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► To cite this version:

Lise Pinault, Malo Pilloix, Grégory Bernard, Daniel Joly, Sébastien Gogo, et al.. The 1949 Atlas of French peat deposits, a starting point for a National Inventory of peatlands. *Soil Use and Management*, 2023, 39 (3), pp.1040-1056. 10.1111/sum.12919 . hal-04192260

HAL Id: hal-04192260

<https://hal.science/hal-04192260>

Submitted on 13 Sep 2023

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The 1949 Atlas of French Peat Deposits, A Starting Point for a National Inventory of Peatlands

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Abstract

50% of European peatlands are in a damaged state. While intact peatlands are natural carbon sinks, degraded sites release important amounts of greenhouse gases into the atmosphere, contributing to global warming. Restoration of the hydrological functionality of peatlands has proved to be an efficient tool to avoid these emissions. In France, Tuffnell & Bignon's ministerial report (2019) emphasized the need for peatlands' integration into the National Low Carbon Strategy, targeting carbon neutrality by 2050. However, current knowledge regarding French peatlands' distribution and carbon stocks is insufficient and does not allow decision makers and managers to prioritize areas for restoration. The most complete database to date is the 1949 Atlas, an inventory of exploitable peat deposits that was conducted during WWII for peat exploitation as fuel. Until its digitalization, the latter database was archived and never used in a scientific study. It provides detailed information about peatland surfaces, peat thicknesses and carbon contents at that time. We estimated peat carbon stocks from French peatlands to be 111 Mt C in 1949 for 63,290 ha identified as peaty sites, the equivalent of 3% of the organic carbon contained in the upper 30 centimeters of French soils. 34% of this stock was held in Lower Normandy (37.7 Mt C) and 12% in the Picardy's region (13.0 Mt C), in large lowland peatlands. However, not all peatlands were prospected in the 1949 inventory and the characteristics of the prospected peatlands may have changed with anthropic disturbances of the last decades, such as

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1111/sum.12919](https://doi.org/10.1111/sum.12919)

draining or climate change. These first results highlight the need for a recent inventory of French peatlands and carbon stocks based on local data aggregation. Data from the 1949 Atlas could help constituting this new inventory but should be validated before being used to describe the present.

Keywords

Peatland, carbon stock, peat depth, carbon content, restoration, inventory

1. Introduction

Peatlands are defined as areas with or without vegetation with a naturally accumulated peat layer at the surface (Joosten & Clarke, 2002). Constant waterlogging and anaerobic conditions restrict microbial activity and mineralization processes in peatland ecosystems. Consequently, organic matter, and the carbon it contains, accumulates faster than it degrades, at a rate varying between 0.5 and 1 mm per year since the last glacial period (Minasny et al., 2019). In the long term, peatlands are important carbon sinks (Parish et al., 2008) and play a major role in the carbon cycle (Gorham, 1991). At a global scale, they only cover 3% of the world's land surface (Z. Yu et al., 2010; Xu et al., 2018) but they store 550 to 694 Gt of carbon, representing 34 to 43% of organic carbon contained in soils (Parish et al., 2008). One individual bog holds on average 1,400 tons of carbon per hectare for each 2 m of peat depth (Roßkopf et al., 2015). However, current strategies lie in carbon emissions mitigation in degraded peatlands (Leifeld & Menichetti, 2018; Loisel et al., 2014). For centuries, these natural environments have been largely exploited for fuel, drained, harvested for horticulture and used for grazing, cultivation and forestry across the world (Joosten, 2009; Minasny et al., 2019). In Europe, for instance, around 50% of peatlands are estimated to be degraded (Tanneberger, Appulo, et al., 2021). In France, although peatlands cover smaller surfaces than in north-western, nordic and eastern European countries, these habitats have also been affected by anthropic disturbances (Andersen et al., 2017; Muller, 2018). Drainage affects water table depth, the main factor controlling greenhouse gas (GHG) fluxes (Evans et al., 2021). The decrease

of the water table favors aerobic conditions enabling the mineralization of organic matter, a process which is hindered when constant waterlogging is present. As a result, the given peat site turns into a carbon source, emitting as CO₂ the accumulated carbon (Holden, 2005; Leifeld & Menichetti, 2018; Tanneberger, Abel, et al., 2021). Peatlands in the European Union (EU) emit around 5% of total GHG anthropic emissions of the EU, making it the second largest GHG emitter from drained peatlands in the world (Tanneberger, Appulo, et al., 2021).

In this context, there is a real challenge to restore these environments, both to conserve the specific biodiversity they shelter and to limit GHG emissions, thereby mitigating climate change. This issue is all the more important as climate change is itself accelerating the degradation of peat ecosystems through feedback loops (Gorham, 1991). Restoration has proved to be an efficient tool to mitigate carbon emissions in disturbed peatlands (Andersen et al., 2017). Bonn et al. (2014) estimated the potential amount of GHG emissions avoided by restoration of drained and degraded European peatlands to be between 4.64 and 34.06 t CO₂-eq ha⁻¹ yr⁻¹.

In France, public demand for peatland restoration is growing strongly. Since 2015, following the Paris Agreement, parties to the United Nations Framework Convention on Climate Change (UNFCCC), including France, agreed to pursue efforts to limit the increase of global average temperature to 1.5°C above pre-industrial levels (Tanneberger, Abel, et al., 2021). As a sign of commitment, France put in place the Low Carbon National Strategy, a policy targeting the challenging goal of national carbon neutrality by 2050. To achieve this objective, the government aims to reduce GHG emissions in sectors such as agriculture, manufacturing, transportation and construction industry. In sectors where GHG emissions reduction is impossible, especially in the land sector, focus is placed on compensating residual emissions (Ministère de la Transition Ecologique et Solidaire, 2020). For this purpose, the government aims to expand forest area, increase storage of processed wood or modify agricultural practices through an agro-ecological approach (Pellerin et al., 2020), to promote carbon storage in the soil (Ministère de la Transition Ecologique et Solidaire, 2020). Although wetlands play a significant role

in mitigating climate change, none of the proposed measures are relevant to wetland management (Erwin, 2009; Harenda et al., 2018). In 2019, French deputy Tuffnell and senator Bignon (2019) insisted on the need to integrate peatlands into the Low Carbon National Strategy. The authors proposed restoring around 100,000 hectares of peatlands in France as a nature-based solution to mitigate climate change. Some French sites have already been restored within the framework of European projects such as the LIFE "*Réhabilitation fonctionnelle des tourbières du massif jurassien franc-comtois*" (LIFE13 NAT/FR/76; 2014-2021) or the LIFE Anthropofens (LIFE18 NAT/FR/00906; 2020-2025). However, the restoration work to be done is still extremely vast. The majority of peatlands in France probably remain significant contributors to global warming.

One of the main issues is that there is currently no complete national inventory to help meet this public demand. Knowledge regarding French peatlands' localization, state of degradation and carbon stocks is insufficient to implement a national restoration program. In the metropolitan territory, various national and regional inventories exist but they are incomplete and the level of expertise they provide varies greatly from one region to another. The most complete database on French peatlands is the Atlas Inventory from 1949 which is, strictly speaking, an inventory of exploitable peat deposits. It was conducted for a national prospecting campaign between 1941 and 1945 aiming to estimate peat stock in metropolitan France for fuel use. This inventory is old and incomplete, as some regions were not inventoried. Yet, it remains a crucial database to get detailed information on French peatlands 80 years ago, especially since measures on carbon content and peat depth, used to estimate exploitable peat volume, are available in this database.

The objective of this study is to, firstly, provide an initial assessment of total French peatland surface and carbon stock in the mid-20th century by using the Atlas of French peatlands published in 1949. Secondly, the exploration of this database will enable a detailed assessment of the main characteristics of the surveyed peatlands, regarding carbon contents, bulk densities and mean thicknesses, both regionally and nationally. Lastly, the focus will be shifted to understanding to what extent these first

estimations can help characterize the current state of French peatlands. This will eventually provide valuable insights on how to better implement mitigation strategies and understand the contribution of this ecosystem to French GHG emissions.

2. Materials & methods

2.1 Presentation of the database: the 1949 Atlas

The French peatlands' document from the Ministry of Industry and Trade (1949), later called the 1949 Atlas, was used in this study. The objective behind this 80 years-old survey was to identify peat deposits for extraction. During the period of war, where fuel was in short supply, peat usage was considered as an alternative. The Atlas considered peatlands with a geological definition, an environment where peat has formed. Peat was defined in the Atlas as "*a living plant mass on the surface, dead and browned below this surface, which undergoes a slow alteration and is transformed little by little in depth into a soft, brown or blackish substance, more or less spongy, in which the dead debris of plant tissues can be well distinguished*" (Ministère de l'industrie et du commerce, 1949a). Alsace and Nord-Pas-de-Calais regions were not prospected during World War II. Small-sized peatlands located in montane regions were also ignored as they were considered difficult for extraction. Nonetheless, it is as of now the largest French national database on peatlands and a key tool to give a first estimation of peatlands' carbon stocks in metropolitan France.

The document is presented in paper form and divided to three parts. The first part is a guide that summarizes the state of knowledge on peatlands during the 1940s. Information on the history of prospecting, the geology, the chemistry and the legal regime of peatland sites are provided. An economic study related to peat exploitation is included as well. The second part gives the characteristics of the surveyed peatlands, classified by catchment. Each peatland is identified by a code. Measurements of surface (in ha), thickness, volume of peat, ash content, water level, date of the survey and details of previous site exploitation are available in the report. The final part of the Atlas presents cartographic information on all surveyed peaty sites, based on military maps at 1/80,000 scale. The annotation of the

code on the map makes it possible to retrieve additional information given about peat in the second part of the report. Peatlands were delineated by surveyors on the field using core sampling each 100 meters along transects (or 50 meters if the peatland was less than five ha; 200 meters if it was more than 50 ha). Depending on the size of the prospected site, three to eight samples of 500 grams were collected and measurements of their water and ash contents were later made in the laboratory. Each sample was a mix of peat collected near the surface, at mid-depth and near the bottom, to take into account the vertical variability of these physical-chemical parameters (Ministère de l'industrie et du commerce, 1949b).

2.2 Digitization of the 1949 Atlas

The 54 plates of the Atlas were scanned and georeferenced with QGIS 2.18 (QGIS Development Team, 2009. QGIS Geographic Information System. Open Source Geospatial Foundation. URL <http://qgis.osgeo.org>), using fixed in time objects as control points (road intersections, bridges...). Atlas maps are not always very precise. Collation of the military maps between them may be a source of shifts of a few millimeters for instance. Aerial photographs from the 1950's (IGN Raster2018, orthoimagery.orthophotos. 1950-1965), faithfully georeferenced to current orthophotos, were therefore used as a reliable base to georeference these maps. The degree of accuracy of the atlas maps required a deformation of the initial image using the Thin Plate Spline transformation and the nearest neighbor resampling method when executing the georeferencing command in QGIS.

Peatlands were delimited based on georeferenced maps and their codes were indicated on the attribute table. A total of 1939 peaty sites were delimited as polygons. These polygons were at times relocated to match their position on the map, following the book's comments. Then, information about the catchment, surface, mean thickness and volume of each peat site were joined to our shapefile, based on each peatland's code. The database is available with restricted access and referenced with a DOI on Dat@OSU (Ministère de l'Industrie et du Commerce et al., 2021).

2.3 Exploitation of the database: peat properties and carbon stock estimation

Peat carbon storage was estimated at regional and national scales as (Gorham, 1991; Minasny et al., 2019; Rudiyanto et al., 2018; Warren et al., 2017; Z. C. Yu, 2012; Zauft et al., 2010):

$$C_{peat} = V * C_d \quad (1)$$

where C_{peat} is carbon stock (kgC); V is peat volume (m^3), the product of surface (m^2) and peat thickness (m); C_d is peat carbon density ($kgC.m^{-3}$), i.e. the product of bulk density (BD) ($kg.m^{-3}$) and carbon content (C_c) ($kg.kg^{-1}$).

Peat volume

To calculate peat volume (V), we did not use surface values (ha) given by the 1949 Atlas because of their approximate nature. Instead, we calculated the surface of each peatland polygon using the \$area function in QGIS's field calculator, in square-meters. The Atlas provides mean thickness values for almost all inventoried peatlands. The number of thickness points per site used to calculate the mean thickness is unknown. Three sites located in the north of France did not give any thickness. For the latter sites, we used a value corresponding to the average thickness of the catchment they belonged to. Even if these values do not reflect the real thickness of the site, they allow us to gain sufficient precision to represent the local conditions of the sites. Moreover, the error from this approximation did not intrinsically alter the final result.

Carbon content

Carbon content (C_c) varies depending on the type of peat, i.e. the vegetation it is composed of and its degree of decomposition, from fibric to sapric. *Sphagnum* peat has higher carbon content than fen peat as it contains more than 50% of organic carbon, while fen peat has a median value of 29-44% (Roßkopf et al., 2015). Moreover, carbon content tends to decrease when the degree of decomposition increases; therefore, it is negatively correlated with the degree of oxidation and mineralization of peat substrates

(Roßkopf et al., 2015). Carbon content can be deduced from the mass of organic matter (Equation 2) (Agus et al., 2010; Cubizolle, 2019; Minasny et al., 2019):

$$C_c = \frac{C_{OM}}{1.885} \quad (2)$$

where C_{OM} is the content of organic matter in one sample (%) and the denominator is a C_{OM} to C_c conversion factor of 1.885 used for converting organic matter to organic carbon content. In a conventional way, 1.724 is the most commonly used conversion factor (Agus et al., 2010) but it is often inappropriate for peat (Klingenuß et al., 2014). Therefore, we calculated C_c from a factor of 1.885 corresponding to the average C_{OM}/C_c ratio deduced for sphagnum (2.05), vascular plants (1.73), brown moss (1.83) and amorphous peats (1.93) (Klingenuß et al., 2014). C_{OM} was calculated from the ash content (C_{Ash}) (%) values provided by the Atlas for 759 sites. C_{Ash} is the mineral matter in peat and was obtained through loss in ignition, in a gradually heated oven. The methodological guide of the Atlas does not provide further details about the temperature of the oven. C_{Ash} is the remaining material once the organic matter content (C_{OM}) is removed. Consequently, C_{OM} can be deduced as $C_{OM} = 100 - C_{Ash}$. Up to four ash content values per polygon could be indicated in the atlas. In this case, the average value was used for calculations.

For the remaining 1,180 peatlands with no measurements for ash content, we used an estimated value of carbon content determined by spatial interpolation. Polygons of peatlands for which we had precise carbon content values (n=759) were converted into centroids. Then, we used these point values to create a continuous surface from which unknown values could be predicted. We performed an ordinary kriging using the *Geostatistical Analyst* tool in the ArcGIS 10.8 environment (ESRI, 2019). To limit error in prediction, the interpolation was not performed on the national scale but rather region by region (n=759). We separated metropolitan France into six large areas (North-Centre, Brittany-West of France, South-West, Pyrenees, Auvergne, Vosges-Jura, Alpine valleys) delimited according to the spatial autocorrelation between the carbon content points. The Moran index (I) allowed us to verify that our points did indeed follow a clustered distribution (I = 0.38; z score = 31.82) as the closer it is to one, the more the

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data is perfectly clustered. Moving forward, the Hot Spot Analysis (Getis-Ord g_i^*) from ArcGIS allowed us to delimit these clusters. We used the "Fixed distance band" method and a distance band of 63,000 meters, the minimum distance for any point to have at least one neighbor. This tool allowed us to locate hotspots and coldspots, i.e. points that are close to each other and have a significantly higher or lower carbon value than the average (Getis & Ord, 1992; Rossi & Becker, 2019). The identified clusters (Appendix 2) were used as a basis for the regional division. This subdivision into six regions is also based on the fact that, from one region to another, peatlands have different characteristics depending on elevation and climate. The delimited zones are in part overlapping with large French climatic areas (Joly et al., 2010). Grouping the peat bogs into homogeneous zones thus provides a more appropriate response to the semi-variogram. Each region had between 15 (Pyrenees) and 254 points (North-Centre) and was individually interpolated by ordinary kriging. The model selected in the *Geostatistical Analyst* tool for each interpolation was chosen to follow as carefully as possible the data distribution on the semi-variogram. The accuracy of predictions was verified using cross validation at national scale (Figure 1) and root mean square error (RMSE) (Equation 3) for each region and at national scale.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (p_i - m_i)^2} \quad (3)$$

Where m_i is the measured value and p_i the predicted value at position i .

Regional interpolations yield a reasonable Root Mean Square Error (RMSE = 0.045). Biggest prediction errors were generally made for values with lowest carbon contents (Figure 1). Lastly, the values of the interpolated raster were sampled for all the peatlands lacking carbon content values.

Bulk density

Bulk density (BD), generally expressed in g.cm^{-3} or kg.m^{-3} , is the solid soil mass (M_s) divided by the total soil volume (V_t), i.e. the ratio between the mass of a dry sample and the volume of the fresh sample (Agus et al., 2010). Peat BD is low compared to mineral soils (Minasny et al., 2019). BD varies between types of peats, primarily influenced by the degree of decomposition of the peat (thus varies with depth)

and its plant composition. Degree of decomposition and BD are positively correlated; hemic peats tend to have higher densities than those of fibric peats (Boelter, 1969; Okruszko & Ilnicki, 2002; Payette & Rochefort, 2001; Roßkopf et al., 2015). Besides, Roßkopf et al. (2015) showed that *Sphagnum* peat, a typical bog peat, has a BD varying between 90 and 100 kg.m⁻³ while BD for fen peats is higher and ranges from 100 to 350 kg.m⁻³. Fen peats have higher BD since they can be subject to influx of mineral material during water runoff, increasing their ash content.

The introductory document of the Atlas indicates BD values that range from 100 to 1,060 kg.m⁻³ depending on the type of peat. However, these values are a lot higher than those found in literature, probably due to an inappropriate sampling methodology in 1949. Consequently, we choose not to use these data and to deduce BD from carbon content values instead, as literature demonstrates that higher BD can be found in peatlands where carbon content is low, and vice versa (Roßkopf et al., 2015). Such a relationship has been demonstrated in the literature for peat and other organic soils under agricultural use in Germany (Wittnebel et al., 2021). In our case, 72 data (Appendix 1) from 17 peer datasets were reviewed, where BD and carbon content showed a strong negative correlation according to Pearson correlation coefficient ($R^2= 0.67$, $pvalue<0.05$) (Figure 2). Normality assumption of the independent variable (*Bulk density*) was not met to construct a linear regression model (Shapiro test: $pvalue<0.05$). Therefore, a log10 base transformation was applied onto the bulk density data to improve normality of the distribution (Shapiro test: $pvalue>0.05$). BD (in kg.m⁻³) was then estimated using Equation 4.

$$\log BD = -1.95C_C + 3.06 \quad (4)$$

2.4 Regional carbon stocks

In order to obtain the most accurate regional estimations, carbon stocks of peatlands crossing two regions were recalculated proportional to the area included in each region. The intersection was produced based on the old delineation of French regions, prior to 2015. Since the regions were then

smaller, it made it possible to provide more accurate and detailed results than if we had used boundaries of the new regions.

Peatland's size varies noticeably within each region and, therefore, each entity cannot carry the same weight in regional and national means. Consequently, to give an accurate regional estimation, mean area per peatland, BD, carbon content and carbon stock per hectare per meter of peat thickness of each peatland was weighted proportional to its size. As shown in Equations 5 and 6, weighted mean (\bar{X}) and weighted standard deviation ($\hat{\sigma}$) by area were used to estimate these 5 parameters.

$$\bar{X} = \frac{\sum_{i=1}^n (x_i w_i)}{\sum_{i=1}^n w_i} \quad (5)$$

Where w is the weight, i.e. the area; x is the value of the parameter.

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^n w_i (x_i - \bar{X})^2}{M \sum_{i=1}^n w_i}} \quad (6)$$

With M being the number of weights.

2.5 CO₂ emission potential

The emission potential of peatlands represents the amount of carbon dioxide (CO₂) that could be released from the peat carbon stock if the entire stock was depleted. It was assessed as follow using the carbon to CO₂ conversion factor (Equation 7).

$$\text{CO}_2\text{potential} = C_{\text{peat}} \times 3.67 \quad (7)$$

3. Results

3.1 French peatlands distribution in 1949

For the surveyed area, 63,285 ha were identified as peatlands in 1949, which represents 0.11% of the total national metropolitan surface. Peatland ecosystems could be found in almost all inventoried regions (Figure 3). Nonetheless, peatlands' distribution across the national territory was not

homogeneous but rather clustered. Main clusters of peatlands were located in montane or mid-montane areas, i.e. Massif Central (Auvergne), Jura (Franche-Comté), Vosges (Lorraine) as well as in the Armorican Massif (Brittany). At that time, peatlands also were numerous in the northern part of France, along a diagonal line extending from Pays de la Loire to Nord-Pas-de-Calais, though they were more dispersed than in mountainous areas. Conversely, the 1949 Atlas data showed very few peatlands in the Mediterranean part of the southern quarter of France and in some lowland areas such as Burgundy, Centre region and the north of Lorraine.

More precisely, along with montane areas, Brittany hosted greater numbers of peatlands (Limousin, n=273; Auvergne, n=267; Brittany, n=260). However, these peatlands were smaller than in lowland areas from the North and Southwest of France, where peaty sites were less abundant, more dispersed, but often occupied bigger surface areas in 1949. Indeed, when considering the area occupied by peatlands compared to the total area of the region, Lower Normandy (0.6% of total land use) and Picardy (0.3%) had the highest peatland coverage. Mean surface area per peaty site tended to be significantly above average (= 32.0) in Lower Normandy (248.7 ha per site), Upper Normandy (109.2 ha per site) and Pays de la Loire (84.8 ha per site) while the mean surface per peatland only was 15.2 ha for Limousin, 24.4 ha for Franche-Comté, 13.1 ha for Auvergne and 13.1 ha for Brittany (Table 1), although peatland densities were important in these regions.

3.2 Peatland properties and carbon stocks in 1949

In metropolitan France, for 63,290 ha of peatlands prospected by the Ministry of Industry and Commerce, carbon stock amounted to 110.5 MtC in 1949. This is equivalent to a CO₂ emission potential of 405.6 MtCO₂. Considering all peatlands were not inventoried in 1949, this national estimation of total carbon stock could be even greater. Furthermore, mean weighted carbon peat density was 716 ± 77 tC.ha⁻¹.m⁻¹ (Table 1).

Nonetheless, local reality is much more complex since carbon stocks contained in peatlands were distributed unevenly across the national territory (Figure 4). Carbon stock in a peatland is directly influenced by the volume of peat, itself a product of surface area and peat thickness. Based on the inventoried peatlands from the 1949 Atlas, carbon stocks ranged from 64 tons for a peatland in the Oise watershed in Picardy (0.17 ha) to 12.0 Mt C for the Marais de Douve (3,279 ha) in Lower Normandy. The 5 largest peaty sites represented 21% of French peaty surface area, 35% of peat volume and 34% of French carbon stock while the 15 largest peaty sites were equivalent to 37% of French peaty surface, as well as 51% of peat volume and 50% of total carbon stock.

Geographically, the greatest organic carbon stocks were located in the largest peatlands of the territory in the northern and north-western regions of France (Table 1): Lower Normandy (34.5 MtC), especially in Cotentin, Picardy (12.0 MtC) and Pays de la Loire (7.4 MtC), in marshes of Brière more specifically. Lower Normandy stood out from other regions as it contained 34% of the carbon stock from French peatlands, including 12.0 MtC or 11% of this stock in a single peatland, the one of Douve Marshes which is the 2nd largest peaty site of France (3,279 ha) after Brière marsh (3,312 ha). Rhône-Alpes region constituted an exception in eastern France as its peatlands held 11.0 MtC, i.e. France's 3rd largest carbon stock after Lower Normandy. That is because peatlands located on the western border of the Alps, along the Rhône Valley from Valserhône to Lyon, were numerous (n=134) and large (40 ha per site) compared to peatlands of the Jura, Vosges and the alpine range. In contrast, regions in mountain areas (Auvergne, Franche-Comté, Midi-Pyrénées, Limousin) had lower carbon stocks as they represented smaller surfaces than peatland in plain regions and had lower BD (Table 1).

3.3 Characteristics of lowland and mountain peatlands

Elevation of the French peaty sites inventoried in 1949 followed a bimodal distribution (Figure 5), with one peak at 0-100 meters (n=400) and a second one, slightly less pronounced, at 800-900 meters (n=175). Peatlands of these two groups showed very distinct characteristics when studied according to this altitudinal separation (Figure 5). Above 500 meters (n=922), each site was, on average, characterized by

a small surface (mean 14.7 ha), low thickness (mean 1.5 ± 0.9 m) and a high carbon content in its organic matter (mean $48 \pm 4\%$) which was associated with a lower mean BD (137 ± 34 kg.m⁻³). As a consequence, these peatlands had lower carbon stocks per hectare per meter of peat thickness (642 ± 58 tC.ha⁻¹.m⁻¹). At the opposite, at moderate elevation (<500 m), this value was on average of 737 ± 69 tC.ha⁻¹.m⁻¹ for 1,018 peaty sites. Those peatlands tended to be wider (48.3 ha), had greater peat thicknesses (2.7 ± 1.8 m), lower carbon content ($41 \pm 5\%$) and higher BD (184 ± 49 kg.m⁻³), which resulted in higher carbon densities.

4. Discussion and conclusion

4.1 *An unpublished tool to study French peatlands and their carbon stocks*

The analysis of the 1949 inventory data provides an initial overview of the distribution of French peatlands as well as their carbon stock within the metropolitan territory. Areas identified as peatland rose to 63,285 ha, i.e. 0.1% of national metropolitan territory but the authors of the Atlas estimated the French total peatland area to be much greater than this value. Indeed, the sampling effort targeted biggest exploitable deposits, especially in lowland regions (Figure 5), and many sites were missed by the Atlas. Therefore, in the introductory document of the 1949 inventory, it is estimated that, in addition to the 45,900 ha surveyed (a higher value of 63,285 ha is obtained if areas of the digitalized Atlas are recalculated with QGIS), 39,100 ha could also potentially be exploited, accounting up to nearly 85,000 ha of exploitable peatlands. Furthermore, in a more speculative estimation, the authors argue that, by including non-exploitable montane peatlands, this area could be extended to 100,000 ha, accounting for 0.2% of the metropolitan surface area. This means that the inventory surveyed only 46 % (45,900 ha) of national peatlands in 1949 and that 54% of peatlands were not prospected. This ratio is similar to the surface area estimated by Joosten (2009) (140,000 ha). However, it is clearly below the values given in other European inventories in which the surface area of French peatlands is estimated to range, with some uncertainty, between 275,000-315,700 ha, i.e. 0.5% to 0.6% of the total land use (Julve & Muller,

2017; Montanarella et al., 2005; Tanneberger et al., 2017). The variability of the national peaty surface estimates originates from the wide range of data sources used by those studies. The estimate from Montanarella *et al.* (2005), is unusually high as it comes from the European Soil Database, which includes low thickness soils of 10 to 30 cm. Tanneberger *et al.* (2017)'s estimation originates from an inventory carried out by the French Observation and Statistics Department (*Service de l'Observation et des Statistiques, SOeS*) in 2012 (Figure 6), as well with unknown sources. SOeS inventory is based on regional data aggregation but the quality of this data is unequal from one region to another. For some regions such as Pyrenees, peaty surfaces seem unusually high with regard to the physical and climatic contexts. On the other hand, in regions known to be rich in peatlands, many peaty sites do not appear in the SOeS's cartography from 2012 (e.g. Picardy or Brittany) as compared to the 1949 Atlas (Figure 6). Moreover, methodologies used to map peatlands in SOeS inventory are very heterogeneous as some inventories were made for this work in 2012, other were older (1996-2007) (Service de l'Observation et des Statistiques, 2013).

The carbon stock estimation of 110.5 MtC in 1949 is similar to what can be found in literature. Byrne et al. (2004) estimated this stock to 91 MtC and Joosten (2009) to 150 MtC, while they calculated these stocks from much more approximate values of surfaces, peat depths, BD and carbon contents. The carbon stock we estimated is equivalent to 3% of the organic carbon stored in the upper 30 centimeters of all French soils according to the INRA (3,585 MtC) (Pellerin et al., 2020). Therefore, our calculation shows the carbon stock of French peatlands is much lower than in regions of northern Europe such as Scotland, where peatlands store 1,620 MtC i.e. 56% of organic carbon from soils (Chapman et al., 2009). Nonetheless, it is still significant considering that peatlands only cover a tiny fraction of the French territory and that this stock is probably higher since barely half of the peatlands were inventoried in 1949. However, the percentage of peatlands that were not inventoried in 1949 may be high but this does not mean that our carbon stock estimation would be twice below the reality. Non-inventoried peatlands were for many sites already exploited and shallower sites, which weigh less in the stock estimation because of their lower peat volumes.

From this stock, the CO₂ emission potential from French peatlands was estimated to 405.6 MtCO₂ in 1949. It is almost the equivalent of all French annual GHG emissions for 2018 (419.1 MtCO₂eq) (Commissariat général au développement durable, 2019a), while the inventory is far from being exhaustive. Peatlands thus appeared in 1949 as a major carbon sink, yet an important part of peat volume and carbon stocks had already been lost from histosols at this date. Indeed, traces of peatland exploitation go as far back to the Middle Age, especially in lowland region such as Picardy (Cubizolle, 2019). Peat extraction peak was even reached in 1850, with 500,000 tons extracted in a year (Ministère de l'industrie et du commerce, 1949a).

4.2 A clear distinction between fens and bogs regarding peat properties

French peatlands in 1949 could be categorized into 2 groups based on their elevation (Figure 5). In mid-montane regions, from medium to high elevations (above 500 m), peatlands had higher carbon contents and lower BD as the majority of such peatlands are ombrotrophic (Cubizolle, 2019; Julve & Muller, 2017), also known as peat bogs. They are mostly supplied by precipitation waters, in wet climatic contexts like mountainous (Auvergne, Jura) and/or very humid environments. Water supply from precipitation favors acidification of the environment and limits decomposition of organic matter by microorganisms, a phenomenon maintained by the ability of Sphagnum mosses to keep these drastic conditions (Francez, 2000). Conversely, peatlands at lower elevations had moderate carbon contents but higher BD. Those values are especially influenced by large alkaline fens at lower elevations, which formed in alluvial zones where drainage is low (Francez, 2000), in Cotentin for instance. These habitats have a minerotrophic functioning; they are supplied by a water table close to the surface or by surface runoffs in a calcareous context. These richer waters favor a less acidic environment and give space for more easily decomposable plants to grow, which explains higher BD values. Furthermore, the mineral input from runoff increase the mean ash content.

At a national scale, the weighted mean for all inventoried sites in 1949 is 716 tC.ha⁻¹.m⁻¹. Overall, our results are in the same range as estimates of carbon stock per hectare per meter of peat found in the

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literature, as those vary from 665-669 tC.ha⁻¹.m⁻¹ for fens (Wittnebel et al., 2021; Roßkopf et al., 2015) to 560-700 tC.ha⁻¹.m⁻¹ (Gübler & Seidl, 2020; Wittnebel et al., 2021; Roßkopf et al., 2015) for bogs. Our values for peatlands under 500m of elevation (737 ± 69 tC.ha⁻¹.m⁻¹), dominated by fens, and peatlands above 500m (642 ± 58 tC.ha⁻¹.m⁻¹), dominated by bogs, do not seem aberrant. Moreover, Wittnebell et al. (2021) also found higher values for fens (665 tC ha⁻¹) than bogs (628 tC ha⁻¹) for the upper meter of peat.

Even though division by elevation (Figure 5) is overlaid to the classic separation between fens and bogs, it is nevertheless necessary to be extremely cautious in these generalizations. Indeed, Figure 5 does not depict the wide variety and complexity of local climatic, geological and geomorphological conditions that created a diversity of peatlands across France. Most of the time, minerotrophic and ombrotrophic functioning coexist on the same site (Lhosmot et al., 2021; Tanneberger et al., 2017). Moreover, bogs and fens cannot be categorized solely by elevation. Elevation values below 500 meters, for example, include all peatlands in Brittany while the characteristics of the latter actually are closer to montane peatlands than lowland peatlands, e.g. being characterized by high rates of carbon content.

4.3 Limits related to the age of the document and its historical context

The 1949 Atlas is a crucial source of data providing a better understanding of French peatlands carbon stocks. It is also the only inventory that acquired large-scaled information on peat ash content and thicknesses. Despite being valuable, these data should be considered cautiously, notably because of the tools used between 1941-1945 to delimitate peaty areas. The surveys were made with a needle probe, which did not guarantee that the crossed material was effectively peat and not mud or gyttja, i.e. a sediment very-rich in organic matter, found at the bottom of lakes or marshes. As a consequence, the delimitation of some sites was sometimes approximately defined by authors and could include areas with little or no peat. Moreover, the prospectors had few time to prospect a large surface. Therefore, they acknowledge the fact that peat thicknesses measurements were not always as regular as they wanted, leading to inaccuracies in mean peat thickness given for each site. Other problems of delimitation included: wrong localization of peatlands indicated by the authors, imprecision of military

maps leading to inaccurate positioning of sites on the maps during the digitization process and incorrect assignment of site codes or matching between the note and the code of the Atlas. These elements may create an additional bias in our study and could influence the total peat surface and volume estimated from the Atlas.

Moreover, the 1949 inventory only took into consideration less than half of the French peaty surface area at that time and is hence incomplete. Consequently, the surface area and carbon stocks numbers estimated (Table 1) do not constitute exhaustive values. Prospections were done between 1941-1945 during the Second World War so the inventory does not provide any data for Alsace for example, while peatland presence is attested in the Vosges and northern Vosges (Figure 6) (Service de l'Observation et des Statistiques, 2013). The absence of some peatlands from the 1949 inventory is linked to the objectives set behind the prospecting campaign. Indeed, peatlands were inventoried as places where to extract of peat and defined on geological rather than ecological criteria (Cubizolle, 2019). Consequently, peatlands where extraction was deemed to be impossible for logistical, technical, financial or administrative reasons were not incorporated in the Atlas. This includes long-term cultivated peatlands, already exploited peatlands and high montane peatlands, difficult to access, small and therefore unprofitable. As a consequence, mapped surfaces from 1949 Atlas in alpine and Pyrenean ranges probably are far less extended than what they really are.

We also should keep in mind that carbon content values were, for 1,180 peatlands, extrapolated from ash content values. Thus, the RMSE is around 4.91 for the full set of points but the quality of prediction actually is variable from one region to another depending on the size of the sample per region. As an example, RMSE is 6.53 for the alpine valley cluster (n=48) and 2.02 for the Massif Central cluster which has a more reliable sample size (n=254). We also saw that low carbon content values were underestimated during the interpolation step; this means that total carbon stock may be underestimated as well since peatlands with low carbon contents have higher BD and are larger in size, which increases the error in estimation. Similarly, BD values are extrapolated from these carbon content values that may

also lead to uncertainty. The use of a BD value extrapolated for each peatland allows us to refine our results, as we consider the variability of this parameter for each type of peatland rather than using an average value for all peatlands. However, the BD values used to produce the linear regression model derive from the literature and cannot substitute for data acquired on the field. Our carbon stocks estimations should be interpreted while considering the latter elements.

Above all, the 1949 Atlas is 80-years-old and peatland surfaces given in this document may no longer reflect the current situation of peatlands. The trend of surface diminution that was prevalent in Europe between 1949 until now, notably for wide minerotrophic peatlands, was likely to have occurred in France as well (Cubizolle, 2019; Tanneberger et al., 2017). Although peat extraction became anecdotal after 1950 in France, extraction pits and drains remain active years after the cessation of the activity. Besides, many peatlands were drained and converted to agricultural fields, for example in the North of France, or forestry zones (poplar cultivars in plains, spruce plantations in the Jura...) (Julve & Muller, 2017). The drainage of peatlands for agriculture began in the Middle Ages but increased during the 20th century with agricultural intensification. In addition, nowadays, climate change causes more regular and prolonged droughts that negatively affect water table depths (Bertrand et al., 2021) and may contribute to the subsidence of peaty surfaces. In Franche-Comté, for example, one of the only French regions where a recent complete inventory of peatlands is available (Moncorgé & Gisbert, 2016), the loss of peaty areas between 1949 and 2022 is estimated to be 1,060 ha. This corresponds to a diminution of 24% of Franche-Comté's total peatland surface when compared with the 1949 inventory. Given the imprecision of the 1949 inventory and its lack of exhaustiveness, it is reasonable to consider that this number does not give a strict surface loss and that it should be relativized, especially since methods of delineation differ between the two inventories. However, other European (Joosten, 2009) or French regional studies (Agrosol, 2021; Deudon, 2018; Moncorgé & Gisbert, 2016) give sufficient clues to affirm that most of the French regions likely followed a trend to surface decreasing or environmental degradation. This is a real issue as it implies that carbon held by these peatlands in 1949 may have been partly released into the atmosphere as CO₂, contributing to global change. Furthermore, it means that

the characteristics of peat given in the 1949 inventory for each region may have qualitatively changed in some sites, as processes of OM mineralization can be reactivated in degraded peatlands. For instance, it has been proved that carbon content decreases with increasing degree of decomposition whereas BD rises when the degree of decomposition increases (Päivänen, 1969; Roßkopf et al., 2015; Sinclair et al., 2020). A study in Germany also demonstrated that the concentration of peat organic matter was lower in drained peatlands when compared to an intact peatland (Wang et al., 2021), resulting in lower peat carbon concentrations as this variable is dependent on organic matter content. These changes can concern the upper part of the peat column or the whole column, depending of the extent to which the water table has been lowered. Therefore, the 80-year-old values from the 1949 inventory should be used with great caution as they may be inaccurate to characterize current peatland sites and their carbon stocks.

4.4 Towards an update of the national peatland inventory

80 years ago, the Atlas inventory did not give a complete overview of French peatlands and, today, it cannot be used as a reference database to describe the current situation of peatlands. Yet, the demand for information about localization, peat volume, carbon stocks and CO₂ potential emissions is increasing.

In 2018, the IPCC (Masson-Delmotte et al., 2018) indicated that, to limit global temperatures rise below 2°C and even 1.5°C, net carbon dioxide emissions from human activities should decrease to zero before 2050. In France, the Low Carbon National Strategy is the national path to reduce the country's GHG emissions. To do so, the IPCC (2019) underlined the importance of peatlands conservation and restoration, especially by rewetting these ecosystems to increase the water table back to pre-draining levels. Scientists consider peatland restoration as one of the main solutions for maintaining carbon storage function and limiting degraded peatlands' contribution to climate change via CO₂ emissions. In 2019, a report from the French platform on biodiversity and ecosystem services (Efese) insisted on the need to have a sustainable land management that conserves and protects carbon stocks and other

ecosystem functions and services (Commissariat général au développement durable, 2019b). Tuffnell & Bignon (2019) also pleaded for restoration of these ecosystems in a ministerial report insisting on the need for a National Restoration Program aiming to restore 100,000 ha of peatlands, i.e. the totality of the metropolitan peatland area, to be implemented between 2020 and 2030.

To know precisely how French peatlands contribute to this national goal and thus implement a real program of restoration of degraded sites, decision-makers and managers of natural spaces need cartographic tools that can help them prioritize sites but data we possess right now is insufficient. The 1949 Atlas offers precious yet old data about physical-chemical properties of peat and their distribution. Since the 80-90's, many environmental management structures started to implement an inventory of peatlands on their intervention territory. However, these inventories do not rely on the same methodologies and lack homogeneity, especially since some survey peat thickness, vegetation type or the presence of anthropic pressures while other only give localization of the peaty sites. In 2012, Observation and Statistics Department (*Service de l'Observation et des Statistiques, SOeS*) carried out, with the help of the national center of knowledge, sustainable management and evaluation of peatlands (*Pôle-Relais tourbières*), a first aggregation of these regional data. Total peatland area estimated from this aggregation of regional inventories is 79,005 ha. Though, as seen above, the obtained result is very incomplete, only gives information about surfaces (Figure 6) and the inventories used for this aggregation are very heterogeneous (Service de l'Observation et des Statistiques, 2013).

In view of these observations, the main issue is therefore to create a complete national inventory to know where are French peatlands and main carbon stocks located. A bottom-up approach based on local data aggregation, by animating a network of natural spaces managers, should be preferred over global soil maps, as observed in other studies (Biancalani et al., 2014; Tanneberger et al., 2017). There is also urgency to acquire data on peat thicknesses, carbon contents and bulk densities, data that are very little available in France, although they can significantly limit the error obtained during the calculation of national and regional carbon stocks (Chapman et al., 2009). It should be accompanied by elements to

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characterize the state of deterioration of each inventoried peatland, using ecological and geographical indicators as water table depth (Evans et al., 2021), vegetation state (Šimanauskienė et al., 2019) or land use (Tanneberger, Moen, et al., 2021). The latter, for example, is known to create wide variations in CO₂ emissions whether the peatland is “natural” or cultivated (Biancalani et al., 2014; Bonn et al., 2014). Knowing the peatland’s ecological state is a necessary element in a prospective approach because it is used to determine the vulnerability of a carbon stock and, therefore, the degree of urgency to restore a peatland which may shift from carbon sink to source after human disturbance. Such an inventory should also include information about the protection status of the site, as well as socio-economic variables like property status and land use, often omitted in ecological studies while they directly influence restoration costs, administrative burden and, consequently, possibility of intervention. Eventually, it is important for this database to be centralized and standardized within existing national databases, such as the Wetland Data Network (*Réseau Partenarial des Données sur les Zones Humides*) so that it can be easily accessed and downloaded by its users.

Data from the 1949 Atlas, although obsolete in some aspects, should help implement a new inventory of French peatlands and carbon stocks. The 1949 Atlas highlights regions where peatlands are located and where they can be found in the highest densities. By providing indications on the areas where the probability of finding peatlands is the highest, it indicates which regions should be investigated in priority for future inventories. Moreover, this inventory constitutes the only data available about peat thicknesses and ash contents in France. These data should be however verified to take into consideration the evolutions of peatlands in 80 years, as physical-chemical properties of peat may have changed through decades. Furthermore, a new national inventory should also include an additional work about “former mires”, that-is-to-say sites characterized by peat deposits but lacking living peat-forming vegetation. Such study could be supported by the 1949 inventory. Indeed, an undefined number of peatlands inventoried in 1949 may not be identified as such nowadays because the peatland’s typical vegetation has disappeared due to drying. At a bigger depth, though, peat remains and keeps on decomposing in the absence of anaerobic conditions that slow down the mineralization processes.

Identifying these peatlands is of real concern since they may be the biggest contributors to global warming, but often are excluded from conservation and restoration actions as they shelter little to no typical peatland biodiversity (Moncorgé & Gisbert, 2016).

Acknowledgements

This research was funded by the *Zone Atelier Arc Jurassien* (ZAAJ), member of the French LTSER network. The *Pôle relais tourbières* (French information center on peatlands) supervised and made possible the digitization work. Special thanks are given to the *Conservatoire d'Espaces Naturels de Franche-Comté* for sending a recent inventory of peatlands in their region, allowing comparisons with 1949 data. The authors would like to thank A. Abi Nader and B. Dheenathalayan for revision of the article and English corrections.

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Captions

Figure 1: cross validation for CC values from 1949 inventory (759 sites) with a) predicted values versus measured values and b) prediction errors for measured values. Measured CC values are estimated from the ash values and converted to organic carbon using the soil organic carbon to soil organic matter conversion factor.

Figure 2: Carbon content proportion and bulk density relation using data from literature (72 data). Black circles refer to bulk density values expressed in \log_{10} , while blue asterisks represent bulk densities in kg.m^3 .

Figure 3: Exploitable peat deposits' distribution across metropolitan France according to the 1949 Atlas.

Figure 4: distribution of carbon stocks (tC) from peatlands across French metropolitan territory in 1949.

Figure 5: Distribution of elevation among studied entities (n=1939) and peat characteristics (weighted means) for peatland under and above 500m of elevation.

Figure 6: Peatlands distribution according to the 2012 inventory from *Service de l'Observation et des Statistiques* (SOeS) (orange), compared to the Atlas from 1949 (blue). Green polygons show peatlands inventoried in both inventories.

Table 1: characteristics of metropolitan France peatlands per region (number of sites, total area of peatlands, weighted mean area per site, weighted mean carbon content, weighted mean bulk density, total carbon stock, total carbon dioxide emissions, peat carbon stock per ha per meter of peat depth and mean elevation) according to the 1949 Atlas. Highest values for each column are in bold.

Appendix 1: carbon content (Cc) proportion and bulk density (BD) (g.cm^{-3}) data found in literature (n=72)

Appendix 2: Coldspots and hotspots for Cc values using Getis-Ord g_i^* 's tool on ArcGis. Limits of clusters are based on spatial autocorrelation.

Table 1: characteristics of metropolitan France peatlands per region (number of sites, total area of peatlands, weighted mean area per site, weighted mean carbon content, weighted mean bulk density, total carbon stock, total carbon dioxide emissions, peat carbon stock per ha per meter of peat depth and mean elevation) according to the 1949 Atlas. Highest values for each column are in bold.

Region	n	Total peatland surface area (ha)	Site mean surface area (ha) $\pm \bar{\sigma}$	Mean thickness (m) $\pm \bar{\sigma}$	Mean BD (kg.m ⁻³) $\pm \bar{\sigma}$	Mean Cc (%) $\pm \bar{\sigma}$	Cpeat (tC)	Proportion of total carbon stock	Cpeat (tC.ha ⁻¹ .m ⁻¹) $\pm \bar{\sigma}$	CO ₂ emissions potential (t.CO ₂)	Elevation (m) $\pm \sigma$
Aquitaine	65	2,235	34 \pm 71	2.3 \pm 1.3	224 \pm 57	37 \pm 6	4,010,000	4%	800 \pm 77	14,718,000	87 \pm 116
Auvergne	267	3,500	13 \pm 16	1.9 \pm 1.1	133 \pm 26	48 \pm 9	4,087,000	4%	633 \pm 55	14,998,000	1,107 \pm 156
Lower Normandy	43	10,695	249 \pm 714	4.9 \pm 1.2	172 \pm 20	42 \pm 2	37,693,000	34%	725 \pm 34	138,334,000	151 \pm 103
Burgundy	18	1,030	57 \pm 120	1.2 \pm 0.4	241 \pm 37	35 \pm 4	1,045,000	1%	831 \pm 49	3,834,000	192 \pm 200
Brittany	260	3,395	13 \pm 66	1.0 \pm 0.6	157 \pm 28	45 \pm 3	2,308,000	2%	692 \pm 46	8,470,000	180 \pm 85
Centre	65	1,827	28 \pm 47	1.5 \pm 0.9	200 \pm 41	39 \pm 4	2,090,000	2%	771 \pm 44	7,669,000	143 \pm 143
Champagne-Ardenne	75	2,588	35 \pm 144	1.2 \pm 0.4	176 \pm 27	42 \pm 3	2,202,000	2%	730 \pm 46	8,082,000	117 \pm 70
Franche-Comté	182	4,444	24 \pm 70	1.8 \pm 0.6	125 \pm 11	49 \pm 2	4,941,000	4%	617 \pm 28	18,132,000	860 \pm 222
Upper Normandy	23	2,511	109 \pm 344	3.8 \pm 1.0	144 \pm 20	46 \pm 3	6,141,000	6%	662 \pm 42	22,539,000	59 \pm 53
Ile-de-France	52	1,717	33 \pm 37	3.1 \pm 1.5	185 \pm 28	41 \pm 3	3,961,000	4%	748 \pm 52	14,538,000	74 \pm 35
Languedoc-Roussillon	34	355	10 \pm 12	1.9 \pm 1.1	127 \pm 9	49 \pm 1	416,000	0%	622 \pm 22	1,526,000	1,060 \pm 230
Limousin	273	4,140	15 \pm 19	0.9 \pm 0.4	151 \pm 48	46 \pm 5	2,610,000	2%	670 \pm 63	9,578,000	714 \pm 118
Lorraine	116	613	5 \pm 7	1.3 \pm 0.8	142 \pm 31	47 \pm 5	511,000	0%	653 \pm 68	1,877,000	713 \pm 243
Midi-Pyrénées	21	180	9 \pm 11	2.2 \pm 1.6	162 \pm 45	44 \pm 5	276,000	0%	694 \pm 72	1,013,000	889 \pm 433
Nord-Pas-de-Calais	44	798	18 \pm 29	1.5 \pm 0.7	237 \pm 31	35 \pm 3	1,016,000	1%	829 \pm 35	3,730,000	55 \pm 161
Pays de la Loire	88	7,462	85 \pm 402	1.5 \pm 0.7	166 \pm 45	44 \pm 5	7,984,000	7%	704 \pm 61	29,302,000	84 \pm 63
Picardy	139	6,403	46 \pm 176	2.8 \pm 1.2	191 \pm 48	41 \pm 5	13,034,000	12%	749 \pm 74	47,835,000	42 \pm 23
Poitou-Charentes	70	3,985	57 \pm 104	1.7 \pm 1.1	189 \pm 37	40 \pm 4	5,178,000	5%	753 \pm 56	19,004,000	40 \pm 31
Provence-Alpes-Côte d'Azur	9	53	6 \pm 4	0.8 \pm 0.5	164 \pm 22	44 \pm 3	30,000	0%	707 \pm 49	108,000	1,401 \pm 249

Rhône-Alpes	134	5,355	40 ± 133	2.5 ± 2.3	213 ± 81	39 ± 7		10%	769 ± 96	40,319,000	773 ± 422
Total	1,9 39 †	63,285	32 ± 164	2.4 ± 1.7	174 ± 50	43 ± 7	110,52 0,000	100%	716 ± 77	405,608,00 0	508 ± 438

† Indicated sum gives the number of peaty sites in the 1949 Atlas. It is inferior to the sum of all lines because sites overlapping two regions were divided in two distinct polygons, thus counting twice.











