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Reconstructing European forest management from 1600 to 2010

M. J. McGrath[1], S. Luyssaert[1], P. Meyfroidt[2], J. O. Kaplan[3], M. Buergi[4], Y. Chen[1], K. Erb[5], U. Gimmi[3], D. McInerney[1,*], K. Naudts[1], J. Otto[1,], F. Pasztor[1], J. Ryder[1], M.-J. Schelhaas[6], and A. Valade[7]**

[1]Laboratoire des sciences du climat et l'environnement, IPSL, CEA-CNRS-UVSQ, 91191 Gif sur Yvette, France
[2]F.R.S.-FNRS & Université catholique de Louvain, Earth and Life Institute, Georges Lemaître Centre for Earth and Climate Research, 3 Place Pasteur, 1348 Louvain-la-Neuve, Belgium
[3]Institute of Earth Surface Dynamics, Université de Lausanne, Géopolis, 1015 Lausanne, Switzerland
[4]Swiss Federal Research Institute, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
[5]Institute of Social Ecology, Alpen-Adria-University Klagenfurt-Wien-Graz, Schottenfeldgasse 29, 1070 Vienna, Austria
[6]Alterra, Droevendaalsesteeg 3, 6708 PB Wageningen, the Netherlands
[7]Institut Pierre Simon Laplace, Place Jussieu 4, 75010 Paris, France
[*]now at: Coillte Teoranta, Irish State Forestry Board, Newtownmountkennedy, Co. Wicklow, Ireland
[**]now at: Helmholtz-Zentrum Geesthacht, Climate Service Center 2.0, Hamburg, Germany

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Correspondence to: S. Luyssaert (sebastiaan.luyssaert@lsce.ipsl.fr)

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Abstract

European forest use for fuel, timber and food dates back to pre-Roman times. Century-scale ecological processes and their legacy effects require accounting for forest management when studying today's forest carbon sink. Forest management reconstructions that are used to drive land surface models are one way to quantify the impact of both historical and today's large scale application of forest management on today's forest-related carbon sink and surface climate. In this study we reconstruct European forest management from 1600 to 2010 making use of diverse approaches, data sources and assumptions. Between 1600 and 1828, a demand-supply approach was used in which wood supply was reconstructed based on estimates of historical annual wood increment and land cover reconstructions. For the same period demand estimates accounted for the fuelwood needed in households, wood used in food processing, charcoal used in metal smelting and salt production, timber for construction and population estimates. Comparing estimated demand and supply resulted in a spatially explicit reconstruction of the share of forests under coppice, high stand management and forest left unmanaged. For the reconstruction between 1829 and 2010 a supply-driven back-casting method was used. The method used age reconstructions from the years 1950 to 2010 as its starting point. Our reconstruction reproduces the most important changes in forest management between 1600 and 2010: (1) an increase of 593 000 km^2 in conifers at the expense of deciduous forest (decreasing by 538 000 km^2), (2) a 612 000 km^2 decrease in unmanaged forest, (3) a 152 000 km^2 decrease in coppice management, (4) a 818 000 km^2 increase in high stand management, and (5) the rise and fall of litter raking which at its peak in 1853 removed 50 Tg dry litter per year.

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1 Introduction

European forest use for fuel, timber and food dates back to pre-Roman times (Perlin, 2005). Diverse forest uses have been documented for western Europe (UK, Belgium, Denmark, Netherlands, Germany, Switzerland), southern Europe (Spain, Italy, Greece), eastern Europe (Hungary) and northern Europe (Sweden, Finland) (Kirby et al., 1998; Emanuelsson, 2009). Common uses fell into two broad categories: timber removal (harvesting, thinning, and coppicing) and non-timber removal (branches, leaves, and undergrowth removed for livestock usage through litter raking, pollarding, and grazing). One of the most visible legacies of centuries-long intensive forest use is a shift in species distribution across central Europe where forest managers replaced a substantial share of the deciduous vegetation by coniferous tree species (Kuusela, 1994). This anecdotal evidence in combination with references to increasing restrictions on common forest use (Farrell et al., 2000) supports the hypothesis that European forests have been intensively used for centuries, with forest cover reaching lows around the year 1850 followed by a turnaround in forest area (Mather, 1992; Meyfroidt and Lambin, 2011).

In the last decades forest management has been reported to have important impacts on the carbon balance (Schlamadinger and Marland, 1996), resulting in its inclusion in the Kyoto Protocol as a tool to mitigate climate change and to buy time while CO_2 emissions from land cover change and fossil fuel burning could be reduced. More recently, evidence is accumulating that forest management (defined as forest remaining forest but undergoing tree or other biomass removal, clear cuts, fire suppression, and/or species change) may also have substantial effects on the atmospheric CO_2 concentration (Hudiburg et al., 2011, 2013; Keith et al., 2014) and may also affect the surface climate through changes in albedo, evapotranspiration and surface roughness (Jackson et al., 2005, 2008; Randerson et al., 2006; Rotenberg and Yakir, 2010; Luyssaert et al., 2014; Otto et al., 2014). Hence, to fully understand the impact of large scale application of forest management, taking into consideration only the carbon balance is not

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sufficient. Models need to be developed to examine the effects of forest management on the surface climate (e.g., Naudts et al., 2014). Simulation experiments with these models, driven by historical management reconstructions, can help to better appreciate the impact and legacy of historical forest management on today's climate. Future projection experiments, driven by realistic forest management scenarios, are a first step to quantify the potential impact of forest related policies.

About a decade ago the land cover change community faced similar issues and made substantial progress through reconstructing land cover changes. At present these reconstructions are mainly derived from combining reconstructed population densities with agricultural models, guided or constrained by historical research, archaeological findings and pollen records (e.g., Fyfe et al., 2014). Although individual reconstructions differ considerably (Kaplan et al., 2012), it has been recognized that land cover changes (including deforestation for the purpose of agricultural expansion) have contributed almost 20 ppm to today's elevated atmospheric CO_2 concentrations and that this contribution is not just limited to the last decades but goes back at least 1000 (Pongratz et al., 2009b) and possibly even 6000 years (Olofsson and Hickler, 2008). Understanding past impacts of land cover changes on today's carbon balance and surface and atmospheric climate has helped to better appreciate the impact of humans on their environment (Pongratz et al., 2009a; Pitman et al., 2009; Kaplan et al., 2010) and to develop numerical models that can simulate the impact of future changes in land cover (Pitman et al., 2011).

Similar to the historical land cover studies, several groups have studied the impact of forest management on the contemporary (1950–2010) forest carbon sink over Europe (Seidl et al., 2011; Bellassen et al., 2011b; Zaehle et al., 2006). These groups reduced forest management to "age class management", which consists of regular thinning followed by a clear cut. By doing so the model can be driven by an age class reconstruction, rather than a management reconstruction. Several methods have been proposed and used for age class reconstructions of European forests (Bellassen et al., 2011b; Seidl et al., 2011; Vilén et al., 2012). As a result, forest age reconstruction exists for the

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period 1950 to 2010 over Europe. A first attempt to create a forest management map for the year 2000 for Europe was completed by Hengeveld et al. (2012). However, while this map originally started off as an effort to indicate the current management strategies across Europe, it ended as a map which depicts optimal management strategies based on purely rational forest managers. Although this effort could be a valuable starting point for developing future forest management scenarios, it is of limited interest for historical reconstructions.

In this manuscript, we reconstructed historical forest management for four contrasting but widely used management strategies (see Sect. 2.4.1) with the purpose to spin-up soil carbon and biomass pools for the year 1600 for European-wide simulations. Management reconstructions from 1600 to 2010 are needed to drive transient model experiments simulating the impact of forest management on the carbon budget as well as the surface and atmospheric climate. In this paper, we present the data sources and algorithms that were used to construct the forest management maps in as great of detail as possible. Application of these maps in model experiments will be the subject of future studies.

2 Material and methods

2.1 General approach

Annual spatially explicit wood demand and supply was estimated for the period from 1600 to 1829, based on various sources (Table 1). Wood supply was based on estimates of historical annual wood increment and land cover reconstructions (see Sect. 2.3). Demand accounted for the fuelwood needed in households, wood used in food processing, charcoal used in metal smelting and salt production, and timber for construction (see Sect. 2.2). The estimate was based on reconstructed individual needs and population estimates. Coppice management was assumed to satisfy the fuelwood demand whereas charcoal and construction wood were assumed to come from

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deforestation and high stand management. Comparing estimated demand and supply resulted in spatially explicit reconstructions of the share of forests under coppice, high stand management and forest left unmanaged (see Sect. 2.4.1). For the reconstruction between 1829 and 2010 a supply-driven back-casting method was used. The method used a 1950 to 2010 age reconstruction as its starting point. The general idea of such an approach is straightforward: a high stand 90 years old at the end of 1950 must have been cut and replanted at the end of 1860, before which it was either a high stand or a coppice. If, based on the demand and supply approach, it was decided that the stand was already under high stand management in 1859, and the rotation length of the species is 120 years then the stand was assumed to be 120 years old in 1859.

The above approaches for 1600 to 1828 and 1829 to 2010 resulted in $0.5^{\circ} \times 0.5^{\circ}$ resolution maps containing the amount of forest area (in m^2) required to be managed under high stands and coppice to satisfy estimated wood demand (from 1600–1828) and age class reconstructions (1829–2010). Usage with ORCHIDEE-CAN (Naudts et al., 2014), the land surface model of our choice, requires that the previously assigned management types and surface areas are assigned to specific tree species or species groups. The final product is thus a map which describes the forest area, the area of each species and the management strategy used for that species for each pixel. All variables may change from one year to the next.

Finding comprehensive data to parametrize and validate these historical activities is not currently possible. Hence, a variety of proxy information was used. These proxies, their usage and underlying assumptions are discussed in more detail below. We deliberately separated the carbon removal activities into various forms of wood harvesting and litter raking, which is expected to allow easier incorporation of future advances into the proposed procedure. As such, the resulting maps should be considered as a starting point rather than a final data product.

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2.2 Reconstructing wood and litter demand for 1600–1828

Historical wood demand primarily comes from the following sectors: fuelwood, industrial charcoal production (e.g., iron smelting, salt and glass production), and timber (e.g., shipbuilding and construction). Although each of these sectors is treated in a different way in this manuscript, most estimates rely on historical population maps available in the HYDE 3.1 database (Klein Goldewijk et al., 2011). These maps are only available for certain years, e.g., 1600, 1700, 1710, 1720, etc. Instead of using the map for 1600 to cover the whole range of 1601 to 1699, we used linear interpolation to fill in the missing years. The same is true for the decadal data, i.e., 1701–1709, 1711–1719, etc. up until 2005, which is the latest year in the database.

2.2.1 Fuelwood demand (1600–1828)

Before electricity became available, household energy requirements can be divided into two categories: cooking and heating. The energy required for cooking depends on the local diet because different foodstuffs and food quality require different cooking times. The amount of wood required for cooking in pre-industrial Europe ranged from 533 to 1067 kg per person per year. The lower number comes from using wood itself as the fuel, while the higher number comes from converting wood to charcoal first. Despite the lower efficiency, charcoal is often preferred as a fuel, in particular in urban areas, due to lower transport costs and lower production of particulate matter. To simplify matters these general estimates were assumed valid across Europe.

The required energy for heating depends on temperature, housing insulation, number of people in the household, furnace efficiency and other heat sources. As a first approximation we accounted for heat as by-product of cooking and the additional heating requirement was calculated solely based on temperature, more specifically heating-degree-days. Heating-degree-days quantify the total energy that is needed to keep the minimum indoor temperature above a threshold. It is calculated by multiplying the number of days by the number of degrees the mean temperature is below a temperature

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threshold, generally set at 15.5 °C in Europe (Spinoni et al., 2015). Heating degree days range from around 1000 to 4000 from the Mediterranean to Scandinavia, respectively. The heat released from cooking was estimated to already heat 50 to 400 m^3 of air per year up to this threshold in Scandinavia and the Mediterranean, respectively. An additional 30 m^3 of air were assumed to have been heated to compensate for the fact that heat from cooking in summer did not contribute to the heat requirements during winter. This required an additional 24 to 97 kg of wood per person per year from the Mediterranean to Scandinavia, assuming a heating efficiency of 10 %. Wood demand for heating was calculated as the product of air volume, air density, heat capacity of air, heating degree days and heating efficiency divided by the wood caloric values (Table 1).

The above numbers for cooking and heating were combined to give four fuelwood estimates, using different combinations of (1) fuelwood demand calculated based on 100 % charcoal usage or 100 % wood usage, and (2) European heating demand based on Scandinavian or Mediterranean per capita heating wood demand. Given the inherent uncertainty in these numbers, a simple mean was calculated between all four scenarios to give the final fuelwood demand maps.

2.2.2 Industrial wood and charcoal demand (1600–1828)

Between 1600 and 1828, wood and charcoal were used in the industrial production of salt, beer, metal and glass. Certain of these uses require a higher temperature than what can be achieved using wood directly, e.g., iron smelting, although other large scale uses, e.g., brewing, could have made use of either wood or charcoal. For simplicity, we assumed that salt, beer and distillates were produced with wood as the fuel source, while ceramics, glass and metal works used charcoal as a fuel source.

By 1600 much of the salt production from brine springs had stopped in favour of sea salt production and rock salt mines (Bergier, 1989), which consume much less wood than the evaporation of brine. We incorporated only production from sites which are known to have operated after 1600 (Table 2). For these sites, the period of operation,

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the average annual production over different periods, and the salt content of the brine are known. The amount of wood required depended on the production volume and the salt content of the brine (Bergier, 1989). For brine with a concentration of 250 kg m^{-3}, 400 kg of wood produced 400 kg of salt, while ten times as much wood was needed for the same amount of salt at a brine concentration of 50 kg m^{-3} (Radkau, 2012). We used a linear function to interpolate between these concentrations. Given that the spatial resolution of our maps is on the order of 50 km and that pipeworks rarely extended more than 40 km (Bergier, 1989; Mantel, 1990), all of the wood demand from salt production was placed in the pixel where the brine spring was located.

In northern and eastern Europe, where grape cultivation was difficult or impossible, beer was consumed daily by all social classes. Alcoholic beverages were an important source of the much needed caloric intake (Sournia, 1990) and a popular medicine (Aymard, 1979). We assumed an average annual consumption of 300 l of beer and distillates per person per year, which consumed 4.8 kg of wood per litre of beverage (Unger, 2004). Drinks but also food were prepared, served, consumed, processed, stored and transported in ceramics consuming 360 kg wood per person per year for producing 45 kg ceramics per person per year (Petrie, 2012; Sinopoli, 1999). Spatial population estimates (Klein Goldewijk et al., 2011) were scaled by these per capita demands to provide spatially explicit wood demands maps for 1600–1828.

Historical annual per capita usage of metals has been reported to be 1.5 kg for iron and lead and to range between 0.2 and 0.0002 kg for copper, silver, gold, tin, and zinc (Table 1). Total wood requirements for metal works were calculated assuming that 81 kg of wood, prior to charcoal conversion, was needed to smelt 1 kg of metal and by making use of the HYDE population estimates (Klein Goldewijk et al., 2011). The glass industry also consumed charcoal mainly for potash production, and less for the melting process itself (Mantel, 1990). As there were many local production sites and production could be easily moved to regions with accessible wood resources (Perlin, 2005), the historical production has been poorly documented. During the Napoleonic era (Warde, 2006), however, wood demand for glass and iron production has been estimated up

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to 3 Mm^3 each in central Europe. In the absence of other data, we assumed the wood demand for glass and iron as identical between 1600 and 1828.

2.2.3 Timber production (1600–1828)

The use of wood as a building material varied both spatially and temporally, and it was often substituted by loam, stone, straw and brick. By restricting our estimate to between the years 1600 and 1828, the use of concrete in homes or other structures can mostly be ignored, since its use was largely abandoned after Roman times until after 1850 (Sutherland et al., 2001). We assumed that the share of other building materials remained constant during 1600–1828 in Europe and that building construction better relates to gross domestic production (GDP) than to population, as more productive societies were able to build larger houses and buildings.

Spatially explicit estimates for gross domestic production per capita of Europe for the time period from 1600 to 1828 were created using the gross domestic production per capita, expressed in the hypothetical international currency Geary-Khamis dollars (GK$), for years and countries for which it has been previously estimated (Bolt and van Zanden, 2013). When needed, missing values were filled through spatial or temporal interpolation. Next, estimates of wood used for construction in Spain and England in 1660 and 1700 (Table 1), were combined with spatially interpolated gross domestic production estimates to calculate a construction wood usage of 18×10^{-5} and $7.2 \times 10^{-5}\ m^3\ person^{-1}\ GK\$^{-1}$ for Spain and England, respectively. For simplicity, the result was rounded to $10^{-5}\ m^3\ person^{-1}\ GK\$^{-1}$ and used for all of Europe. Subsequently, this value was scaled to the spatially explicit gross domestic production estimate between 1600 and 1828.

Timber shortage was early on reported as a critical issue, especially for naval shipyards (Perlin, 2005). However, this shortage was due to very specific requirements, e.g. long sailing masts or specially shaped oak wood for the body, and not because of a general lack of timber (Appuhn, 2000; Radkau, 2012). Shipbuilding demand was estimated to be around 1 % of the total wood demand by the end of the 1700s, with a lower demand in earlier periods (Warde, 2006). Despite its political, military and economic importance we neglected the impact of shipbuilding activities on the historical wood demand in Europe due to its comparatively minor significance regarding total wood consumption.

2.2.4 Litter demand (1600–1828)

Towards the end of the middle ages, farmers began to keep their cattle inside during winter, which led to a demand of forest litter to absorb animals' wastes (Mantel, 1990). Initially forest litter was used as it was easily available, cheap and, contrary to straw, had no other uses such as construction (Binding et al., 1986). In spring, the waste-soaked litter would then be spread on the fields as a form of fertilizer. From 1750 throughout the 1800s litter demand increased significantly (Selter, 1995; Schenk, 1996) in the course of the agrarian modernization, which promoted indoor feeding of cattle year round (Mantel, 1990). The expanding railroad network, however, made straw more easily available for areas without grain production, and forest litter collection was abandoned towards the end of the 1800s and beginning of the 1900s. From this, it was assumed that litter raking started at a modest level during the first years of our simulations (1600), peaks in the mid-1800s, and fades out afterwards.

European maps of litter demand were based on historical livestock estimates (Krausmann et al., 2013), taken to be equal to 0.6, 0.5, and 0.3 head of livestock person^{-1} for northern, central, and southern Europe, respectively. For this application, the dividing parallels between northern, central and southern Europe were taken to be respectively 55 and 45° N latitude. It has been reported that 200 to 480 kg of dry litter were collected per livestock unit per year (Bürgi, 1999). We further assumed that 480 kg litter per livestock unit per year corresponded to the peak demand for the study period (see Sect. 2.4.1).

First, litter maps were generated from the livestock density maps using peak demand for all years from 1600 to 1828 and 1829 to 2010. Next, these initial litter maps were

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multiplied by a correction factor (Table 1) to account for the temporal evolution in litter demand. The correction factor was tuned to give the desired behaviour, based on historical information from Switzerland (Bürgi, 1999).

2.3 Reconstructing wood supply

Wood supply was calculated from annual forest area and wood increment estimates. Wood increment was assumed to differ for coppice and high stand management and thus partly depends on the wood demand.

2.3.1 Forest area and species composition (1600–2010)

Historical forest area was reconstructed by making use of three different data sources: (1) the tree species maps of Brus et al. (2012), (2) the land cover map of Poulter et al. (2015) (further abbreviated as P&M), and (3) the historical land use maps of Kaplan et al. (2012, 2009) (further abbreviated as K&K). Maps (1) and (2) were combined by taking the fractions of bare soil, grasses, and crops inside Europe from P&M. The forests inside Europe from the P&M map were replaced by the more detailed species composition fractions in the Brus et al. (2012) map, scaling the sum of the Brus et al. (2012) fractions to be equal to the total forested fractions present in the P&M map inside Europe. Details about the correspondence of the forest species in Brus et al. (2012) and the plant functional types (PFTs) used in the ORCHIDEE land surface model can be found in Naudts et al. (2014).

The European tree species map (Brus et al., 2012) is only available for the year 2000 whereas the P&M map is available for 2000, 2005 and 2010. As we are interested in historical forest management back to 1600, this combined species/land cover map had to be extended through historical land use maps. Although the same procedure could be done with any historical land use map (such as those of Pongratz et al., 2009b), we have chosen to use the K&K maps because they were developed over Europe and they have a strong anthropogenic signal compared to many alternative land use reconstructions.

Our reconstruction contained 28 PFTs whereas the historical maps of K&K, which were used to reconstruct the historical forest area, only contain three classes, i.e., crop, pasture and forest. The procedure used to convert the three land cover classes into the 28 classes was based on that of de Noblet-Ducoudré et al. (2010). In brief, for a given year x, per pixel, the crop fractions in the P&M maps were scaled to match the total crop fraction from the K&K map for year x; the ratio of C3 to C4 crops on the historical K&K map were kept identical throughout the period, as the K&K maps do not distinguish between C3 and C4 vegetation. If there were no crops on a pixel in P&M but there were crops in the same pixel on the historical K&K map, the C3/C4 ratio of the neighbouring pixels on the P&M map was used to determine the C3/C4 ratio in our reconstruction. Throughout this study, neighbouring pixels were defined as pixels touching either an edge or a vertex of the current pixel, i.e., there are eight possible neighbours.

Next, the amount of grassland on the pixel was computed using the pasture fraction on the K&K map and following a procedure similar to the crop fraction above. The K&K maps have a pasture fraction, while the contemporary P&M map only has C3 and C4 grass fractions; C3 and C4 refer to the photosynthetic pathway in the grass and give no indication of management. The extent of unmanaged grassland is therefore not known. If the pasture fraction on the K&K map was lower than what was present on the P&M map, the reconstruction takes the P&M grassland fraction, under the assumption that managed and non-managed grasslands can coexist on the same pixel and that present day non-managed grasslands fraction is at its historical low. If the K&K pasture fraction was greater than the grassland fraction present on the P&M map, our reconstruction made use of the K&K fraction and the difference in surface area was made up by leaving crops untouched and reducing the forest fraction. The C3/C4 ratio was treated in the same way as for crops, i.e., kept constant for each pixel throughout the period. If the fractions of crop or pasture usage were greater than the total vegetative fraction

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present on P&M, we did not increase the vegetative fraction. Instead, all forests were replaced. In essence, we assumed that the non-vegetative fraction of the pixel has not changed in the past 400 years. Furthermore, all sub-grid level water was classified as bare soil.

Over the course of the past several hundred years, the species composition of European forests has changed as much as the extent of the forests. The largest difference is the large-scale planting of coniferous species, resulting in modern forests which are significantly more conifer-rich than historical forests (Kuusela, 1994). While forests in Europe have been heavily managed for centuries, and while human activities had certainly changed the species composition at certain scales already before 1600 (i.e., the introduction of chestnut *Castanea sativa* Mill.), it's likely that the composition of growth forms (e.g., coniferous vs. non-coniferous forests) in 1600 closely resembled that of natural vegetation on scales of tens of kilometres, which is what we are interested in here. Therefore, we have scaled the conifer fraction of the forests on our pixels in 1600 to be equal to that found in the natural vegetation map of Bohn et al. (2000).

The question remains how to make the transition from the conifer fraction in 1600 towards the conifer fraction found in our reconstruction for the year 2010. For this purpose, the European countries were divided into "early" and "late" conversion countries. Early countries, i.e. Germany, the Netherlands, Belgium and Switzerland, began experimenting with large-scale conifer plantations sooner than the rest of Europe (Mantel, 1990; Bürgi and Schuler, 2003). In these countries, the conifer fraction is kept constant from 1600 to 1800, then linearly increased to the 2010 conifer fraction. For the rest of Europe, the same linear transformation starts in 1850. This represents one possible transformation method, simulating a slow establishment of conifer plantations.

2.3.2 Wood production (1600–1829)

Contemporary mean annual wood increment for 16 European countries calculated from forest inventory data ranges from 0.6 $m^3\,ha^{-1}$ in Greece to 9.5 $m^3\,ha^{-1}$ in Germany, with a value of 3.8 $m^3\,ha^{-1}$ for the combined productivity of all countries listed (Table S3 in

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Ciais et al., 2008b). The same study demonstrates that annual forests productivity increased from 250 to 350 Tg between 1970 and 1990, without a significant increase in the forested area. For Austria annual wood increment was reported to double between 1830 and 2010, with most of the change happening in the past few decades (Erb et al., 2013). This suggests that European forests are more productive now than historically (Spiecker, 1999; Pretzsch et al., 2014), probably in part due to improved management, nitrogen deposition and carbon dioxide fertilization. Therefore, using current productivity numbers to estimate the historical wood supply would be incorrect.

We used the increment estimates of Ciais et al. (2008b) for each of the countries listed, filling in countries for which no estimates were available by taking an average of the neighbouring pixels. To correct for the increase in productivity, we differentiated between countries in western Europe, where nitrogen deposition is the greatest, i.e, UK, France, Germany, Switzerland, Netherlands, Ireland, Denmark, Belgium, and Austria, and the rest of Europe. Annual increments for forest in western Europe were scaled down by a factor of 2 prior to 1920, in accordance with what is reported by Erb et al. (2013). After 1920 we linearly increase the productivity of every country to its current value by 1990. This gives estimates for forest productivity in Germany, France and England around 1700–1800 which are within the 2.8 to 3.8 $m^3 ha^{-1}$ of timber independently reported for the same time period (Warde, 2006). Despite the simplifications underlying this approach, central European countries have the highest productivity throughout the reconstruction which we believe correctly reflects an earlier implementation of more advanced sylvicultural practices in central Europe.

The annual wood increment gives a maximum annual wood supply for sustainable harvests. To simplify the calculations it was assumed that the annual increment was harvested annually. Hence, this approach does not require to explicitly account for clearcuts and other management interventions.

Wood production maps from 1600 to 1828 were made by using the historical forest maps above (see Sect. 2.3.1) and the productivity estimates. For each year between 1600 and 1828 (the final year of the wood demand maps), the total forest area in a grid

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cell was estimated. This area is compared to the forest area for the same grid cell in the following year. If the forest area in the current year is greater than the forest area in the subsequent year, this difference is multiplied by the annual wood increment for that pixel and the resulting wood amount stored as "land cover change". If the current forest area is less than the subsequent year's forest area, the newly planted area will be taken into account only in the following year. In any case, the rest of the forest area for the current year is multiplied by the increment and stored under "harvest". For the final year of the calculation (1828), "land cover change" is still available, as the historical PFT maps have been created up until the present day and therefore the map from 1829 exists and can be used even if the demand map is not calculated for 1829.

2.4 Reconstructing forest management

2.4.1 Defining forest management strategies

Although forest management has developed a wide range of locally-appropriate and species-specific strategies, the nature of this study requires a limited number of contrasting strategies that are expected to be relevant at the spatial resolution (e.g., 50 km × 50 km) of global and regional modeling studies. To this aim four management strategies were distinguished based on their expected impact on the biogeochemical and biophysical processes: (1) FM1: no human intervention. Expected to result in tall, vertically and horizontally complex canopies with a closed nutrient cycle. (2) FM2: high stands with thinning and harvesting based on stem diameter and stand density. Expected to result in tall, homogeneous canopies with open nutrient cycles. (3) FM3: coppicing with harvesting of aboveground biomass, based on stem diameter. Expected to result in medium-high, homogeneous canopies with open nutrient cycles. Note that at present it is not possible to simulate coppicing-with-standards in ORCHIDEE-CAN. (4) FM4: short rotation coppicing with harvesting of all aboveground biomass based on age, using rotations of less than 6 years. Expected to result in short, homogeneous

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canopies with intensive nutrient exports and possibly requiring fertilisation to maintain productivity.

We have chosen not to divide our management strategies into biogeographic regions since we considered that regardless of region and species composition, the net biogeochemical result from the different management types is to transfer woody-biomass (and carbon) from the forest into an agricultural PFT or to remove it completely from the ecosystem (as harvest). The net biophysical result will be driven by changes in canopy structure and vegetation height. We believe that the first order effect of forest management can be quantified without accounting for management differences between biogeographic regions. The lack of available data for parametrization and validation discourages introducing too much detail at this time.

2.4.2 Two sets of forest management maps

Using the demand and supply estimate, a first set of general maps (GEN-MAP) was made but independent of the historical land cover maps (see Sect. 2.3.1). These maps list the forest area under each management type required to meet the wood demand (see Sect. 2.2; from 1600 to 1828) and match the reconstructed age class structure (see Sects. 2.4.4 and 2.4.5; from 1829 to 2010) for each pixel. In the GEN-MAPS, we report only the land areas of high stand management and coppicing required. Short rotation coppice are not included in these maps, as short rotation coppices were not used significantly historically. Unmanaged forest is not included in the maps since that fraction is estimated as a residual of the total amount of forest area on a given pixel, and land cover data are not used in this step. If the total forest area required in GEN-MAP is greater than the forest area found in a given pixel on a historical land cover map, the user will have to decide how to prioritize and manage this conflict.

Rather than simply assigning forest areas to the different management types as is the case for the GEN-MAPS, we went one step further and assigned forest area and tree species to the different management types. The resulting maps (ORC-MAP) can be directly read into the ORCHIDEE-CAN model. These maps take into account the

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historical land cover maps as well as a few model-specific constraints (see Sect. 2.4.6), resulting in maps which list, for every pixel, the amount of forest required under coppice, high stand and short rotation coppice management to meet demand and age-class information. The ORC-MAPS, as opposed to the GEN-MAPs, do contain fractions of unmanaged forest, although there is no short rotation coppice area.

2.4.3 GEN-MAP (1600–1828)

The general maps before 1828 simply represent how much forest is required to satisfy the wood demand. Initially, only high stand management and coppicing were considered. The reason for this is that our pre-1829 maps are based entirely on wood demand. The approach assumes that coppicing is done to meet fuelwood demand (see Sect. 2.2.1), while industrial wood demand (see Sect. 2.2.2) was met using high stands. A simplified approach to calculate historical forest productivity is used here, as outlined in Sect. 2.3.2. In order to distinguish between high stand and coppice systems, the productivity for a pixel estimated as explained in Sect. 2.3.2 was decreased by 10 % for high stand forests and increased by 10 % for coppice. This differential productivity reflects the fact that the historical productivity estimates are averages over all forest ages, while the productivity of coppice systems will be higher because they don't have to grow a complete new root system after harvest (Bursehel and Huss, 2003).

These productivity estimates were then used to calculate the area of managed forests that needs to exist on this pixel to meet the wood demand. All fuelwood for cooking and heating was assumed to come from coppicing whereas all other wood was assumed to come from high stand forests. For example, if 120 m^3 of fuelwood is required in a pixel where coppice produces 3.0 $m^3\,ha^{-1}$, 40 ha of forest is coppiced for this year. Note that in the GEN-MAP approach the required surface area under management may be greater than the total area of the pixel if the demand is very high.

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2.4.4 GEN-MAP (1829–1949)

The period after 1829 was characterized by the onset of so-called scientific forest management (Farrell et al., 2000) resulting in the abandonment of coppicing, pollarding and litter raking in favour of a production-oriented forestry, which is still used today, i.e., high stand management. Following 1829, our forest management reconstruction therefore gradually replaced coppicing by high stand management such that it reproduces the reconstructed modern European age class structure (Vilén et al., 2012). Although non-timber forest usage (e.g., litter raking) persists at present on local scales (Kirby et al., 1998), it is no longer considered significant for large-scale modeling applications over Europe.

Age class reconstructions are available in five-year intervals from 1950 until 2010 and include the following age classes: 1–20, 21–40, 41–60, 61–80, 81–100, 101–120, and > 120 years (Vilén et al., 2012). To our knowledge, this age reconstruction is the only European age reconstruction that has been validated (Vilén et al., 2012) and the year 1950 was therefore used as the target age structure for our management reconstruction. The age classes reconstruction does not cover all European countries. The most notable missing countries in terms of surface area are Belarus and Ukraine. We therefore used an iterative filling procedure under the assumption that the age class structure of neighbouring pixels is likely to be correlated. For this, any European pixels which were not found on the age class map but were touching pixels that were on the age class map were given a target distribution equal to the average of neighbouring pixels. This procedure was repeated until all pixels were given a value. After the iterations had finished, a few pixels, mostly small islands, remained untouched. For these pixels we used the value of the nearest neighbouring pixel. In addition, the areas for each age class were interpolated between the years of the reconstruction to give maps for every year between 1950 and 2010. Note that the European age class reconstruction (Vilén et al., 2012) contains no direct information on the applied forest management.

We applied a so-called backcasting age reconstruction (Bellassen et al., 2011a) that is mainly based on an assumed rotation length (Table 4; Kuusela, 1994). The backcasting method was employed to give the desired amount of high stand management for every pixel between 1829 and 1950. This implies that 1829 is the first year in which the reconstruction method switches from "demand-driven" to "backcasting". The backcasting algorithm formalized the following assumptions: (1) between 1829 and 1949 there was a strong trend towards high stand management to better match the changing wood market, (2) a stand converted to high stand management remained under high stand management with the sole exception being a revival of coppice management during the World Wars and inter-bellum, and (3) unmanaged forest were converted to production systems because forest protection was negligible.

In addition to its straightforward implementation the backcasting algorithm needs to deal with several specific cases. For the 1829 map, we checked the fraction of forests under high stand management in 1828 which was estimated by the demand based approach (see Sect. 2.4.3). If the surface area of forests underhigh stand management in 1829 is greater than the area we would expect based on A121 in 1950, the FM distribution for 1828 was also used for 1829 on the pixel (Fig. 1a). If the fraction of high stand forest in 1828 is less than expected based on A121, forests under coppice in 1828 were converted into high stand management in 1829 until a forest area of at least A121 was obtained in 1829 (Fig. 1b). If we had no coppice in 1828, the amount of high stand forests was increased while keeping the coppice fraction at zero (Fig. 1c) so that the total amount of managed forest required in the pixel increases. This procedure was repeated for all age classes and to obtain smoother maps, it was assumed that 1/20 of the forest in, for example, age class A101 was planted every year between 1830–1849.

Coppicing is known to have been important (Emanuelsson, 2009; Bursehel and Huss, 2003) and it still exists in significant quantities especially in southern Europe and France (Kuusela, 1994), however, it is uncertain how much coppice forest existed historically. Since coppiced forests were seldom on rotations longer than 35 years (Bursehel and Huss, 2003; Kuusela, 1994), we assumed that the fraction of coppice forests on

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a pixel is smaller than the amount of forests in the 1–20 and 21–40 year age classes. We further assumed that 50 % of forests between 1–40 years old in 1950 were under coppice management throughout their life thus, in our example, dating back to 1910 when the 40 year old forest was planted (Fig. 1a–c).

The following two cases provided respectively an upper bound on the area of high stand forest or a lower bound on the area of coppice in a pixel between 1828 and 1949. The algorithm checked and accounted for these cases only after the procedure described in the previous paragraphs was performed. (1) The area of high stand forest in 1828 may have been larger than required by the age class maps for 1950. In this case, we created a linear transition between the areas in 1828 and 1950. This represented a situation of early modern forestry, with conversion of coppice to high stands occurring earlier than what can be observed in the age-class data (Fig. 1a). (2) There is a possibility that the amount of coppice in 1828 was less than what was required in 1950. In this case, the amount of coppice was held constant until 1910. Between 1910 and 1950, the amount of coppice was increased linearly to the required amount in 1950 (Fig. 1c). Increasing coppice accounted for increased forest usage during the first (1914–1918) and second (1939–1945) World War.

Furthermore, the amount of coppice area between 1829 and 1950 could face one of two situations. Either the amount of coppice forest in 1828 was greater than what is required in 1950, or it is less. In the former case, we convert coppice area to high stands as required to reproduce the age reconstruction. For example, assume that in 1850 there are 10 000 ha of coppice and no high stands, and in 1950 there are 1000 ha of coppice and 4000 ha of 81–100 year old forest, and no other age classes populated (Fig. 2a). From 1850–1869, the amount of coppice forest needs to be reduced by 200 ha per year to match the amount of high stand forest by 1950 (the total 4000 ha is converted evenly over the 1850–1869 time period). In addition, 1000 ha of high stand is introduced between 1910–1950, as our method takes 50 % of the youngest two age classes in 1950 as coppices, implying that the other 50 % are managed as high stands. This method will not bring new forest under management until there are no further cop-

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pice forests to convert, which does not happen in this case (Fig. 2b). As the GEN-MAPS are not constrained by actual forest area on the pixel, these “new forests” are not taken from any other management type.

Following the algorithm outlined above we created general management maps from 1829 to 1949 which include the forest area needed per pixel to match the wood demand in 1828 and reconstructions of Vilén et al. (2012) in 1950, ignoring any historical maps detailing forest area. This means that values of forest area given during this time period may be substantially larger than the total area of the pixel.

2.4.5 GEN-MAP (1950–2010)

The percentage of coppiced forest in many European countries including in Belgium, Luxembourg, France, Hungary, Italy, the former Yugoslavia, Albania, Bulgaria, Spain, Portugal, and Greece varied from 10 to 50 % in 1990 (Kuusela, 1994). The area under coppice was linearly decreased from the 1950 value to its 1990 value reported in Kuusela (1994). Missing data were assigned coppiced areas based on nearest neighboring pixels. For Finland, Sweden, and Norway a target fraction of 0.01 was set as these regions do not have an extensive history of coppicing (Emanuelsson, 2009). All pixels were assumed to contain the same percentage of coppiced forest area as the country value in 1990 and the 1990 coppiced areas were held constant until 2010. The maps from 1950 to 2010 have the same total forest area as Vilén et al. (2012).

2.4.6 ORC-MAPS (1600–2010)

The GEN-MAPS described above are 0.5° resolution maps containing the forest area (in m^2) required to be managed under high stands and coppice management to satisfy the estimated wood demand from 1600 to 1828 and the age reconstruction maps of Vilén et al. (2012) from 1829 to 2010. For usage by the ORCHIDEE-CAN model, however, the assigned management types need to be: (1) allocated to a specific tree species or species groups, and (2) combined with historical land cover maps to respect the total forest area within a pixel.

An ORCHIDEE-CAN specific map lists a single forest management strategy for each plant functional type (PFT) on a pixel. The ORCHIDEE-CAN model targeted in this study consists of 28 PFTs, including bare soil, three grassland types, three agricultural types, and 21 forest types. Some of these forest PFTs are parametrised to represent individual tree species, while others are more general metaclasses (Naudts et al., 2014). The first step is to decide which PFTs are allowed to be managed in which style? Obviously none of the non-forest PFTs can be managed as forests. Additionally, conifers cannot be coppiced due to phylogenetic constraints (with the exception of *Taxa baccata* L.). This leaves twelve deciduous PFTs which can be left unmanaged or be managed as a high stand or a coppice. The nine coniferous PFTs can only be managed as a high stand or left unmanaged.

For each year between 1600 and 2010, our land cover reconstruction (see Sect. 2.3.1) and the GEN-MAPS map (see Sects. 2.4.3, 2.4.4 and 2.4.5) were consulted. For each pixel, the forest PFTs were sorted by size from largest to smallest, in terms of surface area. Priority was given to coppice management because under our assumptions, coppice provided wood for primary needs such as cooking and heating. Hence, deciduous PFTs, starting from the dominant species, were put under coppice management if the demand required that more than 15 % of the pixel was put under coppice management. If so, PFTs were managed as coppice until the total coppice forest area in GEN-MAP was exceeded or there are no more deciduous PFTs. At that point, whether solely conifers or both conifers and deciduous PFTs were available depended on the pixel. Starting from the largest stand, these were put under high stand management only if the demand required that more than 15 % of the pixel was put under high stand management. If so, PFTs were managed as high stand until the total high stand area in GEN-MAP was exceeded or there were no more forest PFTs. The 15 % threshold was introduced to avoid artefacts from the fact that one PFT is assigned a single management strategy. For example, a pixel dominated by few PFTs, say 90 % of PFT1 and 10 % of PFT2, and with a low fuelwood requirement, say 5 % would nevertheless be for 90 % under coppice because the algorithm dictates to start with the dominant PFT. The 15 % threshold protected against this artefact. Any remaining forests were left unmanaged.

Furthermore, a cap was set on the maximal share of unmanaged forest within a pixel during the 20th century. The cap starts at 100 % in 1910 (i.e., a whole pixel can be left unmanaged) and reduces to 15 % by 1950.

3 Results and Discussion

3.1 Land cover reconstruction

As a base layer for our management reconstructions, we used the reconstruction of land cover change by Kaplan et al. (2012). Pre-industrial agricultural land use in Europe is substantially higher than in other common reconstructions (Pongratz et al., 2008; Klein Goldewijk et al., 2011). Following Kaplan et al. (2012), our reconstruction mirrors their central assumption that European countries experienced forest transitions during the mid 1800s (Mather, 1992; Mather et al., 1999; Mather and Fairbairn, 2000; Meyfroidt and Lambin, 2011). In Europe, forest area reached its all time low around 1850 after which encroachment and afforestation made the forest area increase again to surpass the forest area of 1600 only in the late 1900s (Fig. 3). In this study, forest area was further detailed by filling-in tree species fractions and their spatial and temporal dynamics. The 539 000 km^2 increase in conifer area outnumbers the decrease in deciduous forest by 55 000 km^2. While conifers made up 29 % of the forest area in 1600, their present day share has increased to over 56 %. Since 1600, the net increase in conifer forests is thus the single most important net land dynamic and exceeds the net change in agricultural land by a factor of ten (Fig. 3).

It is well documented that Europe's present day species distribution does not reflect its natural vegetation (Kuusela, 1994; Kenk and Guehne, 2001). It has been estimated

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that between years 1500 and 2000 about 1300 different vascular plants species were introduced in Germany alone (Scherer-Lorenzen et al., 2000). Most of these neophytes were introduced for agricultural uses but at least 11 tree species were introduced in forestry (Schulze et al., 2015). In addition to introducing new species, humans are thought to have affected the distribution and share of tree species by favouring one species over another. Favouring beech (*Fagus sylvatica* L.), for example, is thought to be responsible for the decrease of fir (*Abies alba* Mill.) (Tinner and Lotter, 2006). For the period under study, planting conifer species outside their natural growing area (e.g., *Pinus sylvestris* L. and *Picea abies* H. Karst.), the introduction of new species (e.g., *Pseudotsuga menziesii* Franco and *Picea sitchensis* Carriére) (Schulze et al., 2015), the conversion of mixed boreal forest into homogeneous conifer forests (Gao et al., 2015) and the onset of a production-oriented forestry all contributed to a dramatic change in European species distribution. Recent efforts in converting conifer forest back to mixed or deciduous forest (Kenk and Guehne, 2001; Zerbe, 2002) were not accounted for and, therefore, not reflected in our reconstruction (Fig. 3). Although such efforts received substantial attention in the forestry literature, their large scale spatial extent remains to be quantified (Kenk and Guehne, 2001).

In this study, the reconstruction of changes in species distribution is based on anecdotal evidence as found in historical archives (Mantel, 1990) and forced to match present day observations (Brus et al., 2012). Although our reconstruction uses national estimates for trends in conifer coverage, the neighbourhood function that was used to decide which conifer species was planted during conversion accounts indirectly for climatic preferences of tree species. By design, however, our reconstruction cannot be expected to reproduce small scale patterns such as the preferential use of spruce at elevated cool sites. This limitation is partly compensated for by the rather coarse resolution (i.e., $0.5^\circ \times 0.5^\circ$) of the reconstruction.

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3.2 Demand and supply (1600–1828)

The 410 year time span of our reconstruction by far exceeds the 100 to 150 year life expectancy of a European forest. Living archives for forest management are thus absent for most of our reconstruction period. Given that forest management aims at satisfying diverse resource demands, we believe that in the absence of these archives, forest management can be reconstructed by making use of wood demand and supply estimates. Between 1600 and 1828, our estimates indicate that more than half of the wood demand came from the industrial production of ceramics, glass, beer, distillates and metal works (Fig. 4). The remaining demand was mainly for construction and fuelwood with wood for salt production being negligible. These estimates assume unlimited access to forest resources. However, as early as 1717, the estimated demand exceeds the estimated supply in our reconstruction. Given that *Sylva* or *A Discourse of Forest-Trees and the Propagation of Timber in His Majesty's Dominions* by the English writer John Evelyn (1664) and Colbert's ordinance from 1669, known as *l'aménagement forestier*, were likely inspired by locally decreasing forest resources, a European-wide cross-over five decades later seems reasonable. If our estimates reflect history, the cross-over may have reshaped society by triggering a search for alternative energy sources and by playing a role in the colonial wars in search of wood resources to close the demand–supply gap (Perlin, 2005); two events of which the consequences still affect today's society.

The demand–supply gap suggests unresolved issues with our estimates on the demand side, the supply side or both the demand and supply sides. At the European scale our historical supply and demand estimates are of the same magnitude as present day wood production and consumption which provides empirical evidence that our historical estimates are at least feasible. Furthermore, independent estimates for fuelwood demand indicate that our estimates are on the low end (Table 3). A cross check of the charcoal demand based on our methodology against a single independent estimate indicates a five fold overestimate by our method for England in 1700 (Table 3).

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The mismatch in surface area was further amplified because we used a productivity of $4\,m^3\,ha^{-1}$ whereas the independent estimate used $6.5\,m^3\,ha^{-1}$. The latter seems closer to present forest production than to historical production expected in 1700. For Finland, however, total wood demand obtained with our methodology appears to be on the low side (Table 3). Validation against independent estimates thus suggest that our demand estimate has a realistic order of magnitude and leans towards the low end of available estimates.

Similar to our approach for construction wood, the demand for glass and iron could have been scaled to gross domestic production. Given the negligible share of the wood demand for glass production, its scaling method is likely not relevant for our reconstruction. Such a scaling method could, however, more easily account for the decreasing marginal consumption of wood with increasing gross domestic production per capita. Such an approach would increase realism by partly decoupling wood demand from population growth but requires more data to establish the relationship between gross domestic production per capita and the consumption of glass, metal and construction wood.

As both the total forested area and the production per unit of land area increased between 1600 and 2010, the estimate for historical wood supply should be lower than the present day supply. The increase in area of forest land since 1600 is well established and is reflected in numerous historical documents as well as regional maps dating back to the late 1700s. One of the most compelling examples of such maps are the Ferraris maps which archived land cover of the Austrian Netherlands (now largely Belgium) with great detail (Ferraris, 1777). When combined with more recent topographic surveys, a clear and objective picture emerges of the land cover changes. Similar maps exist across Europe, e.g., Atlas de Trudaine (France, 1740–1780), Atlas of Napoleonic Cartography in Italy (1795–1815) and the Gyllenhielms atlas (Småland, Sweden, 1633–1655). It is this type of information that forms the scientific basis of land cover reconstructions including that of Kaplan et al. (2012), which was used in this study.

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It is well established that productivity has increased over the past six decades and this increase has been attributed to: (1) the use of more productive, often exotic, species (for example *Pseudotsuga menziesii* Franco and *Picea sitchensis* Carriére), (2) elevated atmospheric nitrogen deposition (Jarvis and Linder, 2000; Magnani et al., 2007; Spiecker, 1999), (3) CO_2 fertilisation (Norby et al., 2005, 2010) and climate change (McMahon et al., 2010; Fang et al., 2014), (4) an almost complete abandonment of practices such as forest grazing (Hobbs, 1996; Brathen et al., 2007) and litter raking (Dzwonko and Gawron, 2002; Bürgi and Gimmi, 2007; Gimmi et al., 2012), and (5) a more scientific approach to forest management (Farrell et al., 2000). Combining historical archives with bookkeeping methods suggests that productivity has increased by 100 % since 1830 (Erb et al., 2013). Resampling *Fagus sylvatica* L. and *Picea abies* H. Karst. showed increased tree growth of 32 to 77 % and increased stand volume growth of 10 to 30 % since 1870 (Pretzsch et al., 2014). An analysis covering the period 1970 to 1990 documents a general increase in productivity all over Europe by 25 % in 20 years time (Ciais et al., 2008b). The 100 % increase in productivity applied in this study should thus be considered a high rather than a low estimate. Consequently, our estimate of historical wood supply should be considered low rather than high.

If site-level productivity by 1600 was only reduced by 30 % and thus agreed with relatively short-term observations (Pretzsch et al., 2014; Ciais et al., 2008b), the demand would not have exceeded the supply until after 1815. Applying present day definitions to forest and harvest for our reconstruction could also have contributed to an underestimation of the wood supply. When pressure on forest resources was high, it cannot indeed be excluded that branches, twigs and litter were collected and burned. Although it is labour intensive, stumps may have been uprooted and used for charcoal production (Perlin, 2005) which could increase the supply by 15 to 25 % in the boreal and temperate zone and even 25 to 50 % for Mediterranean species (Fernández-Martínez et al., 2014). Furthermore, the strict separation between forest and agricultural lands emerged only at the onset of scientific forestry and modern nation-states (Mather, 1992; Meyfroidt and Lambin, 2011). The aforementioned early maps confirm that hedges, tree rows and solitary trees between and within fields and grazing lands were abundant in agricultural landscapes, in particular in the extensive heathlands used for rough grazing. A tree cover of 15 % across agricultural lands, suggesting common use of agroforestry, would delay the cross-over by 15 years. Finally, importing 25 Tg of wood C, which is a quarter of today's import (Ciais et al., 2008a), would have delayed the cross-over by 40 years. It seems unlikely, however, that fewer people with a much smaller logistical capacity than today could have imported such a volume even from Europe's forest rich colonies.

The reconstruction of wood demand applies a relationship between population density, economic development, and consumption. However, wars and collapses of political systems may have decoupled population growth from wood demand for years to decades. Our reconstructions, for example, show no drop in demand during the Thirty Years War (1618–1648), as is expected based on building dates of roughly 200 000 woody structures across Europe (Büntgen). During wars and crises forest resources may even have regenerated from earlier (over)use (Mather et al., 1999). Regions with resource scarcity may have imported commodities such as glass and iron rather than importing the wood to produce these products themselves. Furthermore, we may have overestimated the share of charcoal which in turn would lead to a substantial overestimation of the wood demand. A unit of energy released by charcoal required twice as much wood in its production compared to burning wood directly (see Table 1). Recycling may have been more common than thought, e.g., decommissioned construction wood may have been used as fuelwood. Recycling all construction wood as fuelwood would reduce the wood demand by 25 % and delay the cross-over by 60 years.

During the centuries under study, industrial procedures evolved, e.g., slag from Roman iron works was re-used thus requiring less energy for smelting (Perlin, 2005), a procedure was discovered to use coked coal rather than charcoal for the extraction of iron (Perlin, 2005), and as a consequence wood as a construction material was replaced by iron (Perlin, 2005). It is not clear whether these increases in efficiency resulted in higher production for the same amount of wood consumption or effectively

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reduced the wood demand. Present day studies show that in a market economy, effective substitution is only likely under resource scarcity (York, 2012). Finally, alternative energy sources such as solar and wind energy (for example, for pumping water into evaporation pans for salt production (Perlin, 2005)), burning of peat, manure and agricultural residuals (Perlin, 2005; de Zeeuw, 1978) and the initially local raise in the use of coal (Pound, 1979) may all have contributed to a lower wood demand than estimated in this study. We interpret these data as a clue that the replacement of wood as an everyday fuel source in the home likely began to occur in the early 1800s (cf. Mather and Fairbairn, 2000).

Although the cross-over of demand and supply suggests that more work is needed and that most likely both estimates need to be better constrained, the key question for this study is whether these estimates are expected to substantially affect our forest management reconstructions. The assumption that wood did not travel outside the 50 km × 50 km pixels is the backbone for answering this question. This appears to be a fair assumption, in particular for salt production where channels to guide the brine rarely exceeded 40 km (Bergier, 1989; Mantel, 1990). Transport of fuelwood was limited especially in areas with no convenient river transportation (Warde, 2006). However, other evidence does indicate that long-range timber transport was common. Transport of fir in Roman times, for example, covered hundreds of kilometers (Küster, 1994).

Following the assumption of limited wood transport, the management maps are largely affected when wood supply exceeds wood demand at the pixel level because in this case, a fraction of the forest will remain unmanaged. If however, wood demand exceeds its supply, as is common from our reconstruction, all forest in the pixel will be managed but the mismatch between demand and supply is not propagated into neighbouring pixels or to subsequent time steps. Given the priority rules that were set to allocate the fractions to different management practices, an unsatisfied demand is likely to result in a higher share of coppice management compared to high stand management. Despite the mismatch between wood supply and demand, our management maps will correctly reflect that forests were under pressure but may result in a biased

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allocation of the management strategies towards coppice management. In 1600, our reconstruction suggest that at the pixel level, the percentage of unaccounted-for demand across Europe is around 40 % and increases to around 65 % by 1820. This reflects the increased forest pressure due to increasing population, and provides support of increased incentive for transitioning to alternative fuel sources.

3.3 Litter demand

Finding comprehensive data to parameterize and validate historical litter-based activities is not currently possible. To our knowledge, there exist two quantitative studies on traditional non-timber forest uses (Gimmi et al., 2012, 2008). The quantitative studies were localized in Swiss valleys, and showed that the model results were sensitive to data like litter demand for livestock and straw production rate, data which are impossible to find for all of Europe for different times between 1600 and 2010. Present day soil carbon stocks that experienced historical litter raking where estimated to be 2 % lower than they would have been in the absence of litter raking (Gimmi et al., 2012). The effects of litter raking on the nutrient balance of soils is expected to be more important than its effect on the carbon balance (Gimmi et al., 2012).

When litter raking is accounted for in ORCHIDEE-CAN simulations, the litter maps give an estimate of the amount of litter to be removed from each grid cell at the end of every year. If a grid cell does not have enough litter to cover the demand, we remove all but we do not attempt to take any litter from surrounding grid cells. Litter raking was used for wintering livestock, with the manure collected and spread on the fields in the spring. Hence, ORCHIDEE-CAN adds the carbon contained in the raked litter to the litter pools of any agricultural PFTs on the grid square. Owing to the tight link between forest use and agriculture in this epoch, the main result of litter raking is thus clear: carbon which would enter the forest soil if the litter would not have been raked got diverted to litter pools outside the forest. At its peak litter raking was estimated to collect 50 Tg of dry litter and thus redistributed 25 Tg of carbon and 0.5 Tg of nitrogen

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(or 5 % of present day nitrogen fertilisation of Europe, Schulze et al., 2010) towards croplands.

3.4 Forest management reconstruction

3.4.1 Trends in forest management

Our forest management reconstruction shows a clear and continuous decrease in unmanaged forest between 1600 and 1950 (Fig. 5). A spatial representation shows that between 1600 and 2010, unmanaged forest was mainly lost in Scandinavia and eastern Europe (Fig. 6a, b). Although few will argue against the reconstructed decline, a share of 30 % unmanaged forests in 1600 cannot be confirmed (or rejected) at the European scale. The gain in unmanaged forest since 1950, which is scattered over Europe, reflects a modest but increasing effort in forest conservation and the recent trend towards abandoning management by an increasingly urban population. Our reconstruction suggests that 17 % of the forest are unmanaged. At present the share of untouched forest or forest with minimal human intervention is, however, estimated to be just below 5 % (Schnitzler, 2014). However, that does not include a notable fraction of public and private forest which are only lightly managed and with harvest rates well below the annual increment (Levers et al., 2014). Overestimation of unmanaged forests may also be partly caused by classification issues. The ORC-MAPS were prepared to be used with ORCHIDEE-CAN and based on a remote sensing product. Given that ORCHIDEE-CAN currently does not distinguish between forest and shrubland, dense shrubland was classified as forest and sparse shrubland as grasslands. After 1950, our forest management relies on forest inventory data which, by conception, exclude shrubland. Our reconstruction algorithm thus classified dense shrubland as unmanaged forest. Although classifying shrubland as forest results in overestimating basal area and vegetation height over much of the Mediterranean region (Naudts et al., 2014), the consequences of considering shrubland as unmanaged ecosystems are expected to be minor.

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The abrupt decreases in 1829 and 1950 in unmanaged forests in Figure 5 are due to Finnish and by extension Scandinavian forestry. In 1950, Finland had a lot of forests that, according to the inventory data, were more than 121 years old. Given that these forests were in the inventory data and thus under commercial use in 1950 our algorithm has put all these forests under management in 1829. In 1829, the backcasting algorithm thus required much more managed forests than the demand–supply algorithm that was used prior to 1829. Furthermore, the algorithm caps the unmanaged forests in the 20th century (see Sect. 2.4.6). Recall that the cap starts at 100 % in 1910 (i.e., a whole pixel can be left unmanaged) and reduces to 15 % by 1950. The cap was found to be redundant until 1932 but became substantial after 1942. By then, the maximum amount of unmanaged forest on a pixel was capped at 30 %, which is the case for many pixels. Hence, the algorithm placed a lot of previously unmanaged forests under management between 1940 and 1950. Although its origin is an artefact of the algorithm it happens to relate to a decade in which a lot of unmanaged forest were harvested to support post-war reconstruction efforts (Statistics Finland, 2007).

Coppice management groups diverse forest management strategies that leave the root system intact but may differ in rotation length, tree species and wood use depending on region and climate. Although the wood from coppice stands was often used as fuel wood in households, its use is also documented for construction, agriculture, viticulture, and tannin production (Emanuelsson, 2009). Part of its popularity was due to its ecological stability, flexibility in management and common rights. Throughout history, coppicing has been the basis for silvo-pastoral systems with temporary cropping, husbandry, hunting, gathering and beehives (Emanuelsson, 2009). Between 1600 and 1828, population growth drove the reconstructed wood demand resulting in an increasing share of coppice management albeit accompanied by an overall decrease in forest area (Fig. 5). Following 1828, an increasing substitution of fuel wood by coal and construction wood by metals made coppice lose its importance (Fig. 6e, f). Coppice stands were converted or neglected. At present, independent estimates suggest 15 % of the European forest is currently under coppice. Outside the coppice strongholds in South

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East Europe (Fig. 6f), high stand forests in Europe often show relics of the typical features of coppice management. Although there is little doubt that coppice management substantially decreased since 1600, the reconstructed share of 36 % coppice in 1600 cannot be confirmed (or rejected) at the European scale.

During the World Wars and the inter-bellum, our reconstructions suggest a revival of coppice management (Fig. 5). Whether this reflects reality is uncertain but during the wars, rotations were considerably shortened to meet the increased demand. For example, in the New Forest, UK, all conifers of 20 to 35 year where cut between 1940 and 1946 (Forestry Comission, 2013). Although the reconstruction suggests that coppice management in 2010 is at its lowest in over 400 years (Fig. 5), it has been re-discovered because of its contribution to biodiversity (Lüpke et al., 2011) and as a source of renewable bioenergy (Lemus and Lal, 2005). In the latter case, fewer species and shorter rotations are used compared to traditional coppice management, explaining the term short rotation coppice (SRC). At present short rotation coppice is limited to about 500 km^2 (Leek, 2010) and was therefore not considered substantial enough to be accounted for in our reconstruction.

In the late 1700s it was realized that when used in a controlled manner, forest could produce wood without being destroyed. This changing attitude towards natural resource management was reflected by the establishment of German, Austrian and French forestry schools (Farrell et al., 2000) and is considered the start of the so-called scientific forest management which is based on the idea that productivity of forests is stable over time. The focus on productivity resulted in the widespread use of conifers at sites that were previously only occupied by deciduous tree species. Since the late 1700s a variety of management strategies that differ in objectives and intensity and frequency of the interventions has emerged (Pretzsch, 2009). This variety is grouped as high stand management in our reconstruction. Following centuries of forest destruction this then-new approach to land management may have contributed to a steady increase in forest area over Europe (Fig. 5), along with broader economic, technological, cultural and political changes (Meyfroidt and Lambin, 2011).

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Our management reconstruction also allocates forest to high stand management prior to the birth of scientific forest management. Given the specific objective of our reconstruction, i.e., studying large scale effects of forest management, it was considered acceptable to both classify scientific forest management in the late 1700s and unplanned forest use prior to the late 1700s as high stand management. In both approaches, some wood is removed prior to the final harvest, and tall vegetation is maintained. Although the outcome of scientific high stand management is expected to be sustained production, the outcome of unplanned management could be either sustained production, degradation or even forest destruction. Given the success of scientific high stand management in sustaining wood production and providing other ecosystem services, its increasing use and dominance between 1600 and 2010 (Fig. 5) are to be expected.

3.4.2 Quality of the reconstructions

Although 80 % of the data and expansion factors used in this reconstruction (see Table 1) are justified by previous research, its spatial and temporal representativeness remains unknown as the data are most often based on local case studies. Estimates of several components are based on sparse data, and for these components, it was not possible to separate the data in parameterization and validation sets. Where sufficient data were available (Table 3), the reconstruction was compared against validation data. Although our reconstruction performs reasonably well across space and time, the quality and representativeness of the validation data is unknown. Given the lack of quality-checked data for validating our reconstructions, we aimed for the highest transparency by listing all assumptions made to reconstruct forest management (Table 1). Wood removal activities were deliberately separated by various forms of wood harvesting and litter raking, which is expected to allow easier incorporation of future advances. The resulting maps should thus be considered as a starting point for future developments on the topic rather than a final data product.

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The uncertainty of the forest management reconstruction must be considerable given that it relies heavily on population and land cover reconstructions which are also uncertain (Klein Goldewijk and Verburg, 2013; Kaplan et al., 2012). When creating the ORC-MAPs it was assumed that within a pixel, a single tree species was managed with a single strategy. Large artefacts from this assumption were avoided by only putting a tree species under a specific management strategy if the demand required that more than 15 % of the pixel was put under that specific management (see Sect. 2.4.6). Many of the previous assumptions are believed to be of minor importance compared to this 15 % threshold. Therefore, the effect of the 15 % threshold was tested by recreating the ORC-MAP for a threshold of 5 and 25 %. The trends in forest management between 1600 and 2010 were found to be insensitive to the specific threshold used (Fig. 5). Although different settings for this threshold could result in a 5 to 25 % increase or decrease in the surface area for given management strategy, these changes are not random and tend to favour one management strategy over another. Hence, using a different threshold values rarely changed the dominance of a certain strategy within a given time period.

In this study, demand and supply maps were used to reconstruct forest management between 1600 and 1828 and a supply-based backcasting method was applied to reconstruct forest management between 1829 and 2010. This implies that except for the year 1829, the management reconstruction for a single year was based on a single approach. Continuing the reconstruction of demand and supply maps would enable us to constrain the management reconstruction between 1829 and 2010 by an independent data set. It remains to be tested whether this would really result in more reliable management maps. An extended and improved estimate of the supply should depend on the reconstructed forest management because different management strategies will supply different amounts and dimensions of wood. Also, a demand map between 1829 and 2010 would have to deal with a very dynamic period in terms of energy consumption and wood use. In the end, the uncertainty of the 1829 to 2010 demand reconstruction may be so large that it would only marginally constrain the backcasting

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method. By contrast, the backcasting method relies on a more restricted dataset with fewer assumptions.

3.4.3 Ways forward

Future efforts of reconstructing forest management could move this field forward by considering the following:

1. Our reconstruction builds on land cover reconstructions (Kaplan et al., 2012, 2009) but does not interact with this land cover reconstruction. Simultaneous consideration of both wood demand and the food demand that currently drives these land use reconstructions during their creation would increase the internal consistency of the land use and thus the forest management reconstructions.

2. An inter-disciplinary team with access to physical land science, historical archives in local languages, archaeological archives and expertise in economic history could better constrain the physical, sociological and economic aspects that underlie the forest management reconstruction. A broader expertise would not only further internal consistency of the reconstruction but is likely to increase in the number of data sources that could be used for parametrization and validation.

3. The historical species distribution is one of the few components of the reconstructions which could be improved based on comprehensive evidence by making use of pollen, charcoal and genetic records. Recent efforts in bringing together pollen records from across Europe (Trondman et al., 2014) and studies on genetic lineages (Petit et al., 2002, 2008) are expected to refine and better constrain the spatial and temporal resolution of future reconstructions of species distribution. Charcoal dating and analyses (Robin et al., 2013) could add further detail on species occurrence.

4. The limited sensitivity tests we conducted suggested that that better knowledge of the supply side will be essential as well as better understanding wood trade

and both production techniques and demand of energy-intensive products such as metals.

3.5 Data and map availability

ORCHIDEE-CAN is a version of the land surface model ORCHIDEE that was developed and parametrized to simulate the biogeochemical and biophysical effects of forest management (Naudts et al., 2014). Applications making use of the full potential of ORCHIDEE-CAN require a spatially and temporally explicit description of forest management as boundary condition and, hence, the need for a reconstruction of forest management as presented in this study. Contrary to the forest management reconstruction, the demand and supply maps are intermediate products and not essential to drive ORCHIDEE-CAN. Wood supply, for example, is at present calculated by ORCHIDEE-CAN. In the future, modeled wood supply, rather than our supply map, could thus be used to derive the most likely management strategy. Nevertheless, it was decided to also distribute the demand and supply maps to facilitate other research groups to further improve our forest management reconstruction, and possibly to be used for other purposes. The demand, supply and management maps as well as the coded algorithms (scripts in the R language) can be requested from one of the authors. Every use of (part) of these maps and their underlying data other than the original products (Table 1) should cite this paper. It is strongly advised to contact the authors to verify correct use and interpretation of the maps.

4 Conclusions

By making use of land use reconstructions, present day vegetation maps, tree species maps, expansion factors and forest age reconstructions, we created general (GEN-MAP) and model specific (ORC-MAP) historical forest management maps. Where the GEN-MAPS can serve as a starting point for other modelling groups to create their own maps, the ORC-MAPS were created to be used with the ORCHIDEE-CAN land surface model. The ORC-MAPS assign a management strategy (unmanaged, high stand management or coppice management) to each forest PFT in Europe. Our reconstruction reproduces the most important changes in forest management between 1600 and 2010: (1) an increase of 593 000 km^2 in conifers at the expense of deciduous forest (decreasing by 538 000 km^2), (2) a 612 000 km^2 decrease in unmanaged forest, (3) a 152 000 km^2 decrease in coppice management, (4) a 818 000 km^2 increase in high stand management, and (5) the rise and fall of litter raking which at its top in 1853 removed 50 kg dry litter per year.

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Table 1. Summary of various data sources used to reconstruct forest management between 1600 and 2010. The years listed are the years of the dataset which were used in this work, not necessarily all the years available. The following abbreviations were used: GDP for Gross Domestic Production, pers for person, live for head of livestock, S for southern, C for central, and N for northern.

Component	Data	Comments
General		
Historical population maps	1600–2000	Klein Goldewijk et al. (2011); HYDE
Historical GDP data	1600–2000	Bolt and van Zanden (2013); Maddison
Wood density	400 $kg\,m^{-3}$	Engineering Toolbox
Carbon content	50 %	Lamlom and Savidge (2003)
Charcoal calorific value	30 $MJ\,kg^{-1}$	Engineering Toolbox
Wood calorific value	15 $MJ\,kg^{-1}$	Engineering Toolbox
Pre-industrial wood to charcoal mass loss ration	4	Menemencioglu (2013); Kammen and Lew (2005)
Fuelwood – Cooking		
Energy demand	8 $GJ\,pers^{-1}\,y^{-1}$	ASTRA and Reddy (1982)
		Upscaled by population. People would use charcoal for cooking instead of wood for transport and air quality reasons, even if charcoal is less efficient. Energy demand is taken to be similar all over Europe despite differences in diet and climate. It was assumed that only wood was used as an energy source.
Fuelwood – Heating		
Temperature threshold	15.5 °C	Spinoni et al. (2015)
Heating degree days S. Europe	1000 day K	Spinoni et al. (2015)
Heating degree days N. Europe	4000 day K	Spinoni et al. (2015)
Personal space	30 $m^3\,pers^{-1}$	Assumed
Heating efficiency	10 %	Assumed
		Upscaled by population. The energy released while cooking was used for heating. It was assumed people would use 50 % charcoal and 50 % wood for heating for transport and air quality reasons, even if charcoal is less efficient.

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Table 1. Continued.

Component	Data	Comments
Salt production		
Wood demand for brine of 250 $kg\,m^{-3}$	1 $kg\,kg^{-1}$	Radkau (2012)
Wood demand for brine of 50 $kg\,m^{-3}$	10 $kg\,kg^{-1}$	Radkau (2012)
Production	Table 2	Bergier (1989) Upscaled by production. Steady production of the mines through time. Brine was transported no more than 25 km through pipeworks. It was assumed that only wood was used as an energy source.
Beer and distillates		
Consumption	300 $l\,pers^{-1}\,y^{-1}$	Unger (2004)
Wood demand	4.8 $kg\,kg^{-1}$	Unger (2004) Upscaled by population. It was assumed that only wood was used as an energy source.
Ceramics and brick		
Consumption	45 $kg\,pers^{-1}\,y^{-1}$	Sinopoli (1999); Petrie (2012)
Wood demand	2 $kg\,kg^{-1}$	Kishore et al. (2004) Upscaled by population. It was assumed that only wood was used as an energy source.
Metal works		
Iron consumption	1.50 $kg\,pers^{-1}\,y^{-1}$	Sim and Ridge (2002); Wilson (2007); Craddock (2008); Wikipedia
Lead consumption	1.45 $kg\,pers^{-1}\,y^{-1}$	Wilson (2007); Wikipedia
Copper consumption	0.27 $kg\,pers^{-1}\,y^{-1}$	Wilson (2007); Wikipedia
Silver consumption	0.004 $kg\,pers^{-1}\,y^{-1}$	Wilson (2007); Wikipedia
Gold consumption	0.0002 $kg\,pers^{-1}\,y^{-1}$	Wilson (2007); Wikipedia
Tin consumption	0.022 $kg\,pers^{-1}\,y^{-1}$	estimate
Zinc consumption	0.07 $kg\,pers^{-1}\,y^{-1}$	estimate
Wood demand	81 $kg\,kg^{-1}$	Sauder and Williams (2002) Adapted from production estimates from the Roman Empire. Tin and zinc consumption is scaled to copper based on typical bronze and brass alloys. Upscaled by population. Iron and lead included military as well as domestic uses. These estimate includes both metal melting and working. Wood estimates are prior to charcoal conversion. Charcoal is only mandatory for iron smelting. However, the assumption was made that the preferred fuel for kilns and furnaces is charcoal because charcoal burns at higher temperatures and for ease of transport to production sites.

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Table 1. Continued.

Component	Data	Comments
Glass production		
Total wood demand for glass	similar to metal works	Warde (2006)
		Upscaled by metal production. Wood estimates are prior to charcoal conversion and it was assumed only charcoal was used.
Timber		
Construction spending Spain	$18.0 \times 10^{-5}\,m^3\,pers^{-1}\,GK^{-1}$	Bolt and van Zanden (2013); Iriarte-Goñi and Ayuda (2008)
Construction spending England	$7.2 \times 10^{-5}\,m^3\,pers^{-1}\,GK^{-1}$	Bolt and van Zanden (2013); Clark (2004)
		Upscaled by gross domestic production. The share of different building materials was assumed constant and a relationship between construction and gross domestic production was assumed.
Shipbuilding		
Share in wood demand	1 %	Warde (2006) Not accounted for.
Litter raking		
Livestock density N. Europe	$0.6\,live\,pers^{-1}$	Krausmann et al. (2013)
Livestock density C. Europe	$0.5\,live\,pers^{-1}$	Krausmann et al. (2013)
Livestock density S. Europe	$0.3\,live\,pers^{-1}$	Krausmann et al. (2013)
Litter demand	$200\text{–}480\,kg\,live^{-1}\,y^{-1}$	Bürgi (1999)
Correction factor 1600–1850	$LD(y) = 0.75\exp(-(y-1850)^2/3000)+0.25$	Tuned to Bürgi (1999)
Correction factor 1851–2010	$LD(y) = 1.0\exp(-(y-1850)^2/1000)$	Tuned to Bürgi (1999)
		Upscaled by population. The correction factor was fitted such that agricultural litter use peaked in 1850 and was abandoned completely by 1950. Northern Europe was defined as the land mass above 55° N, central Europe was located between 45 and 55° N and southern Europe the land below 45° N. Forage collection was not considered.

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Table 1. Continued.

Component	Data	Comments
Land cover changes		
Historical land use maps	1600–2000	Kaplan et al. (2012)
Land cover map	2010	Poulter et al. (2015)
Tree species map	2010	Brus et al. (2012)
Natural vegetation	1600	Bohn et al. (2000)
		No upscaling required.
Annual wood increment		
Annual wood increment	3.8 $m^3\,ha^{-1}$	Country level productivity from Table S3 in Ciais et al. (2008b)
Reduction factor	2 (–)	Erb et al. (2013)
		Upscaled by land cover maps. Contemporary estimates of annual wood increment is restricted to stem wood increment.
GEN-MAPS (1600–1828)		
Annual productivity of coppice	Country level productivity +10 %	Assumed based on Bursehel and Huss (2003)
Annual productivity of high stand	Country level productivity −10 %	Assumed based on Bursehel and Huss (2003)
		No upscaling required. Coppicing was used to meet the fuelwood demand (i.e., cooking and heating), while high stands management was used for all other wood uses.
GEN-MAPS (1829–1949)		
Age class reconstruction	1950–2010	Vilén et al. (2012)
Rotation high stand	50–180 years	Table 4
Rotation coppice	35 years	Bursehel and Huss (2003); Kuusela (1994)
Relaxation for transitions	20 years	Assumed
		No upscaling required. Missing pixels in the age class reconstruction were linearly interpolated assuming age class structure between neighbouring pixels is similar. It was assumed that 50 % of forests between 1 and 40 years old in 1950 were under coppice management throughout their life. The backcasting algorithm formalized the following assumptions: (1) permanent transition to high stand management, (2) revival of coppice management during the World Wars and inter-bellum, and (3) unmanaged forest were taken into production.

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Table 1. Continued.

Component	Data	Comments
GEN-MAPS (1950–2010)		
Coppice fraction (1990)	10–50 %	Kuusela (1994)
Coppice fraction Fenno-Scandinavia (1990)	1 %	Assumed based on Emanuelsson (2009)
		No upscaling required. All pixels were assumed to contain the same percentage of coppiced forest area as the country value. The 1990 coppiced areas were held constant until 2010.
ORC-MAPS (1600–2010)		
General maps	1600–1828	This study, see Sect. 2.4.3
General maps	1829–1949	This study, see Sect. 2.4.4
General maps	1950–2010	This study, see Sect. 2.4.5
Land cover reconstruction	1600–2010	This study, see Sect. 2.3.1
Management threshold	15 %	Assumed
Unmanaged threshold	100 % in 1910	Assumed
	15 % by 1950	Assumed based on Schnitzler (2014); Levers et al. (2014)
		No upscaling required. The demand for wood products from coppice management was satisfied before the other wood demands. Dominant PFTs were managed first.

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Table 2. Summary of European salt mine characteristics important for wood consumption during 1600–1900. The final two columns are estimates based on information found in Bergier (1989).

Mine	Location	Brine [$g\,L^{-1}$]	Years of Production	Production [tons per year]
Halle an der Saale	51.48° N, 11.97° E	250	1600–1699	6000
			1700–1799	3500
Lüneburg	53.25° N, 10.42° E	250	1600–1649	20 000
			1650–1699	15 000
			1700–1749	10 000
			1750–1799	5000
Hallein/Salzburg	47.68° N, 13.10° E	50	1600–1649	20 000
			1650–1699	15 000
			1700–1749	10 000
			1750–1799	5000
Hallstadt/Bad Ischl	47.72° N, 13.63° E	250	1600–1649	50 000
			1650–1699	40 000
			1700–1799	10 000
Saulnois (Lorrain F)	49.12° N, 6.18° E	150	1600–1699	8000
			1700–1799	25 000
			1800–1899	10 000

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Table 3. Summary of independent information, thus not used to create our estimates, for European wood demand from around 1600 to 1900.

Summary	Source	Reconstructed
Fuelwood		
2–2.5 $kg\,pers^{-1}\,day^{-1}$ in Northwest and central Europe from 1500 to 1830.	Warde (2006)	0.9 $kg\,pers^{-1}\,day^{-1}$
1.4 $kg\,pers^{-1}\,day^{-1}$ in Madrid in 1680	Warde (2006)	0.9 $kg\,pers^{-1}\,day^{-1}$
4.7 $m^3\,pers^{-1}\,y^{-1}$ in Sweden in 1800	Warde (2006)	0.8 $m^3\,pers^{-1}\,y^{-1}$
1–2.3 $m^3\,pers^{-1}\,y^{-1}$ in Italy before 1861	Warde (2006)	0.7 $m^3\,pers^{-1}\,y^{-1}$
Energy demand was 9 $GJ\,pers^{-1}\,y^{-1}$. Fuelwood pressure on forests in Switzerland declined by the end of the 1800s since coal became used significantly from 1850.	Mather and Fairbairn (2000)	5 $GJ\,pers^{-1}\,y^{-1}$
In Paris, per capita fuelwood consumption amounted 1.8 $m^3\,pers^{-1}\,y^{-1}$ cubic meters in 1815. Fuelwood consumption started falling in 1830s in France due to the rise of coal.	Mather et al. (1999)	0.9 $m^3\,pers^{-1}\,y^{-1}$
From 1800, the wood demand was 4 $m^3\,pers^{-1}\,y^{-1}$ for urban populations in Finland. Wood demand started to decline around 1840.	Myllyntaus and Mattila (2002)	0.4 $m^3\,pers^{-1}\,y^{-1}$
From 1800, the wood demand was 9.5 $m^3\,pers^{-1}\,y^{-1}$ for rural populations in Finland. Wood demand started to decline around 1840.	Myllyntaus and Mattila (2002)	0.9 $m^3\,pers^{-1}\,y^{-1}$
In 1700, 2.3 $Tg\,y^{-1}$ of firewood produced in England. Wood had mostly been replaced by coal after 1810 in England.	Clark (2004)	1.9 $Tg\,y^{-1}$
In 1700, firewood production required 1.83×10^6 acres (740 000 ha) of coppiced land.	Clark (2004)	1.2×10^6 ha

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Table 3. Continued.

Summary	Source	Reconstructed
Timber		
53 % of total wood consumption as sawn timber in Europe in 1920, varying from 15 to 96 % of the total wood production based on the country	Zon and Sparhawk (1923)	N.A.
In Austria the total wood production consisted of 66 % fuelwood in 1877	Weigl (2002)	N.A.
In Austria the total wood production consisted of 34 % construction wood in 1877	Weigl (2002)	N.A.
Charcoal production		
30.6×10^6 feet^3 (0.866 Mm^3) for iron production in England in 1700	Clark (2004)	3.8 Mm^3
Iron production in England in 1700 required 330 000 acres (133 000 ha) of woodland	Clark (2004)	950 000 ha
Total wood demand		
In 1800, each Finn consumed 20 m^3 pers^{-1} y^{-1}	Myllyntaus and Mattila (2002)	5 m^3 pers^{-1} y^{-1}

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Table 4. Rotation length by tree species and country collected from Kuusela (1994). If an explicit year is not given, the year 1990 (the date of the latest dataset used) is assumed. Region names are listed in bold font and are defined in Kuusela (1994).

Region/Country	Species	Years	Rotation lengths [years]
Northern	Pine	1990	80–120[a,c]
	Spruce	1990	70–90[a,c]
	Pine	1990	110–180[b,c]
	Spruce	1990	90–140[b,c]
Finland	–	–	–
Norway	–	–	–
Sweden	–	–	–
Central			
Denmark	Pine	1990	50–150
Germany West	Conifers	1920s–1930s	80
	Fir	1920s–1930s	90
	Spruce and fir	1980s	80–100[c]
	Pine and larch	1980s	100–120[c]
	Oak	1980s	140–180
	Beech	1980s	120–140
Germany East	–	1990	"the rotations are somewhat shorter [than those in the rest of the region]"
Poland	–	1990	"the rotations are somewhat shorter [than those in the rest of the region]"
Czechoslovakia	–	1990	"the rotations are somewhat shorter [than those in the rest of the region]"
Atlantic	Pine	1990	50–60
	Other conifers	1990	50
	Oak/beech	1990	120–150
Ireland	–	–	–
United Kingdom	Broadleaf	1990	120

[a] Southern part of the region.
[b] Northern part of the region.
[c] Actual rotation ages are often 10–20 years longer than prescribed.

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Table 4. Continued.

Region/Country	Species	Years	Rotation lengths [years]
Sub-Atlantic	–	–	–
Netherlands	–	1990	"rotation ages are relatively short compared with those in Central Europe"
Belgium	–	–	–
Luxembourg	Conifers	1990	80
	Broadleaf	1990	130
France	Broadleaf	1990	140
	Spruce and fir	1990	"long rotation"
Alpic	–	–	–
Austria	–	1990	"relatively long"
Switzerland	Conifers	1990	80–250
	Broadleafs	1990	80–180
Pannonic	–	–	–
Hungary	Pine	1990	60–70
	Other conifers	1990	60–70
	Oak	1990	90–110, 70–100[d]
	Beech	1990	100–120
	Poplar	1990	15–30, 15–40[d]
	False acacia	1990	15–30, 30–35 (up to 75)[d]
	Coppice/Coppice with standards	1990	30–75
Romania	Confiers	1990	100–110, 100–140[d]
	Broadleafs	1990	100–120, 100–140[d]

[d] Differing values given at different places in the text.

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Table 4. Continued.

Region/Country	Species	Years	Rotation lengths [years]
Mediterranean West	Maritime pine	1990	50
	Other pines	1990	60–100
	Cork/oaks	1990	150–200
	Eucalyptus	1990	8–15
	Poplars	1990	8–20
	Coppice	1990	8–20
Portugal	–	–	–
Spain	–	–	–
Mediterranean Middle	–	1990	"...regimes used in the coniferous forest...resemble those applied in Central European regions although rotation ages are shorter"
Italy	–	1990	"Part of the stands are grown to high rotation ages"
Yugoslavia	–	–	–
Albania	–	–	–
Mediterranean East	–	–	–
Bulgaria	–	–	–
Greece	–	–	–

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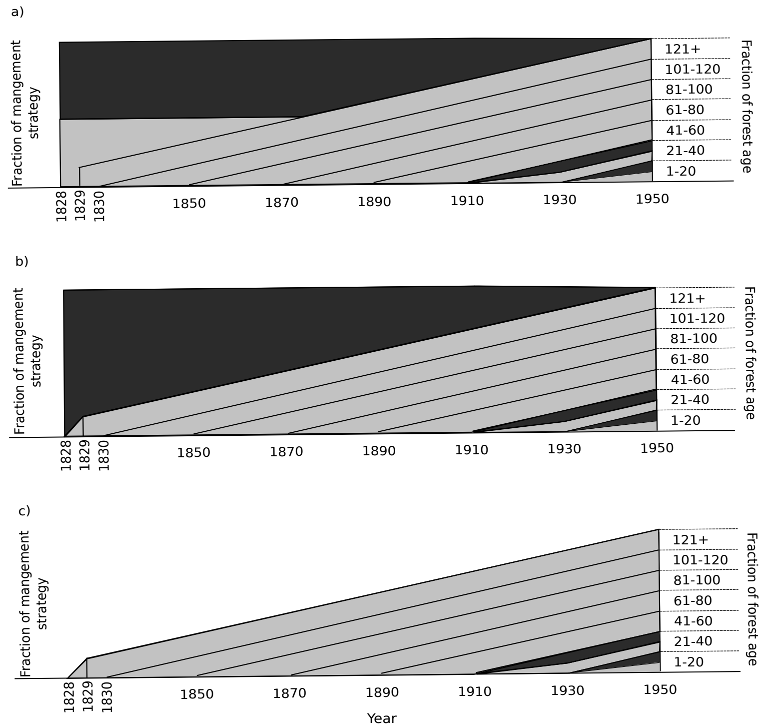

Figure 1. Conceptual presentation of the common forest management transition at the pixel level and how they were dealt with in the reconstruction. **(a)** In 1828 the demand–supply approach resulted in more high stands then expected from the backcasting method. **(b)** The surface area of high stand forest in 1828 is less than expected based on backcasting. **(c)** No coppice management in 1828 based on demand–supply but there is coppicing in 1829 based on backcasting. Dark grey shows coppice management, light grey shows high stand management.

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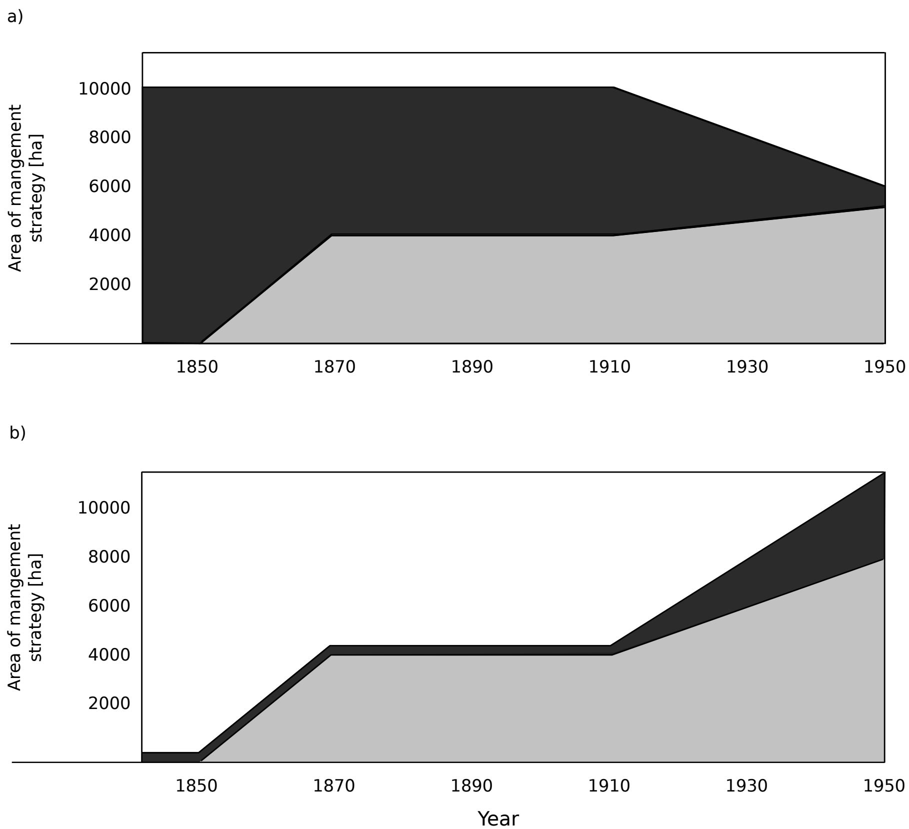

Figure 2. Conceptual presentation of the common forest management transition at the pixel level and how they were dealt with in the reconstruction. **(a)** The amount of coppice area in 1850 was higher than what is required in 1950. **(b)** The amount of coppice area in 1850 was lower than what is required in 1950. Dark grey shows coppice management, light grey shows high stand management.

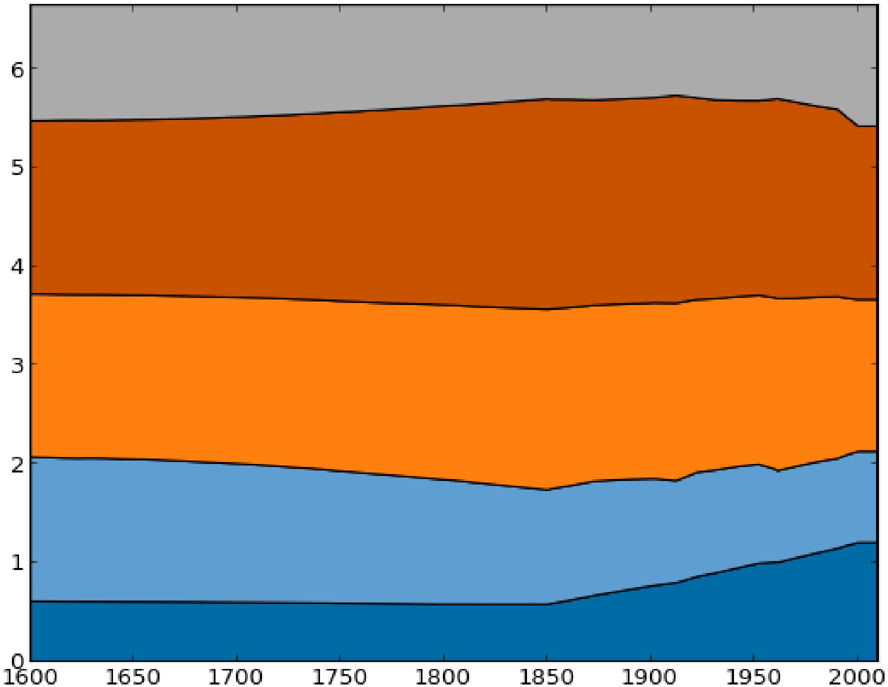

Figure 3. Land surface area in 10^6 km^2 covered by forest (blue), grassland (orange), cropland (brown) and bare soil (grey) between 1600 and 2010. The forest area is further separated in coniferous (dark blue) and deciduous (light blue).

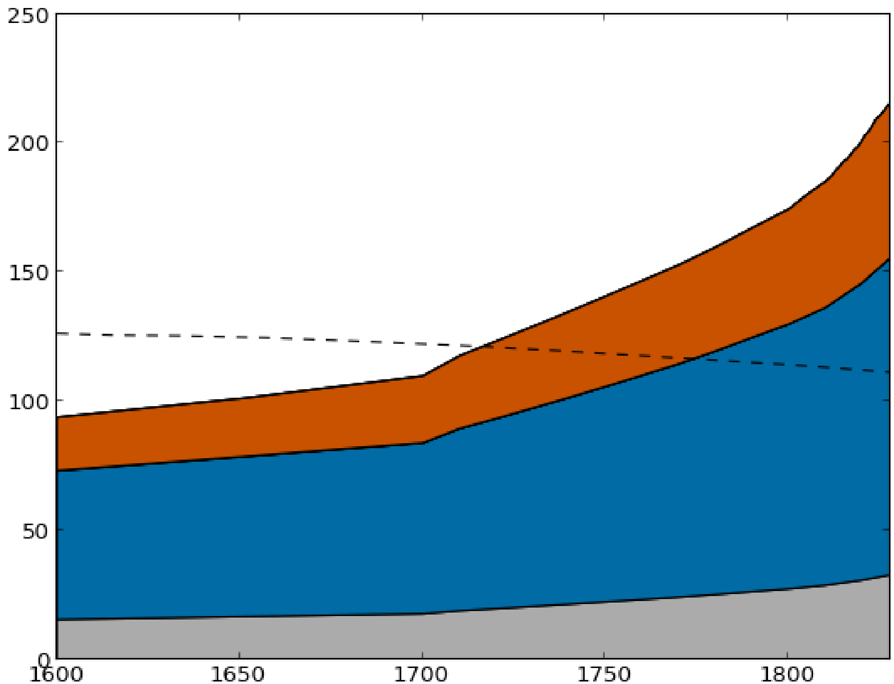

Figure 4. Total estimated wood demand (stacked surfaces) and wood supply (dashed line) in Tg C between 1600 and 1829. The wood demand distinguishes between fuelwood for households (grey), fuelwood for salt production (not visible), fuelwood for industrial processes (blue) and timber used for construction (brown). Expansion factors and assumptions of this reconstruction are detailed in Table 1.

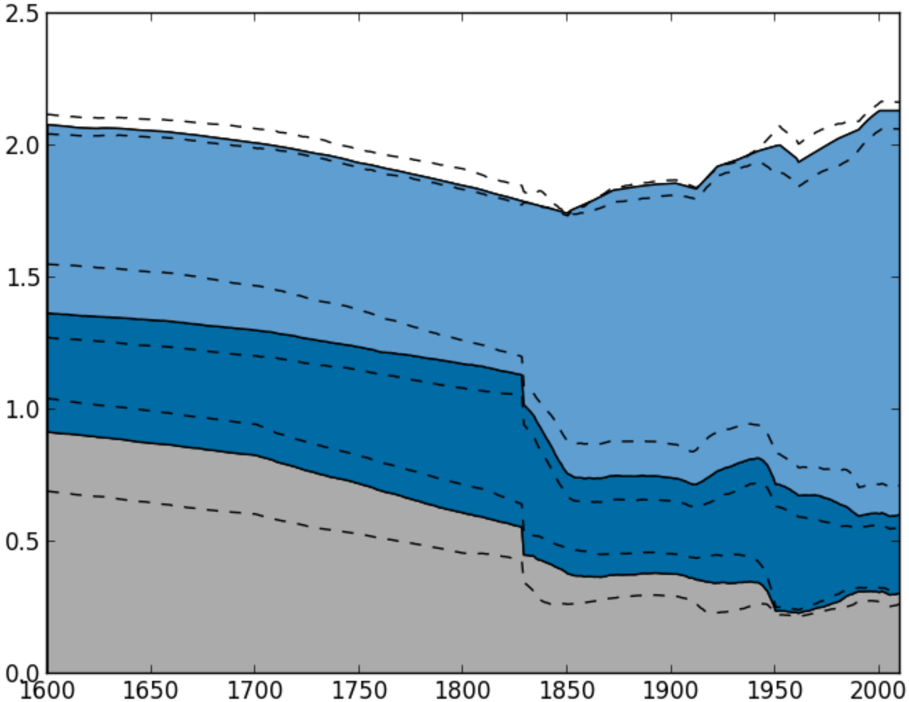

Figure 5. Total area (10^{12} km^2) of unmanaged (gray), high stand (light blue) and coppice (dark blue) forests between 1600 and 2010. The full lines show the best available estimates whereas the dashed lines show the sensitivity of the management reconstruction to the "minimal importance" threshold (see Sect. 2.4.6).

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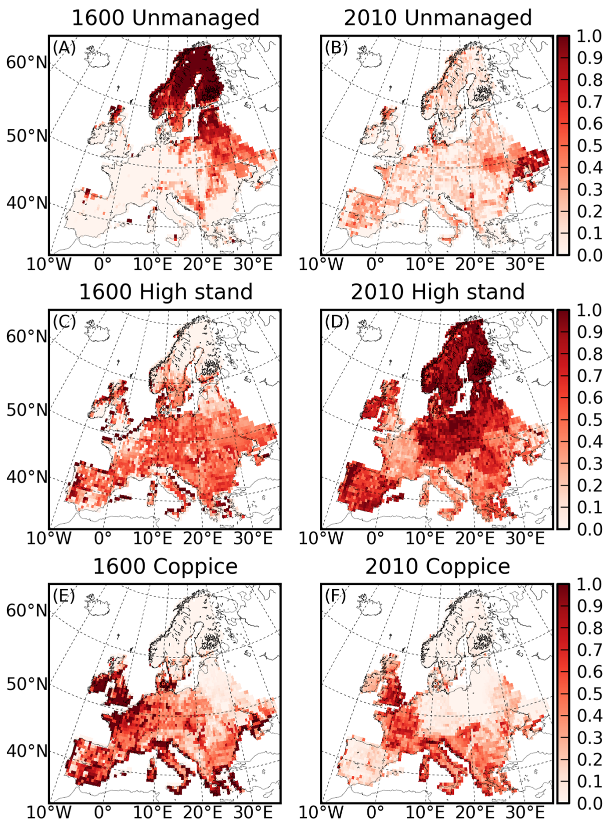

Figure 6. Distribution of management strategies over Europe. **(a)** Unmanaged forests in 1600 and **(b)** in 2010. **(c)** High stand forests in 1600 and **(d)** in 2010. **(e)** Coppice management in 1600 and **(f)** in 2010. The colorbar shows the fraction of the forest managed by a given strategy. Pixels along the coastlines often contain few forests, frequently resulting in the entire pixel being under a single management strategy.

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