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From woodfuel to industrial wood: A socio-metabolic reading of the forest transition in Spain (1860–2010)

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A B S T R A C T

After centuries of deforestation, many, mostly industrialized countries have recently been experiencing net increases in forest area and biomass stocks, a phenomenon described as 'Forest Transition'. In this article, we analyse the Spanish forest transition over the last 150 years from a socio-metabolic perspective. We provide the first estimation on forest surface, wood production and biomass stocks and we relate these changes to the socio-metabolic transformations of Spain's economy. Between 1860 and 1950, within a context of organic metabolism and growing population pressure, the stock of forest biomass decreased by 25.3%, falling to its lowest level in c. 1950. By conducting a decomposition analysis, we show that deforestation (i.e., declining forest area) explains 33.7% of the decrease in stock, while the reduction of biomass density accounts for 66.3%. Since 1950, and coinciding with the industrial socio-metabolic transition, forest biomass stocks multiplied by a factor of 2.5. Cropland intensification, the outsourcing of land use to third countries and agricultural policy encouraged the expansion of forest areas. Nevertheless, the substitution of firewood with fossil fuels was the main explanatory factor of the stock increase, since it enabled a dramatic decline in wood appropriation and the consequent increase in biomass density.

1. Introduction

Human societies have shaped ecosystems for millennia (Ellis et al., 2021). Since the introduction of agriculture, human societies have expanded and intensified cropland and pastureland areas, reducing the world's forests by an estimated 45% (McNeill, 2000). This process has brought about important social and environmental consequences including large amounts of CO_2 emissions, biodiversity loss and human displacements (Bonan, 2008; Chazdon, 2008; Bond, 2009; Davin and de Noblet-Ducoudré, 2010). Deforestation began earlier in regions such as Europe, where it is estimated that one third of the original forest area was cleared by the seventeenth century (Williams, 2003; Kaplan et al., 2009). Meanwhile, in other regions such as Latin America, Africa or Southeast Asia, deforestation was more pronounced during the twentieth century (Ramankutty and Foley, 1999; Barbier, 2010) and remains a pressing environmental challenge in the 21st century (Baccini et al., 2017). However, from around the nineteenth century, especially in industrialized countries, the deforestation process was reversed, i.e. net gains in forest areas were observed. Throughout the twentieth century, this pattern spread to many other regions, particularly to rich and temperate countries (see a review in Meyfroidt and Lambin, 2011).

In the 1990s, the process of national net forest area gain following long-term deforestation was described as 'Forest Transition' (e.g. Mather, 1992; Grainger, 1995; Rudel, 1998). The issue rapidly took centre stage within environmental sciences (Meyfroidt and Lambin, 2011). Ultimately, forest recovery has become a paramount environmental goal, connected to, among other aspects, biodiversity conservation and climate-change mitigation targets (Mouri et al., 2016; Rudel et al., 2020). Because forests are among the most biomass dense terrestrial ecosystems, their recovery constitutes an effective strategy to sequester carbon from the atmosphere and, thus, to mitigate climate change. Therefore, identifying *where, when* and *why* forest transitions are taking place has become a central topic within environmental studies and policy.

Several major pathways towards the forest transition have been identified (see Rudel et al., 2005; Meyfroidt and Lambin, 2011; Iriarte-Goñi, 2019). The "economic growth" pathway refers to a process whereby industrialization leads to rural exodus, the mechanisation of agriculture and the abandonment of less productive agricultural areas; the "forest scarcity" pathway prevails when forest product shortages result in forest protection or incentives to reforest lands for productive purposes. In addition, the outsourcing of deforestation to other territories ("globalisation") has been identified as a possible trajectory, leading to forest transitions in one place at the expense of deforestation

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elsewhere (Pfaff and Walker, 2010; Pendrill et al., 2019; Jadin et al., 2016a, 2016b).

However, within the forest transition literature, very few studies examine the process from a socio-metabolic perspective, that is, seeking to explain changes in the forest area as a result of the general changes of a society's use of energy and materials (for exceptions see: Myllyntaus and Mattila, 2002; Gingrich et al., 2021). The 'social metabolism' framework, in analogy with the biological concept of metabolism, studies a society's exchanges of energy and materials with its environment (Haberl et al., 2019). The 'socio-metabolic transitions', i.e. changes in a society's exchange of energy and materials and its environment, generate direct and indirect impacts on land cover and land use, including forest land uses (Krausmann et al., 2008). For example, the use of mineral coal led to the recovery of forest density previously used to produce firewood and charcoal (Sieferle, 2001). Similarly, the use of motorised equipment powered by fossil fuels led to the freeing of surface area previously used for feeding animals for traction. By adopting a socio-metabolic perspective, our starting hypothesis is that 'there is an intimate relation between patterns of socio-economic flows of materials and energy – and land uses' (Krausmann, 2001; Krausmann et al., 2008:24). The socio-metabolic approach not only provides us with a proper theorical framework to better understand land-use change, but also with a flexible and powerful methodological approach to quantify biophysical flows between ecosystems and societies in the long-term (e.g., Tello et al., 2014; Soto et al., 2016; Gingrich et al., 2021).

A number of national and regional case studies have analysed the impact of the socio-ecological transition in land use change and land use intensification (Krausmann, 2001; Kuskova et al., 2008; Parcerisas et al., 2012; Tello et al., 2014). Focusing on the forest transition, previous research has highlighted the effects of multiple enabling conditions connected to social metabolism, including agricultural intensification (Jadin et al., 2016a, 2016b), international trade (Pendrill et al., 2019; Ingalls et al., 2018), and energy use (Magerl et al., 2022; Gingrich et al., 2021). Multiscalar studies have shown that long-term national-level forest change may be the effect of very diverse trends within a country (Magerl et al., 2022; Le Noë et al., 2020), but so far, no such analysis has been conducted for a Mediterranean country.

The aim of this paper is to provide insights into Spain's forest transition at both national and subnational levels from a socio-metabolic perspective. On the one hand, we provide a biophysical characterisation of long-term dynamics in Spanish forest ecosystems, focusing on flows and stocks of biomass in the period 1860–2010. On the other hand, we analyse how the general changes in Spain's economic metabolism help to explain the changes in the country's forest ecosystems. Specifically, the objectives of this study are to:

1. Characterise and analyse the Spanish forest transition in historical perspective. Based on historical sources (forest inventories, agricultural statistics and modelling), we estimate changes in Spain's forest area and biomass stocks over the long term, identifying three types of forests at the provincial level.
2. Quantify biomass flows in forest ecosystems, distinguishing total Net Annual Increment (i.e., annual growth of woody biomass), domestic extraction (i.e., annual harvest of wood including residues) and final uses of wood, distinguishing fuelwood and wood raw material.
3. Through decomposition analysis, quantify the components of historical changes in forest area, biomass production and biomass stocks.
4. Analyse historical changes in 'forest metabolism' – i.e. changes in area, production, and functionality – in relation to changes occurring within the overall economic metabolism.

The text is structured as follows: in the next section, we describe the conceptual framework, methods and sources used. The third section presents the results regarding the changes in land use, biomass flows and biomass stocks, examining the drivers of change related to flows and stocks by means of a decomposition analysis. In the discussion section, we link our results to relevant literature on forest dynamics in Spain, changes in Spanish social metabolism, and changes in ecosystem characteristics. We end by providing some concluding remarks.

2. Materials and methods

2.1. Conceptual framework and system boundaries

In this study, we consistently assess the forest area, forest biomass stocks, and associated forests biomass fluxes of Spain for 50 provinces in the period 1860 to 2010. Fig. 1 summarises the main variables analysed, which interact as follows:

$$NAI_{ijt} = DE_{ijt} + R_{ij} + \Delta S_{ijt} \quad (1)$$

We define Net Annual Increment (*NAI*) as the total amount of woody biomass produced in a given territory in a given year. By including all woody biomass production, as well as natural mortality of wood, *NAI* equals net primary productivity minus productivity of annual biomass. This definition of *NAI* is more inclusive than definitions commonly used in forest inventories, which exclude woody biomass below a certain threshold, as well as natural mortality (Tomter et al., 2016). *DE* is the share of *NAI* extracted by society that ends up having a socio-economic use. *R* is the biomass recycled within the agroecosystems, i.e. the wood and branches that fall into the fields on their own or during harvesting. ΔS refers to the biomass stock change, which can have positive or negative values, if forest stocks increase or decrease respectively. Subindexes identify the boundaries of the study, consisting of: *i*, each of Spain's 50 provinces; *j*, three different forest types considered; and *t*, the year.

In this research we only focus on woody living biomass, including stem trees, large and thin branches and roots, but excluding dead wood, litter, leaves and understory, as well as soil organic carbon. Living biomass represents a large share of total carbon stocks in forest systems, accounting for an average of around 42% of global biomass carbon stocks and around 44% of Europe's biomass carbon stocks (Pan et al., 2011), and it is the carbon pool most sensitive to regional and historical changes (Gingrich et al., 2007; Le Noë et al., 2020).

We also focus the analysis of biomass extraction on woody biomass, excluding other practices of forest use, such as grazing or collection of wild fruit and nuts. With respect to extracted biomass flows, that is, the biomass flows that have a socio-economic use, we identify two major end uses as stated in Eq. (2):

$$DE_{ijt} = WRM_{ij} + FW_{ij} \quad (2)$$

Where *WRM* is the wood used as raw material i.e. roundwood for construction and infrastructure (e.g. to build houses, furniture, sleepers, lamp posts, etc.) or softwood for pulp. *FW* stands for woodfuel i.e. parts of biomass devoted to energy uses, mainly heating in industry and homes.

Finally, changes in forest biomass stocks (S) are quantified as the difference in biomass stocks between two consecutive years.

2.2. Sources and estimation procedure

We independently assessed the three major variables quantified in this study: stock, domestic extraction and NAI of forest biomass, based on historical statistical data. The main sources used are shown in Table 1.

In 1965 to 2010 the estimation of stocks is based on Spain's National Forest Inventories (hereon NFI), carried out at a provincial scale between 1965 and 2009 (more details in MAPA, 2019b). Three NFI exist (the last one concluded in 2007) and a fourth one is ongoing. We use three benchmarks for 45 provinces and four benchmarks for 5 provinces. The NFIs provide information on biomass stock and biomass density,

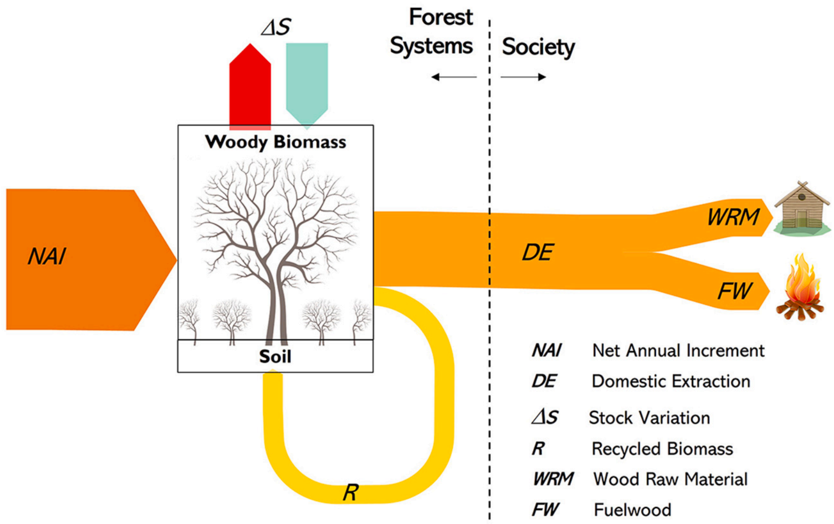

Fig. 1. Biomass flows considered in this study.

Table 1
Summary of sources used in this research. Asterisks refer to high (***), medium (**) and low (*) robustness of the data presented.

Variable	Years	Robustness	Sources
Forest Area	1860–1930	**	Infante Amate and Iriarte Goñi (2017), JCA (1905, 1914, 1923), GEHR, Grupo de Estudios de Historia Rural (1994)
	1930–1960	**	Anuarios de Estadística Agraria (1929-), Estadística Forestal Española (1940-1971)
	1960–2010	***	National Forest Inventories (1965–2010) (MAPA, 2019b),
Stocks (and biomass density)	1860–1960	**	Based on Infante Amate and Iriarte Goñi (2017) and 1960–2010 data
	1960–2010	***	National Forest Inventories (1965–2010) (MAPA, 2019b).
Net Annual Increment	1860–1960	*	Literature review retrieved from Infante Amate et al. (2014)
	1960–2010	**	National Forest Inventories (MAPA, 2019b), Anuarios de Estadística Agraria (1929-), Estadística Forestal Española (1940-1971), Iriarte-Goñi and Infante-Amate (2019). Barciela et al. (2005).
Domestic Extraction	1860–2010	***	Infante Amate and Iriarte Goñi (2017), Iriarte-Goñi and Infante-Amate (2019), based on Spanish Agricultural and Forestry Statistics.
Recycled	1860–2010	**	Based on factors provided by Montero et al. (2005).

distinguishing between coniferous and deciduous forests. To fill the gaps, we retrieve annual series of Forest Area from Agricultural Census and Forestry Statistics. Carbon densities per province and land-use type were annually estimated through linear interpolation using NIF benchmarks. Then, we multiply every land-use category by its specific carbon density. For 1860–1960, we used a different approach due to data scarcity: We first estimated historical series of the forest area (more details below), identifying three main types of forest in Spain: (1) High forest (also registered in recent statistics as forest for timber production, “Monte Maderable”), generally dominated by conifers and oaks in inland and Mediterranean shore, or by beeches, oaks, chestnut trees, ash trees and eucalyptus in the Atlantic fringe of the country, all of them oriented mainly towards timber production, although before c. 1950 it used to be more multifunctional, having the extraction of rosin, cork and other wild goods an important relevance (GEHR, 2003); (2) Coppice (also registered as forest for firewood production, “Monte Leñoso”), dominated by *Quercus* (oak) species. The main use of these types of forest has traditionally been the provision of firewood and other forest products. Coppice occasionally includes spontaneous and unmanaged revegetation of abandoned surfaces; (3) Open forest, less densely covered with trees, generally of the genus *Quercus*. Although forest statistics are not always consistent over time, open forest largely refers to the ‘*dehesa*’, or pastures, an agroforestry system that combines dispersed oak or cork oak trees with livestock and, occasionally, herbaceous crops. Our estimation is carried out by concatenating the data of different historical agrarian and forestry sources (see Table 1). Subsequently, we calculate woody biomass stocks using historically-adjusted biomass density factors for each forest type and each province drawn from the NFIs, following Infante Amate and Iriarte Goñi (2017). In Mediterranean areas, the difference between forest and shrubland is not always clear. Although historical records do not always specify the criteria to delimit forest area, no major shifts in category appear to have taken place during our study period, given the stability of the data series. In recent censuses, areas qualify as high forest and coppice when trees occupy over 20% of total area, while in the case of open forest the minimum tree cover is 5% (see Alberdi et al., 2016).

Domestic extraction of biomass is directly taken from Iriarte Goñi (2017), Infante Amate and Iriarte Goñi (2017) and Iriarte-Goñi and Infante-Amate (2019), who consistently estimate wood appropriation in Spain from 1860 onwards at provincial level building on historical statistics on wood production.

For NAI, we followed two different strategies. Between 1965 and 2010, the estimation is based on biomass stock variations recorded by the NFI, minus extracted biomass, and minus biomass losses associated to fires (data retrieved from MAPA, 2019a). For the period between 1860 and 1960, we conducted a comprehensive literature review of historical forest production. In particular, we retrieved a total of 52 observations from the historical literature related to the three major forests types (more details in Infante Amate et al., 2014; Infante Amate and Iriarte Goñi, 2017). NAI is estimated by multiplying historical data on wood production by a constant biomass expansion factor (Montero et al., 2005). In this time period, recycled biomass is estimated as the NAI minus domestic extraction and stock variation, following Eq. (1).

2.3. Decomposition analysis

We quantified the relative contribution of main drivers of change in

NAI, extraction and biomass stocks so as to explain forest dynamics in different stages of the time series. To do so, we conducted an additive decomposition analysis using the Logarithmic Mean Divisia Index (LMDI) (Ang, 2005).

In the case of NAI, we quantify the effect of changes in forest area (F), change in productivity due to the relocation of production to more or less productive provinces (*r*), and changes in productivity due to increase or decline of per-area production within a province (p_i):

$$NAI = F\cdot\frac{F_i}{F}\cdot\frac{NAI_i}{F_i} = F\cdot r\cdot p_i \tag{3}$$

$$\Delta NAI = \Delta F + \Delta r + \Delta p_i \tag{4}$$

In the case of extraction (DE), we investigate also socioeconomic dynamics impacting wood harvest, i.e.: population change (*P*); change in forest land available per capita (*f*); change in productivity (*p*), representing the cumulative effect of *r* and p_i above; and change in the share of biomass produced finally extracted (*s*). The last factor has dramatically changed thorough history. Historically most woody biomass produced was appropriated while in recent decades, characterized by forest abandonment, a large part of forest produce is not harvested:

$$DE = P\cdot\frac{F}{P}\cdot\frac{NPP}{F}\cdot\frac{DE}{NPP} = P\cdot f\cdot p\cdot s \tag{5}$$

$$\Delta DE = \Delta P + \Delta f + \Delta p + \Delta s \tag{6}$$

To understand drivers in stocks (S) dynamics, we distinguish the effects of forest area change (F), change in regional distribution of forest (r), and change in biomass density in a given province (d_i), that is, biomass per hectare:

$$S = F\cdot\frac{F_i}{F}\cdot\frac{S_i}{F_i} = F\cdot r\cdot d_i \tag{7}$$

$$\Delta S = \Delta F + \Delta r + \Delta d_i \tag{8}$$

3. Results

3.1. Forest cover change

The forest area in Spain decreased uninterruptedly from the very first historical records until the mid-twentieth century, falling from 14.1 million hectares (Mha) in 1860 to 12.4 Mha in 1950. Subsequently, Spain underwent its forest transition, i.e. a shift towards a net gain in forest area. Between 1950 and 2010, the forest area rose by 50.4%, reaching 18.6 Mha, or two thirds of the country's total area. The increase in forest area was, therefore 6.5 Mha. By contrast, cultivated area declined only by 2.6 Mha in this period. Therefore, at least 3.9 Mha of forest expansion had to result from conversion of previous pasture or uncultivated land, particularly by the active reforestation policies carried out between the 1950s and the 1980s.

The evolution of major forest types was not homogeneous (Fig. 2a): Coppice and open forests declined continuously until well into the twentieth century. These two forest types were dominated by broadleaved species, especially the *Querqus* (oak). They were mainly dedicated to producing woodfuel and in some cases, when combined with pastures, particularly in the case of *Dehesa*, to livestock production. Conversely, high forests, mainly dominated by conifers dedicated to raw material production, continuously spread until well into the twentieth century, even as the country's total forest area declined. From the 1950s onwards, when the rest of the forest types began to expand, the increase accelerated even further.

The forest areas and their historical changes were distributed unevenly across Spain. The forest transition unfolded during the1900s in some provinces while it did not take place in other provinces until the late twentieth century. Clearly differentiated forest specialisation patterns emerged across provinces. The largest forest areas have traditionally been concentrated in the mountain areas of Northern and Atlantic Spain, in contrast to the southern and eastern parts of the country with drier and warmer climates. As shown in Fig. 3, this imbalance has increased over time and, today, most forests are located in the northern, more productive provinces. Regarding forest types, a

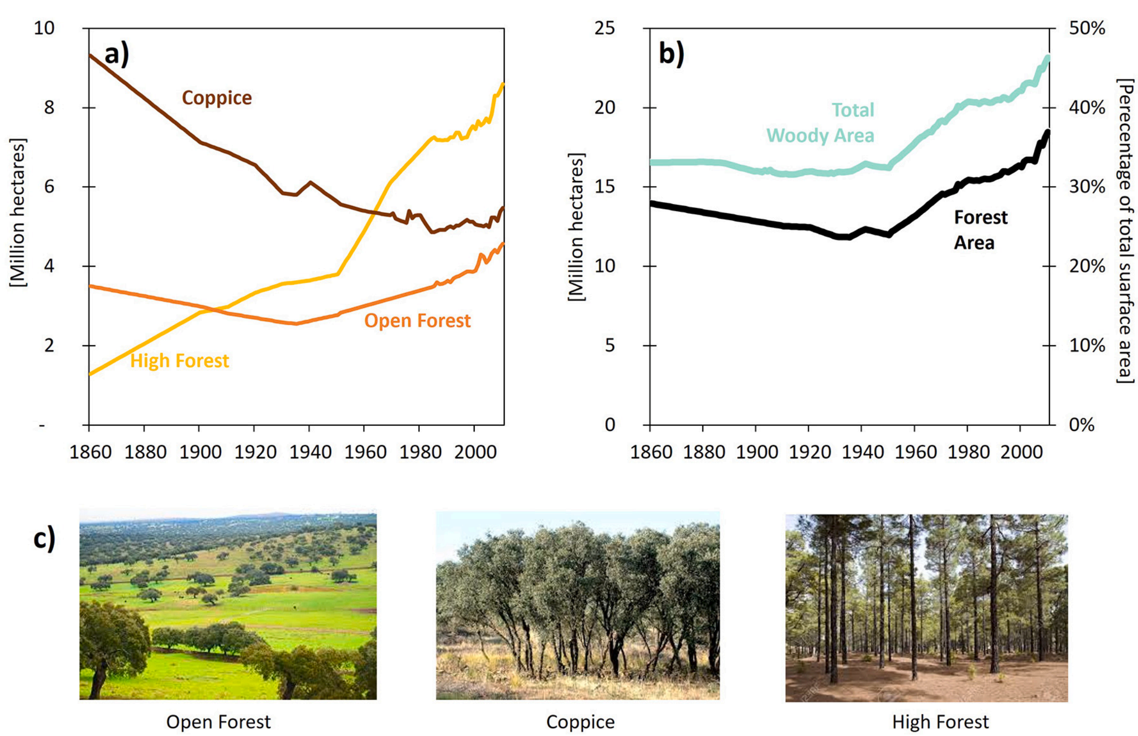

Fig. 2. (a) Forest area, distinguishing the main tracts of woodlands. (b) Total forest area and total woody area, including woody crops (olive grove, vineyard and other woody fruit trees). (c) Illustration of the three forest types considered in this study. Data on woody crops retrieved from Infante Amate and Iriarte Goñi (2017).

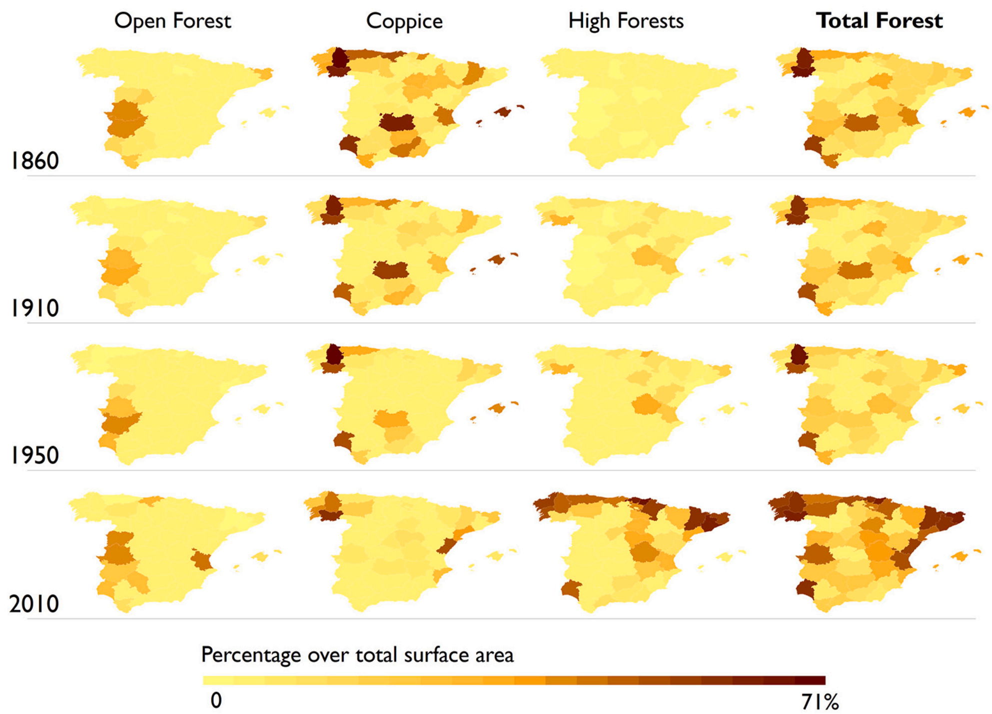

Fig. 3. Forest area provincial distribution, distinguishing three major Spanish forest types: Open Forests, Coppice, and High Forests.

large concentration of high forests in the northern and main mountain ranges can also be observed, especially in more recent decades. Coppices were equally distributed over different provinces, though over time, they also tended to become more concentrated in the north. Finally, open forest has traditionally been concentrated in specific provinces, especially in the south western part of the country where most *dehesa* pasturelands are located.

3.2. Biomass flows: production, extraction and use

Biomass flows changed distinctly over the period (Fig. 4a). NAI remained relatively stable until the mid-twentieth century and increased strongly thereafter, accounting for approximately 15 Tg/yr, with slight decreases between 1860 and 1900 (−6%) caused by forest degradation and deforestation; these were followed by moderate increases until 1950 (+21.9%) due to the shift towards high forest and the increasing cultivation of fast-growing species. Between 1950 and 2010, NAI multiplied by a factor of 2.5 and reaching 41.9 Tg/yr.

Human appropriation of woody biomass exhibits a more fluctuating trend. We can identify four main periods (Fig. 4b): (i) between 1860 and 1914, during which the appropriation fell by 21.0%, mainly due to the replacement of firewood by coal; (ii) between 1914 and 1950, during which we can observe a new increase (6.9%), due to mineral coal shortages caused by the World Wars (1914–1945), the Spanish Civil War (1936–39) and the resulting post-war period, which gave rise to a ‘return to firewood’; (iii) between 1950 and 1980, during which the sharpest fall in recent history was documented (−31.9%), due to a rapid transition to fossil fuels, as we will discuss below; and (iv) since 1980, extraction has grown once more (+ 20.9%), this time due to rising industrial uses and a modest return to bioenergy. In 2010, extraction accounted for 13.4 Tg/yr, that is, 70.3% of the value recorded for1860.

Fig. 5 shows a diagram of the main biomass flows in forest systems at four different times, distinguishing between types of end use: energy and non-energy. Between 1860 and 1914 we can observe a continuous

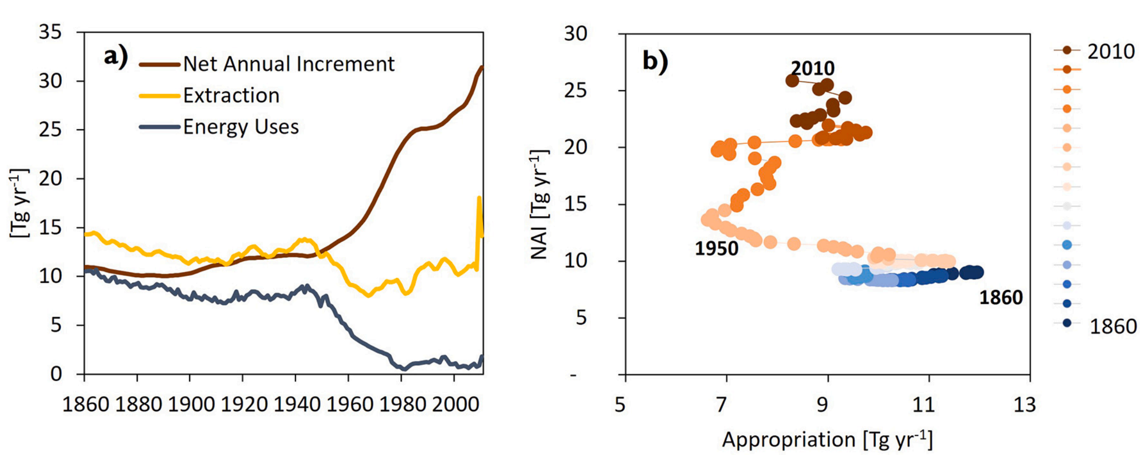

Fig. 4. Biomass flows in Spain’s forest systems. (a) Annual series of Net Annual Increment, Extraction and Energy Uses of extracted biomass. (b) Relation of Net Annual Increment and extracted biomass. All in Teragrams of dry matter.

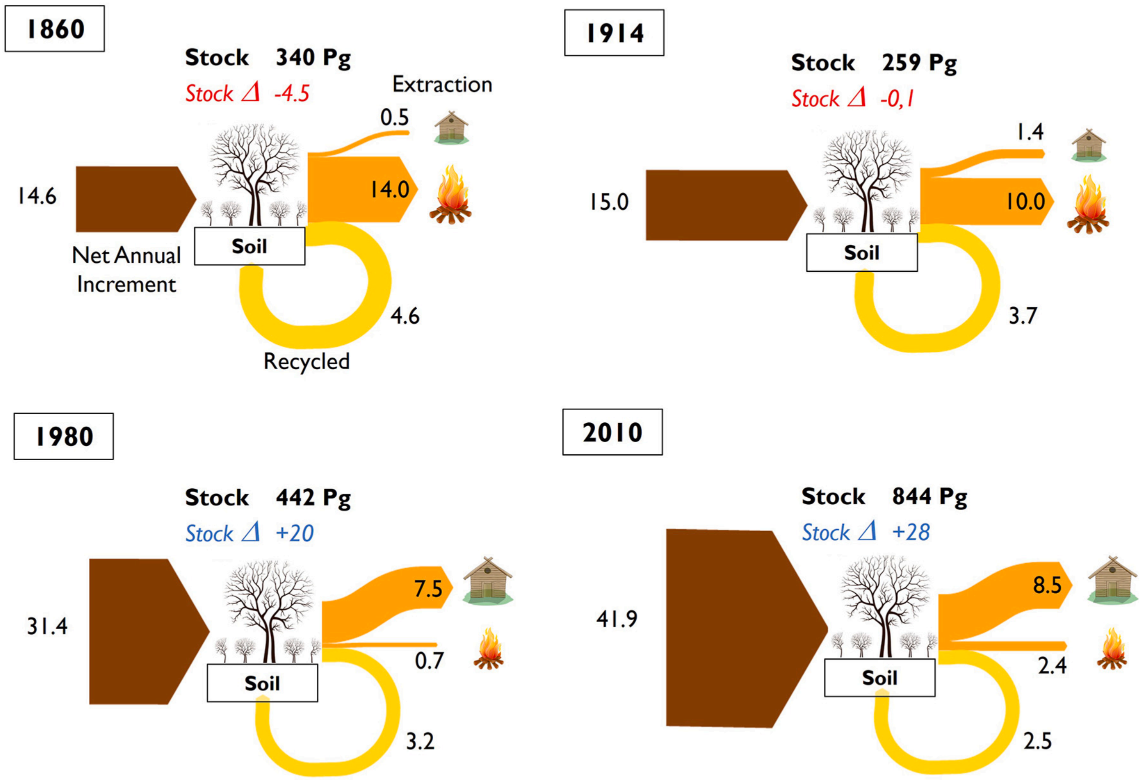

Fig. 5. Forest biomass flows in 1860, 1914 1980 and 2010. All the data is in Teragrams of dry matter per year except the stocks, in Petagrams.

decline in the energy use of firewood, from 14.0 Tg/yr to 10.0 Tg/yr, with even higher figures when measured per inhabitant (894 Gg/cap/yr to 357.4 Gg/cap/yr, respectively). Conversely, during this period, industrial uses almost tripled. Between 1914 and 1950, the transition came to a halt, as we will discuss below. In 1980, when the energy transition was consolidated, the energy uses of forests fell to historical lows (0.7 Tg) while non-energy uses rose to 7.5 Tg. Total extraction fell slightly between 1914 and 1980. The most dramatic change, however, was in the type of use moving from a system oriented to producing fuels (for households and industry) to a new one oriented to producing raw materials (mainly timber for building materials, e.g. doors, windows frames and furniture, and pulpwood for paper). Until 2010, this pattern was consolidated except in the case of non-energy uses, which rose to 2.4 Tg. Although a return to bioenergy can be observed, current levels are much lower than those of pre-industrial systems.

3.3. Biomass stocks

The relationship between DE and NAI changed over time, leading to major impacts on biomass stocks. During the second half of the nineteenth century, we can observe that the extraction of woody biomass always exceeded the NAI (Fig. 4). This situation caused the stock to decrease continuously between 1860 and 1935, from 308.0 Tg to 207.2 Tg (Fig. 6). Between c. 1935 and 1950, the country experienced a change in trend due to the special circumstances of the Civil War and the post-war period: cultivated areas declined and forests and scrublands increased due to agricultural abandonment. However, in turn, some forest areas lost biomass density because firewood extraction grew, due to shortages of other energy sources. Biomass stocks can be observed to have undergone a major transformation between 1950 and the present day, growing by 381%. During this period, the NAI grew sharply, as we have seen above (248.0%). Up to c. 1980, the NAI increased as extraction declined, leading inexorably to stock increases. However, after that date, extraction grew once more and stocks increased despite this. This

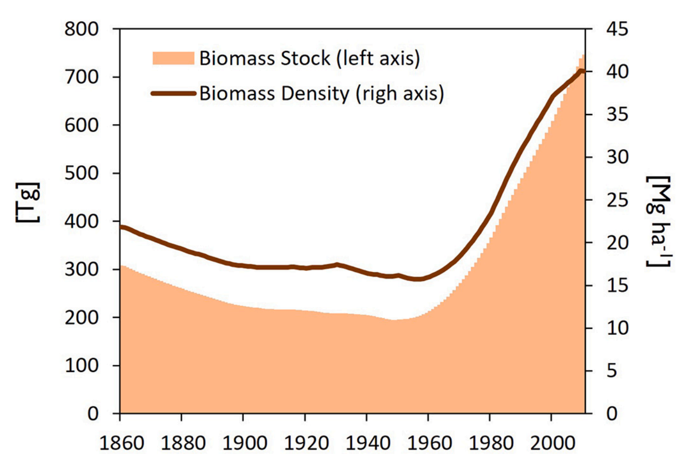

Fig. 6. (a) Carbon stock of forest living biomass, values in Teragrams on the left axis. (b) Biomass density in Megagrams per hectare on the right axis.

was possible because the NAI exceeded extraction levels. In other words, high NAI levels allowed stocks to increase even as harvest levels rose.

We can observe that forest biomass stocks have been unevenly distributed geographically and that this imbalance has increased over time (Fig. 7). Despite representing only 10.6% of the total area, the Atlantic provinces, located on the country's northern coast, accounted for 36.2% of the biomass stock in 1860; by the beginning of the 21st century this share represented half of total stocks. Two factors explain the large increase in this part of the country. First, as we have seen in Fig. 3, during the period of study, a higher share of Spain's forest area was concentrated here. Second, the northern forests, due to their environmental conditions, are more productive and consequently biomass density is higher. In 1860, their biomass density (i.e. biomass in dry matter per hectare) was 68.9 Mg ha^{-1} (85% higher than that of the rest

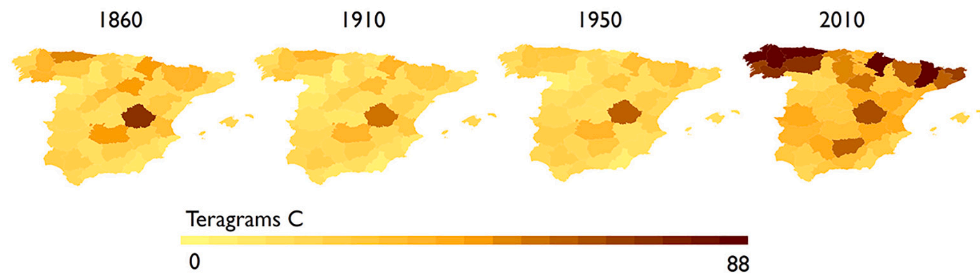

Fig. 7. Provincial distribution of woody biomass carbon stocks, in Teragrams of dry matter. Additional information can be found in the Supplementary Material.

of the country). By 2010 this value rose to 207.7 Mg ha^{-1} (over three times higher). The density gap has grown significantly throughout history. (See Fig. 8.c)

3.4. *Drivers of change in forest biomass flows*

In this section, through decomposition analyses, we analyse the drivers of the changes undergone by NAI, extraction and biomass stocks. We present the results per decade, but we also distinguish two extended periods of change: before 1950, when the metabolism was still organic and the variables under study underwent less dramatic changes; and after 1950, once the transition to industrial metabolism had begun and the forest system was at the forefront of more rapid changes.

In the case of the NAI, the processes explaining the slight growth

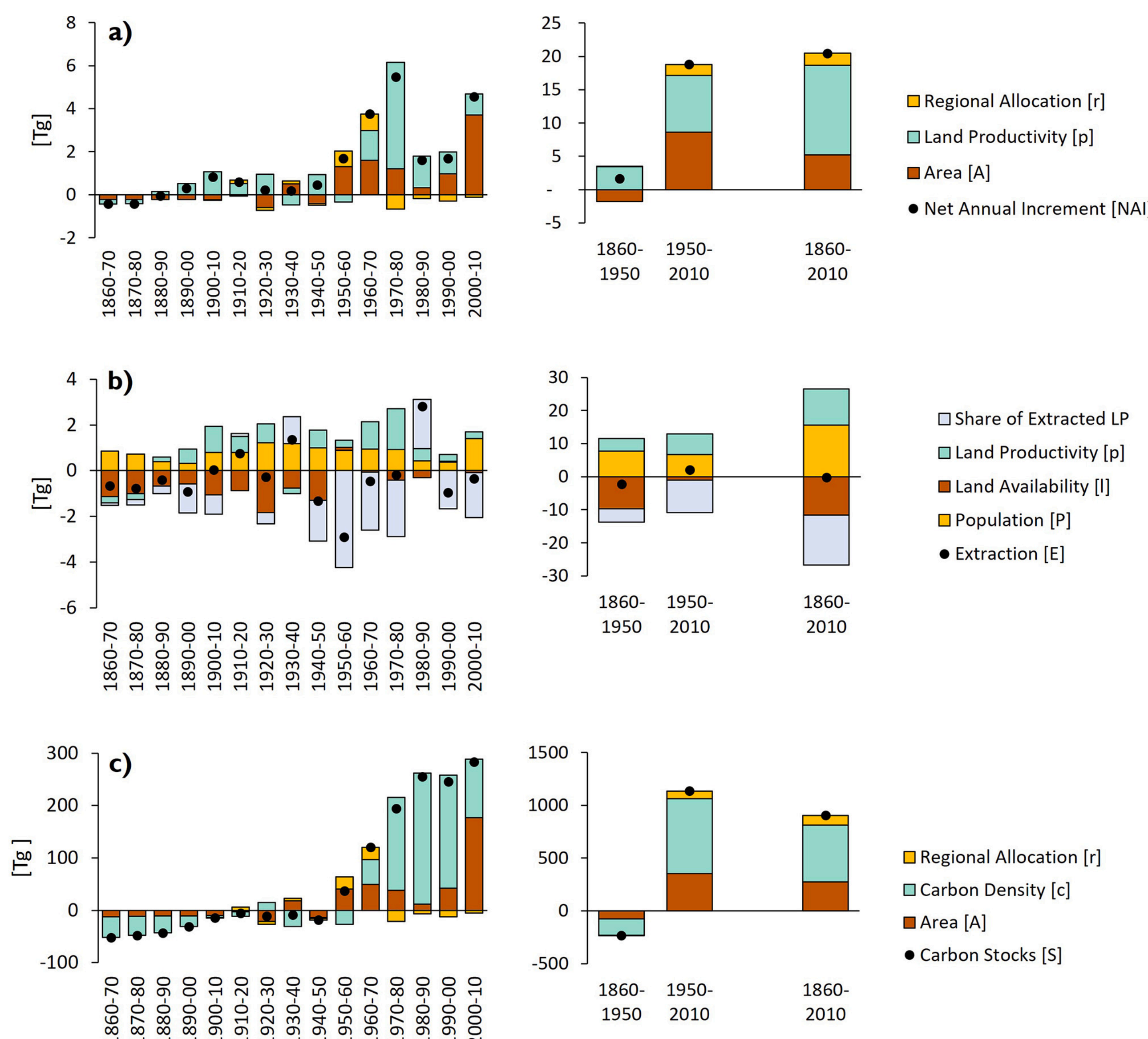

Fig. 8. Decomposition analysis to explain variations of (a) Net Annual Increment, (b) extraction of woody biomass in Spain's forest systems and (c) Carbon Stocks. Petagrams of dry matter.

until the mid-twentieth century are a reduction in forest area which was compensated by increases in land productivity, due to the introduction of fast-growing species. From 1950 both the area (46.0% increase) and the productivity grew. Productivity increase was not only due to the change in species and management, but also to the location of the area in the more productive areas. In fact, the special location explains 9% of the increase in NAI from 1950.

In the case of extraction, the reductions observed throughout most of the study have different explanations depending on the period analysed. Until c. 1950 the decrease in the area reduced the availability of firewood for extraction. This effect compensated the higher demand generated by the increase in the population and the slight increase in productivity. From 1950, although the area increased, and the production per hectare and the population pressure increased demand, the energy transition led to a fall in demand for firewood. In other words, the percentage of the biomass extracted of total biomass produced in the forest systems decreased.

In the case of stocks, the differences before and after1950 are much clearer. Before 1950, we can observe a continued decline in stock, rather than a sharp drop, due both to deforestation (33.7% of the change) and mainly to forest degradation, that is, the reduction of biomass per hectare (66.1%). The stock accelerated continuously thereafter, especially because of increases in density (59.6%), but also because of net forest area increases (30.3%) and, to a lesser extent, because of the relocating of surface areas to more productive areas (10.1%). Interestingly, over this period, relocation effects were particularly notable between 1950 and 1970, when reforestation plans were implemented, as discussed below.

4. Discussion

4.1. Spain's pathway to the forest transition

After centuries of deforestation, Spain initiated its forest transition in the 1950s, the last country to do so of the 21 European states included in the review by Meyfroidt and Lambin (2011). Although forest area expansion is very recent, in the case of Spain, the process unfolded extremely fast. According to our estimates, forest areas declined between 1860 and 1950 by 0.16% a year, mainly due to the expansion of cultivation areas, while they grew by 0.84% between 1950 and 2010. This growth is even more spectacular when measured in terms of biomass stock rather than surface area. While the forest area increased by 50.4% between 1950 and 2010, the stock grew by 281.4%. The increase in forest area was accompanied by a strong growth in woody biomass density, from 35.9 Mg ha^{-1} in 1950 to 86.8 Mg ha^{-1} in 2010. This evolution seems to have been exceptional by international standards. According to the FAO (2015), Spain was the fifth country in the world in terms of growth of "carbon stock in living forest biomass" between 1990 and 2015, while also being the largest and second most populated country among the top five. The study by Kauppi et al. (2006) shows a similar pattern. In short, Spain's forestry transition was a late but extremely rapid process internationally.

Another characteristic described in this study is the different forest transition trajectories in terms of geography and forest-type. While some provinces exhibited net increases in their forest area from the beginning of the twentieth century, others showed continued deforestation. Moreover, forest area distribution was highly unbalanced between provinces, and this imbalance has grown over time due to more forest area being concentrated in the more productive provinces of the north. Different trajectories can also be identified regarding forest types. The high forest surface area never stopped growing because most high forest plantations are oriented towards production or conservation (e.g. to halt erosion). From the end of the nineteenth century, with the upsurge in scientific forestry, projects were extended to expand high forest surface areas, (e.g. Ximenez de Embun, 1928). In Spain, however, the reforestation boom took place in the period 1950–1980 with the programmes initiated by the Franco dictatorship to expand wood production and water reservoirs protection (Iriarte Goñi, 2017). Later, it grew again due to the incentives of the EU's Common Agricultural Policy (Vadell et al., 2019). Meanwhile, coppices and pasture lands, with traditional tree species, continued to decline well into the twentieth century, coinciding with a greater abandonment of crops and pastures (Varela et al., 2020). Spain thus displays elements of both major forest transitions described by Rudel et al. (2005): the "forest scarcity" pathway, characterized by political intervention towards forest recovery and expansion, and the "economic growth" pathway, characterized by rural exodus and spontaneous forest recovery. The national accounts of the 'forest transition' however conceal major internal divergences, both geographical and those related to forest types. Future research should take these divergences into consideration.

4.2. Forest transition through the lens of socio-metabolic transition

Between 1860 and 1950, the Spanish economy remained eminently 'organic' in the way described by Wrigley (1988), that is, it still presented an agrarian-type metabolism (Fischer-Kowalski and Haberl, 2007). While 97.8% of the materials consumed in the 1860s were biomass, by 1950 this figure had declined to 72.3%, and in the 1970s to only one third (Infante-Amate et al., 2015). As in the rest of the pre-industrial economies, most goods and services came from land-based products (Kander et al., 2014). Environmental, technological and social restrictions for land intensification led to the expansion of cultivated areas as the main way to increasing agricultural production (Pujol et al., 2001), and the consequent provision of food, feed, fibres and raw materials. This resulted in competition with forest surfaces and ultimately in deforestation. In addition, forests were also under pressure to provide pasture for livestock, and energy in the form of woodfuel or charcoal. This situation meant that the extraction of biomass generally exceeded the NAI, leading to drops in forest stock.

The forest metabolism in Spain changed radically in the mid-twentieth century, coinciding with major changes occurring in the economy's metabolism (see Table 2). Forest area expansion, whether caused by the abandonment of agricultural activity or by planned reforestation, requires the 'freeing' of land, whether this be cultivated, pasture or non-productive land. This process had two major drivers in late twentieth-century Spain. First, the increase of agricultural productivity and the decoupling of livestock production from the territory. Spain achieved a 171.3% increase in agricultural productivity, measured in kg of dry matter per hectare, between 1960 and 2008 (Soto et al., 2016). The second driver was the outsourcing of land beyond the country's borders. At present, Spain's land embodied in net imports accounts 8.6 Mha of cultivated land and a total of 9.7 Mha including forestry and pasture (Infante-Amate et al., 2018).

These processes have affected forest area growth in several complementary ways. On the one hand, agrarian intensification has been characterized by a strong growth of irrigated areas, which, since the 1950s, was achieved by constructing large water reservoirs throughout the territory (Aguilera et al., 2019a, 2019b; Vila-Traver et al., 2021; Duarte et al., 2014). This system was closely linked to reforestation, since it was necessary to cover the areas surrounding the swamps with trees to prevent them from clogging, due to erosion. Many extensively used grasslands were reforested for this objective. At the same time, reforestation was also spreading because of increasing timber demands coming from urbanisation, the construction of infrastructures and especially the development of paper industries (Iriarte-Goñi, 2013). Agricultural intensification, land externalization, and also the rapid industrial growth process, are all associated in one way or another with the industrial metabolic transition that the country experienced in the second half of the twentieth century.

On the other hand, the forest transition is much more pronounced when analysed in terms of stocks rather than surface area. This is because biomass density increases strongly when the NAI exceeds

Table 2
Indicators of changes to Spain's economic metabolism and forest metabolism. The GDP data are taken from Prados de la Escosura (2017), the rural population from Collantes and Pinilla (2011), the fertilizer data from Barciela et al. (2005), agricultural work data from Maluquer and Llonch (2005), and materials consumption from Infante-Amate et al. (2021).

		1950	1960	1970	1980	1990	2000	2010	Δ1950–2010
Forest Surface area	[Mha]	12.1	13.3	14.7	15.6	15.8	16.4	18.6	↑1.5
Forest biomass stock	[Tg]	195.6	213.4	217.8	366.0	489.8	608.8	746.2	↑3.8
Other socio-metabolic indicators									
GDP /capita (2011$*000)	[$ 2011]	4.2	6.1	11.5	17.1	23.3	30.2	32.9	↑7.8
Rural Population	[%]	49	44	35	28	26	24	20	↓2.45
Agricultural Workers	[%]	49.6	40.2	28.5	19.5	11.3	7.2	4.3	↓11.6
Nitrogen Consumption in Agriculture	[Gg]	86.9	242.8	614.8	984.8	1074.2	1279.2	941.0	↑10.8
Domestic Material Consumption	[Tg]	114.9	158.2	260.2	357.2	478.3	663.2	569.4	↑5.0
Physical Trade Balance	[Tg]	−0.4	5.2	38.5	51.6	77.7	125.0	103.6	¿?

extraction. Which factors are behind the NAI increase and which are behind the decrease in extraction? Beyond the factors identified in this study (i.e., increasingly effective location of forest production), additional factors had an undeniable effect on the NAI increase: (i) an increase in fast-growing species – in Spain, the cover of conifers and eucalypts grew from 18% of the forest area in 1930 to more than half in 2010 (Infante Amate et al., 2014); (ii) a reduction in nutrient exports from agroforestry systems due to the abandonment of extensive livestock production – since the mid-twentieth century, Spanish livestock farming has undergone a radical shift, from extensive to intensive systems based on imported feed (Lassaletta et al., 2014; Soto et al., 2016); (iii) though more difficult to quantify in historical perspective, high atmospheric nitrogen deposition and the positive effects of increasing atmospheric CO_2, which are considered to play a relevant role (Ciais et al., 2008).

In the case of extraction, the decrease can be mainly explained by the increase in the use of fossil fuels, which replaced firewood in industry and, mainly, in households, the major consumers of wood (Infante Amate et al., 2014; Iriarte-Goñi and Infante-Amate, 2019). Fossil fuels played the role of 'subterranean forests', as pointed out by R. P. Sieferle (2001). The 'energy transition' was, therefore, a key factor in explaining woody biomass density increases (Gingrich et al., 2021). This coincided with the parallel growth of timber extraction for industrial uses and also for the export of wood pulp (from the 1970s onwards). However, this process was not intense enough to reduce the stock of biomass. There are two reasons for this. First, because logging was concentrated in areas of the country with higher forest productivity (the north and the Atlantic front) and was organised through high-yield silvicultural treatments, combining felling with replanting that allowed extracting wood without reducing existing stocks (Iriarte-Goñi, 2013). Second, because the increase in forest areas due to the abandonment of crops and pastures was so intense that it played a fundamental role in raising stocks.

The connections between forest change and the socio-metabolic transition point towards problem shifts described as "hidden emissions of forest transitions" (Gingrich et al., 2019), i.e. emissions outside the forest sector enabling the carbon sink in forests. In Spain, forests sequestered 216 Tg CO_2-eq between 1950 and 2010, which represents 16.1% of the CO_2 emitted by fossil fuels (13.4 Pg CO_2). This percentage is somewhat above the European average, which stood at 10% between 1950 and 2007 (Ciais et al., 2008). Though the carbon sequestration of forests plays a key role in mitigating climate change, forests are far from being able to absorb the emissions linked to fossil fuel use. Even in Spain, where the stock has increased sharply, it barely covers a fraction of total fossil fuel emissions. Obviously, not all CO_2 emissions are attributable to energy transition, i.e. to the replacement of firewood with fossil fuels. Assuming the consumption of firewood per inhabitant had remained stable between 1950 and the present, an additional consumption of 768.6 Tg of firewood would have been necessary over the entire period. This additional consumption would have generated 1.1 Pg of CO_2. In other words, emissions associated with the replacement of fossil fuels with CO_2 account for 52% of forest carbon uptake during this period. Obviously, this estimate is based on a theoretical scenario, since a certain share has been replaced with renewable energies with a lower carbon footprint.

In addition, the two main drivers of forest expansion, that is, agriculture intensification and land use outsourcing through agrarian imports, also constitute sources of emissions. In the case of agrarian intensification, there are no conclusive estimates available of the 'carbon footprint' of Spanish agricultural production as a whole. However, the CO_2-eq emissions accumulated between 1950 and 2010 associated with traction and irrigation amount to 0.86 Pg (Aguilera et al., 2019a, 2019b), while the loss of soil organic carbon in croplands has amounted to 0.6 Pg CO_2-eq (Aguilera et al., 2018). To this, we must add soil emissions of N2O and the emissions linked to the manufacture of fertilizers, pesticides and infrastructures such as greenhouses. In addition, many other problems such as soil erosion, loss of biodiversity or pollution by nutrients can be also related to intensification (e.g. Guzmán et al., 2018; Lassaletta et al., 2014). In the case of land use outsourcing, today, the territory virtually occupied outside Spain's borders can be observed to be much larger than the forest area expansion, as described above (Infante-Amate et al., 2018). The impact of this process in terms of CO_2 has yet to be determined. However, these preliminary data reveal that tremendous increases in carbon stock and annual CO_2 sequestration leave a notable 'carbon footprint'.

4.3. *Implications for sustainable forest dynamics*

Forest recovery constitutes a major global environmental priority because of the positive effects on mitigating climate change, increasing biodiversity and providing many other environmental services (Bonan, 2008; Chazdon, 2008; Bond, 2009; Davin and de Noblet-Ducoudré, 2010). However, our analysis highlights that forest recovery in the past has been a side-effect of industrialization, rather than a viable solution to its environmental impacts. The forest transition has sequestered carbon in significant amount, but come at the expense of biodiversity, and of a functional and spatial externalization of forest services. Building on these findings, we identify several leverages for future forest recovery to genuinely contribute to a sustainability transformation:

Firstly, we have seen that the forest transition was capable of storing significant amounts of carbon in Spain, not only in non-forested areas, but also through recovery of previously-degraded forest land. This is in line with research finding that potential biomass in forests is far above the currently observed levels (Erb et al., 2018; Luyssaert et al., 2008). In order to enhance forest C sequestration in existing and expanding forests, further management and a reduction of harvest appear as potential solutions (Ruiz-Peinado et al., 2017). In addition, Mediterranean forest management needs to explicitly address the risk of forest fires, likely to expand in the future due to climate change, thus avoid monocultures of highly flammable tree species (some pines or eucalyptus) (Montiel Molina et al., 2019; Iriarte-Goñi and Ayuda, 2018).

Secondly, in order to comply with the second major ecological sustainability challenge of our time, i.e. biodiversity loss (IPBES, 2019), sustainable forest management will need to safeguard biodiversity. Specifically, the proliferation of fast-growing species described in the literature since the 1980s (Ortega Hernández-Agüero, 1989; Chauvelier, 1990; Arrechea, 2002) has been in opposition to such aims, and future forest management needs to foster more biodiverse ecosystems in order to reverse this trend. In addition, forest expansion patterns in Mediterranean areas have added to the abandonment of traditional agriculture's more diverse landscapes and may be impoverishing biodiversity (Agnoletti, 2014; Marull et al., 2015; Otero et al., 2015; Cervera et al., 2019). Striving for a combination of ecological forest recovery and the conservation of traditional agroforest mosaic landscapes could foster both carbon sequestration and biodiversity conservation.

Finally, in order to avoid problem shifts related to the spatial and functional externalization of forest production (i.e., imports of feed from Latin America allowing domestic forest expansion, and increasing use of fossil energy reducing woodfuel extraction), we argue that major shifts in consumption will be necessary that diverge from previous pathways of the socio-metabolic transitions (Creutzig et al., 2018). Specifically, shifts in diets have shown to reduce pressure on land demand and enable agroecological intensification while sparing land for forest conservation, even for a growing population (Theurl et al., 2020, Billen et al., 2021). Similarly, a major shift in energy use will be required to steer away from fossil energy dependency while guaranteeing good living conditions for all (Millward-Hopkins et al., 2020).

5. Conclusions

The forest transition in Spain has unfolded late, compared to other European countries, but very rapidly. As of 1950, after centuries of deforestation, Spain recovered more than 50% of its forest area while woody biomass stock multiplied by a factor of 2.5, also due to an increase in biomass density, the product of spatial reconfiguration and a fundamental change of forests' role in societal resource provision. We argue that the temporal dynamic is due to both a relatively late shift towards fossil energy carriers, and important forest conservation policies adopted in the 20th century.

Until 1950, in a context of agrarian metabolism, tree-covered areas decreased due to competition for cultivated areas, and lost density due to overexploitation. The increase in forest area that took place from 1950 was due to the freeing of cultivated and pasture land. This release was a result of agricultural intensification, based on non-renewable external inputs, which helped to increase productivity and to outsource land use to third countries, through international trade in agricultural products. On the other hand, the biomass stock increase was due to the decline in extraction of woodfuel replaced by fossil fuels, while the NAI grew. At the same time, the extraction of wood as raw material increased, linked to industrial metabolism changes. However, this process did not reduce stocks because it was concentrated in high productivity areas, and also because forestry management combined extractions with reforestation. Overall, the transition to industrial metabolism led to a forest metabolism transition characterized by an increase in area and stocks, reductions in overall levels of forest extraction, and a functional change – its role as a key fuel supplier gradually shifted towards that of a raw material supplier.

Increasing forest cover is one of today's major environmental goals. For the case of Spain we have highlighted that a significant success in forest expansion, especially over the last three decades, when carbon stocks have grown while harvests have increased, came at the expense of a major socio-metabolic shift with global environmental implications. From a territorial viewpoint, uncontrolled forest growth may led to undesired effects regarding the territory's cover and use as well as uncontrolled forest fires. From a socio-metabolic perspective, we can identify and quantify the changes in the rest of a country's materials economy linked to forest cover increase, including: agricultural intensification, land use externalization, or the use of fossil fuels as a substitute for forest products. In order for future forest recovery to genuinely contribute to sustainability targets, production and consumption of forest products, food and energy will need to deviate from current trajectories.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107548.

References

Agnoletti, M., 2014. Rural landscape, nature conservation and culture: some notes on research trends and management approaches from a (southern) European perspective. Landsc. Urban Plan. 126, 66–73.

Aguilera, E., Guzmán, G.I., Álvaro-Fuentes, J., Infante-Amate, J., García-Ruiz, R., Carranza-Gallego, G., de Molina, M.G., 2018. A historical perspective on soil organic carbon in Mediterranean cropland (Spain, 1900–2008). Sci. Total Environ. 621, 634–648.

Aguilera, E., Guzmán, G.I., de Molina, M.G., Soto, D., Infante-Amate, J., 2019a. From animals to machines. The impact of mechanization on the carbon footprint of traction in Spanish agriculture: 1900–2014. J. Clean. Prod. 221, 295–305.

Aguilera, E., Vila-Traver, J., Deemer, B.R., Infante-Amate, J., Guzmán, G.I., González de Molina, M., 2019b. Methane emissions from artificial waterbodies dominate the carbon footprint of irrigation: a study of transitions in the food-energy-water-climate nexus (Spain, 1900-2014). Environ. Sci. Technol. 53 (9), 5091–5101.

Alberdi, I., Sandoval, V., Condés, S., Cañellas, I., Vallejo, R., 2016. El Inventario Forestal Nacional español, una herramienta para el conocimiento, la gestión y la conservación de los ecosistemas forestales arbolados. Ecosistemas 25, 88–97.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33 (7), 867–871.

Anuarios de Estadística Agraria, 1929. https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/.

Arrechea, E., 2002. La gestión forestal en los espacios naturales protegidos: el ejemplo del Parque Natural del Moncayo. Ecosistemas 2, 1–7.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., Houghton, R.A., 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science 358 (6360), 230–234.

Barbier, E.B., 2010. Scarcity and Frontiers: How Economies Have Developed through Natural Resource Exploitation. Cambridge University Press.

Barciela, C., Giráldez, J., Gehr y López, I., 2005. "Sector agrario y pesca", en Carreras, A. y. In: Tafunell, X. (Ed.), Estadísticas históricas de España. Siglos XIX y XX, 2 ed. Fundación BBVA, Madrid, pp. 245–356.

Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B., Sanz-Cobena, A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. One Earth 4 (6), 839–850.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320 (5882), 1444–1449.

Bond, I., 2009. Incentives to Sustain Forest Ecosystem Services: A Review and Lessons for REDD (No. 16). IIED.

Cervera, T., Pino, J., Marull, J., Padró, R., Tello, E., 2019. Understanding the long-term dynamics of forest transition: from deforestation to afforestation in a Mediterranean landscape (Catalonia, 1868–2005). Land Use Policy 80, 318–331.

Chauvelier, F., 1990. La repoblación forestal en la provincia de Huesca y sus impactos geográficos. Instituto de estudios Altoaragoneses, Huesca.

Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. science 320 (5882), 1458–1460.

Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, S.L., Cescatti, A., Liski, J., Freibauer, A., 2008. Carbon accumulation in European forests. Nat. Geosci. 1 (7), 425.

Collantes, F., Pinilla, V., 2011. Peaceful Surrender: The Depopulation of Rural Spain in the Twentieth Century. Cambridge Scholars Publishing.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M., De Bruin, W.B., Dalkmann, H., Weber, E. U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Chang. 8 (4), 260–263.

Davin, E.L., de Noblet-Ducoudré, N., 2010. Climatic impact of global-scale deforestation: radiative versus nonradiative processes. J. Clim. 23 (1), 97–112.

Duarte, R., Pinilla, V., Serrano, A., 2014. The water footprint of the Spanish agricultural sector: 1860–2010. Ecol. Econ. 108, 200–207.

Ellis, E.C., Gauthier, N., Goldewijk, K.K., Bird, R.B., Boivin, N., Díaz, S., Watson, J.E., 2021. People have shaped most of terrestrial nature for at least 12,000 years. Proc. Natl. Acad. Sci. 118 (17).

Erb, K.H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Luyssaert, S., 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553 (7686), 73–76.

Estadística Forestal Española, 1940-1971. Estadística Forestal de España. Ministerio de Agricultura. https://www.miteco.gob.es/es/biodiversidad/estadisticas/forestal_estadistica_forestal_1940_1971.aspx.
FAO, 2015. Global Forest Resources Assessment 2015 Desk Reference. Food and Agriculture Organization, Rome.
Fischer-Kowalski, M., Haberl, H. (Eds.), 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar Publishing.
GEHR, 2003. Bosques y crisis de la agricultura tradicional. Producción y gestión de los montes españoles durante el franquismo (1946-1979). In: Sebastián Amarilla, J.A., Uriarte Ayo, R. (Eds.), Historia y economía del bosque en la Europa del sur (siglos XVIII-XX). Prensas Universitarias de Zaragoza, Zaragoza, pp. 283–372.
GEHR, Grupo de Estudios de Historia Rural, 1994. Más allá de la" propiedad perfecta". El proceso de privatización de los montes públicos españoles (1859-1926). Historia Agraria 8, 99–152.
Gingrich, S., Erb, K.H., Krausmann, F., Gaube, V., Haberl, H., 2007. Long-term dynamics of terrestrial carbon stocks in Austria: a comprehensive assessment of the time period from 1830 to 2000. Reg. Environ. Chang. 7 (1), 37–47.
Gingrich, S., Lauk, C., Niedertscheider, M., Pichler, M., Schaffartzik, A., Schmid, M., Erb, K., 2019. Hidden emissions of forest transitions: a socio-ecological reading of forest change. Curr. Opin. Environ. Sustain. 38, 14–21.
Gingrich, S., Lauk, C., Krausmann, F., Erb, K.H., Le Noë, J., 2021. Changes in energy and livestock systems largely explain the forest transition in Austria (1830–1910). Land Use Policy 109, 105624.
Grainger, A., 1995. Forest transition: an alternative approach. Area 27, 242–249.
Guzmán, G., Aguilera, E., García-Ruiz, R., Torremocha, E., Soto-Fernández, D., Infante-Amate, J., González de Molina, M., 2018. The agrarian metabolism as a tool for assessing agrarian sustainability, and its application to Spanish agriculture (1960-2008). Ecol. Soc. 23 (1).
Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 1.
Infante Amate, J., Iriarte Goñi, I., 2017. Las bioenergías en España. Una serie de producción, consumo y stocks entre 1860 y 2010.
Infante Amate, J., Soto Fernández, D., Iriarte Goñi, I., Aguilera, E., Cid, A., Guzmán, G., González de Molina, M., 2014. La producción de leña en España y sus implicaciones en la transición energética. Una serie a escala provincial (1900–2000)(No. 1416). Asociacion Espa–ola de Historia Economica.
Infante-Amate, J., Soto, D., Aguilera, E., García-Ruiz, R., Guzmán, G., Cid, A., González de Molina, M., 2015. The Spanish transition to industrial metabolism: long-term material flow analysis (1860–2010). J. Ind. Ecol. 19 (5), 866–876.
Infante-Amate, J., Aguilera, E., Palmeri, F., Guzmán, G., Soto, D., García-Ruiz, R., de Molina, M.G., 2018. Land embodied in Spain's biomass trade and consumption (1900–2008): historical changes, drivers and impacts. Land Use Policy 78, 493–502.
Infante-Amate, J., Vila, J., Fernández, E.A., Sanjuán, Á., Oropesa, F., de Molina, M.G., 2021. Las bases materiales del desarrollo económico en España (1860-2016). Un estudio desde el metabolismo social. Cuadernos Económicos de ICE 101, 185–213.
Ingalls, M.L., Meyfroidt, P., To, P.X., Kenney-Lazar, M., Epprecht, M., 2018. The transboundary displacement of deforestation under REDD+: problematic intersections between the trade of forest-risk commodities and land grabbing in the Mekong region. Glob. Environ. Chang. 50, 255–267.
IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://ipbes.net/global-assessment.
Iriarte Goñi, I., 2017. El contexto socio económico de las repoblaciones en España (1939-c.1980), en Pemán García, J. Iriarte Goñi, I. y Lario Leza, F.J., La restauración forestal de España. MAPAMA-SECF.
Iriarte-Goñi, I., 2013. Forests, fuelwood, pulpwood, and lumber in Spain, 1860-2000: a non-declensionist story. Environ. Hist. 18 (2), 333–359.
Iriarte-Goñi, I., 2019. "Transición forestal" y cambio económico. El caso de los bosques españoles en el largo plazo (1860-2000). Historia Industrial 75, 11–39.
Iriarte-Goñi, I., Ayuda, M.-I., 2018. Should forest transition theory include effects on forest fires? The case of Spain in the second half of the twentieth century. Land Use Policy 76, 789–797.
Iriarte-Goñi, I., Infante-Amate, J., 2019. Continuity, Change, and Geographical Differences in Spain's Firewood Consumption: A New Estimation (1860–2010).
Jadin, I., Meyfroidt, P., Lambin, E.F., 2016a. International trade, and land use intensification and spatial reorganization explain Costa Rica's forest transition. Environ. Res. Lett. 11 (3), 035005.
Jadin, I., Meyfroidt, P., Lambin, E.F., 2016b. Forest protection and economic development by offshoring wood extraction: Bhutan's clean development path. Reg. Environ. Chang. 16 (401–4), 15.
JCA, 1905. Pastos y prados. Junta Consultiva Agronómica, Ministerio de Agricultura, Industria, Comercio y Obras Públicas, Madrid.
JCA, 1914. Avance estadístico que en España representa la producción media anual de pastos, prados y algunos aprovechamientos y pequeñas industrias zoógenas anexas. Junta Consultiva Agronómica, Ministerio de Fomento, Madrid.
JCA, 1923. Avance estadístico de la producción de agrícola en España. Junta Consultiva Agronómica, Ministerio de Agricultura, Industria, Comercio y Obras Públicas, Madrid.
Kander, A., Malanima, P., Warde, P., 2014. Power to the People. In: Power to the People. Princeton University Press.
Kaplan, J.O., Krumhardt, K.M., y Zimmermann, N., 2009. The prehistoric and preindustrial deforestation of Europe. Quat. Sci. Rev. 28 (27), 3016–3034.
Kauppi, P.E., Ausubel, J.H., Fang, J., Mather, A.S., Sedjo, R.A., Waggoner, P.E., 2006. Returning forests analyzed with the forest identity. Proc. Natl. Acad. Sci. 103 (46), 17574–17579.
Krausmann, F., 2001. Land use and industrial modernization: an empirical analysis of human influence on the functioning of ecosystems in Austria 1830–1995. Land Use Policy 18 (1), 17–26.
Krausmann, F., Schandl, H., Sieferle, R.P., 2008. Socio-ecological regime transitions in Austria and the United Kingdom. Ecol. Econ. 65 (1), 187–201.
Kuskova, P., Gingrich, S., Krausmann, F., 2008. Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: an energy transition under changing political regimes. Ecol. Econ. 68 (1–2), 394–407.
Lassaletta, L., Billen, G., Romero, E., Garnier, J., Aguilera, E., 2014. How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961–2009). Reg. Environ. Chang. 14 (2), 785–797.
Le Noë, J., Matej, S., Magerl, A., Bhan, M., Erb, K.H., Gingrich, S., 2020. Modeling and empirical validation of long-term carbon sequestration in forests (France, 1850–2015). Glob. Chang. Biol. 26 (4), 2421–2434.
Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455 (7210), 213–215.
Magerl, A., Matej, S., Kaufmann, L., Le Noë, J., Erb, K., Gingrich, S., 2022. Forest carbon sink in the US (1870–2012) driven by substitution of forest ecosystem service flows. Resour. Conserv. Recycl. 176, 105927.
Maluquer, J., Llonch, M., 2005. Trabajo y relaciones laborales, en Carreras. In: Tafunell, X. (Ed.), Estadísticas históricas de España. Siglos XIX y XX, 2 ed. Fundación BBVA, Madrid, pp. 1155–1245.
MAPA, 2019a. Estadísticas de Incendios Forestales. https://www.mapa.gob.es/es/desarrollo-rural/estadisticas/Incendios_default.aspx.
MAPA, 2019b. Inventario Forestal Nacional. https://www.mapa.gob.es/es/desarrollo-rural/temas/politica-forestal/inventario-cartografia/inventario-forestal-nacional/default.aspx.
Marull, J., Otero, I., Stefanescu, C., Tello, E., Miralles, M., Coll, F., Diana, G.L., 2015. Exploring the links between forest transition and landscape changes in the Mediterranean. Does forest recovery really lead to better landscape quality? Agrofor. Syst. 89 (4), 705–719.
Mather, A.S., 1992. The forest transition. Area 24, 367–379.
McNeill, J.R., 2000. Something New under the Sun: An Environmental History of the Twentieth-Century World (the Global Century Series). WW Norton & Company, Pujol et al, p. 2011.
Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: prospects for an end to deforestation. Annu. Rev. Environ. Resour. 36, 343–371.
Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: a global scenario. Glob. Environ. Chang. 65, 102168.
Montero, G., Ruiz-Peinado, R., Muñoz, M., 2005. Producción de biomasa y fijación de CO2 por los bosques españoles. INIA - Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Madrid.
Montiel Molina, C., Karlsson Martín, O., Galiana Martín, L., 2019. Regional fire scenarios in Spain: linking landscape dynamics and fire regime for wildfire risk management. J. Environ. Manag. 233, 427–439.
Mouri, G., Nakano, K., Tsuyama, I., Tanaka, N., 2016. The effects of future nationwide forest transition to discharge in the 21^{st} century with regard to general circulation model climate change scenarios. Environ. Res. 149, 288–296.
Myllyntaus, T., Mattila, T., 2002. Decline or increase? The standing timber stock in Finland, 1800–1997. Ecol. Econ. 41 (2), 271–288.
Ortega Hernández-Agüero, C., 1989. El libro rojo de los montes españoles. Adena-WWF, Madrid.
Otero, I., Marull, J., Tello, E., Diana, G.L., Pons, M., Coll, F., Boada, M., 2015. Land abandonment, landscape, and biodiversity: questioning the restorative character of the forest transition in the Mediterranean. Ecol. Soc. 20 (2).
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Ciais, P., 2011. A large and persistent carbon sink in the world's forests. Science 333 (6045), 988–993.
Parcerisas, L., Marull, J., Pino, J., Tello, E., Coll, F., Basnou, C., 2012. Land use changes, landscape ecology and their socioeconomic driving forces in the Spanish Mediterranean coast (El Maresme County, 1850–2005). Environ. Sci. Pol. 23, 120–132.
Pendrill, F., Persson, M., Godar, J., Kastner, T., 2019. (2019) Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environ. Res. Lett. 14, 055003.
Pfaff, A., Walker, R., 2010. Regional interdependence and forest "transitions": substitute deforestation limits the relevance of local reversals. Land Use Policy 27, 119–129.
Prados de la Escosura, L., 2017. Spanish Economic Growth, 1850–2015. Palgrave, p. 201.
Pujol, J., Prieto, L.F., de Molina, M.G., Garrabou, R., 2001. El pozo de todos los males. Crítica, Barcelona.
Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Glob. Biogeochem. Cycles 13 (4), 997–1027.
Rudel, T.K., 1998. Is there a forest transition? Deforestation, reforestation, and development 1. Rural. Sociol. 63 (4), 533–552.
Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E., 2005. Forest transitions: towards a global understanding of land use change. Glob. Environ. Chang. 15 (1), 23–31.
Rudel, T.K., Meyfroidt, P., Chazdon, R., Bongers, F., Sloan, S., Grau, H.R., Van Holt, T., Schneider, L., 2020. Whither the forest transition? Climate change, policy responses, and redistributed forests in the twenty-first century. Ambio 49, 74–84.
Ruiz-Peinado, R., Oviedo, J.A.B., Senespleda, E.L., Oviedo, F.B., del Río Gaztelurrutia, M., 2017. Forest management and carbon sequestration in the Mediterranean region: a review. For. Syst. 26 (2), 10.
Sieferle, S.P., 2001. The Subterranean Forest. The White Horse Press, Cambridge.

Soto, D., Infante-Amate, J., Guzmán, G.I., Cid, A., Aguilera, E., García, R., de Molina, M. G., 2016. The social metabolism of biomass in Spain, 1900–2008: from food to feed-oriented changes in the agro-ecosystems. Ecol. Econ. 128, 130–138.
Tello, E., Valldeperas, N., Olles, A., Marull, J., Coll, F., Warde, P., Wilcox, P.T., 2014. Looking backwards into a Mediterranean edge environment: landscape changes in El Congost Valley (Catalonia), 1850-2005. Environ. Hist. 20 (3), 347–384.
Theurl, M.C., Lauk, C., Kalt, G., Mayer, A., Kaltenegger, K., Morais, T.G., Haberl, H., 2020. Food systems in a zero-deforestation world: Dietary change is more important than intensification for climate targets in 2050. Sci. Total Environ. 735, 139353.
Tomter, S.M., Kuliešis, A., Gschwantner, T., 2016. Annual volume increment of the European forests—description and evaluation of the national methods used. Ann. For. Sci. 73 (4), 849–856.
Vadell, E., De-Miguel, S., Fernández Centeno, G., Robla, E., Lerner, M., Pemán, J., 2019. La forestación de tierras agrícolas: balance de un instrumento de política forestal, para el cambio del uso de la tierra. Cuadernos de la SECF 45 (2), 1–20.
Varela, E., Pulido, F., Moreno, G., Zavala, M.A., 2020. Targeted policy proposals for managing spontaneous forest expansion in the Mediterranean. J. Appl. Ecol. 57, 2373–2380.
Vila-Traver, J., Aguilera, E., Infante-Amate, J., de Molina, M.G., 2021. Climate change and industrialization as the main drivers of Spanish agriculture water stress. Sci. Total Environ. 760, 143399.
Williams, M., 2003. Deforesting the Earth: From Prehistory to Global Crisis. University of Chicago Press, Chicago.
Wrigley, E.A., 1988. Continuity, Chance and Change: The Character of the Industrial Revolution in England. Cambridge University Press.
Ximenez de Embun, J., 1928. Algunos aspectos del problema de la restauración forestal. España Forestal 144, 20-2 and 49-52.