From natural to cultural mires during the last 15 ka years: An integrated approach comparing 14C ages on basal peat layers with geomorphological, palaeoecological and archaeological data (Eastern Massif Central, France)

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This paper studies mire initiation modalities from the Late-Glacial to the Holocene by comparing radiocarbon ages on basal peat layers (112 sites from the Eastern French Massif Central — EFMC) with long-term land cover changes. We developed a semi-quantitative method based on the degree of openness and on Anthropogenic Impact Factors (AIF scores) from palaeoecological data (mire and lake records). Archaeological information was also considered to evaluate human impact. We compared regional mire development trends with datasets from Northern Europe, Siberia, Alaska and Canada, and with global CH_4 emission. Heterogenous cases of mire initiation were highlighted during the last 15 ka years in the EMFC. From 15 to 11.7 ka cal. BP, some mires and histic horizons occurred, although further research is needed to better understand these peat accumulation phases. Related to the Early Holocene warming, a mire generation established by terrestrialization, in the southern EFMC where geomorphology favoured fens. Bogs also formed by paludification in the whole area between 10 and 7 ka cal. BP. Then, various cases of mire initiation were found from 4.4 to 2.4 ka cal. BP. The high number of mires established since 2.4 ka cal. BP could be related to major anthropogenic changes, indirectly favouring fens (in former ponds for instance) or small bogs (at the back of roads, walls or in abandoned drainage systems). This last generation was typical of Western European mountains and implied that moderate human impact may also produce socio-ecosystems with high ecological value.

1. Introduction

Within a global context of mire loss all over the world, the need to understand the way of development of these ecosystems has become a key issue for nature preservation. Indeed, mainly due to anthropogenic actions affecting water tables (drainage, intensive livestock grazing, conifer plantations, peat extraction, etc.), Earth would have lost almost 16% of peat surfaces, of which about 50% in Europe since the end of the 19th century AD (Joosten et al., 2017; Joosten and Clarke, 2002). This is also a major concern in the Eastern French Massif Central (EFMC), where 20% of the primary peat surfaces have disappeared, and 54% are severely degraded (Cubizolle, 2019; Manneville et al., 2006). Mires could offer sustainable resources and "ecosystem services" when well managed for biodiversity, water resource, and have a carbon sink role (Laine

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et al., 1996; Renou-Wilson et al., 2019). On mires, water saturation generates anaerobic conditions which reduced the degradation of organic matter and contribute to preserve organic matter remains over time (pollen, spores, plant macrofossils, beetles, etc.). The organic-rich stratigraphies from mires constitute a heritage value and those "natural archives" could record evidence of environmental and landscape changes from the past to present (Barber, 1993; Bell and Walker, 2014; Martini et al., 2006).

In middle-mountain areas, favourable humid and fresh conditions are needed to initiate peat accumulation (rainfall >900 mm year^{-1}, and mean annual temperatures <9 °C, according to Cubizolle and Thébaud, 2014), although peat initiation could be triggered by local changes in hydrological conditions. For instance, natural geological barriers (lava flows, landslides, dune formation) can imped drainage, lead to a water balance tipping point, and thus mires can be formed (Andriesse, 1988; Meurisse-Fort, 2008). In addition, human actions could be directly or indirectly involved, sometimes since the Prehistory, specifically where activities were concentrated and included fires, dam or road building (Bussières et al., 1996; Caseldine and Hatton, 1993; Cubizolle et al., 2012; Moore, 1988). Worldwide, climatic and human-induced peat initiations are suitable thanks to large radiocarbon datasets based on the dating of mire basal layers, i.e. when peat initiation began (e.g. Gallego-Sala et al., 2015; Gorham et al., 2007; Korhola et al., 2010; MacDonald et al., 2006; Pontevedra-Pombal et al., 2017; Ruppel et al., 2013). In the Northern Hemisphere, two major peat inception steps are known from 10 to 8 ka cal. BP, and during the last 4.2 ka cal. BP, however diverse hypotheses are assumed to explain these phenomena (i.e. moisture and temperature changes due to climate or human forcing) and sometimes overlap each other (Cubizolle et al., 2012; Hughes and Barber, 2003; Jones and Yu, 2010; Korhola et al., 2010; MacDonald et al., 2006; Ruppel et al., 2013). To go further on these questions, one key challenge is to improve radiocarbon dating approaches by the integration of land cover changes, land use, and archaeological data, to discuss ecosystem trajectories in the course of human or climate forcing from local to larger scales (Stephens and ArchaeoGLOBE Project authors, 2019; Whitehouse et al., 2018).

In this paper, we propose to study a corpus of 112 mires on the Eastern French Massif Central (EFMC) where basal layers were dated by radiocarbon (Fig. 1; see also. Dendievel et al., 2020). To supplement previous studies performed on some parts of the Eastern French Massif Central (Cubizolle et al., 2013, 2012; Cubizolle and Argant, 2006), our research aims at developing a spatio-temporal analysis of mire initiation dynamics on a north-south geographical transect covering more than 350 km, from the Morvan (Burgundy) to the Mézenc Massif (Ardèche Uplands). The most original aspect of this work is devoted to the statistical integration of land cover and land use data thanks to a semi-subjective method using ranked scores (from 0 to 8 points) based on the degree of openness and on the occurrence of direct or indirect anthropogenic indicators (Jouffroy-Bapicot et al., 2013). We also integrated archaeological data syntheses in order to discuss evidence of anthropogenic forcing on peat initiation, linked to water or landscape management for instance. This integrated approach is performed for the first time at the scale of the whole EFMC in order to interpret and discuss past and recent human influence on regional mire ecosystems.

2. Regional settings

2.1. Environmental synthesis

The Eastern French Massif Central (EFMC) is part of a geographical region, which is more than 350 km long and ca. 70 km width (Fig. 1). Our research focuses on the mires located, from north to south, (i) on the Morvan Massif, (ii) on the Bois Noirs and Madeleine Mountains, (iii) on the Livradois-Forez Mountains, (iv) on the Pilat Massif, (v) on the Mézenc-Meygal Massif, and (vi) on the Devès Plateau (Figs. 1 and 2). On the EFMC, the elevation generally increases from north to south: lower altitudes are found on the Morvan Massif (500–900 m a.s.l.), while higher altitudes occur on the Livradois-Forez Mountains (650–1634 m a.s.l.) and, even more, at south, on the Mézenc-Meygal Massif (800–1753 m a.s.l.). Zone (vi), i.e. the Devès area, which is located on the south-western part of the studied area, is a high plateau comprised between 800 and 1421 m a.s.l. (Fig. 1). As regards climate settings, this area is characterized by an oceanic to mountainous climate with strong seasonal temperature variations, which are climaxing at south (Mean Monthly Temp. Mézenc = 5 ± 9 °C versus Mean Monthly Temp. Morvan = 9 ± 8 °C). Rainfall increases at higher latitudes, but since latitudes and relief are negatively correlated in the EFMC (Figs. 1 and 2), annual rainfall ranges from 900 to 1500 mm year^{-1} in the whole area (Antonetti et al., 2006). These environmental settings constitute an essential basis for the establishment of mires by paludification (Fig. 2), in particular for ombrotrophic mires (Fig. 2-c), mostly formed between 900 and 1450 m a.s.l. in the EFMC (Cubizolle and Thébaud, 2014).

From a geological point of view, the EFMC is characterized by a high diversity of Middle Devonian to Late Carboniferous volcano-sedimentary and granite formations (Faure et al., 2009). These formations are found in the Morvan Massif (ca. 370–330 Ma – million years ago), in the Bois Noirs and Madeleine Mountains (330–320 Ma), while the "Velay Dome" (ca. 300 Ma) is the main basement of the Livradois-Forez, Devès and Mézenc-Meygal areas. Crustal melting and rifting created a NW-SE fault network and led to the bedrock uplift, which is found from 500 to 1634 m (i.e. Pierre-sur-Haute peak, Forez), nowadays. Multiple volcanic episodes occurred during Miocene and Pliocene epochs (Mergoil and Boivin, 1993; Nehlig et al., 2003): in the Forez (20–13 Ma), Meygal (14–9 Ma), Mézenc (11–5.7 Ma) and Devès zones (3.5–1 Ma). Basalt, phonolite and trachyte lavas cover the granite basement at some places and culminates at Mount Mézenc (1753 m a.s.l.; Fig. 1). A last volcanic period created numerous maar craters (hydro-magmatic stage) and strombolian cones (0.75–0.02 Ma) in both Devès and Mézenc-Meygal Plateaux (Defive et al., 2011; Nomade et al., 2014; Sasco, 2015). Finally, small glaciers and late Pleistocene periglacial processes (mostly during the Last Glacial Maximum) have left typical moraines and blockstreams in the highest mountains (Forez and Mézenc Massif).

This geological background and the subsequent geomorphological evolutions were significant for the development of spring and slope mires (topogenous and soligenous ones) by paludification because they controlled the volume of water tables, the presence of springs along faults or between rocks, the slopes, and thus the runoff speediness (Fig. 2-a-b). In addition to climate, these contexts were also very important for the establishment of raised bogs, found from the Morvan to the Pilat Massif (Fig. 2-c; Thébaud et al., 2003). Such mires are mainly built by *Sphagnum* accumulations but also include basal wooden contexts with birches (*Betula* sp.), alders (*Alnus glutinosa* L. Gaertn.) or willows (*Salix* sp.). Current surfaces are dominated by heathlands of *Calluna vulgaris* (L.) Hull or by Poaceae, incl. *Molinia caerulea* (L.) Moench, mainly linked to fire regime and agro-pastoral activities. Fluvial mires are scarce because river valleys are generally narrow and steep in the EFMC. Pleistocene eruptions and glaciations were also decisive for peat inception in the southern areas (i.e. Devès and Mézenc-Meygal Plateaux) where limnogenous mires can easily develop by the terrestrialization of maar crater lakes (Ribains Marsh, Narces of Chaudeyrolles, etc.) and on former periglacial lakes established on blockstream

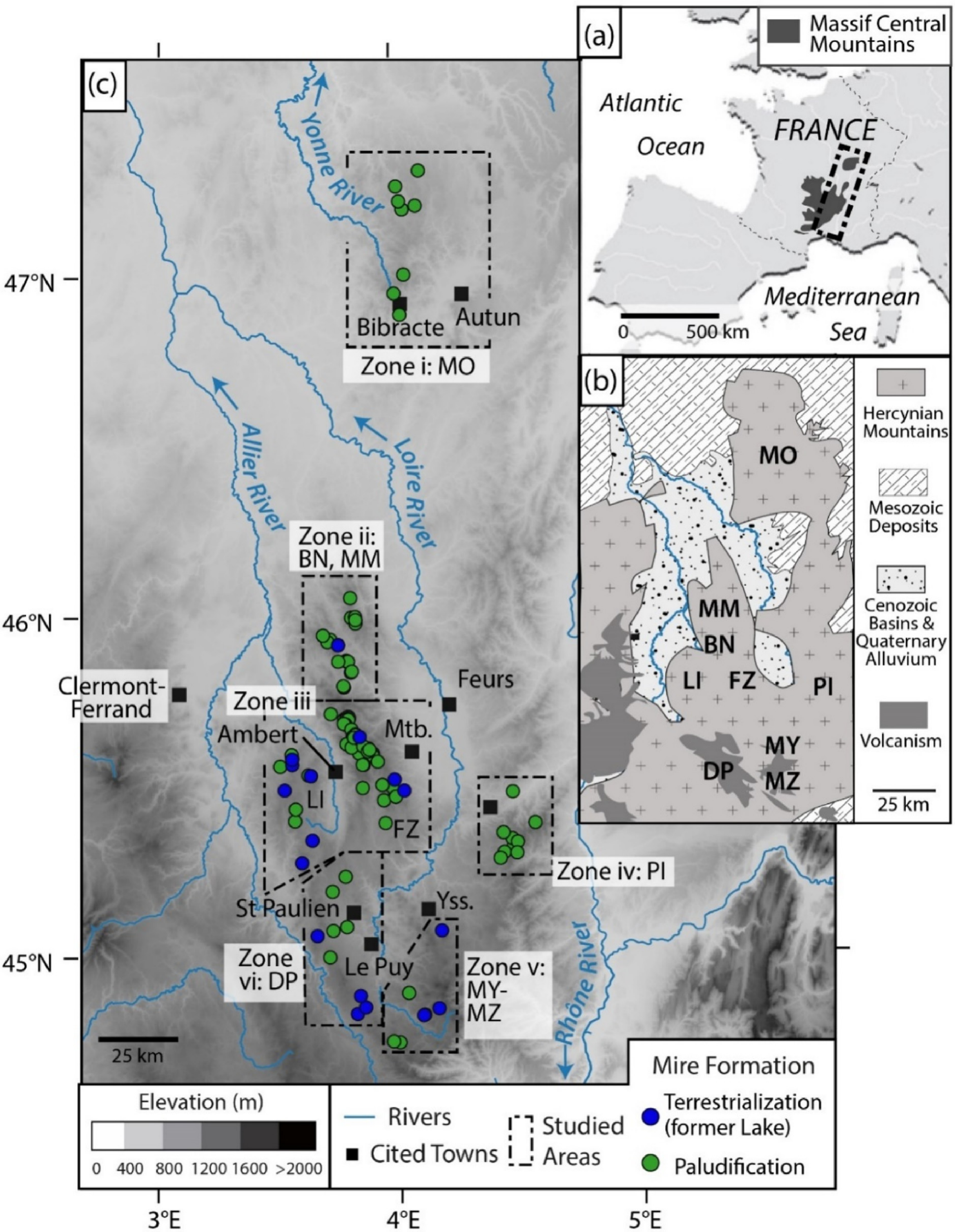

Fig. 1. Map of the mires established during the last 15 ka cal. BP on the Eastern French Massif Central (EFMC). a) Location of the Massif Central Mountains in Western Europe. The EFMC is represented by a square. b) Regional geology. c) Topographical situation of the studied sites of the EFMC. Zones i to vi refer to the natural regions cited in the text: Zone i = Morvan Massif (MO), Zone ii = Bois Noirs (BN) and Madeleine Mountains (MM), Zone iii = Livradois (LI) and Forez (FZ) Mountains, Zone iv = Pilat Massif (PI), Zone v = Meygal (MY) and Mézenc (MZ) Massif, Zone vi = Devès Plateau (DP). Abridged names of cited towns: Mtb. = Montbrison; Yss. = Yssingeaux.

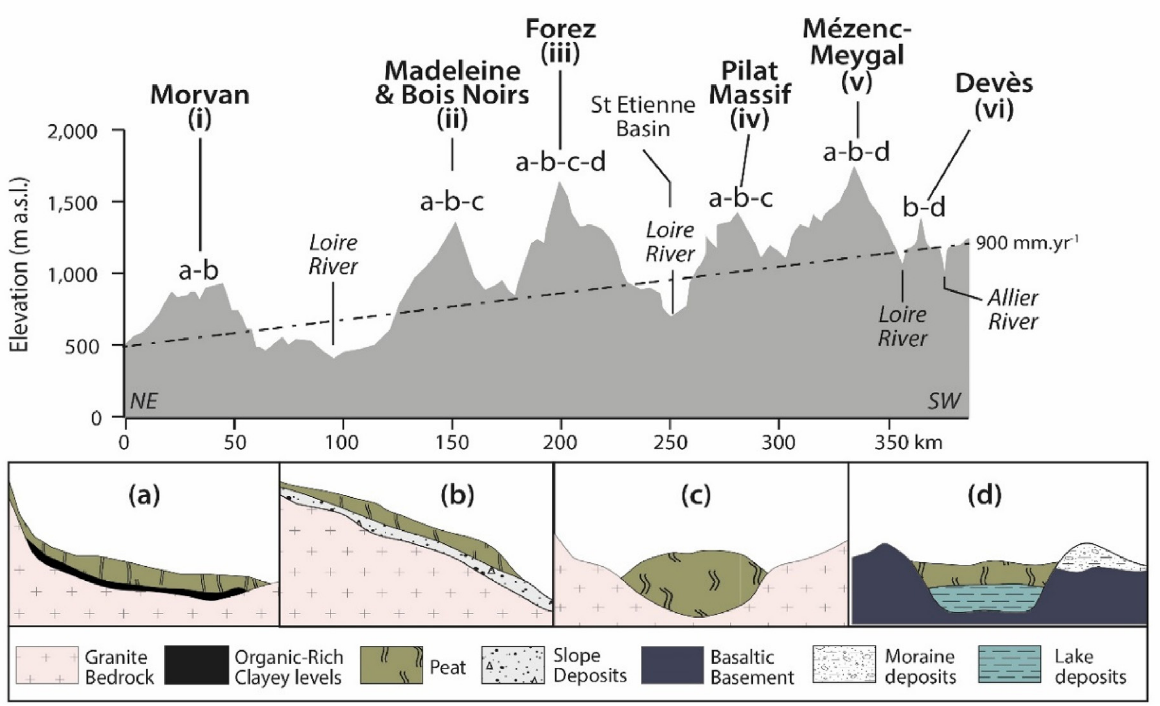

Fig. 2. Distribution of mire types according to the elevation on a north-east (NE)/south-west (SW) transect (EFMC, France). Letters i to vi refer to the natural regions cited in this paper (see also Fig. 1). The dashed line symbolises a mean rainfall of 900 mm/year. Mire types follow the topology established by Cubizolle et al. (2004) and Cubizolle and Thébaud (2014). a) Topogenous mires, b) soligenous mires, c) ombrogenous mires, d) limnogenous mires in a volcanic or periglacial context.

areas or behind moraine-dams (e.g. La Narce du Béage, and Gourd-des-Aillères fens). Furthermore, on these sites, pioneering mire phases, sometimes known as "transiting mires", also offer a very high biodiversity including underwater, floating, emergent and typical mire plants (for a case study, see Dendievel et al., 2019).

2.2. Archaeological background

Giving an overview of past occupations and site densities over time is not easy especially because regions and periods are not documented with the same accuracy in the EFMC. Here, we compiled information from recent syntheses (Cubizolle et al., 2012; Dendievel, 2017; Dendievel et al., 2019; Jouffroy-Bapicot et al., 2013; Scholtès, PhD in preparation).

Neolithic presence is mainly supported by isolated findings of silex blades, arrow heads, ground-stone axes and megaliths, although well documented sites are scarce (Rialland and Letterlé, 2013; Surmély et al., 2001). Early Neolithic occupations have been demonstrated by archaeology and palaeoecology in the southern zone, i.e. Mézenc Massif, around 7.5–6.8 ka cal. BP (Daugas and Raynal, 1989; Dendievel et al., 2019). In the northern zone, human impacts occurred most certainly during the Early Neolithic, but dwellings are mainly known since the Middle Neolithic (6.8–5.8 ka cal. BP), especially on the Mont-Beuvray (Jouffroy-Bapicot et al., 2013; Martineau et al., 2011) and in the Forez floodplain (Georges et al., 2004). Then, archaeological sites spread over the EFMC during Middle to Late and Recent Neolithic (incl. bell-beaker culture). For the Bronze Age (4.4–2.8 ka cal. BP), scattered discoveries – copper or bronze axes and daggers – are dominant, while numerous fortified sites are documented for the Final Bronze Age (3.3–2.8 ka cal. BP) in the whole region (Delrieu et al., 2015; Gabillot et al., 2016). For these periods, pathways and relationships between low-altitude (Loire, Allier, Arroux and Yonne floodplains) and mid-mountain sites for agro-pastoral purposes, lithic and wood resources need to be considered (Georges et al., 2004; Martineau et al., 2011; Milcent and Mennessier-Jouannet, 2007).

During the Iron Age and the Roman period, the number of sites increased in the floodplains, but also in the uplands (Büntgen, 2008; Dendievel, 2017; Fassion, 2013; Kurzaj, 2012; Scholtès, 2019; Simonnet, 1984). At the end of the 1st and of the 2nd Iron Age (2.6–2.4 ka cal. BP and 2.1–2.0 ka cal. BP, respectively), significant fortified sites established on the eastern slopes of the EFMC (Delrieu et al., 2012; Kurzaj and Voruz, 2017). One may cite the Bibracte *oppidum* (Morvan Massif) heading one of the greatest and richest Gallic territories documented by roman texts and archaeology (Guichard, 2013, see also: www.bibracte.fr). After the Roman conquest, former hillforts were progressively abandoned and people usually moved to open-plateau or floodplain cities such as Autun (Morvan), Ambert (Livradois), Usson, Feurs and Moingt (Forez), Yssingeaux (Meygal), Saint-Paulien and then Le Puy-en-Velay (NE Devès Plateau). During this period, we assumed that economic activities were supported by a road network, partly preserved nowadays, connecting the uplands to the floodplains ("via Bolena", "Pal road", "Chassenard/Digoin bridges", etc.) and used until the Modern Period. Examples of worship areas (*fanum*) and vast private domains (*villae*), sometimes equipped with baths, are well known in the EFMC (Fassion et al., 2011; Nouvel et al., 2009; Simonnet, 1984). In spite of few archaeological evidence, early water management is highlighted by the catchment of water from the Pilat to the Monts d'Or to supply the city of Lyon (*Lugdunum*) and by small reservoirs devoted to agro-pastoral purposes on the uplands. During the Late Antiquity and the Early Middle Ages, a lower population density is deduced from fewer archaeological sites, but small towns and some large domains persisted while land use certainly changed (Catteddu, 2009; Dendievel et al., 2019; Phalip, 2002).

From 1.3 to 0.5 ka cal. BP (Middle Ages), a significant increase of archaeological sites is recorded by excavations and medieval texts with stages of castle building (Laffont, 2009) and the establishment of monastic orders (Benedictines, Cistercians, Carthusians: Bépoix and Richard, 2019; Bouvard, 2016). Agriculture and livestock breeding developed from the uplands to the eastern slopes (Bréchon, 1998; Scholtès, 2015). This period is associated to important water management: weirs, dams and ponds formed numerous small reservoirs used for various activities, while the water was delivered by diversion to sawmills or to roller-type mills devoted to floor or oil production (Bouvard, 2011; Véron, 2017). Modern Times (0.5–0.1 ka cal. BP) correspond to a demographic maximum for the EFMC uplands. The landscape was bare and highly cultivated. Moreover, a specialization in animal breeding led to intensive grazing and wetland drainage. The landscape was also managed for firewood production, provided to Paris by the means of fluvial transport (Morvan Massif: Benoit et al., 2004; Poux et al., 2011), or for the delivery of softwood lumber products to the Navy Shipyards of Toulon (Mézenc Massif: Bartoli and Boissier, 2018).

3. Methods

3.1. Sampling and dating basal layers on mires

In order to understand how local morphology could contribute to peat accumulation, a geomorphological approach was performed on the sites presented in this paper (Fig. 1). Usually, during field survey, topo-stratigraphical profiles were based on penetrometer transects (French, 2012). This operation was achieved at varied intervals following the topography complexity (Cubizolle et al., 2012). Each penetrometer-test was located by a Total Station coupled to a hand-handled GPS (e.g. Trimble GEOXT; infra-meter resolution) or directly with a Differential GPS (Stonex or Trimble devices). Subsequently, several cores were generally extracted by using a Russian manual peat corer (Belokopytov and Beresnevich, 1955), or motorised percussion corers (e.g. Makita HM1800) in order to reach basal peat. Cores were then conserved for palaeoecological studies.

The radiocarbon dating of basal peat layers might be difficult because the interface between peat and the underlying organo-mineral layers could be sharp or gradual, depending on local settings (Charman, 2002; Cubizolle et al., 2007). Thus, the presence of basal peat layers was supported by: (i) an accurate description of the peat stratigraphy according to the degree of peat decomposition (Von Post scale) and to the fibric texture, (ii) a consensus-based organic content >30–35% (Joosten et al., 2017), and (iii) by typical micro- or macrofossil assemblages such as Bryophyta fragments and spores (incl. *Sphagnum*), mire trees or shrubs (birches, alders) and herbs such as sedges (Cubizolle, 2019; Cubizolle et al., 2007, 2012). According to these characteristics, we distinguished two types of peat formation process and associated mire-types: terrestrialization of former lakes for minerotrophic mires (fens), paludification for ombrotrophic mires (bogs). For paludification cases, we especially considered the absence of lacustrine, gyttja or clayey deposits and a direct initiation of peat on superficial formations or on the geological basement.

Both AMS and conventional (conv.) radiocarbon dating were performed on the 112 studied sites, according to the quantity of available organic matter: small samples or selected macrofossils for AMS and bulk peat for conv. dating. The dataset is available online at https://doi.pangaea.de/10.1594/PANGAEA.911851 (Dendievel et al., 2020). Beyond these technical differences, peat initiation is a long-term process which could take several centuries. Moreover, Holmquist et al. (2016) recently published a comparison between dates on bulk peat and on macrofossils from mire basal layers and found no significant difference. All radiocarbon measurements (for labs details, please refer to Dendievel et al., 2020) were calibrated CALIB7.0 and the "IntCal13" curve; ages are expressed in thousand years before 1950 (ka cal. BP; 2σ, i.e. 95 %) (Reimer et al., 2013; Stuiver and Reimer, 1993). On some sites, the best interval for peat initiation was calculated by integrated Lithological and Palaeoecological Syntheses (LPS) implying a detailed pollen, macrofossil, diatoms, geomorphological and radiocarbon study at: La Narce du Béage (Dendievel et al., 2019), La Sauvetat, Le Péchay, and Marais de Limagne (Beaulieu et al., 1984); Ribains, Collanges, Freycenet, and La Gimberte (Serieyssol et al., 2012; Tourman, 2007). Information was also obtained from textual archives (ARCH) for very recent mires (75–15 years cal. BP; i.e. AD 1875–1935).

3.2. Characterization of anthropogenic environmental impacts

Numerous palaeoecological works, especially pollen studies, were done in the EFMC since the 1940s with various extraction, counting and representation methods (Beaulieu et al., 1984; Coûteaux, 1984; Cubizolle et al., 2014; Dubois, 1946; Florschütz, 1955; Lemée, 1955, 1939). It is very difficult (or impossible) to accurately compare all of these data. For that reason, we based our synthesis on 26 palaeoecological works performed with modern standards, and associated with regular radiocarbon dating: Jouffroy-Bapicot et al. (2013) on the Morvan Massif, Argant and Cubizolle (2005) and Cubizolle et al. (2014) for the Livradois-Forez, Bois Noirs, Madeleine, and Pilat Mountains, Coûteaux (1984), Dendievel (2017) and Dendievel et al. (2019) for the Mézenc Massif, and Beaulieu et al. (1988, 1984) for the Devès Plateau. The sampling resolution varied from 1 to 10 cm according to peat accumulation or compaction on each site.

Palynological preparation followed standard techniques including organic matter, carbonates and silica removal (by using KOH or NaOH, HCl and HF acid, respectively), before a density segregation and a filtration of pollen grains (Faegri and Iversen, 1989; Moore et al., 1991) on the Morvan and the Béage Plateau (Dendievel et al., 2019; Jouffroy-Bapicot et al., 2013), while a concentration in a dense solution was performed on earlier studies from the Devès Plateau (Goeury and Beaulieu, 1979) and on the Pilat, Livradois, Forez, Bois Noirs (Argant, 1990). After microscopic observations, the identification was achieved with literature references or keys (Beug, 2004; Reille, 1999) and by comparison with modern pollen collections (from the Chrono-Environment Laboratory of Besançon, the ARPA association, the Botanical Institute of the Innsbruck University, and the Aix-Marseille University). For all sites, at least 300 grains and spores per slide were counted and total pollen percentages were based on the sum of vascular plants, excluding wetland or aquatic taxa (e.g. Cyperaceae, *Sphagnum*). Micro-charcoals and Non-Pollen Palynomorphs, incl. microscopic fungal remains of erosion (*Glomus*) or dung indicators (*Podospora*, *Sordaria*-type, *Sporormiella*, etc.), were also taken into account, when available (Morvan and Mézenc Massif), to precise pastoral impact phases on wetlands (Cugny et al., 2010; Dietre et al., 2012; Van Geel and Aptroot, 2006).

Macrofossil studies were also performed on the Forez (region iii: Fassion, 2013) and on the Mézenc Massif (region v: Dendievel, 2017). Based on macroscopic botanical remains (0.2–2 mm), local wetland vegetation and erosion chnages were described. After volume measurement, macrofossils were sieved under a trickle of water, adding a deflocculant solution (KOH, 5%), if necessary. Plant remains (seeds, budscales, leaves, wood fragments), zoological (beetles, fungi), and minerogenic particles (sand grains) were quantified, while the dominant remains were estimated (*Sphagnum* stems, Cyperaceae, and Ericaceae roots). Macrocharcoals were counted during routine analysis. Identifications were performed by using a stereomicroscope and based on reference collections and on literature or photographic atlases (Berggren, 1981, 1969; Cappers et al., 2006; Lévesque et al., 1988; Mauquoy and van Geel, 2007).

Due to the relative data heterogeneity, the statistical comparison was based on the original and published palaeoecological zones established by stratigraphically constrained analyses (CONISS-type; Grimm, 1987). According to Jouffroy-Bapicot et al., (2013), we summed the palaeoecological information by attributing semi-quantitative scores to each zone based on (1) arboreal/non-arboreal pollen ratios that reflect the landscape openness, presence of (2) direct and (3) indirect anthropogenic indicators (Table 1; see Brun, 2011; Jouffroy-Bapicot et al., 2013). We also added macrofossil information, when available: macro-charcoal concentrations were included as a landscape openness indicator, *Euphorbia helioscopia*, *Molinia caerulea* and *Viola* sp. seeds, or *Juncus* seeds and capsules as direct or indirect anthropogenic indicators (Table S1). Guidelines for scoring followed Jouffroy-Bapicot et al. (2013) recommendations (Table 1): from 0 (absence) to 8 points (high impact) for direct indicators, while for openness and indirect indicators scores, the range was limited between 0 and 3 points because it also might derived from natural dynamics (climate change, natural fires, passage of wild animals, etc.). These data were tested by an ANOVA test (grouping by periods) followed by a Tukey HSD post-hoc analysis in *R* (R Core Team, 2018). Due to the study scale (28 cores along a 350 km long transect), we used a boxplot-type representation over time, but this approach most certainly smoothed individual site particularities (such as local interpretation of dominant taxa). In any case, such semi-subjective method was very useful to integrate a wide range of palaeoecological data produced during the last decades, in order to assess vegetation and land use changes at large scales.

4. Results and discussion: mires over the EFMC

4.1. Main trends of peat initiation

Based on an extended dataset of 112 radiocarbon dated sites (https://doi.pangaea.de/10.1594/PANGAEA.911851; Dendievel et al., 2020), we highlighted numerous cases of mire formed by paludification on the whole EFMC (95 sites = 85% of the dataset). Only few cases of terrestrialization are known, mainly located at south (17 cases = 15%). The best documented area is the Forez Massif (eastern part of zone iii – Fig. 1) where 47 sites were found (41% of the data), although the other regions are represented by 29 to 7 mires (Fig. 1).

Taking into account spatial and temporal trends of mire ecosystem developments, we confirmed the presence of two periods highly favourable to peat initiation in the EFMC (1) from 10 to 7 ka cal. BP and (2) from 4.2 to 0.5 ka cal. BP (Fig. 3-a). However, apart from this general schema, we assumed that some histic horizons developed between 15 and 11.7 ka cal. BP, at the end of the Late-Glacial period (from the Bølling-Allerød interstadial to the Younger Dryas). Contrary to high latitude areas, peat formation in the EFMC was mainly due to paludification on wet mineral soils occupied by former terrestrial and swamp vegetations (Kuhry and Turunen, 2006). According to the state of the art, there is no case of “primary mire initiation” on newly formed mineral soil after crustal uplift or deglaciation, even if small ice caps and glaciers existed in the EFMC (Etlicher, 2005).

Then, peat initiation increased between 10 and 7 ka cal. BP (Fig. 3-a). At the beginning of this phase, from 10 to 9.2 ka cal. BP, paludification (bogs) and terrestrialization (fens) occurred together. The latter case generally happened in former maar craters and periglacial lakes on the southern part of the area, i.e. Devès Plateau and Mézenc Massif (Fig. 3-b). In such sites, the first peat layers were generally deposited underwater, after the sink of plant remains from floating peat mats for instance. A recent and detailed study achieved on the La Narce du Béage fen biostratigraphy (Upper Ardèche) described typical flora successions and a very high taxonomic diversity due to the coeval presence of underwater, floating, emergent taxa and terrestrial mire plants during the transition from the lake to the fen ecosystem (Dendievel et al., 2019, Dendievel et al., in press). This phase of regional peat initiation (EFMC) is consistent with other records from Canada to Norway, where numerous lakes filled, and evolved into limnogenous and minerogenic fens (Jones and Yu, 2010; MacDonald et al., 2006; Ruppel et al., 2013). The role of this first phase of peat initiation can also be discussed at a global level because fens are able to store organic carbon and release methane (CH_4). In concert with ice, snow cover, and permafrost melting, the fen formation process is known to be a high CH_4 producer (Beck et al., 2018; MacDonald et al., 2006). As shown by Fig. 3-a, the early period of fen formation in the EFMC was coeval with the highest methane (CH_4) concentrations recorded in Greenland ice cores (Beck et al., 2018; Brook et al., 1996). Then, peat initiation greatly increased at ca. 8.2 ± 0.9 ka cal. BP and was primarily driven by paludification process (Fig. 3-a). During this maximum, small to large ombrotrophic mires (bogs) established from the Morvan to the Ardèche Uplands: all EFMC areas are concerned. These developments of bogs, producing less CH_4, fitted with a major drop in the CH_4 emissions in the Northern Hemisphere (Beck et al., 2018). Interestingly, the maximum peak of mire initiation in the EFMC matches with a global climate change linked to the transition from the Early Holocene to the Middle Holocene (Walker et al., 2012). Actually, contrary to fens established after lake infillings and highly constrained by the geomorphological context, bog ecosystems are mainly supplied by rainfall, which is known to have greatly increased at ca. 8.2 ka cal. BP (e.g. Alley and Ágústsdóttir, 2005; Magny, 2013).

Peat initiation decreased between 7 and 4.4 ka cal. BP, and only few cases of new mires were observed (1 site/250 years) in zones i, iii, iv and v (Fig. 3-b). At Molhiac for instance, peat started to expand from two separate loci, and merged to one single mire after 8.8 ka cal. BP (Cubizolle et al., 2015). Although, on this site, peat lateral expansion continued to gradually increase (2.9–4.5 m^2 $year^{-1}$) until 5.45 ka cal. BP, before falling to very low expansion rates (less than 1.2 m^2 $year^{-1}$) during the Late Holocene. Lateral peat expansion also progressed in numerous sites in Northern Europe during this period (Ruppel et al., 2013). Interestingly, less mire creations and the only expansion of existing bogs observed at large scales fitted with the drop in CH_4 emission (Fig. 3-a). This coherence between CH_4 trend and local mire initiation also matched with

Table 1
Semi-subjective scores for Anthropogenic Impact Factors (AIF) attributed according to the degree of human impact observed in palaeoecological diagrams (after Jouffroy-Bapicot et al., 2013).

	None	Slight	Moderate	High
Degree of openness following arboreal/non-arboreal pollen ratios	0	1	2	3
Presence of indirect anthropogenic indicators	0	1	2	3
Presence of direct anthropogenic indicators	0	2	4	8
Maximum AIF cumulated scores achievable for each cluster (CONISS-type)	0	4	8	14

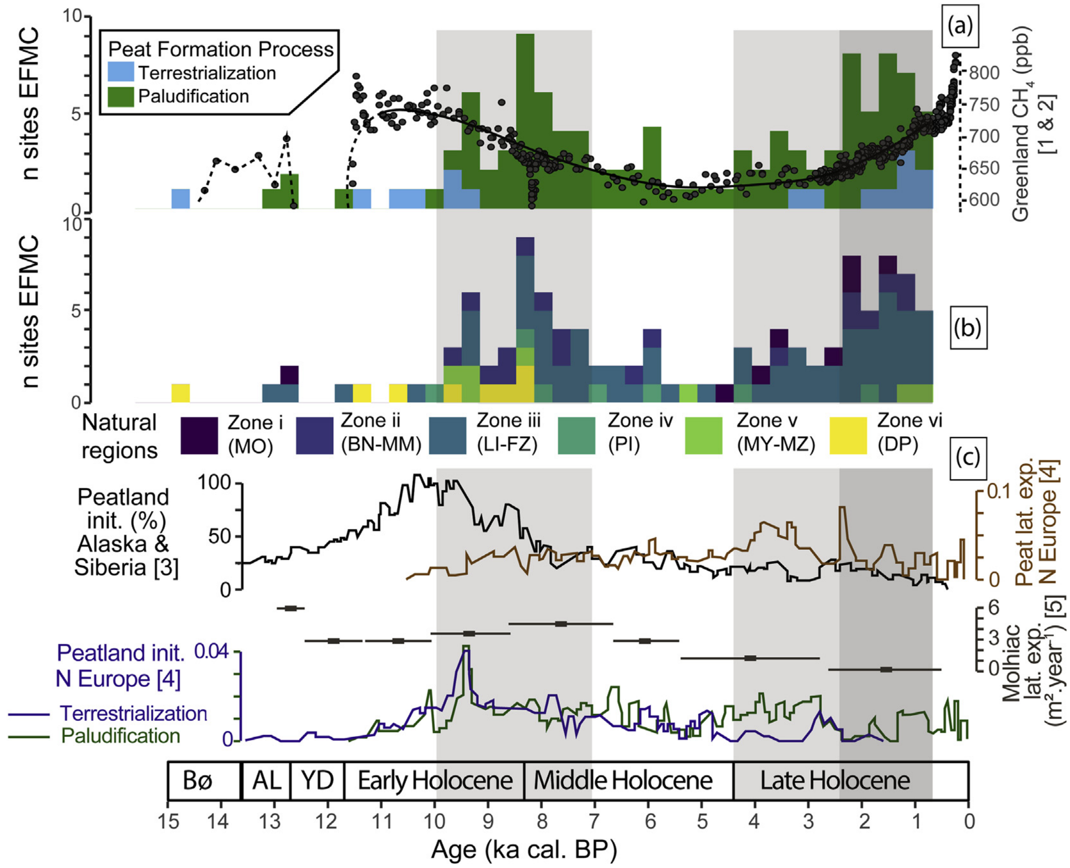

Fig. 3. Comparison of peat initiation trends on the EFMC and in the Northern Hemisphere since 15 ka cal. BP. a) Frequency histogram of peat initiation on the EFMC (n = 112) and comparison with CH_4 emission (points) recorded in the Greenland ice cores. [1] Continuous line = spline model established by Beck et al. (2018) [2] dashed line = model based on Brook et al. (1996). b) Peat initiation ages on each natural region of the EFMC: Zone I (MO) = Morvan; Zone ii (BN-MM) = Bois Noirs and Madeleine Mountains; Zone iii (LI-FZ) = Livradois and Forez; Zone iv (PI) = Pilat Massif; Zone v (MY-MZ) = Meygal and Mézenc Massif; Zone vi (DP) = Devès Plateau. c) Comparison with peatland initiation in the Northern Hemisphere: [3] Cumulative peatland initiation (init.) percentage in Alaska and Siberia (Jones and Yu, 2010); [4] Maximal occurrence frequencies for terrestrialization, paludification and peatland lateral expansion (lat. exp.) in Northern Europe (Ruppel et al., 2013); [5] Mire lat. exp. in the Molhiac mire (EFMC, Cubizolle et al., 2015). Grey bars represent EFMC peat initiation phases. Abbreviations: Bø = Bølling, AL = Allerød, YD = Younger Dryas. For the new Holocene terminology, please refer to Cohen et al. (2018).

worldwide observation from Alaska-Siberia to Northern Europe (Fig. 3-c).

After ca. 4.4 ka cal. BP, the number of newly formed mires increased more and more (Fig. 3-a). The beginning of the phase was coeval with the Late Holocene (Meghalayan) onset and suggested a possible link with global climate changes (Bell and Walker, 2014; Walker et al., 2012). Paludification and terrestrialization occurred together during this period, although the sites are generally smaller than 3 ha, with a peat depth generally limited to 2 m according to Cubizolle et al. (2012). The Fig. 3-a clearly showed the absence of cyclicity in the peat initiation trends on the EFMC and refuted any link with climatic cycles. For example, Cubizolle et al. (2012) compared the EFMC mire phases (zones ii, iii, and iv) with the wet episodes of Magny (2004, 2013) and Barber et al. (2004). They did not identify a clear climate control on mire initiation from 4.4 to 2.5 ka cal. BP, while several cases of anthropogenic landscape modifications led to mire initiation (Cubizolle et al., 2012). Moreover, peat inception reached a maximum during the last 2.4 ka cal. BP (Fig. 3-a). It differed from high latitude sites, where the number of newly formed peatlands decreased since 2.4 ka cal. BP (Fig. 3-c). Indeed, our data suggested a regional development of mires on the EFMC, independent from global records. During the last 2.4 ka cal. BP, the impact of agro-pastoralism on mires have to be addressed in the EFMC, where monastic economic models – mostly working from 1.3 to 0.25 ka cal. BP – were based on extensive livestock breeding and the related manure management (Bréchon, 1998). Other regions of Western Europe also presented similar trends, such as in North-Western Spain where fens mainly developed during the last 2.4 ka years (Pontevedra-Pombal et al., 2017). It is also highly probable that human activities during this period contributed to increase CH_4 emissions, due to fire activities (forest cleaning, grassland and arable land management), cattle breeding (incl. enteric fermentation) and agriculture intensification (Houweling et al., 2008).

4.2. Human impact – mire development relationships

In order to apprehend the links between landscape opening or agro-pastoral practices and mire initiation, we proposed an approach cumulating semi-quantitative scores of Anthropogenic Impact Factors (AIF) coming from 26 palaeoecological records on the EFMC (Fig. 4; see also Table S2). In spite of the heterogeneity of the dataset, this attempt to integrate various palaeoecological data on a region-scale area revealed several phases.

The phase 1 is comprised between 10 and 2.8 ka cal. BP (Fig. 4-b) and could be divided into two parts. From 10 to 4.7 ka cal. BP (Early and Middle Holocene; phase 1a), AIF scores displayed a very low median value of 2, with Q1 and Q3 ranging from 1 to 3 (Fig. 4-b). These scores suggested a densely forested situation and rare local human impacts. Indeed, archaeological sites were very scarce

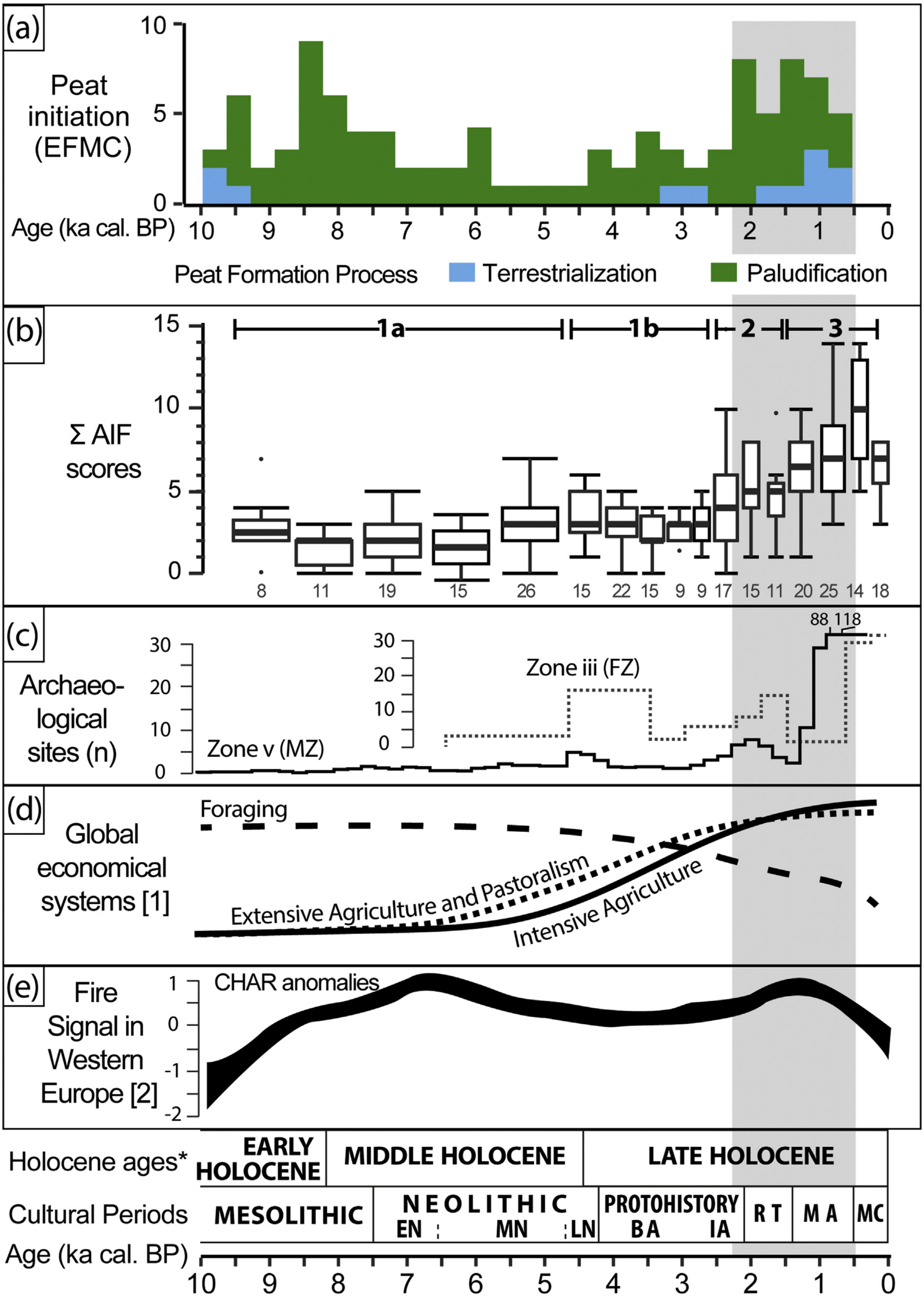

Fig. 4. Peat initiation and human impact during the last 10 ka cal. BP on the EFMC. The grey bar on the right represents the last peat initiation phase from Fig. 3 (since 2.4 ka cal. BP). The timescale indicated below refers to Holocene ages (*for new terminology, please refer to Cohen et al., 2018). Abridged cultural periods: EN = Early Neolithic, MN = Middle Neolithic, LN = Late / Recent Neolithic, BA = Bronze Age, IA = Iron Age, RT = Roman Times, MA = Middle Ages, MC = Modern and Current Times. a) Frequency histogram of peat initiation cases. b) Cumulated semi-quantitative scores for Anthropogenic Impact Factors (AIF) according to palaeoecological data. The three main phases are mentioned above, while the number of analyses is indicated below each boxplot. c) Synthesis of archaeological site frequencies in the studied area: Zone v (MZ; black line) = Mézenc Massif; Zone iii (FZ; dotted line) = Forez Mountains. d) Foraging and agriculture practises according to [1] Stephens and ArchaeoGLOBE Project authors (2019). e) Fire frequencies in Western Europe according to [2] Iglesias et al. (2019).

according to the state of the art in the EFMC, and at global scales too (Fig. 4-c and 4-d). This observation is also consistent with recent syntheses on past land use and occupation in South-Eastern France indicating that the landscape was not really open before 5.7–4.3 ka cal. BP, i.e. during the Final Neolithic Period (Berger et al., 2018, 2019). It suggests a lack of factual links between human activity and peat initiation for this period at the scale of the EFMC (Fig. 4-a). Even if early forest clearing and agriculture episodes existed in the southern zone of the EFMC, it did not modify significatively the hydro-sedimentary dynamics, even locally (Berger et al., 2018). Fig. 4-e also showed that fires notably increased during the main phase of peat initiation (Iglesias et al., 2019; Vannière et al., 2011). In agreement with several authors such as Gallego-Sala et al. (2015), we propose a climate origin for the fens and bogs established during this period. Then, from 4.7 to 2.8 ka cal. BP (phase 1.b), despite an increase of the number of archaeological sites on the EFMC, especially during the Late Neolithic and the Late Protohistory (Mézenc and Forez areas, Fig. 4-c), there was no significant increase of AIF scores (median = 3 ± 2; Fig. 4-b).

A coeval increase of the number of mires in the EFMC and an intensification of human impact based on AIF scores was highlighted after 2.8 ka cal BP (phases 2 and 3: Fig. 4-a and 4-b). It was also suggested by other supra-regional studies, especially those discussing on the Holocene fire signal (Iglesias et al., 2019; Rius et al., 2009) which gradually increased in Western Europe due to anthropogenic activities (Fig. 4-e; Vannière et al., 2011). This phase was also related to the uppermost phases of extension of pastoralism and extensive agriculture in the Mediterranean area and worldwide (maximum after 3 ka cal. BP: Iglesias et al., 2019). Yet, this period was initially wet and cold, characterized by a significant climate deterioration during the Iron Age in Europe (Magny, 2013; Plunkett and Swindles, 2008). Such conditions could locally favour mire initiation as suggested by other works in Western Europe (Barber et al., 2004; Pontevedra-Pombal et al., 2017).

Thus, for the phase 2 (2.8–1.5 ka cal. BP; Fig. 4-b), direct consequences of human activities on peat initiation were very well highlighted. After this tipping point, the AIF median increased up to a value of 4, with Q1 and Q3 ranging from 3 to 6. This increase was mainly supported by the widespread occurrence of direct anthropogenic indicators in the studied sites. It coincided with a maximum of fire events in Western Europe (Fig. 4-e) and with the main periods of archaeological occupation on the studied area: from 2.4 to 1.5 ka cal. BP (end of the 2nd Iron Age – Roman Times) and since 1.3 ka cal. BP (Middle Ages). Agro-pastoralism and intensive agriculture reached almost all regions in the world after 2.5–1.5 ka cal. BP (Stephens and ArchaeoGLOBE Project authors, 2019). In the EFMC, palaeoecological data demonstrated that the landscape was massively deforested from the end of the 2nd Iron Age to the Early Middle Ages, i.e. from 400 BC to 700 AD (Cubizolle et al., 2014; Dendievel et al., 2019; Jouffroy-Bapicot et al., 2013).

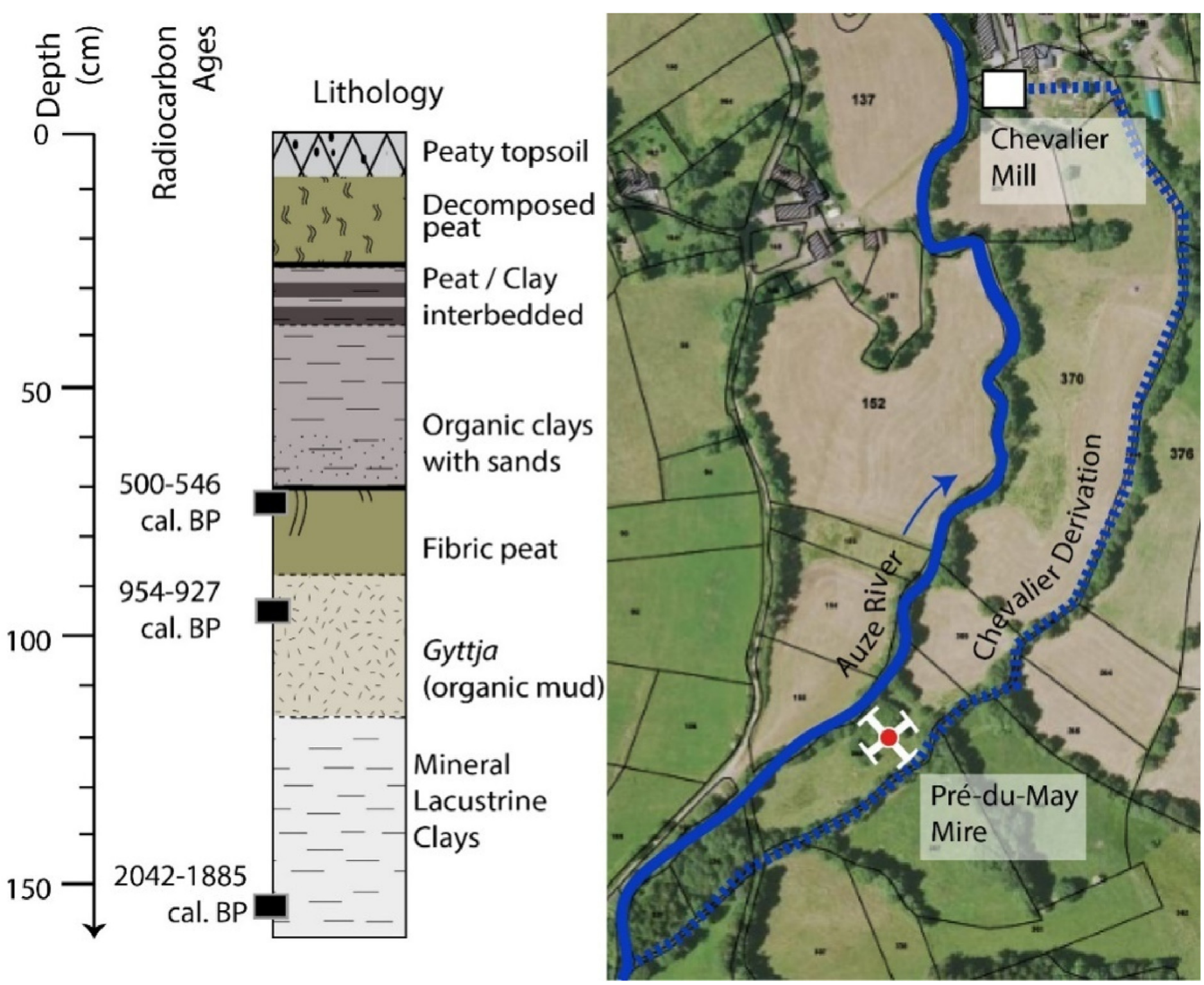

Fig. 5. Peat core, ages and map of the Pre-du-May mire and the Auze River. The Chevalier diversion was most certainly established to supply a mill during the modern period (since 0.5 ka cal. BP). Ages were calibrated with "the "IntCal13" curve (2σ, 95%; cf. Reimer et al., 2013).

Lastly, from 1.5 to 0.25 ka cal. BP (i.e. AD 500–1700; from the Early Middle Ages to the Modern Times), AIF scores continued to increase to a median value of 7, with Q1 and Q3 ranging from 6 to 8 (Fig. 4-b). These important scores are mainly caused by the co-occurrence of multiple direct anthropogenic indicators recorded in high percentages with a high degree of landscape openness (see Table S1 for details). Within this context, the two types of peat initiation process (terrestrialization and paludification) were of upmost importance to discuss. Indeed, the high level of human activities implied the need to have or to build water reserves, such as reservoirs or derivations, for agriculture and pastoralism purposes. After a phase of use related to local occupations, the abandonment of these water structures very likely led to mire initiation by terrestrialization (former ponds for instance) or by paludification (in terrestrial environments). A particularly complex and typical case was found at Pré-du-May, in the Meygal massif (zone v; Fig. 5). A pond most certainly built during the early roman period (ca. 2.0–1.9 ka cal. BP) terrestrialized and evolved into a fen after its abandonment during the Middle Ages (0.9 ka cal. BP). Then, this area was drained, and a diversion was built on the Auze River to supply the mill of Chevalier (Late Middle Ages and Modern Period). Finally, after the 19th century, the mill was decommissioned and the wetland, no longer drained, evolved again into a mire (Fig. 5). Although, without protection, this site is currently subject to increased erosion pressures due to agricultural activities, including overgrazing. Other anthropogenic cases are also known in the Forez massif (zone iii), for instance at Verdier where the building of a road blocked the water drainage and created a mire after 2.3–1.7 ka cal. BP (Cubizolle et al., 2012). At Sauvazoux, another example of mire initiation implied the establishment of a mire back from a dry stone wall after 1.6–1.4 ka cal. BP (Cubizolle and Thébaud, 2014). Major changes in the forest cover have also to be considered as regards local consequences on peatland ecosystems and water tables. Unfortunately, these cases are not well known in the studied region. On some sites, the Middle Ages deforestation led to an increase in surface runoff. At Jonzieq (Forez mountains), a network of ditches was dig to increase drainage and, after its abandonment, peat started to accumulate in the ditches during the last 300 years (Cubizolle et al., 2012). This and other cases suggest that the climate was also probably implied in the water table increase, which favoured mires (Little Ice Age period at Jonzieq), or in the lowering of water table, which enabled the development of trees, such as on the Limagne marsh (Cubizolle et al., 2009–2010). As demonstrated in this paper, coupling ^{14}C dating of basal peat layers, palaeoecological statistical data and geomorphological information provided new insights to apprehend the heritage of anthropogenic activities and climate changes in middle mountain areas where rare data were available.

5. Conclusion

In this paper, we provided an advanced study on mire developments of the Eastern French Massif Central (EFMC) over the last 15 ka cal. BP. Based on 112 well dated sites including minerotrophic and ombrogenic mires (fen and bogs, respectively), this work proposes a local contribution to the global reflexion on mire initiation and climate warming during the first half of the Holocene (e.g. Kremenetski et al., 2003). In a few cases, Late-Glacial histic horizons, accumulating peat during various periods of time, were found (before 11.7 ka cal. BP). Such phenomenon is not understood yet and more research is needed on this field. Then, a major development of mires occurred from 10 to 7 ka cal. BP, induced by climate changes. This episode combined mires formed by paludification (bogs) or terrestrialization (fens). The latter process provided limnogenous mires established on former periglacial lakes at the beginning of the Holocene warming (Preboreal and Boreal chronozones) and was coeval with the apparition of numerous fens in the Northern Hemisphere, more widely. It also coincided with a global increase in atmospheric CH_4, most certainly linked to methane gas emitted during this global phase of fen apparition and of climate warming. Then, after 9 ka cal. BP, only small ombrogenous, topogenous and soligenous mires (bogs, slope and spring mires) established, especially around the 8.2 ka cal. BP event. This generation ended when the number of new mires formed dropped after 7 ka cal. BP.

After a reduced phase of mire initiation (7–4.4 ka cal. BP), a second major generation of mires began during the last 4.4 ka cal. BP in the EFMC. Due to the absence of a systematic correlation with climate changes and the low number of archaeological sites, it is likely that mires formed during this phase resulted from either the local manifestation of climatic settings or human impacts. Finally, a major increase of peat initiation cases occurred during the 2.4 ka cal. BP (maximum). Both paludification and terrestrialization processes were involved. Most of these cases were clearly related to the anthropogenic landscape management as demonstrated by the comparison between the number of mires, the AIF scores (extracted from published pollen, spore and macrofossil data on the EFMC), and micro-regional archaeological syntheses (Dendievel et al., 2019; Scholtès, PhD in preparation). We assumed that an important number of mires was indirectly created by anthropogenic actions blocking the water drainage. This paper highlighted complex cases which include several steps of peat accumulation due to successive terrestrialization (after the infilling of a pond, for instance) and paludification processes (e.g. after the abandonment of drainage networks). Extensive agriculture and pastoralism very likely played a role for peat accumulation in middle mountain ranges by the building of water reservoirs, occupied by mire vegetation after abandonment. As mires are considered as high-value socio-ecosystems offering sustainable resources and services (water, biodiversity, carbon sinks), it is of upmost importance to take into account the anthropogenic origin of the numerous mires of the Late Holocene for the current and future management of these wetlands.

CRediT authorship contribution statement

André-Marie Dendievel: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Isabelle Jouffroy-Bapicot:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Jacqueline Argant:** Writing - original draft, Writing - review & editing. **Antoine Scholtès:** Writing - original draft, Writing - review & editing. **Arnaud Tourman:** Writing - original draft, Writing - review & editing. **Jacques-Louis de Beaulieu:** Writing - original draft, Writing - review & editing. **Hervé Cubizolle:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106219.

Data availability

The radiocarbon database compiled and used in this research paper is freely available internet hyperlink at https://doi.pangaea.de/10.1594/PANGAEA.911851 (Dendievel et al., 2020). It includes site names, coordinates, elevation, detailed information about the dated material, and the radiocarbon ages. Method abbreviations (AMS, conv., ARCH, LPS) are also explained in the text.

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