Ancient forest statistics provide centennial perspective over the status and dynamics of forest area in France

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RESEARCH PAPER

Ancient forest statistics provide centennial perspective over the status and dynamics of forest area in France

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Abstract

• ***Key message*** **Centenary forest statistics informing major attributes of French forests were digitized, checked for consistency, and used to infer forest dynamics. Comparison to forest inventory data highlights increases in forest area and tree diversity, and substantial maturation of forests. Dataset access at** https://doi.org/10.5281/zenodo.3739458
• ***Context*** The history of European forest dynamic remains fragmental. In France, the *Daubrée* statistics (1908) and agricultural statistics (1892, 1929) formed fundamental material to fill this gap.
• ***Aims*** Release, test, and summarize the digitalized dataset. Analyze long-term forest changes in forest area, composition, and structure.
• ***Methods*** Primary data on forest area across NUTS-3 geographic units, split by forest management and ownership categories and dominating tree species (*Daubrée*), were digitized and cross-compared. Centennial changes in forest attributes were assessed from modern forest inventory data.
• ***Results*** Cross-comparison revealed: (1) strong temporal consistency in forest changes over time, (2) systematic and interpretable biases in ownership/management categories between *Daubrée* and agricultural statistics. Strong shift from coppices to high forests, increased prevalence of private ownership, and constant proportion of broadleaf- and conifer-dominated forests were highlighted, with increased tree species diversity at country scale.
• ***Conclusion*** Ancient statistics are shown to play a major role in retrospective land-use and forest policy analysis.

Keywords Historical data · National forest inventory · Forest dynamic · Land-use change · Forest structure · Tree diversity

1 Introduction

As an outcome of past demographic transition and industrial revolution, most European countries have been experiencing a forest transition since the nineteenth century, consisting of a strong regain of forest area (Mather 1992; Meyfroidt and Lambin 2011). While present forests' state has been accurately documented since 1990 with implementation of Forest Europe reporting (Forest Europe 2015) and the increasing implementation of statistical national forest inventory (NFI) programs across Europe (Tomppo et al. 2010), forest dynamics over more ancient time periods remains poorly covered (Mather et al. 1999; Meyfroidt and Lambin 2011). This has prevented from elaborating a clear view on the nature and dynamic of forest changes after the forest transition, including appraisal of areal, structural and compositional forest changes. Such long-term perspective is however of major concern to forest status and ecosystem conservation appraisal (Willis and Birks 2006; Foster et al. 2003).

Across European countries, forests of metropolitan France are those currently experiencing the strongest areal and growing stock changes (Forest Europe 2015). According to the French NFI, started in 1961, French forests have been increasing by almost 17% in area over 30 years (Denardou et al.

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2017). This increase results from both land abandonment (Chakir and Madignier 2006; Cavailhès and Normandin 1993) and forest extension ensuing from natural colonization, and active afforestation programs based on conifer species (afforestation of the Landes de Gascogne in Southwestern France by the mid-nineteenth century, David 1993, Buffault 1942; Restoration of Mountain Terrain (RTM) by the end nineteenth century, Saillet 1991; or afforestation supported by the National Forest Fund (FFN) after WWII, Betolaud 1972), with unquantified consequences on forest area and composition. Also, spontaneous forest maturation may have strongly modified the prevalence of forest management types (e.g., coppice or high forest abundance) together with the growing stock.

With this respect, ancient forest data are fairly available in France as compared with other countries (Mather et al. 1999). The first comprehensive survey of French forests is provided by *Daubrée* statistics of 1908 (Daubrée (Ministère de l'agriculture, FRANCE) 1912; Brenac 1984). Preliminary analysis of these data revealed an increase by + 60% in the forested area over one century (Denardou et al. 2017). These ancient data were not yet based on survey sampling, and methods actually used remain unspecified. Also, no definition of forests based on dimensional and vegetation cover criteria (international forest definition of FAO 2000) was used at this remote period of time, making these figures uncertain as regards how forested land was distinguished from other types of vegetation and land uses.

In this respect, agricultural statistics provide valuable information for both the test of data consistency by cross-comparison approaches, and analyses of forest-area changes. Between 1862 and 1929, five decennial agricultural statistics have been produced by public authorities about every 10–30 years (1862, 1882, 1892, 1902, and 1929; Oberlé 2000). All of them include a section dedicated to forests. In addition to the *Daubrée* statistics of 1908, agricultural statistics from 1892 to 1929 were considered in the present study, with a view to cross-compare ancient statistics, and cover a period distant by around one century to present time for analyses of long-term forest changes.

The three statistical surveys describe forest area according to three categorical variables of interest: (1) the department administrative units, corresponding to the 90 NUTS-3 units of the nomenclature of the European Commission (European Parliament and Council of the European Union 2003) with an area of 3000 to 10,000 km^2 per unit; (2) forest management types, where at least coppices, high forests or coppice-with-standards forests are distinguished. Of note, forest management types primarily reflected objectives of forest planning rather than physical forest structure; (3) the legal category of forest ownership. In addition, *Daubrée* statistics provides areal statistics for major forest tree species of the country, making it possible to infer long-term compositional changes in French forests by comparison with present NFI data that are available yearly on the whole French territory since 2005.

The first objective of this paper was to improve our knowledges about past forest dynamics based on ancient statistics. The underlying goals were: (1) to digitize the three ancient statistics, only found in paper or image format to date, in order to make them available for further analysis; (2) to analyze and cross-compare ancient statistics to evaluate their consistency; (3) to analyze forest dynamics over more than one century, according to forest management types, ownership categories, and forest tree species, where modern NFI were also used. All comparisons between statistics required harmonization of data variables and resolution.

2 Material and methods

2.1 Data description

2.1.1 Data overview

Daubrée statistics *Daubrée* statistics (names after its director) as the first comprehensive forest statistics in France was published in two volumes in 1912. Data were collected by the administration of "Eaux et Forêts" ("Water and Forests", Corvol 2013) between 1904 and 1910 (Brenac 1984). Nevertheless, all data refer to 1908 (Brenac 1984; Oberlé 2000). Protocols for historical data acquisition remain fragmental. Forest data were collected from the archives of "Eaux et Forêts", and from forest owners and associated organization. Forest areal data were provided by public local authorities and ensued from the French land registry (Corvol 2013; IGN 2013). The statistics provides forest information also at a resolution below the NUTS-3 level, i.e. by "canton" administrative units (LAU-1 of the EC, > 3000 units in France; European Parliament and Council of the European Union 2013). While the latter resolution remains out of scope of the present study, it was, e. g., used in Dupouey and Hervé (2013) for spatial inference of forest changes.

One synoptic table of *Daubrée* statistics is reproduced in Annex 1.

Decennial agricultural statistics of 1892 and 1929 Decennial agricultural statistics (Ministère de l'Agriculture - Direction de l'Agriculture 1892; 1929) were intended to provide a comprehensive survey of the agricultural land of the national territory and its associated productions (Hitier 1899; Fromont 1938). A special section is dedicated to forests. We considered data from this section, only.

Decennial agricultural statistics relied on questionnaire surveys of municipalities (Oberlé 2000). Survey results were aggregated by the French administration prior to their publication (Musset 1938).

Agricultural statistics of 1892 (published in 1897 and acquired in 1892, Hitier 1899) and 1929 (published in 1936 and acquired between 1928 and 1933, Musset 1938) also provide information on forest area and harvested volume at the departmental scale.

Forest tables of both decennial agricultural statistics are reproduced in Annex 1.

Complementary data from the French national forest inventory NFI data were used to assess changes in both forest structure and composition over a one-century period.

Inventory data rely on an annual and spatially systematic sampling of forests (Robert et al. 2010; Vidal et al. 2016) and comply with the international FAO definition of forest (FAO 2000). With aggregation of successive years of inventory increasing data precision (Wernsdörfer et al. 2012) a 5-year aggregation of 2006-to-2010 inventories (median year 2008) distant by 100 years from the *Daubrée* statistics was computed.

2.1.2 Standard categorical variables

Daubrée statistics Forest area was split by ownership category and submission to the "Forest regime", associated to legally-binding management rules defined by the forestry code of 1827 (Némoz-Rajot 1998, Annex 2) and isolating: State-owned forests, municipal forests, and forests of other territorial public bodies subjected to forest regime; municipal forests non subjected to the forest regime and private forests (never submitted to the forest regime). In addition to the three forest management types identified in all three statistics (see Introduction), two management types were specific of *Daubrée* statistics: (i) the transient regime of coppice conversion enforced by the forest law of 1827, and aiming at shifting to high forests for timber production (Degron 1998), and (ii) unproductive forest areas. The latter corresponded to marshes, bogs, rocks, and reforestation perimeters of forest protection programs. "Unproductive" hence needs to be understood in the literal meaning of not subjected to tree felling, as these areas are systematically encompassed for estimation of the afforestation rating, yet systematically associated with zero harvested volume.

Daubrée statistics included statistics on forest owners and annual harvested volume. All state variables available are summarized in Tables 1 and 2.

Decennial agricultural statistics of 1892 and 1929 Forest area was classified according to forest management type, ownership category, and forest regime submission (Tables 1 and 2). Both statistics split the area of high forests according to botanical classes (broadleaf- or conifer-dominated forests). Whereas no information on the method used to achieve this distinction (evaluation of class predominance), the significance of compositional mixtures in French forests (Morneau et al. 2008) makes these figures uncertain.

Like in the *Daubrée* statistics, specific forest management types were identified. 1892 statistics includes category decree afforestation perimeters and unproductive coastal dunes solely found in forests subjected to the forest regime. This complies with the temporary or permanent acquisition by the State, of lands dedicated to landscape protection in coastal and mountain areas, as ordinated by successive RTM laws (Saillet 1991; Sonnier 1991). 1929 statistics includes a forest management type related to recently afforested area.

In addition, annual harvested volume is included in both decennial agricultural statistics (Table 2).

French national forest inventory We used the breakdown of the forest area according to ownership category and the forest regime submission (State-owned forests, municipal and other public forests subjected to forest regime, private and other public forests non-subjected to forest regime merged in the NFI process).

Forest area at a NUTS-3 resolution was further broken down by stand vertical structure (i.e., coppice, coppice-with-standards, and high forest). The definitions of these structures are provided in Annex 3.

2.1.3 Tree species composition

This data was available in *Daubrée* statistics and current forest inventory data. In the first one, forest area of a given NUTS-3 unit was split by forest tree species at a 10% resolution, in two broad ownership categories: (i) public forests subjected to the forest regime, (ii) forests not subjected to the forest regime (predominantly private forests). Tree species listed in *Daubrée* statistics varied across NUTS-3 units and were partially described by genus or common names, requesting technical harmonization (Annex 4).

In NFI data, plots (and associated estimated area) are described by a dominant species of the canopy layer of the census strata (trees with diameter ≥ 7.5 cm). 3.3% of total forest area has a non-identified dominant species (open forests).

2.1.4 Statistics for *Bas-Rhin*, *Haut-Rhin*, and *Moselle* units

Territories of three NUTS-3 units (*Bas-Rhin*, *Haut-Rhin* and *Moselle*) were annexed by Germany between 1870 and 1918, and their forests were not described in *Daubrée* statistics and in decennial agricultural statistics of 1892. Owing to the existence of the German statistics of 1907 (Ministerium für Elsaß-Lothringen 1909), we supplemented the statistics to cover the whole territory in *Daubrée* statistics.

German statistics provided information on the legal category of ownership (State-owned forests, municipal forests, and private forests). However, forest areas were not split by

Table 1 Description of variables found in ancient forest statistics and national forest inventory

Statistics	Data resolution	Tree species	Forest area split by	
			Ownership category	Forest management type (or structure type for NFI data)
Decennial agricultural statistics (1892)	86 NUTS-3	—	MPBNS	SC / CWS / HBF / HCF
			PNS	SC / CWS / HBF / HCF
			MPBS	SC / CC / CWS / HF/ DPUD
			SFS	SC / CC / CWS / HF/ DPUD
German statistics (1907) for *Bas-Rhin*, *Haut-Rhin* and *Moselle* units	3 NUTS-3 (*Bas-Rhin*, *Haut-Rhin* and *Moselle*)	—	M	—
			P	—
			SFS	—
Daubrée statistics (1908)	86 NUTS-3, LAU-1 and arrondissements of Paris	15 main tree species and two tree species botanic class (*various broadleaves* and *various conifers*)	MPBNS	SC / CC / CWS / HF / UA
			MPBS	SC / CC / CWS / HF / UA
			PNS	SC / CC / CWS / HF / UA
			SFS	SC / CC / CWS / HF / UA
Decennial agricultural statistics (1929)	89 NUTS-3	—	MNS	SC / CWS / HBF / HCF / RF
			MPBNS	SC / CWS / HBF / HCF / RF
			PBNS	SC / CWS / HBF / HCF / RF
			PNS	SC / CWS / HBF / HCF / RF
			S	SC / CWS / HBF / HCF / RF
NFI (2008[1])	90 NUTS-3	70 tree species	M	C / MCHF / EAHF / UAHF / NS
			P	C / MCHF / EAHF / UAHF / NS
			SF	C / MCHF / EAHF / UAHF / NS

—: not available variables. [1] median year

Ownership categories: *S* forests subjected to the forest regime, *SF* state-owned forests, *SFS* state-owned forests subjected to the forest regime, *M* municipal forests (and other territorial public bodies' forests), *MPBS* municipal forests and other territorial public bodies' forests subjected to the forest regime, *MNS*: municipal forests not subjected to the forest regime, *MPBNS* municipal forests and other territorial public bodies' forests not subjected to the forest regime, *PBNS* other territorial public bodies' forests not subjected to the forest regime, *P* private forests, *PNS* private forests not subjected to the forest regime. Forest management types: *C* coppice, *SC* simple coppice, *CC* coppice conversion (into high forest), *CWS* coppice-with-standards, *MCHF* mixture of coppice and high-forest, *HF* high forest, *HBF* high broadleaved dominated forest, *HCF*, high coniferous dominated forest, *EAHF*, even-aged high forest, *UAHF* uneven-aged high forest, *DPUD* decreed perimeters and unproductive coastal dunes, *RF*: recently afforested forest area, *UA* unproductive area

management type. Thus, German data were used in relation with *Daubrée* statistics solely for information on the total forest area and on forest area split by ownership category.

Bas-Rhin, *Haut-Rhin*, and *Moselle* NUTS-3 units in the 1892 statistics could not be supplemented by German data.

Table 2 Summary of data found in ancient forest statistics and national forest inventory. We provide minimum and maximum values (in square brackets) at NUTS-3 unit scale. Also, we provide totals for the whole of France

	Decennial agricultural statistics (1892)	German statistics (1907) for *Bas-Rhin*, *Haut-Rhin* and *Moselle* units	*Daubrée* statistics (1908)	Decennial agricultural statistics (1929)	NFI (2008[1])
Total forest area (ha)	[2158–522,768] 9,520,000	[125,201–160,485] 445,000	[1810–516,608] 9890000	[2122–626,836] 10,675,000	[25,632–567,423] 16,155,000
Total annual harvested volume (m^3)	[10,596–1,774,267] 27,600,000	—	[2296–1,904,118] 23,500,000	[0–883,400] 4,700,000[2]	[20,070–4,649,477] 44,500,000
Number of private owners	—	—	[73–67,207] 1,530,000	[0–49,589] 1,210,000	—
Afforestation rate (%)	[3.5–56.1] 18.0	—	[3.3–55.4] 18.7	[3.0–66.9] 19.4	[5.1–62.5] 29.4

NFI national forest inventory. –:s not available data. [1] median year. [2] only for timber wood

2.2 Data entry and error correction

Ancient statistics were available in paper textbook format and image format. Areal data were given for each NUTS-3 unit (table rows) and intersections of forest management type and ownership categories (table columns). Marginal totals were also provided. Digitization of the three statistics was the first step of the present work (Audinot et al. 2020). Data from *Daubrée* statistics were digitized only at a NUTS-3 unit. Initial typing errors of different types were identified in ancient statistics by comparing row/column totals, and were corrected. They are summarized in Annex 5.

2.3 Harmonization of statistics

For the purpose of cross-comparison of forest area across the three ancient statistics, categorical variables were harmonized including tree species composition, forest management type, and ownership categories (Annex 4).

As an overview, forest areas by forest management type were found in equal proportions among the ancient statistics (Fig. 1), except for the other forests' areas found smaller, mainly in private forests (0% in 1892, 4.3% in 1908, and 2.1% in 1929, Table 3) in line with their heterogeneity. By contrast, high forests that formed a restricted category in ancient statistics are currently predominant (53%) in the total forest area (Fig. 1). Forest ownership categories were distributed in roughly the same proportions between the three ancient statistics (68% of the forest area was private in 1892, 66% in 1908, and 67% in 1929; Fig. 1).

Moreover, NUTS-3 units' boundaries were unstable between ancient statistics. The standardization of NUTS-3 units' boundaries and the analysis of their potential effects of the forest area changes are provided in Annex 6.

2.4 Data analysis

2.4.1 Principle

Forest area differences between successive statistics, including NFI data, were computed, with NUTS-3 units as the reference population. Forest area differences were analyzed at NUTS-3 level, as a whole, or conditionally to forest management type and ownership categories. Paired *t* tests were used to analyze forest area differences. Maps at NUTS-3 level were produced to detect spatial structures of forest changes.

2.4.2 Cross-comparison of ancient statistics

We analyzed forest area differences over two sets of successive statistics: the ancient periods 1892–1908 and 1908–1929. The following consistency criteria were considered:

- absence of erratic variations between forest area differences at successive periods (1892–1908 and 1908–1929 periods);
- absence of bias in the variables of interest documented in the three ancient statistics (forest management type and ownership category);
- accordance of forest area differences (direction and magnitude) with forest policies at play at both periods (1892–1908 and 1908–1929 periods), and with forest transition features.

2.4.3 Long-term changes in forest area

Forest area differences by NUTS-3 units, forest management types, and ownership categories were also analyzed over two long periods: 1892–1929 (ca. 40 years) and 1908–2008 (ca. 100 years). Over the 1908–2008 period, we analyzed forest area differences at two levels of tree-species composition including botanical classes and tree species.

A synoptic view of periods studied, corresponding statistics, and NUTS-3 populations considered is summarized in Table 4.

3 Results

3.1 Cross-comparison of ancient statistics (1892–1908 and 1908–1929 periods)

3.1.1 Cross-comparison of forest statistics at NUTS-3 units level

Positive forest area differences were found in many NUTS-3 units in 1908–1929 period (70%, Fig. 2), less in 1892–1908 period (49%, Fig. 2). However, the average difference in NUTS-3 forest area was positive and significant at both periods ($p < 0.05$, Table 5). Strong standard-deviations of forest area differences indicated large heterogeneity across NUTS-3 units (Table 5). Yet, differences lower than −2000 ha of forest at both periods were only observed for two NUTS-3 units (Pyrénées-Atlantiques and Gers).

An obvious spatial structure in positive/negative differences was identified (Fig. 2). Over the 1892–1908 period, most NUTS-3 units showing positive differences were situated in Eastern France, essentially formed of public forests, with negative differences located in Western and central France, where forests remain largely private. Over the 1908–1929 period, positive differences extended to northern France, with differences found to reverse in Central and Southern France. Differences in Western France turned null or positive (Fig. 2). Also, some southern NUTS-3 units showed negative

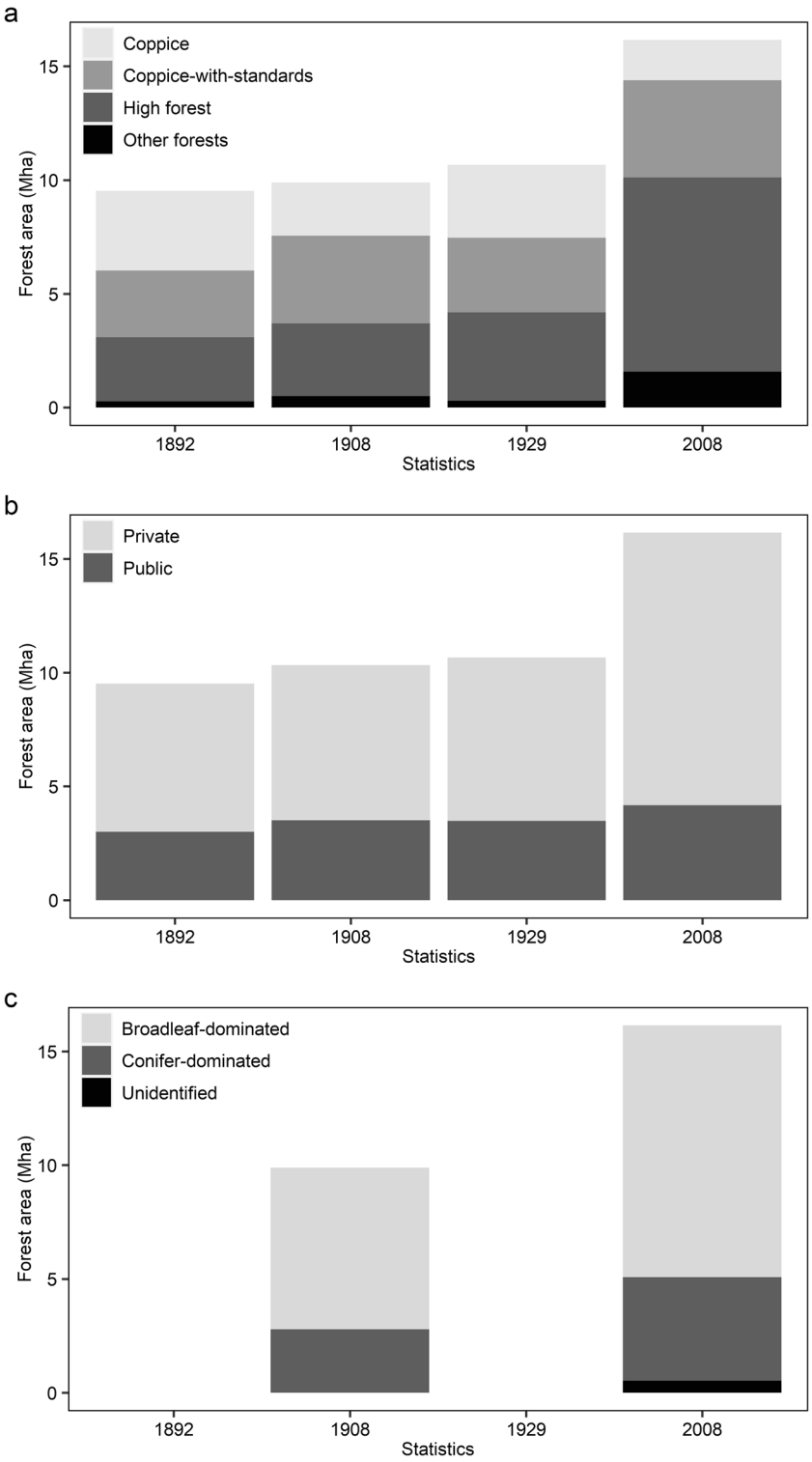

Fig. 1 French forest area split by forest management (**a**), ownership (**b**), and species composition (**c**) categories according to three ancient statistics (1892, 1908, and 1929) and national forest inventory data (2008), *Bas-Rhin*, *Haut-Rhin*, and *Moselle* NUTS-3 units were excluded as these were not documented in the *Daubrée* statistics (German annexation), Corsican NUTS-3, and those surrounding Paris were considered as a single unit. Data about tree species composition do not exist in 1892 and 1929 statistics

differences after positive differences in the previous period (for example forest area in Ariège with + 5000 ha/− 60,000 ha over 1892–1908/1908–1929 periods, respectively). Such shifts suggested a bias in *Daubrée* statistics relative to other decennial agricultural statistics, corresponding to underestimation of private forests.

3.1.2 Cross-comparison of forest statistics by forest management type

The analysis of forest area differences by forest management types showed significant and inverse differences between coppice forests (± over 1892–1908/1908–1929 periods;

Table 3 Summary statistics for the French forest area according to the four data sources under study.

			Forest area ($\times 10^3$ ha)				
			Decennial agricultural statistics (1892)	German statistics(1907) for *Bas-Rhin*, *Haut-Rhin* and *Moselle* units	*Daubrée* statistics (1908)[1]	Decennial agricultural statistics (1929)	NFI (2008[2])
Forest management type by ownership category	Private forest	Coppice	3210	90[3]	2050	2840	1535
		Coppice-with-standards	1515		2430	1900	3420
		High forest	1790		1980	2315	5765
		Other forests	0		280	145	1275
	State-owned forest subjected to the forest regime	Coppice	20	155[3]	25	–	45
		Coppice-with-standards	410		405	–	235
		High forest	460		620	–	1135
		Other forests	200		150	–	85
	Other public forest subjected to the forest regime	Coppice	270	200[3]	260	370	190
		Coppice-with-standards	1000		1015	1370	610
		High forest	575		600	1585	1635
		Other forests	70		75	150	225
	Public forest in total subjected to the forest regime	Coppice	290	355[3]	285	370	235
		Coppice-with-standards	1410		1420	1370	845
		High forest	1035		1220	1585	2770
		Other forests	270		225	150	310
Totals			9520	445	9890	10,675	16,155

[1] without *Bas-Rhin*, *Haut-Rhin*, and *Moselle* NUTS-3 units. [2] median year. [3] breakdown by forest management type not provided in original data. –: not available data

NFI national forest inventory

$p < 0.001$) and coppice-with-standards forests (± over the same periods; $p < 0.001$, Table 5). Hence, 87% of the NUTS-3 units had negative differences over the 1892–1908 period in coppice forests, and conversely 71% of these units had positive differences over the "1908–1929" period Fig. 3). In coppice-with-standards forests, 76% of the NUTS-3 units had positive differences over the 1892–1908 period, while 74% of these had negative differences over the 1908–1929 period, Fig. 3). *Daubrée* statistics thus systematically over-estimated the area of coppice-with-standards forests at the expense of those of coppice forests, as compared to other decennials agricultural statistics.

Table 4 Statistics and population of NUTS-3 units used by study periods, The transition from 89 to 86 department administrative units (NUTS-3) is due to the annexation of the *Alsace-Moselle* region. *Gironde* was excluded from the whole paired *t* tests but it was kept in all other calculations (Annex 4)

Periods	Statistics used				Number of NUTS-3 used in analyzes			
	Decennial agricultural statistics (1892)	*Daubrée* statistics (1908)	Decennial agricultural statistics (1929)	NFI (2008[1])	Whole French forest	Ownership category	Forest management type	Tree species
1892–1908	X	X			86	86	86	
1908–1929		X	X		89	89	86	
1892–1929	X		X		86	86	86	
1908–2008		X		X	89	89	86	86

NFI national forest inventory.[1] median year. X: statistics used

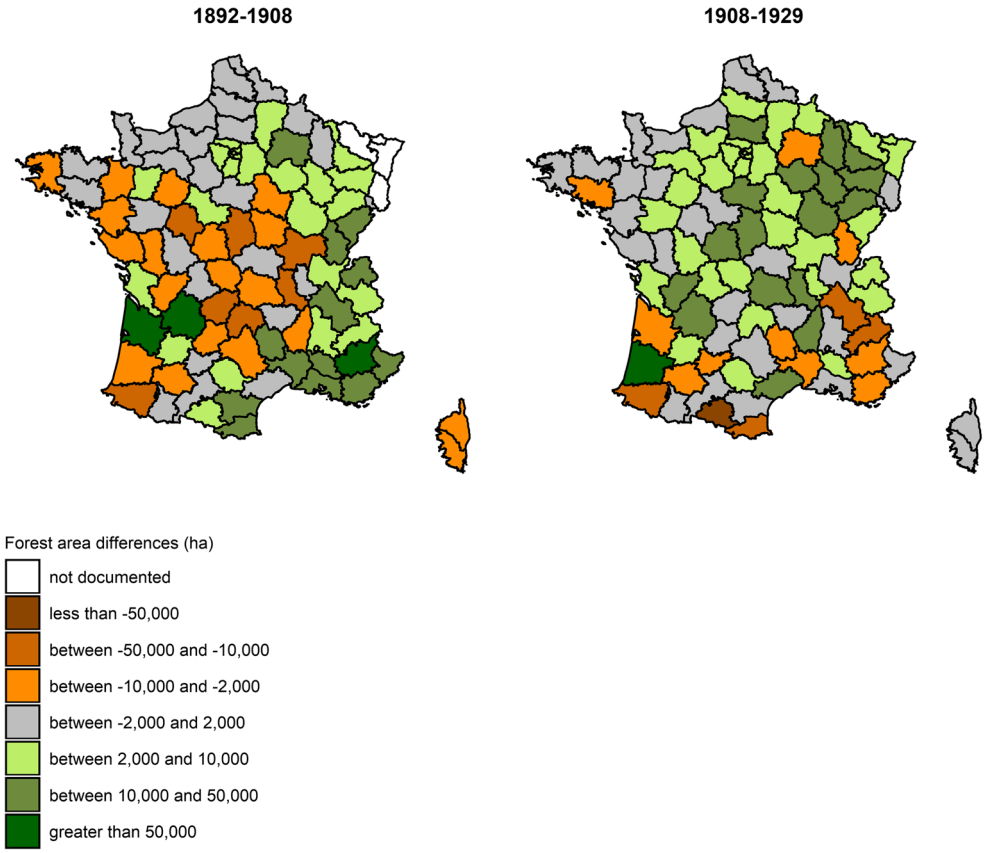

Fig. 2 Forest area differences across NUTS-3 units of the territory over the 1892–1908 and 1908–1929 periods of the statistical cross–comparison, See Fig. 1 for details on NUTS-3 data

The large standard-deviations of forest area differences found in other forests' areas despite their small areas (Fig. 3 and Table 3) pointed out to the heterogeneous definition of this forest management type (Table 5). For example, other forests' areas in *Gironde* and *Landes* showed large differences over the one or two periods (+ 78,000 ha over the 1892–1908 period and − 73,000 ha over the 1908–1929 period in *Gironde*; + 1400 ha over the 1892–1908 period and + 58,000 ha over the 1908–1929 period in *Landes*) at a time of active afforestation, bound to explain these strong differences.

In contrast, means of forest area differences were much more constant in high forests (Table 5) and both positive and statistically significant ($p < 0.01$ for 1892–1908; $p < 0.05$ for 1908–1929, Table 5). Positive differences represented 56% of NUTS-3 units over the 1892–1908 period and 76% units over the 1908–1929 period (Fig. 3).

3.1.3 Cross-comparison of forest statistics by ownership category

Over 1892–1908 and 1908–1929 periods, a substantial fraction of NUTS-3 units showed positive forest area differences in public forests (64% of NUTS-3 units over the 1892–1908 period, 69% of NUTS-3 units over the 1908–1929 period, Fig. 3), however, statistically significant only in the first period ($p < 0.01$, Table 5). The strong increase in public forests area over the 1892–1908 period was in agreement with the spatial structure identified in the Eastern half of France (Fig. 2) where there is a large share of public forest.

Fifty-five percent of NUTS-3 units in private forests also showed a negative forest area differences over the 1892–1908 period. Among them, 68% then had positive differences over the period 1908–1929. Means of forest area differences means between these NUTS-3 units showed inverted differences over the two periods (− 5200 ha/NUTS-3 units over the 1892–1908 period and + 4900 ha/NUTS-3 units over the 1908–1929 period), but these differences were statistically significant only for the 1908–1929 period ($p < 0.01$, Table 5). These results confirmed the underestimation of private forests areas in the *Daubrée* statistics, as inferred in 3.1.1.

Area of private forest in *Gironde* and *Landes* (southwestern France) last showed tremendous differences at a period of active afforestation (+ 110,000 ha in *Gironde* over the 1892–1908 period, + 110,000 ha in *Landes* over the 1908–1929 period).

3.2 Long-term changes in forest area (1892–1929 and 1908–2008 periods)

3.2.1 Historical differences in whole French forest area

Significantly positive forest area differences in total forest area were identified at both periods ($p < 0.001$ in

Table 5 Summary of forest area differences across NUTS-3 units over the four periods under study, Forest area differences calculated for the 1892–1908, 1908–1929, 1892–1929, and 1908–2008 periods according department administrative units (NUTS-3) population. Significance assessed from paired *t* tests

		1892–1908			1908–1929			1892–1929			1908–2008		
		FAD mean ($\times 10^3$ ha)	FAD standard-deviation ($\times 10^3$ ha)	Paired *t* test	FAD mean ($\times 10^3$ ha)	FAD standard-deviation ($\times 10^3$ ha)	Paired *t* test	FADmean ($\times 10^3$ ha)	FAD standard-deviation ($\times 10^3$ ha)	Paired *t* test	FAD mean ($\times 10^3$ ha)	FAD standard-deviation ($\times 10^3$ ha)	Paired *t* test
Total forest area		+ 4.2	16.5	< 0.05	+ 3.8	15.2	< 0.05	+ 8.1	20.7	< 0.001	+ 65.4	57.4	$< 10^{-10}$
Ownership category	Public forest	+ 1.6	4.8	< 0.01	− 0.4	8.6	NS	+1.2	9.2	NS	+ 7.4	10.6	$< 10^{-8}$
	Private forest	+ 2.6	15.9	NS	+ 4.2	14.2	< 0.01	+ 6.8	20.3	< 0.01	+ 58.0	56.2	$< 10^{-10}$
Forest management type	Coppice	− 13.6	15.4	$< 10^{-10}$	+ 10.0	17.8	$< 10^{-5}$	− 3.6	17.0	< 0.1	− 6.6	19.3	< 0.01
	Coppice-with-standards	+ 10.8	15.0	$< 10^{-8}$	− 8.1	14.8	$< 10^{-5}$	+ 2.6	15.0	NS	+ 4.3	47.2	NS
	High forest	+ 4.3	11.7	< 0.01	+ 4.5	15.5	< 0.05	+ 8.8	18.8	$< 10^{-4}$	+ 57.0	40.5	$< 10^{-10}$
	Other forests	+ 2.8	9.1	< 0.01	− 2.5	13.2	< 0.1	+ 0.3	10.5	NS	+ 14.7	12.5	$< 10^{-5}$

FAD forest area difference

1892–1929 period and $p < 10^{-10}$ in 1908–2008 period, Table 5), suggesting a continuous increase in forest area since 1892. The magnitude of the total forest area difference at 1892–1929 period was + 700,000 ha, this corresponding to a relative increase by + 7% and to an annual rate of change by + 0.19% over the 1892–1929 period. However, large standard-deviations of forest area differences indicated that not all NUTS-3 units were subjected to positive differences over this period (30% of NUTS-3 units showed negative differences). Also, the total forest area differences in 1908–2008 period was around + 5,800,000 ha corresponding to a relative difference by + 36% and to an annual rate of change by + 0.45%, thus foot-printing an acceleration in forest areal increases between 1892 and 1929 and 1908–2008 periods ($p < 10^{-7}$).

3.2.2 Historical differences in forest area by forest management type

Forest area differences at both periods showed a decline in coppice forests on almost the whole territory, together with a large increase in high-forests over the 1908–2008 period, indicating a massive change in the structure of these forests over the period. In 1892, the area of coppice forests was of 3,500,000 ha. About one century later (2008), coppice forests have reached 1,700,000 ha, as documented by NFI data. Assuming that ancient coppice forests have fully evolved into high forests, and since the total increase in forest area is 5,800,000 ha, this suggested that an additional + 4,100,000 ha of high forests had another origin than coppice conversion since 1908. High forests, therefore, have formed the majority of afforested or returning forests since 1908 (Fig. 1 and Fig. 4).

Forest area differences in coppice-with-standard forests showed a North-South division over the 1908–2008 period (Fig. 4), with a marked decrease in Northern and Northeastern France (− 1,200,000 ha), where the area of high forests has increased (+ 2,500,000 ha), and a conversely marked increase in South France and Brittany (+ 1,600,000 ha) where coppice forests area has decreased (− 360,000 ha). Maps of forest area differences therefore suggested similar maturation in forest structure (coppice–coppice-with-standards–high forest) across the whole territory, though with a much longer apparent delay in southern France.

3.2.3 Historical differences in forest area by ownership category

Increase in private forests area was found substantial (corresponding to an annual rate of change + 0.27%/+

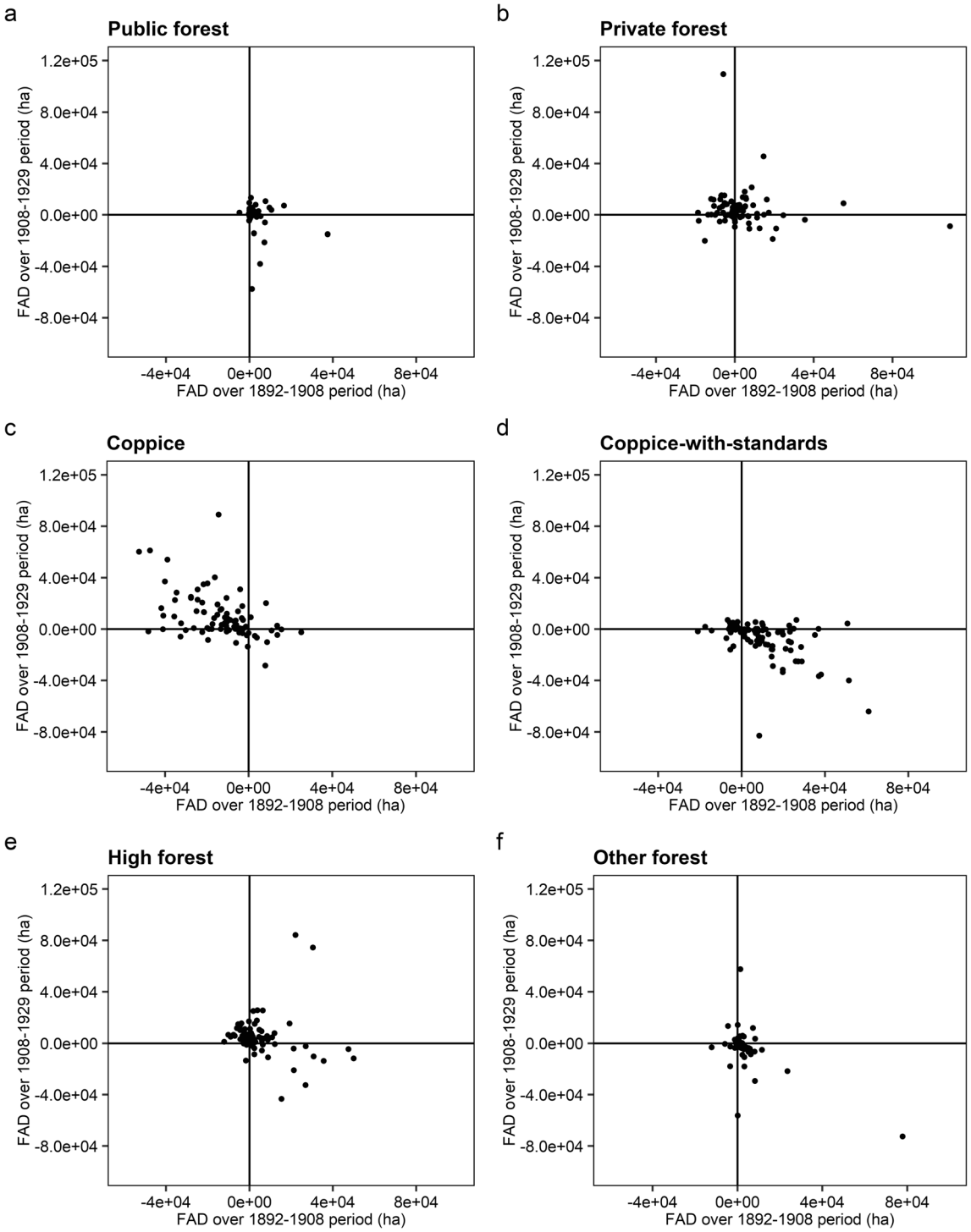

Fig. 3 Comparison of successive 1892–1908 and 1908–1929 periods forest area differences at a NUTS-3 level across forest management and ownership categories, See Fig. 1 for details on NUTS-3 data, FAD, forest area differences. **a** FAD in public forests. **b**: FAD in private forests. **c** FAD in coppice forests, **d** FAD in coppice-with-standards forests, **e** FAD in high forests, **f** FAD for other forests (see Annex 4 of the manuscript)

0.56% over 1892–1929/1908–2008 periods, respectively) and concerned 97% of NUTS-3 units over the 1908–2008 period. In 1908, the area of private forests was of 6,800,000 ha. About one century later (2008),

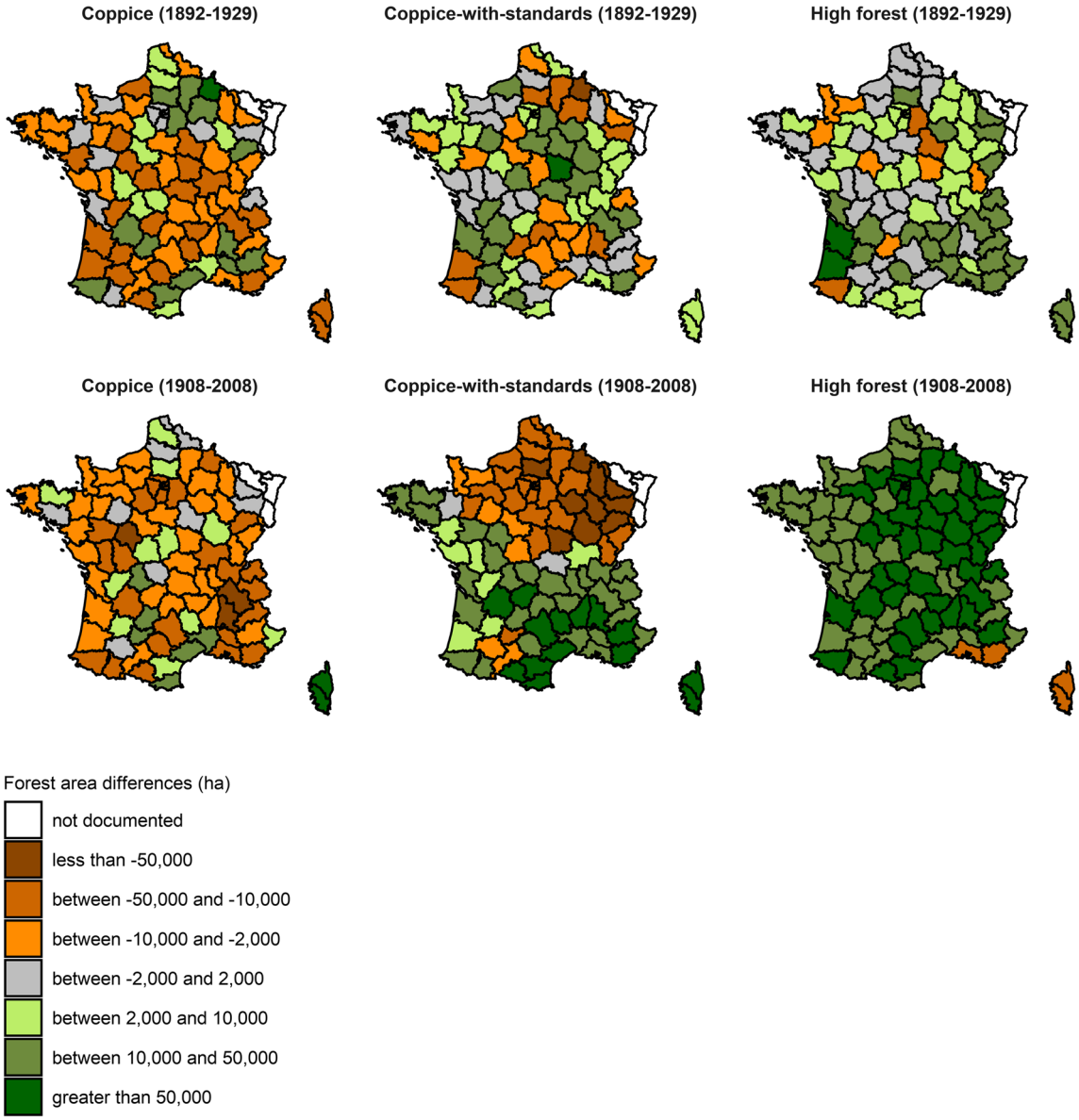

Fig. 4 Changes in forest area classified by forest management type across NUTS-3 units of the territory over the 1892–1929 and 1908–2008 periods, See Fig. 1 for details on NUTS-3 data

private forests area has almost doubled, reaching 12,000,000 ha. In private forests, mean of forest area differences was very strongly significant over the 1908–2008 period ($p < 10^{-10}$, Table 5). As a consequence, whereas two-thirds of French forests were private in ancient statistics, three-fourths of the forest area is nowadays private (Fig. 1).

Public forests also revealed significant differences over the 1908–2008 period (+ 700,000 ha, $p < 10^{-8}$, annual rate of change by + 0.17%, Table 5). The slight increase over 1892–1929 period was not statistically significant ($p = 0.21$, annual rate of change by + 0.39%, Table 5).

3.3 Long-term changes in forest composition

Broadleaf- and conifer-dominated forests showed significant positive differences over the 1908–2008 period (Fig. 5) with extension of broadleaved forests twice as intense in magnitude as in conifer forests (+ 3,600,000 ha, $p < 10^{-10}$ and + 1,600,000 ha, $p < 10^{-7}$, respectively), yet favored in afforestation

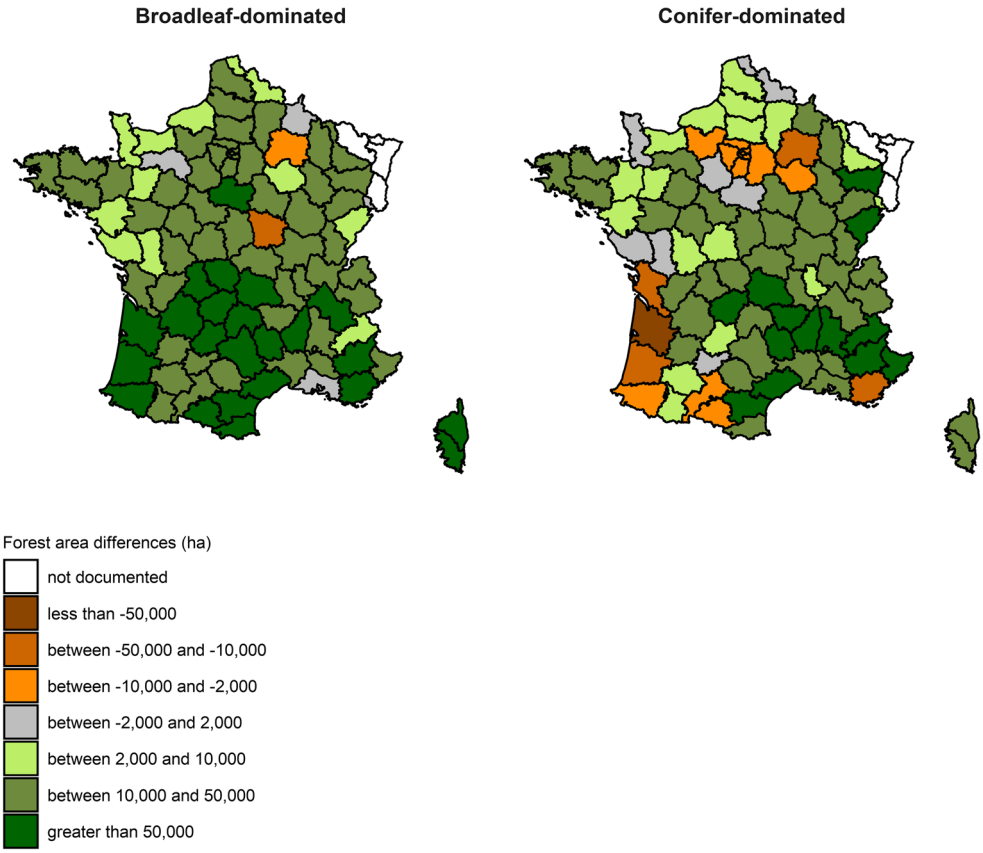

Fig. 5 Changes in broadleaf- and conifer-dominated forest area over the 1908–2008 period across NUTS-3 units of the territory, See Fig. 1 for details on NUTS-3 data

programs. Consistently, various broadleaves also progressed three times faster than various conifers (Table 6 in Annex 4). These relative changes were strikingly similar (+ 34/+38% in broadleaved/conifer forests), making the proportion of these forests unchanged over one century (Fig. 1).

Tree species (without various broadleaves and various conifers) showed a significant positive differences over 100 years (+ 3,900,000 ha or 67% of total extension, $p < 10^{-10}$), indicating that species identified in *Daubrée* statistics had been playing a role in forest extension.

Significant positive areal changes were detected in all tree species/species groups but hornbeam (*Carpinus betulus* L.) and cork oak (*Quercus suber* L.) showing negative and non-significant negative changes (Fig. 6 and Table 6 in Annex 4), two species that were important contributors to coppice production systems in France.

White oaks showed sharp significant positive areal changes (Fig. 6 and Table 6 in Annex 4) in a large part of territory (81% of NUTS-3 units). White oaks privileged in both coppice-with-standards and high forests took advantage of changes in the structure of the French forest.

Norway spruce (*Picea abies* Karst.) and pine species used in afforestation programs showed areal increases by + 40 to + 70% larger than those of, e.g., Silver fir (*Abies alba* Mill.), a coniferous tree species regenerated naturally (Fig. 6 and Table 6 in Annex 4). Also, European larch (*Larix decidua* Mill.) privileged in landscape protection programs of the nineteenth century still showed progression after *Daubrée* statistics (Fig. 6 and Table 6 in Annex 4).

In summary, the strong absolute progression of broadleaved-dominated forests was emphasized, with afforested coniferous tree species and coppice broadleaved species found at extreme magnitudes.

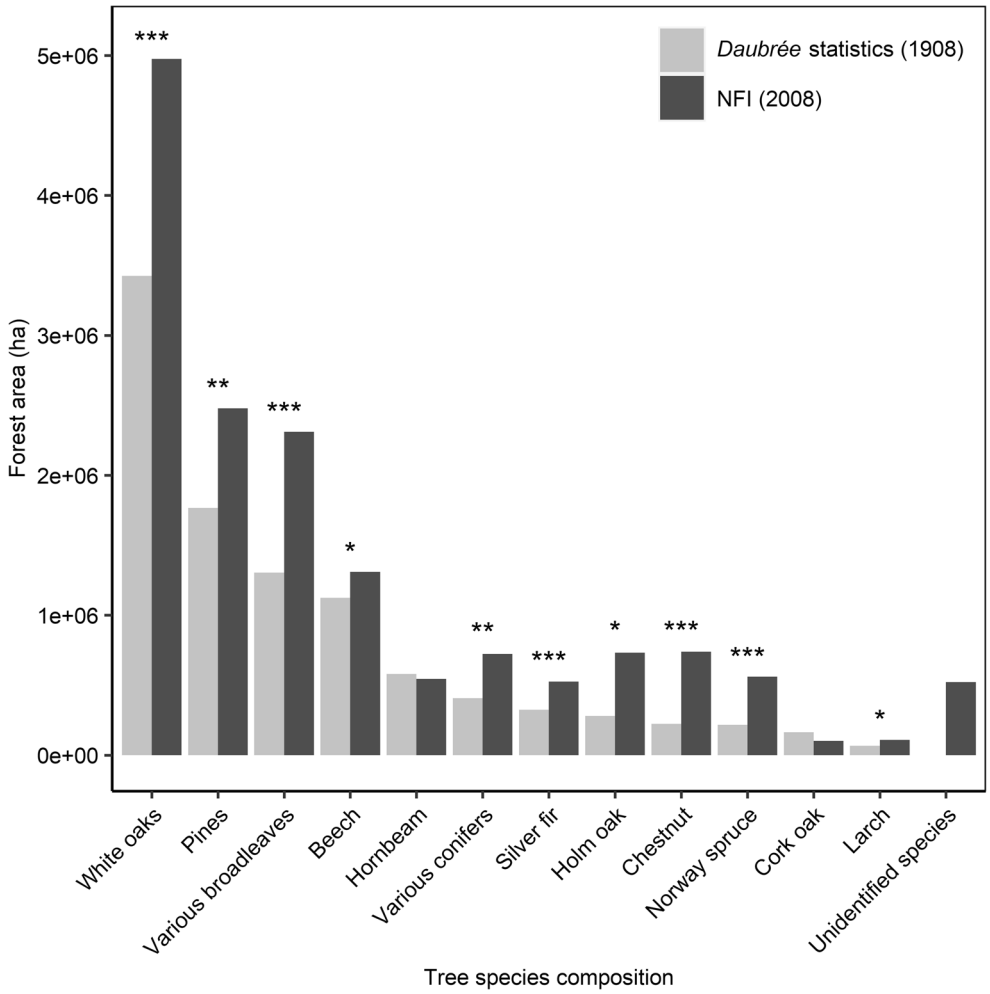

Fig. 6 Changes in forest area classified by dominating tree species/tree species groups of the French forests over the 1908–2008 period, See Fig. 1 for details on NUTS-3 data. Significance of forest area differences was assessed by paired *t* tests across the NUTS-3 population. Individual tree species not identified in the tree species groups white oaks, pines, various broadleaves and various conifers, (*): *p* value < 0.1. **p* value < 0.05. ***p* value < 0.01. ****p* value < 0.001

4 Discussion

4.1 Statistical value of ancient statistics

This study is based on historical sources of forest information: *Daubrée* statistics (1908) completed by a German forest statistic (1907) for *Bas-Rhin*, *Haut-Rhin*, and *Moselle* NUTS-3 units and decennial agricultural statistics of 1892 and 1929. Their supplementations with modern NFI data offered an extended overview on broad long-term forest changes, and in this sense, also increase the value of modern data.

The lack of a clear forest definition and of a specific description of methods used at that time to produce ancient statistics questions their consistency. Also, the absence of foundations in survey sampling at that time period (Frayer and Furnival 1999) and of subsequent error estimation makes these statistics of lower statistical value than modern forest inventory. However, over a long time period, changes in the forest can turn strong enough for these statistics' uncertainties to appear much lower in magnitude than the main shifts detected (Table 5). This suggests their practical use to identify broad patterns and the footprints of past forest policies and natural processes.

Also, despite the reduced availability of information technologies at that time (calculator, computer), only few errors were detected in all of the ancient statistics in comparison to the total number of digits entered (Annex 5). The rate of errors in primary unit figures however remains out of reach.

4.2 Cross-comparison of ancient statistics

4.2.1 Potential systematic biases in *Daubrée* statistics

Forest area differences across NUTS-3 units showed systematic positive shifts in forest area at both periods (1892–1908 and 1908–1929, Table 5). All successive statistics suggested an increase in the total forest area, in line with current knowledge of the French forest transition (Cinotti 1996; Denardou et al. 2017). Yet, many of these units experienced successive increases/decreases in area over the two periods (notably NUTS-3 units of Southern France, Fig. 2), suggesting that either *Daubrée* statistics is biased positively, or decennial agricultural statistics are so, negatively. Over-estimation of forest area in Daubrée statistics may have several causes: a lower attention paid to forests of lower economic interest like Mediterranean forests of southern France or for mountain forest areas, also poorly described in administrative documents (Alps, Pyrenees, and Corsica). Negative forest area differences on 1892–1929 period followed by positives differences on 1908–1929 period affected Massif Central (Fig. 2), mainly private (Dodane 2009) and as such prone to lower attention in *Daubrée* statistics. These regional heterogeneities are discussed in Denardou et al. (2017).

4.2.2 Interplay between political will and past forest reporting

Cross-comparisons suggested a relative bias in the forest area of coppice/coppice-with-standards in *Daubrée* statistics with respect to other decennial agricultural statistics (Fig. 3). Over the 1892–1908 period, coppice forests regressed by 1,200,000 ha and coppice-with-standards forests increased by 930,000 ha. Over the 1908–1929 period, however, coppice forests increased by 860,000 ha and coppice-with-standards forests decreased by 700,000 ha. This over-estimation of coppice-with-standards (including coppice conversion) pattern in *Daubrée* statistics may find root in the coppice conversion policy, hindered by political and economic issues, which promoted a climate of suspicion between the State and the forest administration (Degron 1998). Such context is bound to have led to over-estimations of the conversion effort for better agreement with policy objectives (Corvol 2013). Moreover, the very short study period (1892–1908-1929) with respect to the pace of coppice conversion into high forest makes this evaluation highly dependent on survey processes.

The moderate negative bias in private forests in *Daubrée* statistics (Fig. 3) could stem from forest owners' distrust towards State policies. The difficult economic context of that period (Degron 1998) pushed the State to reflect on the privatization of public forests (Dabat 1920), or to interfere in the management of private forests (Corvol 2013), encouraging private owners to voluntarily underestimate the extent of their forests.

4.3 Increases in the forest area

4.3.1 Returning forests

Forest area differences over a longer time scale (1892–1929 and 1908–2008 periods) highlighted the sharp significant increase in forest area (+ 5,800,000 in whole French forest area and an average + 65,000 ha/NUTS-3 unit over the 1908–2008 period; $p < 10^{-10}$, Table 5) and particularly in private forests (+ 5,100,000 in whole French forest area and + 58,000/NUTS-3 unit over the 1908–2008 period; $p < 10^{-10}$, Table 5). Abandonment of agriculture is alleged to be one of the main drivers of this increase (Chakir and Madignier 2006; Cavailhès and Normandin 1993) and remains acute in rural areas (Denardou et al. 2017).

4.3.2 Afforestation programs

Major afforestation programs have taken place during 19th and 20th centuries including the landscape protection of the RTM program (1860 and 1882, Larrère et al. 1980) which led to planting of 170,000 ha by 1914 (Métailié 1999), and the much more extended FFN program (1946–1999) intended to foster the French forest industry and which reached a net 1.2 million hectares (Dodane 2009). This total afforestation (1400,000 ha) only represented 24% of total forest area increase (5,800,000 ha) over the 1908–2008 period room for undocumented secondary afforestation programs (e.g., *national lottery* program in 1920, Bazire and Gadant 1991), or more largely to natural expansion processes.

4.4 Structural and compositional changes in forests

4.4.1 Structural forest changes

Regarding forest management, the shift between coppice and high forest area over both long periods 1892–1929 and 1908–2008 is obvious (Fig. 4)—while at different stages depending on regions—and it allows concluding that forest conversion (1908–2008 period: − 600,000 ha in coppice, $p < 0.01$ and + 4,900,000 ha in high forest, $p < 10^{-10}$; Table 5) over the territory (Fig. 4) has been a very long-lasting and still ongoing process. Of importance, such process is bound to also have also dramatically increased the forest growing stock (Pignard 2000; Forest Europe 2015).

4.4.2 Compositional forest changes

The two main afforestation policies (section 4.3.2) mainly concerned conifer plantations. For example, the area of Norway spruce plantations in the Massif Central has increased from 360,000 to 610,000 ha over 20 years (Bazire and Gadant 1991). This massive afforestation has supported the idea, widespread in France and Europe (Moriniaux 1999) of an increase in conifer prevalence, at the expense of broadleaves. Whereas we confirmed the significant expansion of conifer-dominated forests (+ 1,600,000 ha, $p < 10^{-7}$), we also showed a parallel massive expansion of broadleaf-dominated forests (+ 3,600,000 ha, $p < 10^{-14}$) over the 1908–2008 period (Fig. 5). Hence, the proportion of broadleaf- and conifer-dominated forests has not changed in a century (Fig. 1), conflicting the view of conifer progression across the territory.

The significant sharp increase in *white oaks* areas (+ 1,500,000 ha over the 1908–2008 period, Fig. 6 and Table 6 in Annex 4) has a dynamic interpretation, as oak species are found in both coppice-with-standards forests and high forests owing to their ability to grow from sprouts (Boppe 1886), and their wood quality has led to favor them in the conversion of coppice. The non-significant small decrease of hornbeam in the 1908–2008 period (− 35,000 ha, Fig. 6 and Table 6 in Annex 4), a species predominantly found in coppice and coppice-with-standards forests due to its ability to sprout (Boppe 1886), is in accordance with conversion in favor of oaks. In addition, maintaining an understory of hornbeam benefits to the oak silviculture (Office National des Forêts 2010).

The significant increases of area in Norway spruce (+ 340,000 ha, Fig. 6 and Table 6 in Annex 4) and in European larch (+ 40,000 ha, Fig. 6 and Table 6 in Annex 4) reflect afforestation conducted by the FFN (Bazire and Gadant 1991; Bouchon 1984). Parallel significant increases in chestnut (*Castanea sativa* Mill., + 520,000 ha), *various broadleaves* (+ 1,000,000 ha), and *various conifers* (+ 320,000 ha) areas (Fig. 6 and Table 6 in Annex 4) can also reflect an effect of tree species diversification in afforestation programs (de Rochebouet 1987).

Note that declining cork oak areas can be explained by a decline in the demand for oak cork (Bugalho et al. 2011). Also, the mortality of cork oak has increased in the Mediterranean region, due to the increased intensity of droughts (Costa et al. 2010).

Statistics over this 1908–2008 period therefore suggested that intensive afforestation programs (RTM, FFN) did not develop at the expense of tree species diversity (Fig. 6 and Table 6 in Annex 4), but instead allowed for a tree species diversity increase at country scale, by introducing new tree species while maintaining and even increasing prevalence of the others. The illustration that of forest transition can increase tree diversity as a country scale is major.

5 Conclusion

- Cross-comparison of the three ancient French forest statistics showed that their exploitation was effective. Specific inconsistencies between the three statistics highlighted directional biases in forest management types and ownership categories, namely in *Daubrée* statistics, and must be dealt with when exploiting the data.
- These ancient statistics can support many fields of research. Examples include the impacts of the two World Wars on forests, the evolution of tree biodiversity, and spatial analyses of land-use change.
- The study of forest-area changes over more than one a century, using the three ancient statistics and NFI data (2008) highlighted features of the French forest expansion, found mainly in private forests, and characterized a slow conversion of coppices into high forests on the whole territory. Moreover, a statistically significant increases in the area of all major tree species found in the early twentieth century, with only minor areal decreases in two species common in coppice systems (hornbeam and cork oak) together with a clear effect of conifer afforestation programs (Restoration of Mountain Terrain and National Forest Fund) were identified, highlighting the major outcome of a long-term increase in major tree diversity across the whole territory.

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Authors' Contributions Conceptualization: Jean-Daniel Bontemps; Methodology: Jean-Daniel Bontemps, Timothée Audinot; Validation: Holger Wernsdörfer, Jean-Daniel Bontemps; Formal Analysis: Timothée Audinot, Jean-Daniel Bontemps; Investigation: Timothée Audinot, Jean-Daniel Bontemps, Holger Wernsdörfer; Data curation: Jean-Daniel Bontemps; Writing – original draft: Timothée Audinot, Jean-Daniel Bontemps, Holger Wernsdörfer; Supervision: Jean-Daniel Bontemps, Holger Wernsdörfer; Project Administration: Jean-Daniel Bontemps, Holger Wernsdörfer; Funding acquisition: Jean-Daniel Bontemps

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Data availability The datasets generated and analyzed during the current study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.3739458

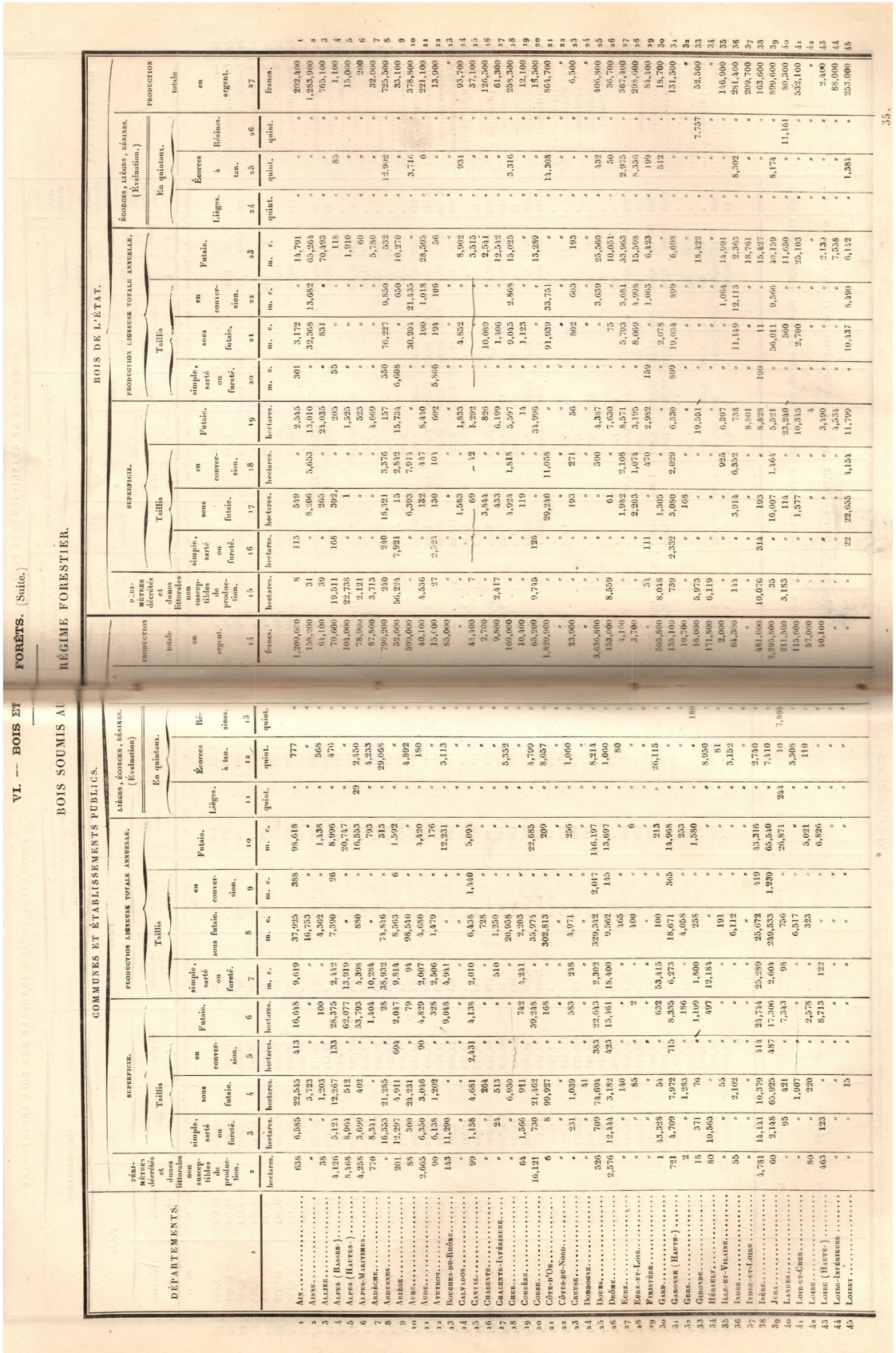
Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Annex 1: Overview of forest data tables in the three ancient statistics as images

DÉPARTEMENTS.	SURFACE TOTALE.	RÉPARTITION DE LA SURFACE TOTALE.					PRODUCTION ANNUELLE.		
		SURFACES IMPRODUCTIVES (rochers, marais, tourbières, etc.).	TAILLIS.			FUTAIE.	BOIS D'ŒUVRE.	BOIS DE FEU.	TOTAL.
			SIMPLE, sarté ou fureté.	SOUS FUTAIE.	en CONVERSION.				
	hectares.	hectares.	hectares.	hectares.	hectares.	hectares.	mètres cubes.	mètres cubes.	mètres cubes.
Ain	69,873	3,382	29,375	29,051	726	7,339	21,095	115,730	136,825
Aisne	74,999	1,453	10,155	61,103	149	2,139	60,176	160,316	220,492
Allier	53,866	1,198	6,241	43,316	23	3,088	18,596	145,001	163,597
Alpes (Basses-)	67,606	1,977	53,643	1,813	–	10,173	5,374	44,181	49,555
Alpes (Hautes-)	27,438	1,511	18,698	63	11	7,155	4,207	12,136	16,343
Alpes-Maritimes	43,499	5,558	10,527	2,784	–	24,630	5,483	23,210	28,693
Ardèche	76,269	1,018	45,098	2,279	–	27,874	41,130	58,195	99,325
Ardennes	78,474	1,127	15,313	50,849	–	11,185	75,450	172,818	248,268
Ariège	61,399	159	21,477	34,584	839	4,340	8,207	55,704	63,911
Aube	94,783	2,895	5,551	57,792	44	28,501	51,154	184,175	235,329
Aude	35,339	1,904	24,859	1,317	–	7,529	19,353	49,136	68,489
Aveyron	68,679	2,170	31,474	10,088	7,212	17,735	10,261	88,594	98,855
Belfort (Territoire de)	8,019	95	2,451	4,021	264	1,188	2,667	21,908	24,575
Bouches-du-Rhône	60,539	4,350	18,513	–	–	37,676	16,459	40,727	57,276
Calvados	34,800	2,487	7,976	21,029	71	3,237	3,941	77,681	81,622
Cantal	48,595	1,939	14,126	7,241	715	24,574	19,431	38,427	57,858
Charente	78,052	4,860	28,441	42,635	–	2,116	8,984	180,955	189,939
Charente-Inférieure	72,036	2,487	36,409	21,851	–	11,289	20,406	227,451	247,857
Cher	103,913	132	14,750	84,644	42	4,345	40,203	278,035	318,238
Corrèze	103,366	2,285	20,714	9,900	107	70,360	5,413	45,951	51,364
Corse	29,989	2,176	4,578	5,463	4	17,768	13,264	21,070	34,334
Côte-d'Or	116,411	403	2,863	103,981	25	9,139	54,894	290,357	345,251
Côtes-du-Nord	32,387	1,168	17,164	9,297	7	4,741	8,905	86,711	95,616
Creuse	30,589	445	10,554	13,042	871	5,677	12,363	79,997	92,360
Dordogne	255,672	689	104,506	80,199	–	70,278	163,304	327,339	490,643
Doubs	40,985	178	8,200	14,057	2,101	16,449	44,421	75,532	119,953
Drôme	123,485	5,077	106,959	511	1,349	9,589	7,614	118,487	126,101
Eure	98,707	1,140	19,153	71,247	–	7,167	23,302	193,821	217,123
Eure-et-Loir	54,273	556	20,396	32,147	74	1,100	8,767	104,080	112,847
Finistère	25,926	17	22,734	–	–	3,175	4,509	71,561	76,070
Gard	90,715	1,057	68,474	14,857	–	6,327	17,987	70,057	88,044
Garonne (Haute-)	49,953	45	9,246	37,129	1,245	2,288	3,878	96,316	100,194
Gers	46,045	196	13,151	29,836	–	2,862	7,763	83,426	91,189
Gironde	407,299	74,657	41,523	34,655	–	256,464	594,168	790,630	1,384,798
Hérault	62,107	7,886	52,840	–	–	1,381	1,331	29,010	30,341
Ille-et-Vilaine	36,861	1,188	14,656	15,982	–	5,035	10,470	92,760	103,230
Indre	67,191	10	–	65,230	–	1,951	11,988	181,694	193,682
Indre-et-Loire	86,873	5,065	60,750	17,762	227	3,069	6,325	157,625	163,950
Isère	119,987	4,364	72,957	18,903	6,000	17,763	47,527	202,667	250,194
Jura	57,692	7,475	8,700	23,322	5,364	12,831	40,825	95,984	136,809
Landes	433,275	1,255	23,091	16,757	–	392,172	1,186,846	436,839	1,623,685
Loir-et-Cher	129,564	5,889	21,646	73,435	6,180	22,414	49,219	238,571	287,790
Loire	50,811	632	10,374	8,796	100	30,909	147,075	56,543	203,618

Fig. 7 Overview of a data table presented in *Daubrée* statistics at a NUTS-3 level



VI. — BOIS ET FORÊTS. (Suite.)

BOIS SOUMIS AU RÉGIME FORESTIER.

COMMUNES ET ÉTABLISSEMENTS PUBLICS.

BOIS DE L'ÉTAT.

DÉPARTEMENTS.	PÉRIMÈTRES décrétés et dunes littorales non susceptibles de production.	SUPERFICIE. Taillis simple, sarté ou furelé.	Taillis sous futaie.	en conversion.	Futaie.	PRODUCTION LIGNEUSE TOTALE ANNUELLE. Taillis simple, sarté ou furelé.	Taillis sous futaie.	en conversion.	Futaie.	LIÉGE, ÉCORCES, RÉSINES. (Évaluation.) En quintaux. Liéges.	Écorces à tan.	Résines.	PRODUCTION totale en argent.
	2	3	4	5	6	7	8	9	10	11	12	13	14
	hectares.	hectares.	hectares.	hectares.	hectares.	m. c.	m. c.	m. c.	m. c.	quint.	quint.	quint.	francs.
1 Ain	638	6,585	22,545	413	16,618	9,019	37,925	388	98,618	"	777	"	202,400
2 Aisne	"	"	3,723	"	"	"	16,753	"	"	"	"	"	1,283,900
3 Allier	38	"	1,203	"	100	"	4,362	"	1,438	"	568	"	765,100
4 Alpes (Basses-)	4,136	5,121	12,267	133	28,375	2,432	7,390	36	8,996	"	476	"	1,100
5 Alpes (Hautes-)	8,568	8,964	512	"	62,077	13,919	"	"	20,747	"	"	"	15,000
6 Alpes-Maritimes	4,258	3,699	402	"	33,793	4,398	880	"	10,533	29	2,450	"	200
7 Ardèche	770	8,351	"	"	1,404	10,284	"	"	703	"	4,233	"	32,000
8 Ardennes	"	16,353	21,235	"	28	38,932	78,846	"	313	"	29,058	"	725,300
9 Ariège	201	12,297	1,911	694	2,047	9,814	8,563	6	1,592	"	"	"	33,100
10 Aube	88	300	24,231	"	94	91	98,540	"	"	"	4,892	"	378,800
11 Aude	2,665	6,350	3,046	90	4,829	2,007	4,680	"	4,420	"	180	"	221,100
12 Aveyron	90	6,138	1,202	"	328	2,506	1,479	"	176	"	"	"	13,900
13 Bouches-du-Rhône	143	11,290	"	"	"	4,941	"	"	12,231	"	3,113	"	"
14 Calvados	"	"	"	"	9,048	"	"	"	"	"	"	"	93,700
15 Cantal	99	1,158	4,681	2,431	4,138	2,010	6,438	1,440	5,094	"	"	"	37,100
16 Charente	"	"	264	"	"	"	728	"	"	"	"	"	126,500
17 Charente-Inférieure	"	24	513	"	"	510	1,350	"	"	"	4,892	"	61,300
18 Cher	"	"	6,930	"	"	"	20,958	"	"	"	5,352	"	298,300
19 Corrèze	64	1,566	911	"	742	4,231	2,203	"	"	"	"	"	12,100
20 Corse	16,121	730	21,462	"	39,248	"	35,974	"	22,685	"	4,799	"	15,500
21 Côte-d'Or	6	8	99,927	"	168	"	302,813	"	209	"	8,637	"	864,700
22 Côtes-du-Nord	"	"	"	"	"	"	"	"	"	"	"	"	"
23 Creuse	"	231	1,039	"	583	248	4,971	"	256	"	1,060	"	6,500
24 Dordogne	"	"	"	"	"	"	"	"	"	"	"	"	"
25 Doubs	526	709	74,694	383	22,643	2,302	329,342	2,017	146,107	"	8,214	"	406,800
26 Drôme	2,576	12,443	3,182	425	13,461	18,400	9,562	145	13,697	"	1,060	"	36,700
27 Eure	"	"	140	"	"	165	"	"	"	"	80	"	367,400
28 Eure-et-Loir	"	"	85	"	2	400	"	"	6	"	"	"	298,600
29 Finistère	"	"	"	"	"	"	"	"	"	"	"	"	84,400
30 Gard	1	43,328	54	"	632	53,415	100	"	213	"	26,115	"	18,700
31 Garonne (Haute-)	791	4,709	7,972	715	8,335	6,273	18,671	365	14,968	"	"	"	131,500
32 Gers	2	"	1,283	"	186	"	4,056	"	253	"	"	180	"
33 Gironde	15	371	76	"	1,109	1,800	258	"	1,580	"	"	"	52,500
34 Hérault	80	10,963	"	"	497	12,184	"	"	"	"	8,950	"	"
35 Ille-et-Vilaine	"	"	55	"	"	"	191	"	"	"	81	"	116,900
36 Indre	55	"	2,102	"	"	"	6,112	"	"	"	3,152	"	281,400
37 Indre-et-Loire	"	"	"	"	"	"	"	"	"	"	"	"	209,700
38 Isère	4,781	14,141	10,379	314	23,734	25,289	25,072	419	33,316	"	2,740	"	163,600
39 Jura	60	2,148	65,925	487	17,306	2,604	249,533	1,239	65,540	244	7,410	7,800	899,600
40 Landes	"	95	421	"	7,343	98	756	"	26,871	"	10	"	80,500
41 Loir-et-Cher	15	371	76	"	"	"	6,517	"	"	"	3,308	"	532,100
42 Loire	80	"	1,907	"	2,578	"	323	"	5,021	"	110	"	"
43 Loire (Haute-)	463	123	220	"	8,713	122	"	"	6,896	"	"	"	2,400
44 Loire-Inférieure	"	"	"	"	"	"	"	"	"	"	"	"	88,000
45 Loiret	"	"	15	"	"	"	"	"	"	"	"	"	253,000

35.

Fig. 8 Overview of a forest data table presented in decennial agricultural statistics of 1892 at a NUTS-3 level

Fig. 9 Overview of a forest data table presented in decennial agricultural statistics of 1929 at a NUTS-3 level

Annex 2: The Forest regime

During the forest transition (dated in the nineteenth century, Mather 1992), a forest law was set in 1827 to protect and restore forest resources, yet property rights embodied in the Declaration of Human Rights of 1789 prevented State's intervention in private ownership, making the forest law limited to public forests in its application, a principle termed the Forest Regime (Némoz-Rajot 1998). All public forests are subjected to the Forest Regime, while private forests are not. Forest regime aims to plan and supervise forest management, to arrange the sale of forest products and ensure the monitoring of forest ownership (Némoz-Rajot 1998). The Forest Regime's definition is as follows: "The forest regime includes all the management rules defined by the Forestry Code and implemented by the National Forestry Commission. It is applicable to the State-owned forests, to the local authorities and to public institutions of public interest. Furthermore, it concerns a number of non-wooded areas such as the perimeters of restoration of mountain land or the zones of the coastal dunes (Aquitaine, Charente-Maritime and Vendée, Nord-Pas-de-Calais)." (INSEE 2016).

Annex 3: Stand structure definition in French national forest inventory (NFI)

Stand structure is observed in the field, and measured by the relative cover rates (crown canopy projection) of vertical high forest and coppice layers. Structure is described only in stands whose relative cover rate is > 40%. Forests with a relative cover rate < 40% are considered to be open forests with no clear structure (6.8% of total forest area). As soon as the relative cover rate of coppice is < 25%, the NFI plot is described as a high-forest. With a relative cover rate of coppice and high-forest is ≥ 25%, plot is described as coppice-with-standards. Otherwise, the plot is described as coppice (relative cover rate of high-forest ≤ 25%). However, the structure of some forests could not be defined (3.0% of total forest area).

Annex 4: Harmonization of statistics

Forest tree species harmonization between *Daubrée* statistics and national forest inventory (NFI) data

Table 6 summarizes the 15 main tree species and the 2 generic categories (various broadleaves and various conifers) described in *Daubrée* statistics. A harmonization was intended for comparison between *Daubrée* and NFI statistics.

A tree species described in *Daubrée* statistics could be found with two different names. This is the case of *Chêne vert* and *Chêne yeuse,* which correspond to holm oak (*Quercus ilex* L.). This distinction proves to come from the difference of species terminology according to the region, as both are never found in a same NUTS-3 unit. Therefore, terminology was merged.

Some tree species groups did not show a single species, but a grouping of species depending on the composition (various broadleaves and various conifers), or two mixed species ("Fir and Spruce" and "Maritime Pine and Scots Pine" (*Pinus pinaster* Aiton. and *Pinus sylvestris* L., respectively) observed only in two NUTS-3 units, *Ain* and *Finistère*). In the first case, we did not change the original tree species group (becoming *v*arious broadleaves and various conifers). In the second case, we observed that when one of the mixed categories was present, the individual categories of the same species were systematically absent. We concluded that the distinction of species in mixed groups had not been made and that the corresponding areas did not refer to mixed-species areas. Thus, for a given category of two species, we conventionally attributed half of the area divided for two of the group to each of the species (for two NUTS-3 units).

The *Daubrée* statistics also refers to a tree species category termed oak in some NUTS-3 units. The absence of pedunculate and pubescent oak tree species (*Quercus robur* L. and *Quercus pubescens* Willd., respectively) in the statistics, and knowledge about their presence at the time of *Daubrée* (Boppe 1889) suggested that the oak category may comprise the area of these two species.

We identify that when the generic oak category was present in a NUTS-3 unit, the other oak tree species identified by *Daubrée* statistics (holm oak, cork oak, sessile oak (*Quercus petraea* Matt. Liebl)) were not present. And conversely, when one of the three oak tree species was present (holm oak, cork oak, sessile oak), the generic oak category was absent. We concluded that for each NUTS-3, oaks could either be described as an individual oak tree species, or only described as oak.

For our analyses, we merged terminology of the generic oak category and sessile oak tree species into a white oaks tree species group.

All the pines of *Daubrée* statistics and NFI data have been grouped in a generic pines tree species group.

Note, for three NUTS-3 units (Côte-d'Armor, Dordogne and Lot), the area of forests subjected to forest regime was null in *Daubrée* statistics.

Concerning NFI, all the species that were not inventoried by *Daubrée* statistics were placed in the two tree species groups of various broadleaves and various conifers. The *white oaks* tree species group was created by adding areas associated with the NFI data of sessile, pedunculated and pubescent oaks. Holm oak and cork oak were analyzed as individual species. Other oaks were placed in various broadleaves tree species group.

Table 6 Harmonized tree species categories and summary statistics for differences in forest areas between *Daubrée* statistics (1908) and national forest inventory data (2008[1]) across NUTS-3 units, Forests area differences according department administrative units (NUTS-3) population were calculated over the 1908–2008 period. Significance of the forest area differences were analyzed using a paired *t* test. Tree species not specified in oak, various broadleaves, and various conifers, yet deduced for the oak group (see Annex 4)

Daubrée statistics' tree species *Seminal terminology / Latin name*		Generic translation used	Harmonization	FAD mean ($\times 10^3$ ha)	FAD standard-deviation ($\times 10^3$ ha)	Total change ($\times 10^3$ ha)	Annual rate of change (%)	Paired *t* test
Chêne	*Quercus robur* L. *Quercus pubescens* Willd. *Quercus petraea* Matt. Liebl	*Oak*	*White oaks*	+ 18	21	+ 1550	+ 0.37	$< 10^{-10}$
Chêne rouvre	*Quercus petraea* Matt. Liebl	Sessile oak						
Chêne vert Chêne yeuse	*Quercus ilex* L.	Holm oak	Holm oak	+ 2.7	39.3	+ 450	+ 0.97	< 0.05
Chêne liège	*Quercus suber* L.	Cork oak	Cork oak	− 0.2	6.5	− 60	− 0.46	NS
Hêtre	*Fagus sylvatica* L.	Beech	Beech	+ 2.8	9.7	+ 190	+ 0.15	< 0.05
Châtaignier	*Castanea sativa* Mill.	Chestnut	Chestnut	+ 7.4	8.2	+ 520	+ 1.20	$< 10^{-9}$
Charme	*Carpinus betulus* L.	Hornbeam	Hornbeam	− 0.6	8.4	− 40	− 0.06	NS
Sapin	*Abies alba*	Silver fir	Silver fir	+ 3.7	7	+ 200	+ 0.48	< 0.001
Epicéa	*Picea abies* Karst.	Norway spruce	Norway spruce	+ 6.1	8.7	+ 350	+ 0.96	$< 10^{-5}$
Pin d'Alep	*Pinus halepensis* Mill.	Allepo pine	*Pines*	+ 8.4	23.5	+ 710	+ 0.34	< 0.01
Pin sylvestre	*Pinus sylvestris* L.	Scots pine						
	Pinus pinaster Aiton.	Maritime pine						
Pin maritime	*Pinus nigra subsp. laricio* Poir. Mair	Laricio pine Mountain pine						
Pin laricio Pin à crochets	*Pinus uncinata* Ramond ex DC.							
Mélèze	*Larix decidua* Mill.	Larch	Larch	+ 1.9	4.2	+ 40	+ 0.49	< 0.05
Feuillus divers		*Various broadleaves*	*Various broadleaves*	+ 11.7	15.1	+ 1000	+ 0.57	$< 10^{-9}$
Résineux divers		*Various conifers*	*Various conifers*	+ 3.9	10.6	+ 320	+ 0.58	< 0.01

FAD forest area difference. *NFI* national forest inventory. [1]: median year

Harmonization of forest management types and ownership categories

We aggregated ownership categories of the three ancient statistics into three/two groups depending on our analyses: (1) State-owned forest, other public forest and private forest; or (2) public forest and private forest (Table 7).

Forest management types were aggregated into four types: coppice, coppice-with-standards, high forest, and other forests' areas (Table 8). Other forests' areas category corresponds to the specific marginal forest management types of ancient statistics. It includes unproductive forest areas of *Daubrée* statistics, decreed perimeters, and unproductive coastal dunes areas of 1892 statistics and recently afforested areas of 1929 statistics. Areas belonging to this forest management type are encompassed in the calculation of the afforestation rates in the three ancient statistics, and were therefore considered as well as other management type. Areas with no forest structure in NFI data, i.e. with a relatively low forest cover, were placed in such other forests' areas.

Table 7 Harmonization of forest ownership categories across ancient statistics and national forest inventory data

Statistics	Ownership category				
Decennial agricultural statistics (1892)	State-owned forests subjected to the forest regime	Municipal forests and other territorial public bodies' forests subjected to the forest regime	Private forests	Municipal forests and other territorial public bodies' forests not subjected to the forest regime	
German statistics (1907) for *Bas-Rhin*, *Haut-Rhin* and *Moselle* units	State-owned forests	Municipal forests (other public forest)	Private forests		
Daubrée statistics (1908)	State-owned forests subjected to the forest regime	Municipal forests and other territorial public bodies' forests subjected to the forest regime	Private forests	Municipal forests and other territorial public bodies' forests not subjected to the forest regime	
Decennial agricultural statistics (1929)		Forests subjected to the forest regime (including State-owned forests and other public forests)	Private forests	Municipal forests not subjected to the forest regime	Other territorial public bodies' forests not subjected to the forest regime
NFI (2008[1])	State-owned forests subjected to the forest regime	Municipal forests and other public forest subjected to the forest regime	Private forests other territorial public bodies' forests not subjected to the forest regime		
Harmonization	State-owned forests subjected to the forest regime	Other public forests subjected to the forest regime	Private forests not subjected to the forest regime		
	Alternate aggregation: Public forests				

NFI national forest inventory. [1] median year

Table 8 Harmonization of forest management types across ancient statistics and national forest inventory data. While these data were merged, national forest inventory data primarily describes the physical forest structure of forest plots, and the three ancient statistics describe forest management types

Statistics	Forest management type					
Decennial agricultural statistics (1892)	Simple coppice	Coppice conversion	Coppice-with-standards	High broadleaved forest	High coniferous forest	Decreed afforestation perimeters and unproductive coastal dunes
Daubrée statistics (1908)	Simple coppice	Coppice conversion	Coppice-with-standards	High forest		Unproductive forest area
Decennial agricultural statistics (1929)	Simple coppice	Coppice-with-standards		High broadleaved forest	High coniferous forest	Recently afforested area
NFI (2008[1])	Coppice	Mixture of coppice and high forest		Even-aged and uneven-aged high forest		Undefined forest structure
Harmonization	Coppice	Coppice-with-standards		High forest		Other forests

[1] median year

Annex 5: Data entry and error correction

In the three ancient statistics, digitization errors of different types were identified by comparing row/column totals:

- miscalculation or typographical error on total statistics (input error when compiling total or printing error, 31 errors found);
- typographical errors on basic figures detected by double-check on horizontal and vertical totals (input error when compiling figures or printing error, 6 errors found);
- missing number (1 error found).

A miscalculation or typographical error on a total was detected when, for a given row and column, only one total was equal to that recomputed. When both row/column totals did not coincide with those recomputed, a typographical error on the basic figure at their intersection or missing number was inferred. Once the error was identified, it was possible to correct it.

All detected errors were corrected. However, primary typographical potential errors on basic figures, thus consistent with both row/column totals could not be detected and corrected.

These errors—as calculated from area and production data—actually represent a small share of the total number of statistics entered (0.005% and 0.003% of figures respectively in decennial agricultural statistics of 1892 and of 1929 and 0.002% in *Daubrée* statistics). The three statistics further showed many errors in the published afforestation rates due to the handling of decimals. These rates were also recomputed.

Annex 6: Department administrative units

Standardization of department administrative units' boundaries

Ancient department administrative units were not systematically identical to current NUTS-3 units and had to be harmonized. The broadest department administrative units (NUTS-3) scale compatible with all four statistics (three ancient ones and NFI) was selected.

Some department administrative units names in the three ancient statistics changed over time (for example: *Charente-inférieure* becoming *Charente-maritime*), and others were sub-divided (*Seine-et-Oise* turned into *Yvelines*, *Essonne* and *Val-d'Oise*; *Seine* turned into *Paris*, *Hauts-de-Seine*, *Seine-Saint-Denis* and *Val-de-Marne*). The latter units were considered as a single one in our analyses. The Corsica region was not separated in two department administrative units in the ancient statistics. We thus considered the island as one single unit for the whole study.

Potential effect of changes in department administrative units' area on forest differences investigated

Differences in total department administrative units' areas across the three ancient statistics were detected. For example, *Alpes-Maritimes* lost 17,900 ha between 1892 and 1908 while *Gironde* gained 24,000 ha over the same period. We investigated the potential average effect of these differences on between statistics forest areal changes using univariate regression analysis, and did not find any significant relationship across the 1908–1929 period ($p = 0.5$, R-squared = 0.005) and across 1908–2008 period ($p = 0.7$, R-squared = 0.002). However, we found a significant positive association across 1892–1908 period ($p < 0.01$, R-squared = 0.096) and in the 1892–1929 period ($p < 0.05$, R-squared = 0.051). This relationship yet turning non-significant without *Gironde* department administrative unit ($p = 0.7/p = 0.2$, R-squared = 0.001/R-squared = 0.018 in the 1892–1908/1892–1929 periods, respectively). In 1817, a prefectural decree ordered the afforestation of 100,000 ha of coastal dunes in *Gironde* and *Landes* (Buffault 1942). The coastal dunes have an area of 124,000 ha (Favennec 1999), and in 1876, they were afforested by over 80,000 ha (Buffault 1942). *Gironde* had strongest area differences (+ 100,000 ha) and strongest forest area differences with *Landes* (+ 100,000 ha for both) over the 1892–1929 period. Consequently, the absence or presence of coastal dunes depending to their status (afforested or non-afforested) in department administrative units provided by the statistics may explain a part of this sharp increase. However, *Landes* showed small area differences over the 1892–1929 period (+ 4000 ha), suggesting an existence of another possible origin of area differences in *Gironde*. As a result, *Gironde* was excluded from the whole paired *t* tests in our analyses. However, it was kept in all other computations (totals, standard-deviations, maximum, and minimum).

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