Forest transition in Spain (1860-2010): A socio-metabolic reading

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Abstract

After centuries of deforestation, many countries (mostly industrialised) have recently been experiencing net increases in their forest area. This phenomenon, known as 'Forest Transition', has been studied with growing interest in recent years. In this article, we analyse the Spanish forest transition over the last 150 years from a socio-metabolic perspective. On the one hand, we present a new dataset based on forest inventories, historical records and modelling, which includes not only forest surface but also wood production and biomass stocks. The new estimates allow for a better description of the biophysical changes in forest ecosystems, estimating the dynamics of production, extraction and stock. On the other hand, we relate these changes to the socio-metabolic transformations of Spain's economy as a whole. 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 66.1%. In many areas forests were replaced with cropland and pastureland and a large amount of the remaining forests were over-exploited. Since 1950, and coinciding with the industrial socio-metabolic transition, forest biomass stocks multiplied by a factor of 2.5. This can be explained by increases in forest area (30.3%), in biomass density (59.6%) and a more optimal location of forests (10.1%). 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 led to a dramatic decline in wood appropriation and the consequent increase in biomass density. Although forest expansion generates undisputed environmental benefits, the forest transition model and the drivers behind it may also cause serious environmental problems that even offset the benefits.

1. Introduction

Since the introduction of agriculture, human societies have continuously expanded cropland and pastureland areas, reducing the world's forests by an estimated 45% (McNeill, 2000). This process 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, 1990; 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 & Foley, 2002; Barbier, 2010). However, from around the nineteenth century, especially in industrialised 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 & 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 et al., 1998). The issue rapidly took centre stage within environmental sciences (Meyfroidt & Lambin, 2011). Ultimately, recovering forest area has become a paramount environmental goal, connected to, among other aspects, biodiversity conservation and climate-change mitigation targets (Mori et al., 2016; Rudel et al., 2020). Therefore, identifying *where, when* and *why* forest transitions are taking place has become a central topic within environmental studies and policy.

The causes of forest transitions have been investigated from different perspectives (see Iriarte-Goñi, 2019). Several major pathways towards the forest transition have been identified (see Rudel et al., 2005; Lambin and Meyfroidt, 2010). The "economic growth" pathway refers to a process whereby industrialisation 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 elsewhere (Pfaff & Walker, 2010; Pendrill et al, 2019; Jadin et al, 2016).

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 & Mattila, 2002; Erb et al., 2008). The 'social metabolism' framework, based on an analogy with the biological concept of metabolism, studies a society's exchanges of energy and materials with its environment. To this end, different methodological tools have been developed that have been successfully applied in many case studies (from local cases to global studies), within different time frames and by researchers from different disciplines (Infante-Amate et al., 2017; Gerber & Scheidel, 2018; 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. For example, the use of mineral coal led to the recovery of forest density previously used to produce firewood and charcoal (Sieferle, 2001). Nevertheless, industrialisation itself increased the demand for forest raw materials and wood with which it began to trade globally, displacing the footprint to other territories (Iriarte Goñi & Ayuda, 2012). On the other hand, the use of motorised equipment powered by fossil fuels led to the freeing of surface area previously used for feeding animals for traction. In short, our starting hypothesis is that 'there is a close relationship between patterns of socio-economic flows of materials and energy – and land uses' (Krausmann et al., 2001:24)

A number of national and regional case studies reveal that during the socio-ecological transition. land-use, in particular agriculture, was intensified (Krausmann, 2001, Krausmann et al., 2003, Kuskova et al., 2008, Infante-Amate et al. , 2018b), resulting in a loss of traditional agrarian landscapes (Cussó et al., 2006; Parcerisas et al., 2012; Tello et al., 2014). However, very few studies theorise or provide evidence regarding the specific case of the forest transition (for exceptions see: Erb, 2012, Gingrich et al., 2016, 2019).

The aim of this paper is to provide insights into Spain's forest transition from a socio-metabolic perspective. On the one hand, we provide a biophysical characterisation of Spanish forest ecosystems, focusing on flows and stocks of biomass; that is, going beyond surface area alterations, we examine forest metabolism changes, understood as the exchanges of energy and materials between forest systems and society. 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 the Spanish forest transition. Based on historical sources (forest inventories, agricultural statistics and modelling), we estimate changes in Spain's forest area over the long term, identifying three types of forests at the provincial level.
2. Quantify biomass flows in forest ecosystems. Following the Material Flow Accounting (MFA) methodologies of 'Social Metabolism' (see Fischer-Kowalski et al., 2011, Krausmann et al., 2008, Guzmán & González de Molina, 2017), we estimate the Net Primary Productivity, domestic extraction and final uses of forest biomass. In this way, we document not only the evolution of land use but also changes in production and forest functions.
3. Quantify biomass stocks. Analysing the forest transition in terms of biomass stock instead of surface area provides better information on its environmental implications (Kauppi et al., 2006; Gingrich et al., 2016), since the role of forests as carbon sinks and their consequent role in mitigating climate change can thus be examined more appropriately. Nevertheless, higher biomass density not always implies higher environmental services.

4. Analyse changes in forest metabolism – i.e. changes in area, production, and functionality – in relation to changes occurring within the overall economic metabolism. To do this, we relate the evidence collected in points 1-3 with existing literature on the Spanish economy's metabolism.

The text is structured as follows: in section two following this introduction, we describe the 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.

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 2016. Figure 1 summarises the main variables analysed, which interact as follows:

$NPP_{ijt} = A_{ijt} + R_{ij} + \Delta S_{ijt}$ [Eq. 1]

Net Primary Productivity (NPP) is the total amount of plant biomass produced in a given territory over a period of time (e.g., Haberl et al., 2007; Keenan & Williams, 2018). *A* is the share of NPP extracted by society and that ends up having a socio-economic use. *R* is the biomass recycled within the agroecosystems, i.e. the wood, branches or leaves 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 (net emissions or sequestration). Sub-indexes identify the boundaries of the study, consisting of: *i*, each of Spain's 50 provinces; *j*, six different forest types considered; and *t*, the year.

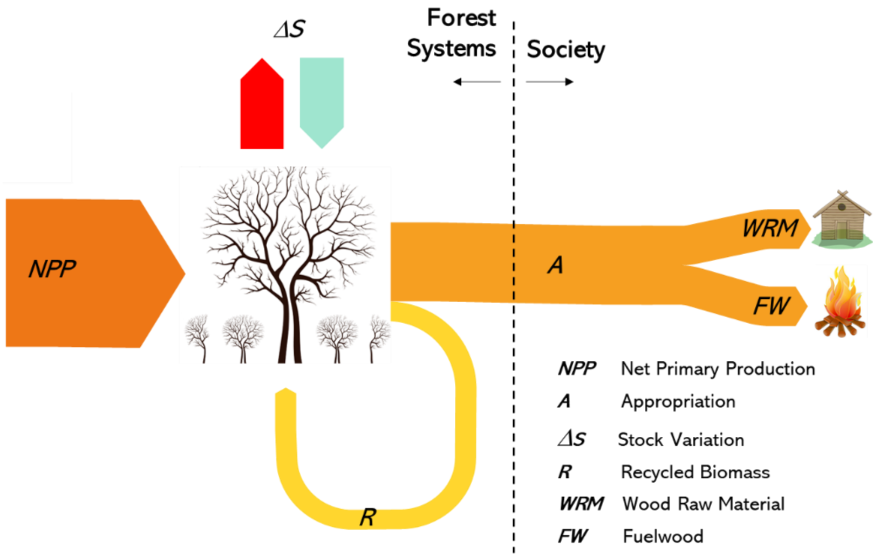
In this research we only focus on living biomass, including stem trees, large and thin branches and roots, excluding dead wood, litter, and soil organic carbon. Living biomass represents a large share of total carbon stocks in forest systems, accounting for an average of around 42% of global biomass 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). It is also much more sensitive to historical changes than the rest of biomass pools, which tend to be much more stable.

With respect to appropriated biomass flows, that is, the biomass flows that have a socio-economic use, we identify two major end uses as stated in equation 2:

$A_{ijt} = WRM_{ij} + FW_{ij}$ [Eq. 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. *WF* stands for woodfuel i.e. parts of biomass devoted to energy uses, mainly heating in industry and homes. The final use of the extractions is necessarily made within Spain's national boundaries, as it does not take international trade into account.

Figure 1. Biomass flows considered in this study.



Finally, we estimate each year's total stock (S) of biomass in the following way:

$$S_{ijt} = S_{ijt-1} + \Delta S_{ijt} \qquad \text{[Eq. 3]}$$

2.2. Sources and estimation procedure

We have independently assessed the three major variables quantified in this study: stock, appropriation and NPP of forest biomass. The main sources used are shown in Table 1.

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, 2011b). 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, distinguishing between coniferous and deciduous forests. For the years before 1960, we first estimate historical series of the forest area, identifying three main types of forest in Spain: (1) High forest, generally dominated by conifers and eucalyptus, and oriented towards production; (2) Coppice, 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 trees with livestock and, occasionally, herbaceous crops (Rigueiro-Rodríguez et al., 2018). Our estimation is carried out by concatenating the data of different historical agrarian and forestry sources (see Table 1). Subsequently, we calculate biomass stocks using historically-adjusted biomass density factors for each forest type and each province drawn from the NFIs, following Infante-Amate & Iriarte- Goñi (2017).

Appropriated biomass is directly taken from Iriarte-Goñi (2017), Infante-Amate & Iriarte-Goñi (2017) and Iriarte-Goñi & Infante-Amate (2019), who estimate wood appropriation in Spain from 1860 onwards, distinguishing between energy and non-energy uses.

In the case of the NPP, we follow two different strategies. Between 1965 and 2010, the estimation is based on biomass stock variations recorded by the NFI minus appropriated woody biomass, and minus biomass losses associated to fires (data retrieved from MAPA, 2019a). For the period between 1860 and 1960, we have conducted a comprehensive literature review of historical forest production. In particular, we have 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 & Iriarte-Goñi, 2017). The NPP is estimated by multiplying historical data on wood production by a constant biomass expansion factor (BEF) (Montero et al., 2007). In this time period, recycled biomass is estimated as the NPP minus appropriation and stock variation, following Equation 1.

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 & Iriarte-Goñi (2017), JCA (1905, 1914, 1923), GEHR (1994)
	1930-1960	**	Anuarios de Estadística Agraria (1929-), Estadística Forestal Española (1941-)
	1960-2010	***	National Forest Inventories (1965-2010).
Stocks (and biomass density)	1860-1960	**	Based on Infante-Amate & Iriarte-Goñi (2017) and 1960-2010 data
	1960-2010	***	NFI (196X, 197X, 200X, 201X)
Net Primary Productivity	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 (1941-), Iriarte-Goñi & Infante-Amate (2019)
Appropriation	1860-2010	**	Infante-Amate & Iriarte-Goñi (2017), Iriarte-Goñi & Infante-Amate (2019), based on Spanish Agricultural and Forestry Statistics.
Recycled	1860-2010	**	Based on factors provided by Montero et al. (2007).

2.3. Decomposition analysis

We have quantified the main drivers of change of NPP, appropriation and biomass stocks so as to explain forest dynamics in different stages of the time series. To do so, we have conducted an additive decomposition analysis using the Logarithmic Media Divide Index (LMDI) proposed by Ang (2005). This model allows us to quantify the effect of different explanatory variables on an analysed variable's variations, translating this effect into the variables' unit of expression.
In the case of the NPP, we distinguish forest area increase (F) from productivity increase, measured as woody biomass produced per hectare (p). We also take into account the effect of regional specialisation (*r),* that is, the share of productivity change due to the fact that production is located in more or less productive provinces, specifically:

$$NPP = F \cdot \frac{F_i}{F} \cdot \frac{NPP_i}{F_i} = F \cdot r \cdot p \qquad \text{[Eq. 4]}$$

$$\Delta NPP = \Delta F + \Delta p + \Delta r \qquad \text{[Eq. 5]}$$

In the case of extraction, we include: the population change (*P*), since it is a decisive consumption element; forest land available per inhabitant *(f)*; productivity, measured as in the previous decomposition (*p*); and the level of socio-economic use of the produced biomass, that is, the share of produced biomass finally appropriated (*s*), specifically:

$$A = P \cdot \frac{F}{P} \cdot \frac{NPP}{F} \cdot \frac{A}{NPP} = P \cdot f \cdot p \cdot s \qquad \text{[Eq. 6]}$$

$$\Delta A = \Delta P + \Delta f + \Delta p + \Delta s \qquad \text{[Eq. 7]}$$

In the case of stocks, we distinguish the effect on the forest area change (S) and biomass density (*d*), that is, biomass per hectare. We also break down the regional factor (r), that is, we analyse the share of density increase that is due to the surface being concentrated in more productive areas, specifically:

$$S = F \cdot \frac{F_i}{F} \cdot \frac{S_i}{F_i} = S \cdot r \cdot d \qquad \text{[Eq. 8]}$$

$$\Delta S = \Delta S + \Delta r + \Delta d \qquad \text{[Eq. 9]}$$

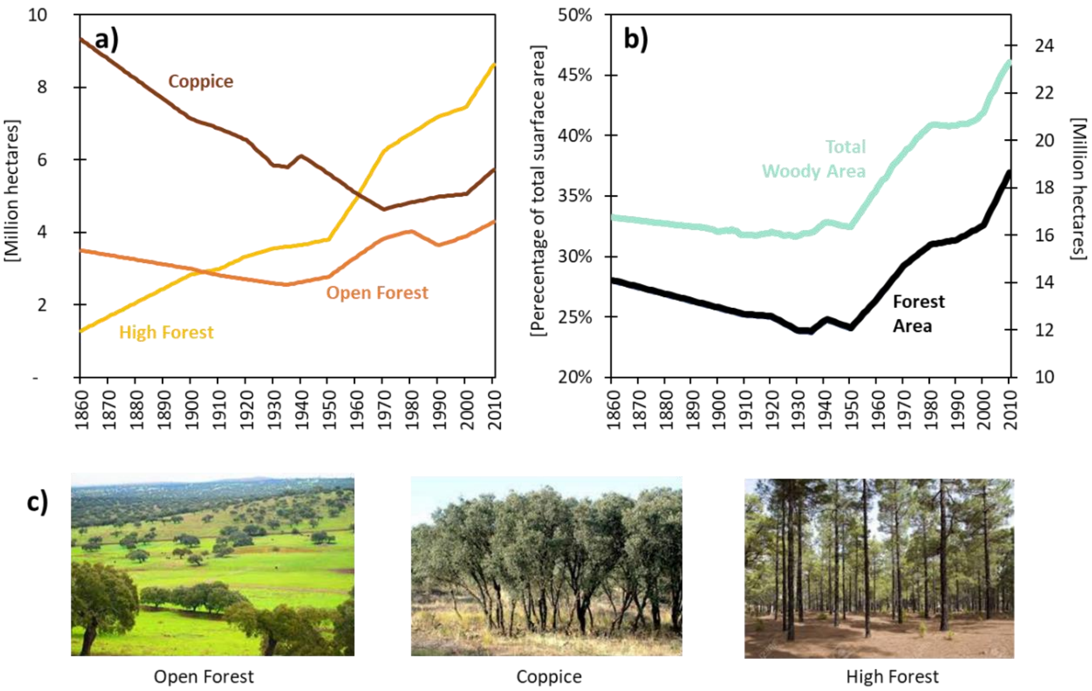
3. Results

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, and covering two thirds of the country's total area. The increase in forest area was, therefore 6.5 Mha while the drop in cultivated area accounted for 2.6 Mha. As a result, almost 4 Mha of that increase had to be spread over old pasture or uncultivated surface areas. Until 1970, the expansion across cultivated areas was very limited. Nevertheless, from that date, scrubland and pastureland began to increase again so forests expansion took place mainly over cropland areas.

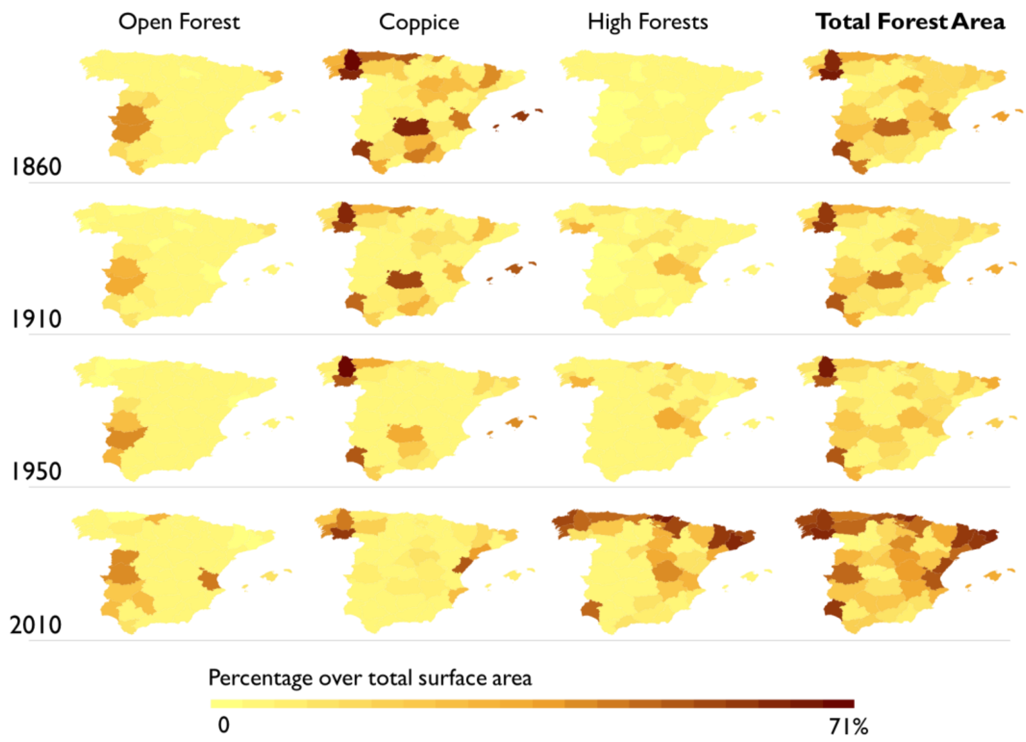
When observing Spain's main types of forest, this evolution was not homogeneous. Figure 2a illustrates how surface areas evolved in the case of the three major forest systems. Two of them, coppice and open forests, declined continuously until well into the twentieth century. These two forest types were dominated by broad-leaved 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 was declining. From the 1950s onwards, when the rest of the forest types began to expand, the increase accelerated even further.

Figure 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.



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 and the mountain areas have traditionally been concentrated in Northern and Atlantic Spain, in contrast to the southern and eastern parts of the country with drier and warmer climates. As shown in Figure 3, this imbalance has increased over time and, today, most forests are located in the northern, more productive provinces. Regarding forest types, a 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.

Figure 3. Forest area provincial distribution, distinguishing three major Spanish forest types: Open Forests, Coppice, and High Forests. Further information can be found in the Supplementary Materials.



<u>3.2. Biomass flows: Production, extraction and use</u>

In relation to biomass flows, we can observe that the NPP remained relatively stable until the mid-twentieth century, accounting for approximately 15 Tg/yr, with slight decreases between 1860 to 1900 (-6%) caused by forest degradation and deforestation; these were followed by moderate increases until 1950 (+21.9%). Between 1950 and 2010, we can observe more dramatic changes: the NPP grew sharply, multiplying 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: (i) between 1860 and 1914, during which the appropriation fell by 21.0%, mainly due to the replacement of firewood by charcoal; (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, appropriation has grown once more (+ 20.9%), this time due to rising industrial uses and a modest return to bioenergy. In 2010, appropriation accounted for 13.4 Tg/yr, that is, 70.3% of the value recorded for1860.

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

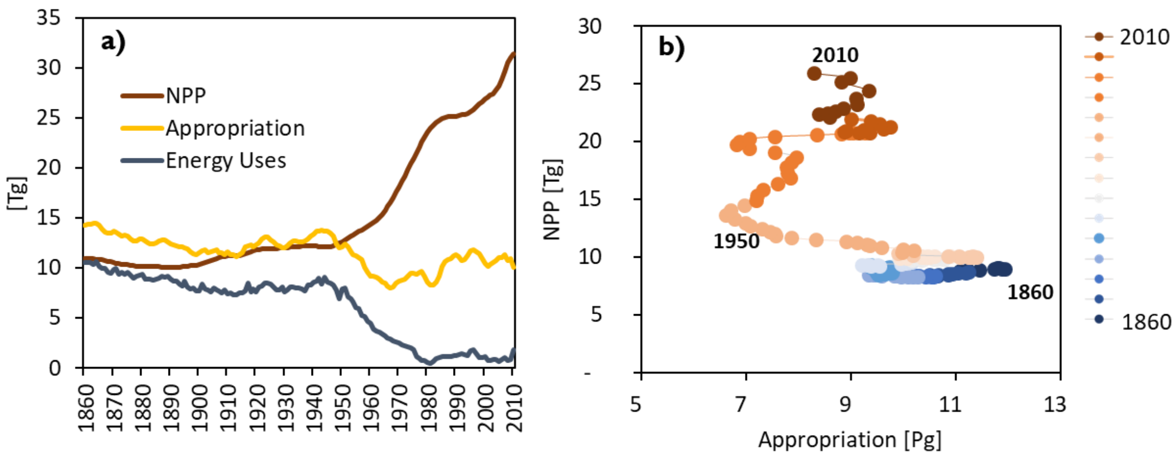
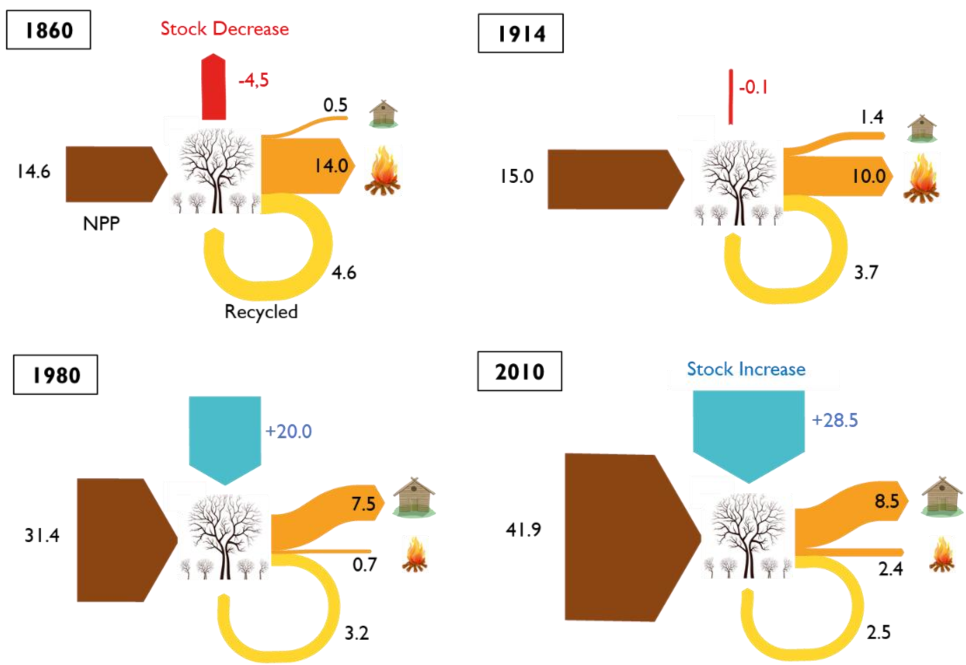


Figure 5 shows a diagram of the main biomass flows in forest systems at four different times, distinguishing between types of end use: energy and non-energy. Between 1860 and 1914 we can observe a continuous decline in the energy use of firewood, from 14.0 Tg/yr to 10.0 Tg/yr, with even higher figures 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 appropriation fell slightly between 1914 and 1980. The most dramatic change, however, was in the type of use. 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.

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



3.3. Biomass stocks

Another significant change visible in Figure 5 is that the relationship between A and NPP changes over time, leading to major impacts on biomass stocks. During the second half of the nineteenth century, we can observe that the appropriation of woody biomass always exceeded the NPP. This situation caused the stock to decrease continuously between 1860 and 1935, from 308.0 Tg to 207.2 Tg. As we will see in the next section, the loss of forest biomass can be explained by a joint process of deforestation and degradation through unsustainable management, that is, with extraction levels exceeding the forest's natural level of replacement, leading to biomass density losses. 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 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 NPP grew sharply, as we have seen above (248.0%). Up to c. 1980, the NPP increased as appropriation declined, leading inexorably to stock increases. However, after that date, appropriation grew once more and stocks increased despite this. This was possible because the NPP exceeded appropriation levels (Figure 4). In other words, high NPP levels allowed stocks to increase even as harvest levels rose. We interpret this coincidence of growing stocks despite high extraction as a recovery from previous depletion.

Figure 7. (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.

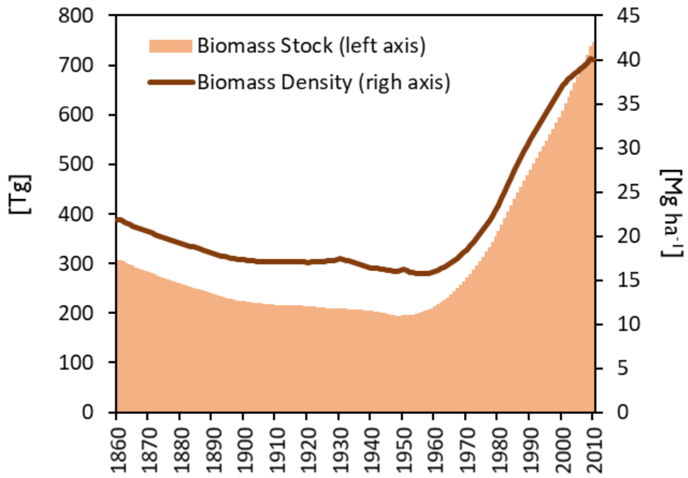
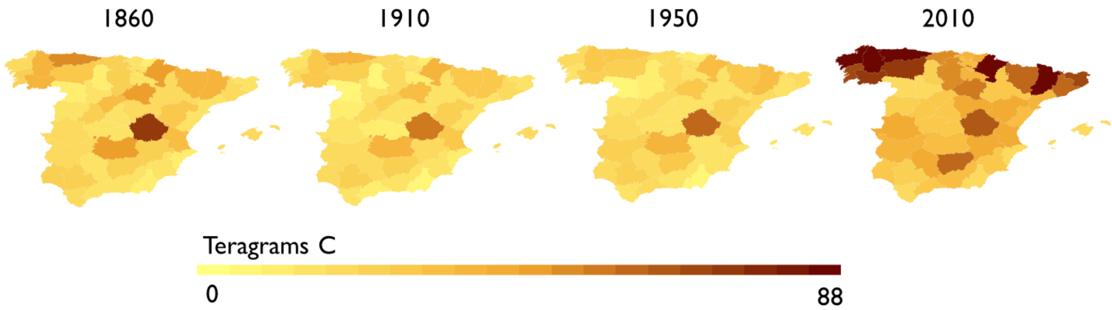


Figure 8. Provincial distribution of woody biomass carbon stocks, in Tetagrams of dry matter. Additional information can be found in the Supplementary Material.



We can observe that forest biomass stocks have been unevenly distributed geographically speaking and that this imbalance has increased over time. 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 end of the twentieth century this share represented half of total stocks. Two factors explain this large increase in this part of the country. First, as we have seen in Figure 3, during the period of study, a higher share of Spain's forest area was concentrated here. Second, the northern forests have a greater productive capacity and a consequent biomass density due to their environmental conditions. 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 of the country) which has risen to 207.7 Mg ha-1 today (over three times higher). In addition to having a higher initial density, the gap has grown significantly.

3.4. Drivers of change in forest biomass flows

In this section, through a decomposition analysis, we describe the drivers of the changes undergone by NPP, 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.

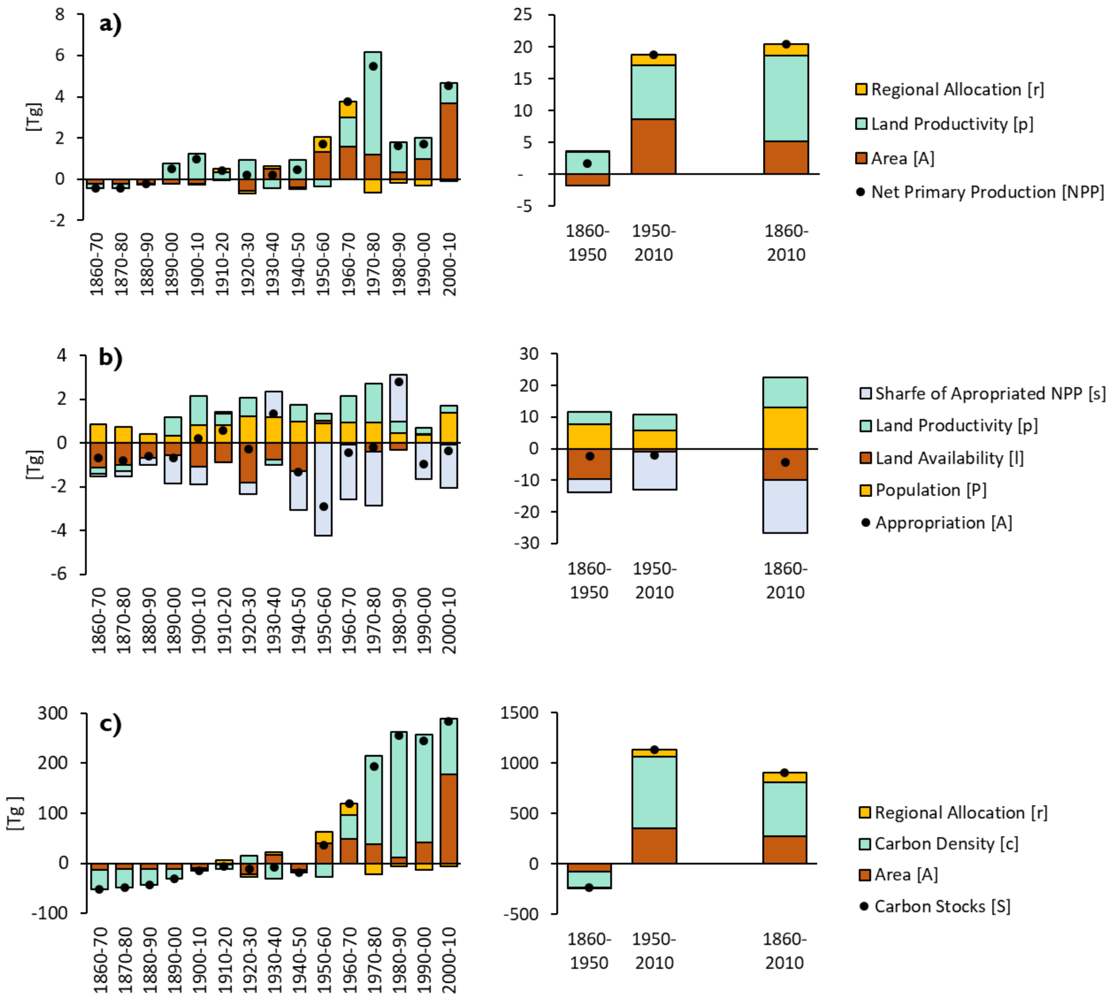
In the case of the NPP, we can observe slight growth until the mid-twentieth century. This relative stability is due to the fact that the reduction in the area was compensated by increases in yields. However, yields increased after c. 1900, due to the introduction of fast-growing species. From 1950 both the area (46.0% increase) and the yield grew. The growth in yield was not only due to the change in species and management, but also to the location of the area in the more productive areas. The special location explains 9%% of the increase in NPP 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 appropriation. This effect compensated the higher demand generated by the increase in the population and the slight increase in yields, leading to lower consumption. From 1950, although the area increased, the yields and the population pressure increased demand and the energy transition led to a fall in demand for firewood. In other words, the percentage of the biomass extracted for energy uses (and materials) of total biomass produced in the forest systems decreased.

Within this apparent stability we can observe sub-periods with major changes. During the final decades of the nineteenth century there was a reduction in pressure as a result of the deforestation processes due to the increase in the cultivated area. In the 1910s and between

c. 1936 and 1950, we can observe an increase in consumption explained by the greater population pressure but also a higher demand for firewood due to the shortage of coal at that time. Between 1950 and 1980 there was an unprecedented decrease in consumption due to the functional change of the forests.

Figure 7. Decomposition analysis to explain variations of: (a) Carbon Stocks, (b) Net Primary Productivity, and (c) appropriation of woody biomass in Spain's forest systems. Always in petagrams of dry matter.



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 Meyforidt 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. Ximénez de Embún, 1933). 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 (Vadel 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). To sum up, the national accounts of the 'forest transition' hide 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 & 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 appropriation of biomass generally exceeded the NPP, 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 1). 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 externalises, in net terms, 8.6 Mha of cultivated land and a total of 9.7 Mha including forestry and pasture (Infante-Amate et al., 2018), in particular for providing feed to the growing livestock needs.

These processes have affected forest area growth in several complementary ways. On the one hand, agrarian intensification has been associated (in addition to the use of treated seeds, fertilizers and petrol-powered agricultural machinery) with a strong growth of irrigated areas, which, since the 1950s, was achieved by constructing large water reservoirs throughout the territory (Aguilera et al., 2019; Vila et al., 2020; Serrano et al.,). 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. At the same time, reforestation was also spreading because of increasing wood demands coming from urbanisation, the construction of infrastructures and especially the development of paper industries (Iriarte-Goñi, 2013). In short, agrarian intensification, land externalisation and the associated phenomena described above, 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 NPP exceeds appropriation. Which factors are behind the NPP increase and which are behind the decrease in appropriation?

Since 1950, the NPP has grown while appropriation has plummeted. According to our results, the NPP increase is linked to a more effective location of production, since the areas have expanded more rapidly in the most productive provinces, and in other areas it is due to a recovery from previous depletion. However, other factors, not quantified in this work, have also had an undeniable effect on the NPP 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, high atmospheric nitrogen deposition and the positive effects of increasing atmospheric CO2, which are considered to play a relevant role (Ciais et al., 2008).

In the case of appropriation, 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 & Infante Amate, 2019). Fossil fuels played the role of 'subterranean forests', as pointed out by R. P. Sieferle (1980). The 'energy transition' was, therefore, a key factor in explaining woody biomass density increases. This coincided with the parallel growth of wood 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.

Table 2. Indicators of changes to Spain's economic metabolism and forest metabolism. The GDP data are taken from Prados de la Escosura (2018), 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. (2015)

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

4.3. Environmental impacts of forest transition

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 (Bonnan, 2008; Chazdon, 2008; Bond, 2009; Davin & Noblet-Ducoudré, 2010). However, the expansion of tree cover can have other problematic impacts that are not always measured. In the case of Spain, the literature has brought to light problems relating to the forest transition. One of them is the proliferation of fast-growing species described in the literature since the 1980s (Hernández-Agüero, 1989; Chauvelier, 1990; Arrechea, 2002). They include the expansion of forest fires that are related to the reforestation of large areas with a single tree species (some pines or eucalyptus) which are highly flammable in dry seasons (Montiel Molina et al, 2019; Iriarte-Goñi & Ayuda, 2018), or water related issues generated by uncontrolled forest cover expansion (Llorents et al., 2005). In parallel, recent studies show that forest expansion patterns in Mediterranean areas add to the abandonment of traditional agriculture's more diverse landscapes and may be impoverishing biodiversity (Agnoletti, 2014; Marull et al., 2014, 2015; Cervera et al., 2019).

However, the problems linked to expanding forest cover do not always arise within the forest system itself. In the case of GHG emissions, Gingrich et al. (2019) identify at least three major forest transition 'hidden impacts': (i) emissions generated from fossil fuels that substitute firewood; (ii) emissions generated by the outsourcing of land use beyond national borders; and (iii) emissions caused by agricultural intensification to free land subsequently occupied by forests.

Between 1950 and 2010, forests stored XX Tg CO_2-eq, which represents 16.1% of the CO_2 emitted by fossil fuels (13.4 Pg CO_2) (ref). 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 a source 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, b), 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 N_2O 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, 2017, 2018; Lassaletta et al., 2015; Infante-Amate et al, 2018a). 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., 2018b). 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'.

Conclusions

In relation to other industrialised countries, Spain's forest transition unfolded very late but occurred more 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. In this study, we show that such changes hide historical discontinuities, different geographical paths within the country and different trajectories according to the type of forest mass. When breaking the analysis down to a geographical or forest species scale, the forest transition story is less linear and more complex.

Changes in the surface area of forestry systems and their biomass stocks and flows are related to changes in the country's economic metabolism. 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 yields 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 appropriation of woodfuel replaced by fossil fuels, while the NPP 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 characterised by an increase in area and stocks, reductions in overall levels of forest appropriation, 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. In this sense, the case of Spain could seem to be an unmitigated success, especially over the last three decades, in which the carbon stock has grown while harvests have increased. However, forest expansion can come with hidden impacts that sometimes go undetected. From a territorial viewpoint, uncontrolled forest growth may lead 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 externalisation, or the use of fossil fuels as a substitute for forest products. Some preliminary results presented in this study suggest that Spain's forest transition may be generating an 'environmental footprint' that limits or even cancels the intended positive effects.

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