as total carbon density per bioregion (c).

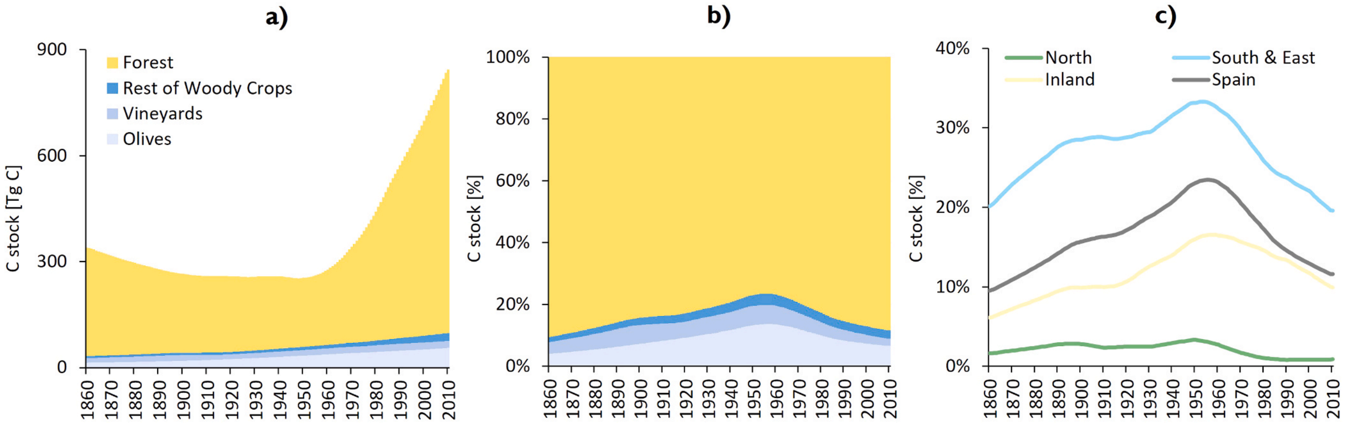

Fig. 5. Carbon stock of living biomass in forests and in woody crops in Spain, in total Teragrams of C (a) and as percentage (b). In Figure SM1 this information is depicted at a regional scale. In panel (c), percentage of woody carbon stocks in croplands per region.

(Figs. 5b and 6). The large concentration of woody crops in these provinces results in a significant contribution of woody crops to the national total C stock. During the period under analysis, they represented 16% of the national total C stock, reaching an all-time high of 24% in the 1950 s, a period of lower forest expansion.

As shown in Fig. 7a, we found a negative correlation between C density in forests and the percentage of woody crops in total woodlands. Given that C density is higher in forest than in croplands, this correlation become stronger in the case of the percentage of C stocks in croplands (Fig. 7b). In both cases, this correlation remains highly significant ($p < 0.001$) when including province and year fixed effects in data panel regression (see Table SM5). The province fixed-effects model controls for unobserved heterogeneity arising from relatively time-invariant idiosyncratic features of provinces (e.g., soil and climate). The time fixed-effect regression tests whether cross- province variation in the share of C stocks in croplands is correlated with forest C density in each year. When considered together, these results show that (a) overall, provinces with higher C density show smaller shares of woody crops in total woodlands. (b) The share of stocks in croplands in individual provinces decreases as C density in forests increases (Fig. 7b). This

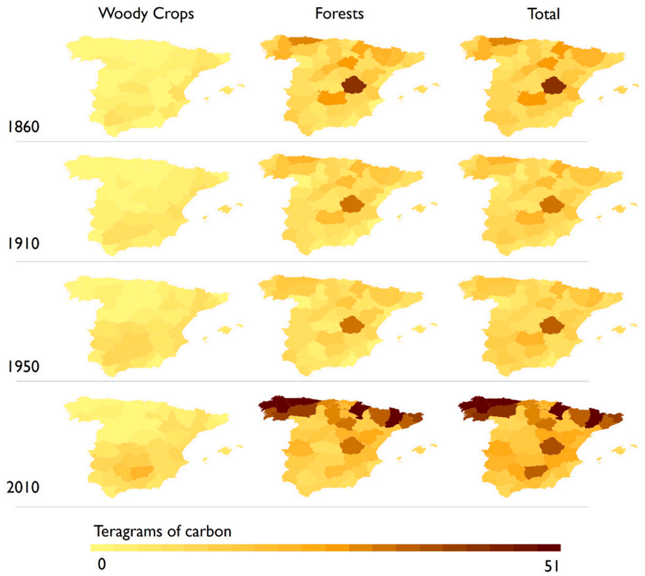

Fig. 6. Carbon stocks of woody biomass in forests, woody crops and in total woodland areas. Teragrams of C. In Figure SM2 and SM3 we depict C stocks normalized per total geographical area and woody area, respectively. In the right column, percentage of woody carbon stocks in croplands.

relationship might be causal, as geographical differences in primary productivity (and C density) are higher in forests than in woody crops. In consequence, in provinces with higher productivity (and C density) in forests the gap is higher, which could incentive the expansion of forestland over cropland.

3.4. *Decomposition analysis*

Fig. 7 illustrates the results of the decomposition analysis of the change in C stocks. Throughout the period analysed, we observe that the total stock growth (amounting to 501 Tg C) was mainly due to increases in biomass density (60% of the impact), followed by an increase in the forest area (35%), resulting from the effect of locating woodlands in more productive areas (5%). Underlying this general trend are different patterns according to the type of woodland and historical period.

In the case of the forest area, the fall that took place until the mid-nineteenth century seems to be largely due to the degradation of forest areas, that is, to the fall in biomass density (which accounted for 66% of the reduction). The rest was the result of deforestation. Conversely, in cultivated areas, the total stock rose continuously. Unlike the case of forest areas, the main cause was the increase in surface area (80% of the impact), with some exceptions, such as the vineyard crisis due to phylloxera in c. 1900 that led to a general fall in stock.

Since 1950, total C stock has substantially increased across all woody areas. In the case of forest areas, the major reason is the increase in density (by 60%) as well as, to a lesser extent, the growth in forest area (by 30%) and the effect of geographical location (17%). That is, the stock increase was due more to the proliferation of denser forest masses (located in more productive areas) than to the increase, in itself, of the forest surface area. This pattern is similar in cultivated areas: while the rise in stock was mainly due, between 1860 and 1950, to the increase in surface area, between 1950 and today it was mostly the result of the increase in density (73%).

4. Discussion

4.1. *A comparative perspective on C trajectories*

The results of our study shed light on the historical trajectories of forest changes in the Mediterranean, taking into consideration the role of woody crops. We identified three major periods in Spain: (i) First, a period of significant drop in C stocks until c. 1900, mainly due to the rapid decline in forest areas and particularly in forest C density, as woody crops grew slightly; (ii) second, a phase of stabilisation between c. 1900–1950, when the forest stock continued to fall, but more slowly, and the crops stock continued to increase; and (iii) finally, a phase of large increase since 1950, mainly explained by the change in the surface and management of forests.

Throughout the analysed period the overall trend was dominated by forestry sector shifts. Globally, the forest area surface declined by 0.11% per year between 1850 and 2015 (Houghton and Nassikas, 2017). Historical information on C stock is much more limited and drawing

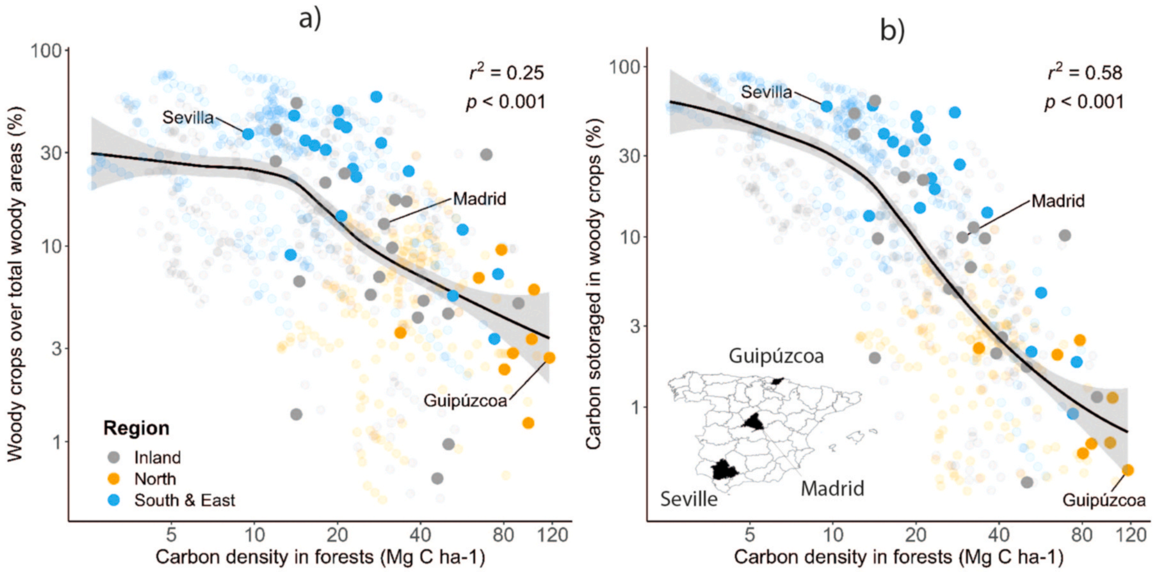

Fig. 7. Correlation between biomass carbon density in forests (in Mg C ha^{-1}) and (a) the percentage of woody crops over total woody areas, and (b) the percentage of biomass carbon stocks in croplands. We only include observations ended in 0 (1860…2010), since some estimations are linearly interpolated between those points. Highlighted dots refer to 2010, transparent dos to observations 1860–2000. Relationships remains significant ($p < 0.001$) in both cases when including provincial and year fixed effects in data panel regression (see Tables SM5 and SM6).

international comparisons is a difficult task. In Finland, it is estimated that the forest volume of standing stock during the reduction phase (between c. 1800 and 1900) dropped by 0.13% per year. In Europe, deforestation levels are very high, but this process took place over many centuries, so annual rates have been low. However, within the new agricultural frontiers that opened outside Europe in the nineteenth century, the process has been much faster. In the case of Wisconsin, Rhemtulla et al. (2009) estimated that the forests' C aboveground stock fell by 0.90% annually between c. 1850 and 1930. Within those borders, tropical countries suffered a more rapid loss of forest area in the last decades of the twentieth century due to increased global demand for agricultural and forestry products. According to Pan et al. (2011), between 1990 and 2000, the fall in C stock in tropical countries was 0.49% per year. In the case of Spain, between 1860 and 1950, the forest area fell by 0.16% per year while the C stock fell by 0.28% per year. That is, loss of forest area was combined, as mentioned, with forest degradation due to overexploitation and thinning (GEHR, 1994; López Estudillo, 1992; Iriarte-Goñi, 2013; Iriarte-Goñi and Infante-Amate, 2019). The C density had indeed begun to stabilise as from 1900 and even rose slightly due to the shifts in forest mix, generating larger areas of high forests. But total stocks continued to drop until the mid-twentieth century because of surface area losses. Spanish forests' C stock seems to have diminished somewhat faster during the deforestation process than in the countries of central and northern Europe. It was, however, much slower than the decline which took place within the new agrarian frontiers (USA, Argentina, etc.) of the nineteenth century C stock increase observed since c. 1950 is mainly explained by the change in the surface and management of forests. The growth in forest areas was much greater than that of other European countries, which stood at 0.15% per year between 1950 and 2000 (Ciais et al., 2008). According to the FAO (2015), Spain is the second country in Europe, after Ireland, with the biggest increase in forest area between 1990 and 2015. Spain's forest transition arrived late but was extremely rapid (Infante-Amate et al., 2022). In the case of C stock, this process was much more intense. Between 1950 and 2010, the woodland stock grew by 3.87% per year, and the forest stock by 4.69%. This value is much higher than that of Europe, whose C stock increased by 1.65% per year between 1950 and 2000 (Ciais et al., 2008). The national case studies providing historical information also depicts smaller growth rates during their Forest Transition. In the case of Finland, an annual growth of 1.2% was estimated between 1912 and 2005 (Liski et al., 2006; Kauppi et al., 2010). According to Gingrich et al. (2022) in Austria the annual increase was 0.6% between 1830 and 2010; in France 1.1% between 1910 and 2010; and in the USA, 1.3% between 1950 and 2010. Comparatively therefore, forest areas in Spain have grown faster than in the surrounding countries due to two factors: surface area expansion and density increases (see Kauppi et al., 2006). Below we review the drivers of such changes.

4.2. Exploring the historical drivers of C stocks patterns

The decline in forested area until 1950 occurred in a complex economic context where, on the one hand, the economy remained heavily reliant on agricultural products. It was, using Wrigley (1988), an organic-type economy. On the other hand, various industrial sectors were developing from the mid-nineteenth century, while urbanization was also growing in some areas of the country. All these processes increased pressure on forests, contributing to the loss of both forested area and C stocks. In the case of agriculture, the Mediterranean agro-climatic characteristics of most of the country (water stress, soil types, and difficulty in sustaining livestock that would generate sufficient organic fertilizers) made it difficult to increase production per hectare with existing technology (González de Molina et al., 2020). As a result, the necessary increase in food production as the population grew focused on expanding cultivated land at the expense of forests, especially coppice forests (GEHR, 1994; Iriarte-Goñi, 2019; Infante-Amate et al., 2022). This dynamic was reinforced in a context of limited food imports under protectionist trade policies that operated for most of the period to promote domestic grain production (Gallego, 2003). At the same time, the energy transition to fossil fuels was only partial before 1950 (Rubio, 2005), so firewood remained in high demand, especially in large rural areas without access to coal, oil, or electricity (Iriarte-Goñi and Infante-Amate, 2019; Garrués Irurzun, Iriarte Goñi, 2022). Additionally, many economic changes during this period, such as the expansion of the railway or telephone network and construction linked to urbanization, required large amounts of timber, mostly sourced from national forests (Iriarte-Goñi and Ayuda, 2008). In this context of high pressure on forest resources, forested area decreased and the surviving forests lost density due to increasing timber and firewood extraction. This situation persisted in Spain until the 1950 s due to the economic hardship generated by the Spanish Civil War (1936–1939) and the long and dramatic post-war period of the 1940 s within the autarkic framework of the Francoist dictatorship (Infante-Amate et al., 2022).

The accelerated increase in the C stock recorded since the mid-20th century can be largely explained by the disruption of the dynamics described above. Specifically, three events associated with the industrial metabolic transition account for the increase in forest area and density. Firstly, the intensification of agriculture and the resulting increase in yields brought about by agricultural modernization (expanded irrigated areas, chemical fertilization, new seeds, and machinery) allowed for "saving" land, leading to a portion of agricultural land (typically the least productive) being converted into forested areas (González de Molina et al., 2020). Secondly, Spain also increased agricultural imports from the mid-20th century, resulting in additional land savings that could be used for other purposes (Infante-Amate et al., 2018, as documented for other countries as well (Meyfroidt et al., 2010). Lastly, the increasing use of fossil fuels and their widespread availability throughout the country via road transportation and expansion of electric grids reduced the demand for fuelwood and alleviated pressure on forests (Carpintero, 2005; Rubio, 2005). This last factor not only explains the increase in forest area but also the rise in C density (Iriarte-Goñi and Infante Amate, 2019). These three factors occurred spontaneously through market mechanisms and align to a large extent with an "economic development path" as proposed by Rudel et al. (2005) or Barbier et al. (2010) as an explanatory approach for forest transitions.

However, the extent and speed of the reforestation process in Spain can also be attributed to various forest policies implemented both at the national and European levels from the 1950 s onwards. Broadly speaking, reforestation policies can be divided into two distinct periods with marked differences. The first period extended from the 1950 s to the 1980 s and was characterized by reforestation policies under the Franco dictatorship. The dictatorship's interest in reforestation was driven by two complementary factors. Firstly, it aimed to increase the production of softwood for expanding industrial sectors during the rapid industrialization of the 1950 s and 1960 s. This was particularly relevant for the paper industry, which required large quantities of pulpwood, as well as the furniture industry based on new shredded plywood boards (Iriarte-Goñi, 2013). To achieve this, an extensive reforestation plan was implemented using fast-growing tree species (such as certain types of pines and eucalyptus) that were suitable for quickly obtaining softwood for processing (Vadell et al., 2019). Concurrently, another set of reforestation efforts focused on stabilizing slopes near large reservoirs being constructed for electricity generation and irrigation expansion (Iriarte Goñi, 2017). In total, reforestation during this first period affected over three million hectares (Vadell, 2016). The second period began in the late 1980 s and was linked, on the one hand, to the guidelines of the Common Agricultural Policy implemented by Spain's accession to the European Union in 1986 (Gafo, 2015), and on the other hand, to the process of political decentralization that took place within Spain and the transfer of forest policy to the Autonomous Regions. In this second period, there were incentives for the transformation of unproductive agricultural land into tree plantations, and at the same time, growing environmental concerns promoted reforestation with autochthonous leafy species, carried out by regional governments (MITECO, 2021). Overall, from the late 1980 s to 2017, 2.2 million new hectares were planted through these processes (Vadell et al., 2016). The greater specialization in timber production in areas with higher forest productivity (Corbelle et al., 2015) also explains the differences in forest biomass stocks.

However, the increase in C stocks since the mid-twentieth century is not only explained by the expansion of forested areas but also by the increase in C density. In this case, the variables that contribute to this phenomenon are more numerous and more difficult to quantify. Density increases when the harvest is below the Net Primary Productivity (NPP). In Spain, firewood extraction dropped dramatically between 1950 and 1980 due to the energy transition: the country stopped using firewood and switched to fossil fuels (Iriarte-Goñi and Infante-Amate, 2019) (Fig. 8a). Nevertheless, extraction stabilized from 1980 onwards and even increased, while density continued to rise because the increase in NPP exceeded the harvest. The rapid growth of NPP may be attributed to various factors, such as those listed below. (i) The proliferation of fast-growing species: in Spain, the area covered by eucalyptus and conifers increased from 2.2 million hectares to 7.6 million hectares between 1930 and 2007 (Infante-Amate et al., 2014). (ii) The growth has occurred in the most productive provinces, particularly in the northwest of the country. (iii) Nutrient extractions by livestock decreased in agroforestry systems. (iv) Productivity increased due to higher nitrogen depositions or the effect of higher atmospheric CO_2 concentration (Keenan et al., 2013). Globally, it is estimated that nitrogen additions to the terrestrial biosphere and CO_2 enrichment have caused an increase in global vegetation C stocks of 2% and 23% of the current stock, respectively, since 1860 (Zaehle, 2013). Quantifying the effect of each of these variables individually goes beyond the scope of this study, but based on indirect evidence, we observe that all of them may have contributed to the increase in NPP and forest stocks in Spain since the mid-twentieth century..

4.3. *The role of woody crops in carbon storage*

Woody crops have a great capacity to store C, both in their biomass and in the soil, and can therefore play a key role in mitigating climate change. This is especially true in areas such as the Mediterranean, where their surface area is extensive. It has been estimated that woody crops accounted for 24% and 28% of living biomass stocks in southern Spain between 1956 and 2007 (Muñoz-Rojas et al., 2011), and 37% and 40% in Greece between 1990 and 2018 (Gemitzi et al., 2021). According to our results, the weight of woody crops went from 9% in 1860 to a maximum of 23% in 1956. These percentages exceeded 50% in some provinces with a high proliferation of woody crops.

The literature suggests that crops such as olive groves can store between 1 and 23 Mg C ha^{-1} in their living biomass, the vineyard, between 0.5 and 21 Mg C ha^{-1}, and other fruit trees between 2 and 31 Mg C ha^{-1} (data retrieved from the references of Table SM3). The amount stored depends on the age of the plant, planting density and management. These levels are lower than in dense forest systems but are much higher than that of arable crops (c. 2 Mg C ha^{-1}) and are near those of scrublands (Muñoz-Rojas et al., 2011).

These values change when soil organic carbon (SOC) is taken into account. According to Aguilera et al. (2018), throughout the twentieth century, arable crops in Spain have stored relatively stable amounts c. 45–50 Mg C ha^{-1} in SOC, while the stock in woody crops fell from 70 to 43 Mg C ha^{-1}, due to changes in the soil's management. Other works on Mediterranean areas report that SOC in the high forests is c. 69 Mg C ha^{-1} (Le Noë et al., 2020), and 64 Mg C ha^{-1} in scrublands (Fonseca et al., 2022). Based on these values and our own results, we provide a tentative estimate of the total C stock in pre-industrial contexts and current contexts of woody crops, herbaceous crops, high forest and scrublands, in the case of Spain (Table 1). These values indicate that the share of living biomass in total C storage increased from 29% to 41% in high forests, while in the case of woody crops this share has almost doubled, from 15% to 27%, due to the combination of increasing biomass and decreasing SOC. Therefore, there importance of biomass in total C storage has increased during the studied period. On the other hand, the data in Table 1) also suggests a great potential to sequester C in woody crops, given that with proper land management they can provide much higher storage than herbaceous crops. These results are in line with global studies indicating an important role of cropland trees in biomass (Zomer et al., 2016) and soil (Ledo et al., 2020) C storage.

4.4. *Indirect effects of carbon stock increase*

The unprecedented increase in the surface area and stocks of woody biomass has brought about significant environmental benefits, especially in the mitigation of climate change. However, some authors warn that the so-called 'forest transition' may be generating effects that often go unnoticed. In relation to GHG emissions, Gingrich et al. (2019) warns that the processes that facilitate forest transition are associated with a 'carbon footprint' which, in some cases, can exceed CO_2 capture. They identified the three processes described next.

(i) Increasing agricultural productivity. Although it frees up land for forests, the activity carries a significant C footprint. In the case of Spain, the harvested production of dry matter in cultivated areas went from 0.7 to 2.2 Mg ha^{-1} between 1900 and 2008 (Soto et al., 2016). Yet the C footprint of this production increased from 7.2 Tg CO_2e yr^{-1} in 1900–33.6 Tg CO_2e yr^{-1} in 2016 (Aguilera et al., 2020b). Annually, current agricultural emissions are more than double the C sequestration in woody areas.

(ii) Outsourcing the use of the territory to other countries. This mechanism frees up land within a country for forest use but externalises emissions from land use changes outside its borders. In the case of Spain, net land imports went from 0.3 Mha in 1950–6.5 Mha in 2010 (Infante-Amate et al., 2018). In the period 2010–14, emissions associated with outsourced deforestation outside Spain amounted 17.6 Tg CO_2 yr^{-1} (Pendrill et al., 2019), while annual C sequestration in woody biomass amounted 13.5 Tg CO_2 yr^{-1}, according to our results.

(iii) Wood fuel substitution. The energy transition to fossil fuels reduces extractive pressure on forests but generates significant CO_2 emissions. In the case of Spain, the forest transition coincided with the growth of fossil fuels, as in other countries (Myllyntaus and Mattila, 2002; Gingrich et al., 2016). Fossil fuels replaced firewood as the main source of energy and, with it, reduced the pressure on forest ecosystems, allowing increases in biomass density. Forest firewood consumption went from 145.5 Tg yr^{-1} in 1950 to only 33.9 Tg yr^{-1} in 2010, with a minimum of 9.0 Tg yr^{-1} in 1981 (Iriarte-Goñi and Infante-Amate, 2019). In the period studied, the cumulative CO_2 emissions associated with the use of fossil fuels amounted to 11.0 Pg. of CO_2, compared to a forest C uptake of 1.8 Pg of CO_2 (Fig. 8b). That is, only 16.5% of the emissions associated with fossil fuels have been sequestered by forests. This percentage is slightly since 1950 (Ciais et al., 2008) and is similar to the 15% obtained for the USA (Hurtt et al., 2002). Naturally, not all emissions are attributable to the forest transition. Assuming that the 1950 level of biomass extraction was maintained until 2010, and that all that biomass was used to produce electricity replacing fossil fuels, this would reduce electricity-related GHG emissions by 31.2 Tg CO_2e yr^{-1}, using coefficients of the electicity energy mix, power generation efficiency and GHG intensity of electricity production by Aguilera et al. (2019).

Another process that may undermine the forest transition's contribution to climate change mitigation is the greater risk of fires, and especially of potentially highly destructive mega-fires (San-Miguel-Ayanz et al., 2013). This risk is increased by many factors that are also involved in the forest transition: low fuelwood extraction, abandonment of grazing activities, and the expansion of coniferous plantations, especially between 1950 and 1980, which increased forest fires between 25 and 30 years after plantation (Iriarte-Goñi and Ayuda, 2018). All these factors favour the risk of mega-fires associated to the expansion of

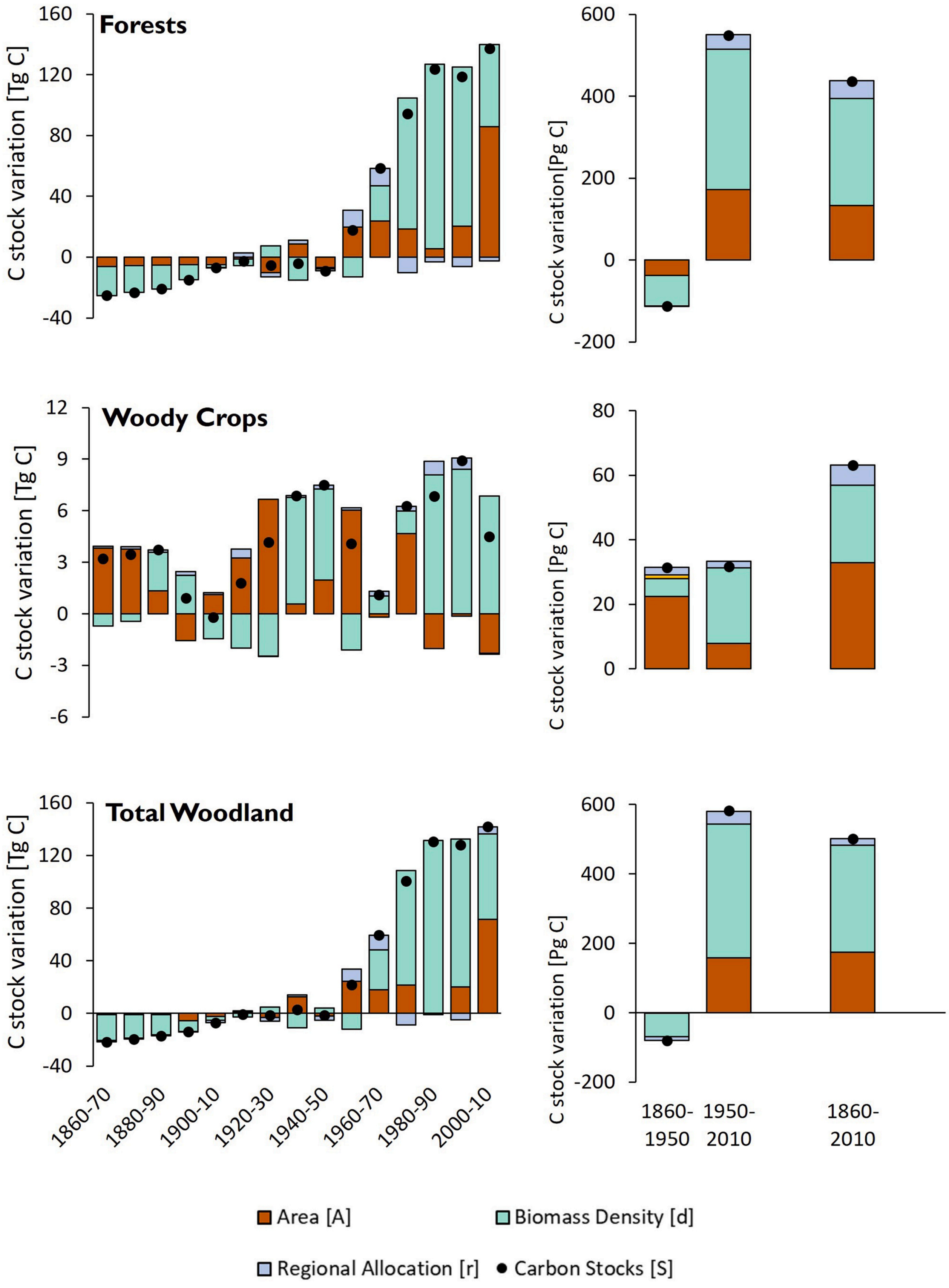

Fig. 8. Decomposition analysis of changes in C stocks (in Teragrams of C) in forest systems, woody crops and total woody area.

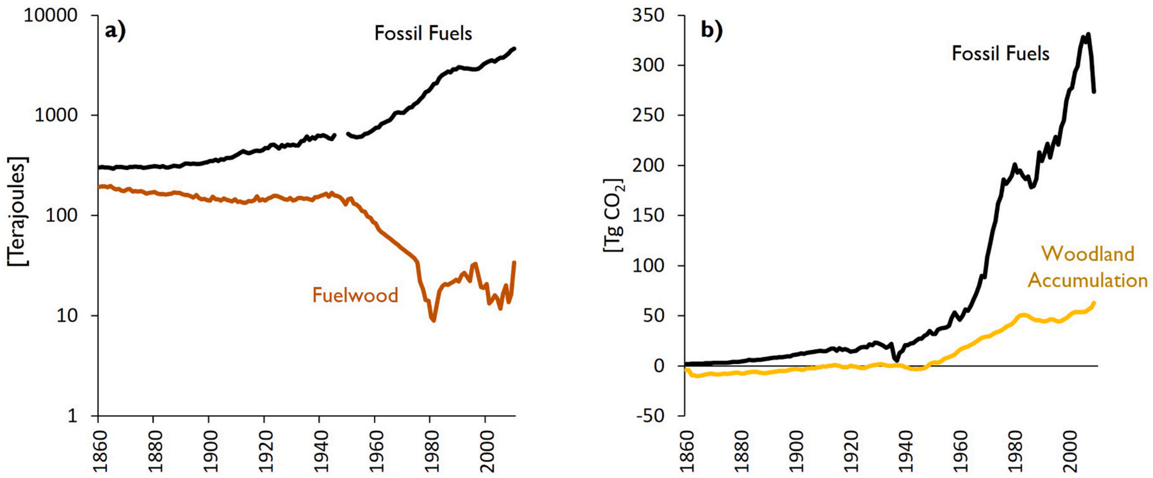

Fig. 9. (a) Energy consumption in Terajoules. (b) Annual fossil fuels CO_2 emissions compared to annual C accumulation (expressed in CO_2 equivalents) in living biomass.

Table 1
Carbon density in preindustrial Mediterranean provinces (before c.1900) and recently (c. 2010) (Mg C ha^{-1}). Data from Aguilera et al. (2018) (1), Muñoz-Rojas et al., 2011) (2), Le Noë et al. (2020) (3), Fonseca et al. (2022) (5) and this paper. Litter not included in the estimation.

	Preindustrial			Today		
	Vegetation	SOC	Total	Vegetation	SOC	Total
Woody	12	68(1)	82	16	45(1)	59
Herbaceous	2	50(1)	52	2	48(1)	47
High Forest	22	53(3)	75	48	69(3)	117
Scrubland	18(2)	64(5)	82	18(2)	64(5)	82

large continuous forest areas with high fuel loads and flammability, in a context of rising heat wave frequency and intensity due to climate change (Aguilera et al., 2020a). Thus, paradoxically, net deforestation can be triggered by the forest transition as a result of these processes, as has been recently observed in Portugal (Oliveira et al., 2017).

5. Conclusions

In recent decades, forest areas and C stock have increased in temperate forests. Such a process, however, is a recent phenomenon we know little of from a historical perspective. In this work, we documented the change in forest cover, C stock and C density in forest areas and woody crops in Spain.

A slow but continuous process of declining C stock could be observed between 1860 and 1950. That loss was caused by deforestation, but, to a greater extent, by the fall in C density due to forest degradation. In Spain, the C stock declined somewhat faster than in central and northern European countries, but much slower than within the old colonial borders, such as the USA, or tropical countries. Between 1910 and 1950, deforestation took place in many areas of Spain due to the advance of woody crops, which partially compensated for the fall in forest stock.

As could be expected, from 1950, the stock grew rapidly and multiplied by 2.5 until 2010. The forest transition began later than in the rest of European countries but has been one of the fastest worldwide. Again, the increase in density surpassed the increase in surface area. Interestingly, the relocation of the forest surface areas in the most productive areas has produced a 9.2% increase in stock since 1950. Woody crops play a key role in C sequestration, especially in a Mediterranean climate where some provinces hold more C than forest areas do.

Carbon stock increase, however, is related to processes with negative effects. Indeed, it has taken place thanks to agricultural intensification, the use of fossil fuels and the outsourcing of land to other countries. These latter processes leave a significant C footprint which must be calculated in order to assess the extent to which woodland C stock increases fail to offset the 'hidden emissions'.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2023.100416.

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