A geographical model for the altitudinal zonation of mire types in the uplands of western Europe: the example of Les Monts du Forez in eastern France

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SUMMARY

The geographical distribution of mires in the oceanic mountain ranges of western Europe cannot be explained without bringing together a number of physical and human factors. In Les Monts du Forez, which are granitic and metamorphic mountains covering an area of 1800 km^2 and rising to an altitude of 1634 m in the east of the French Massif Central, a series of mires on long slopes reflects the effects of changing combinations of these factors with altitude. The scale of variation falls within the limits of bioclimatic levels and is manifest as: the absence of mires at foothill levels below 900 m; small mires of anthropogenic origin and remnant peat at lower mountain levels between 900 m and 1100 m; peat systems where evolution has been more or less affected by human intervention at median mountain levels between 1100 m and 1250 m; large ombrotrophic mires, often naturally convex and dating from the first half of the Holocene epoch, at upper mountain levels between 1250 m and 1450 m; and small established mires that are more or less directly linked to human intervention at sub-alpine levels above 1450 m. The role of human societies appears to dominate, with exceptions in the upper mountain levels. Human influence presents in two forms, both of which are related to the old traditional farming methods of the region: the first is destruction of mires, mostly by drainage, and the second is mire creation through modifications of the hydrology of the valley floor and the vegetation cover. This spatial and multi-factor distribution of mires is a component that should be taken into account in relation to their conservation management.

KEY WORDS: anthropogenic factor; Massif Central; mountains; peatland; physical factor

INTRODUCTION

The objective of this article is to analyse the way in which mires are distributed on the slopes of temperate oceanic mountains in western Europe, and to determine which factors influence the locations of mires and the degree of influence attributable to each factor. The example of Les Monts du Forez mountain range in the eastern part of France will be developed.

A review of the literature shows that interest in this subject amongst the scientific community has diminished over the last thirty years, although geographical distribution factors are not indirectly tackled by analysing the peat types present within an area of interest (Succow & Lange 1984). From the time of von Post and Grandlung (1926), numerous authors have shown that a number of factors are responsible for the geographical distribution of mires. Often, however, these factors had to be tackled separately, and their respective importance depended on the spatial scale at which the studies were conducted. Thus, the role of climate is emphasised in analyses at global (Lappalainen 1996) or continental scales, as carried out mostly in Europe and throughout Scandinavia (Osvald 1925, Sjörs 1950, Ruuhijärvi 1960, Eurola 1962), North America (Damman 1979, Payette & Rochefort 2001) and the former Soviet Union (Botch & Masing 1979). For example, Payette & Rochefort (2001) show that the distribution of mires in Québec-Labrador reflects climatic gradients; of rainfall from west to east and of temperature from south to north. Nevertheless, even at this scale, the majority of authors highlight the importance of the geomorphological and hydrological context, for example the roles of relief (Pajunen 2005) and of permafrost patterns especially at high latitudes (Vitt *et al.* 1994, Payette & Rochefort 2001). Of equal importance are the superficial glacial and periglacial formations at medium latitudes that were inherited from the last ice age (Succow & Lange 1984, Pajunen 2005, Coronato *et al.* 2006). Some classifications at smaller spatial scales consider geomorphological and hydrological factors alone (Stanek 1977, Rieley *et al.* 1992, Charman 2002). Graniero & Price (1999) carried out a more specialised study on the relationships between topography and mire locality, pointing out all influences that can affect the establishment and development of wetland ecosystems on slopes. Finally, the role of man in the process of peat initiation and, therefore, in creating the current distribution of mires, must be considered. This topic has long been discussed, mainly in relation to Holocene mires in the United Kingdom and Ireland. As early as 1956, Walker remarked on the number of archaeological discoveries in the layers of earth immediately beneath peat. Little by little the idea emerged of the responsibility of human societies for the modification of local hydrology that instigated the establishment of mires (Tallis 1964, Smith 1970, Mitchell 1972). If Pennington (1975) had defended the idea that a combination of human and physical factors influence the appearance of mires, Moore (1975, page 267) would have been convinced of the primordial role of human societies in the initiation of at least the blanket peats: "*The age and origin of the blanket peats has been the source of much controversy, but evidence now accumulating links their origin with prehistoric human activity* ". This theory influenced Chambers (1981), Moore *et al.* (1984) and Caseldine & Hatton (1993), but its application hardly moved beyond the borders of the United Kingdom until 2000, when the model was tested in France and its validity demonstrated for certain mires in the French Massif Central (Cubizolle *et al.* 2003, 2004, 2012).

The focus of the present study is to investigate the special relationship between the combinations of factors that explain the distribution of mires along mountain slopes.

STUDY AREA

The mires that were studied are situated in Les Monts du Forez, a mountain range of about 1800 km² in the Massif Central in eastern France (Figure 1). These hercynian mountains are mainly composed of granite and metamorphic rocks that stretch for almost 60 km from north to south, whereas their width does not exceed 30 km. The asymmetrical sides that create the structural context

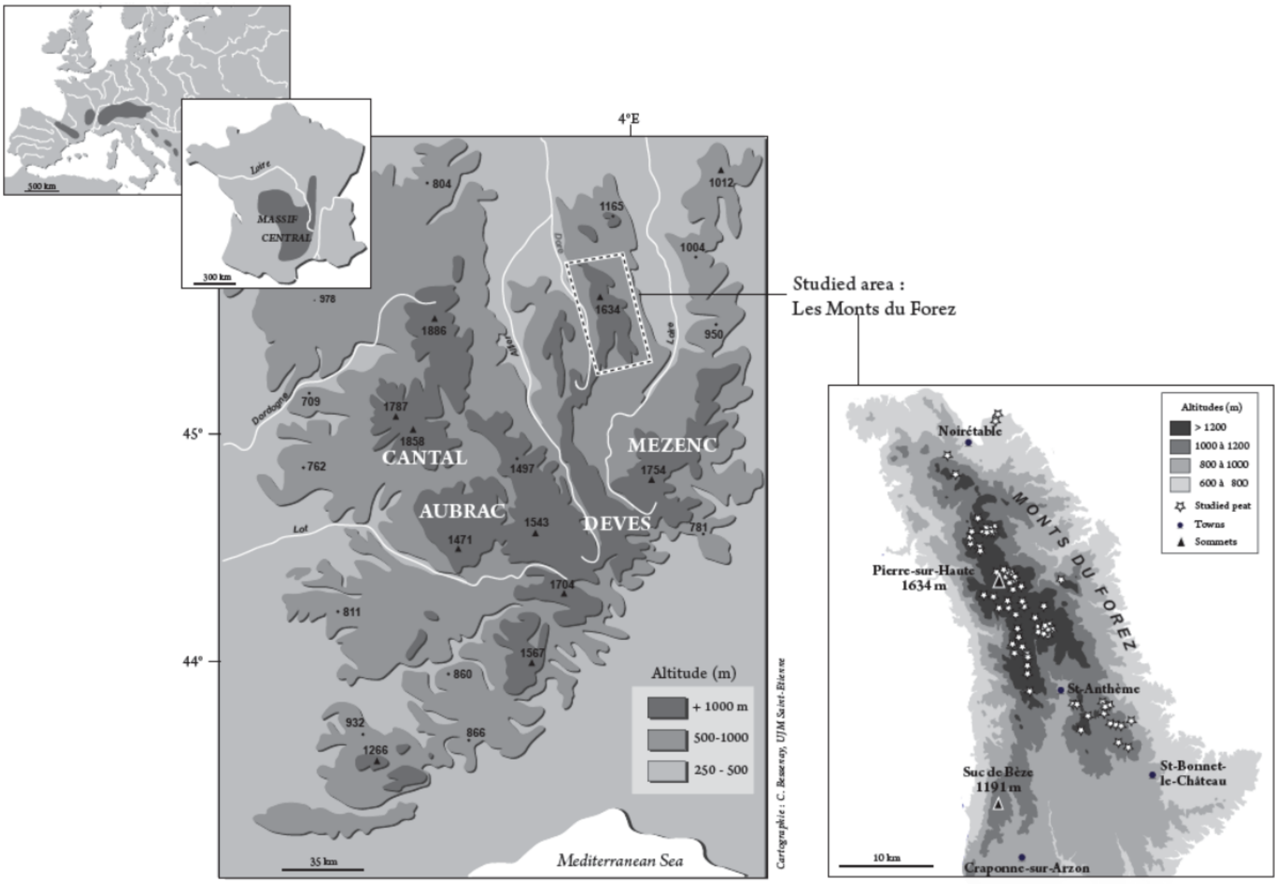

Figure 1: Location of the study area: Les Monts du Forez mountain range in the French Massif Central.

are very marked; the western side is cut by a deep and narrow valley and slopes steeply, and the eastern side takes the form of a slightly inclined plateau connected to the escarpments. The summits, rising above 1350–1400 m within a belt of maximum width 5 km, are a succession of subdued convex hilltops separated by shallow basins. The centre of this belt is dominated by Pierre-sur-Haute, whose summit (1634 m) is the highest point of the range. Finally, the very dense network of associated intra-mountane basins (Ambert and Saint-Anthème basins, Forez basin, *etc*.) is for the most part filled with predominately sandy Tertiary sediments, increasing the division of the relief (Figure 1).

Several layers constitute the weathering profile, which forms a composite aquifer (BRGM 2009, Dewandel *et al.* 2006, Etlicher 2005). From top to bottom, the layers are:

- Glacial (moraines) between 1350 m and 1500 m a.s.l. and widespread periglacial displaced slope deposits (head, bedded grus) up to 800 m a.s.l. and above 1500 m a.s.l., for both of which permeability varies greatly according to the proportions of clay and silt.
- *In situ* regolith (or saprolite), the result of the alteration of silicated rocks during hot and humid Cenozoic periods, is very much broken up below 800–900 m altitude in Les Monts du Forez because it has been partially eliminated by the erosion processes of the Tertiary, associated with the Alpine orogeny (Etlicher 2005). It is generally only few (1–5) metres thick, and its permeability is between 10^{-7} and 5×10^{-6} m s^{-1} (Dewandel *et al.* 2006).
- The fissured layer of the hard granitic and metamorphic rock is thicker (up to 100 m) with permeability between 10^{-6} and 5×10^{-3} m s^{-1}, mainly in the first 15 metres (BRGM 2009, 137–140).

The regional climatic conditions are oceanic, and this character is more pronounced on the west than on the east side. Average annual rainfall ranges from 650–700 mm to 1400–1500 mm, and average annual temperature from 10 °C at 500 m altitude to 3 °C at the summit of Les Monts du Forez (1634 m). Snow cover varies considerably from one year to another. At an altitude of 1100 m it can snow for 100 days with the snow reaching a depth of 2–3 m. On the high ground above 1400 m, the snow cover is more regular and persistent.

From a bioclimatic point of view, the environment that characterises Les Monts du Forez has evolved as a result of the variation in climatic conditions with altitude, the relief, the superficial forms, the soils and the vegetation; but the historical exploitation of the mountain by human societies is of equal importance (Ozenda 1985, Jolly & Lecompte 1988). The traditional farming life in Les Monts du Forez combined cultivation and stock rearing on family smallholdings (Fel 1962, Damon 1972, Cubizolle 1997, Georges 2007), and this way of life was a strong influence in all of the bioclimatic zones. However, the pressure was less at the middle and upper mountain levels, between 1100 m and 1450 m altitude. There are still remnants of the former beech and pine forests, mainly on steep slopes and in areas cluttered with rocks which have come from the breaking-up of the Würm granite wall. In the central and highest part of the Massif, a system of seasonal transmigration to the high pasturelands persisted until 1950–1960.

Les Monts du Forez offer a huge diversity of mires at both lower and higher altitudes. The 75 catalogued mires, of which two-thirds are ombrotrophic, cover a total area of 873 hectares which accounts for less than 1 % of the total area of Les Monts du Forez (Figure 1) (Cubizolle 2005, Cubizolle *et al.* 2013a). They are located at altitudes of 600 m to 1570 m, but 81 % of them are found between 1200 m and 1400 m. Their areas vary considerably, from a few hundred square metres to 245 hectares for the largest of the mire systems.

METHODS

Field survey

All of the mires were studied using geomorphological and hydrological methods in order to establish a comprehensive description of their physical settings. We aimed especially to understand to what extent and in what manner local geomorphology contributed to peat accumulation. Topographical profiles were surveyed with a Leica 403L Total Station and positioned using a Trimble GEOXT GPS. In general, two profiles (one longitudinal section and one cross-section) were completed for each mire.

Plant communities were characterised by means of phytosociological relevés which involved recording of vascular plants, bryophytes and lichens. The relevé data were analysed according to the "sigmatiste" method of Braun-Blanquet (1964), incorporating subsequent method improvements (Gehu & Rivas-Martinez 1981, de Foucault 1986). We used the following general and specific European classification systems: the French National Classification (Bardat *et al.* 2004); Thébaud & Pétel (2008) and Thébaud *et al.* (2009) for ombrotrophic communities; and Thébaud *et al.* (2012) for acid fen communities. Names of plant communities follow the International Code of

Phytosociological Nomenclature (Weber *et al.* 2000). Socio-ecological toposequences were recorded for several mires in order to highlight any ecological gradient on the basis of bio-indicator plant species.

Field sampling

Peat cores were taken with a manual Russian-pattern corer in order to reconstruct mire stratigraphy (De Vleeschouwer *et al*. 2010). The cores were 55 mm in diameter and 60 cm long. The spacing between the coring points varied with the length of the topographical transect and the complexity of the stratigraphy, and ranged from 1 m to 30 m. Additional coring with a motorised percussion drill MAKITA HM 1800 was necessary to core into the superficial deposits underlying the peat. Each histic horizon was described by means of Munsell charts, the von Post test and visual examination of the material.

Laboratory methods

We carried out laboratory analyses of granulometrics and fibres (Levesque & Dinel 1977, 1982; Gobat *et al.* 1991, Grosvernier *et al.* 1995, Cubizolle 2005), and of total organic content estimated by oven-ashing (Heiri *et al.* 2001). There is no consensus on the minimum organic matter content that distinguishes peat from other organic material; proposed values range from 30 % to 70 % (von Kaule 1976, Andreyko *et al*. 1983, Korhola 1992, Korhola 1995, Joosten & Clarke 2002). In our cores we observed that the change from sandy or silty organic facies to peat facies occurred when the organic matter content was between 30 % and 35 %.

Radiocarbon dating

Most of the peat samples selected for radiocarbon dating were 1 cm thick slices of the cores obtained using the Russian peat corer. Generally, the volume was sufficient to use the radiometric method (Piotrowska *et al*. 2011). AMS dating was used mainly for dating samples of unidentified peat material in relation to the palynological analysis. The spacing between sampled cores for radiocarbon dating depended on the size of the mire, as in the methods employed by numerous authors (Smith *et al*. 2004, MacDonald *et al.* 2006, Cubizolle *et al.* 2007, Gorham *et al.* 2007, Cubizolle *et al.* 2012). For each core, several samples from beneath, on and above the basal layers were dated. The Radiocarbon Dating Centre at the Claude Bernard University of Lyon, Beta Analytic Inc. of Miami (USA) and the Centrum voor Isotopen–Onderzoek of Groningen (The Netherlands) carried out the dating. The initial radiocarbon dating was calibrated to BP calendar years using the computer program OxCal 2010 v. 4.1.7 and the calibration curve IntCal 2009 (Reimer *et al.* 2009). Only the oldest dates obtained for the peaty basal layer of each mire are considered here.

RESULTS

The following paragraphs describe the altitudinal zonation of mire types in Les Monts du Forez.

Below 900 m altitude

No mires were catalogued in the foothills below 900 m altitude, which have been cultivated since the Neolithic period (Cubizolle 2005, Georges 2007). Nevertheless, *Sphagnum* was present in two areas.

In the Forez Basin, *Sphagnum* was found on the wooded margins of artificial ponds that were mostly constructed between the 13th and 15th centuries (Degorce 1995). Unfortunately, the *Sphagnum* species of these ponds have never been studied and identified.

On the floors of gently sloping (< 5 %) valleys at 800–850 m altitude, there are patches extending to a few square metres of plant communities dominated by *Sphagnum teres* and *Juncus acutiflorus*. These belong to the Sub-Atlantic phytosociological alliance *Juncion acutiflori* Br.-Bl. *in* Br.-Bl. and Tüxen 1952, and correspond to the *Caro verticillati-Juncetum acutiflori* (Korn. 62) Oberd. 1993 associations which are common at these low altitudes. When grazing of these peaty meadows is abandoned they become overgrown by *Alnus glutinosa* and meso-eutrophic species such as *Lysimachia vulgaris* and *Angelica sylvestris* (*Alnion glutinosae alliance*, Malcuit 1929). The environment is slightly acidic, giving pH readings between 6.4 and 6.8; and the soils are gleysols with a folic A horizon (WRB 2006).

Altitude 900–1100 m

This altitude zone corresponds to the upper part of the area that was historically used for agriculture, but it was colonised by fir forest from the middle of the 20th century. Here we distinguished two types of mires located on the floors of very small valleys.

In the first type, peat accumulation has resulted from a change in water balance due to the presence of a linear earth or stone barrier built across the head of a valley. The purpose of these constructions was either to define areas of farming land or to create paths across areas of wet ground (Cubizolle *et al.* 2004). The areas of these mires range from a few hundred to a few thousand square metres. The vegetation is characteristic of slightly acidic minerotrophic mire (pH between 5.5 and 6.5) and consists of rush communities composed of *Juncus acutiflorus* and *Carum verticillatum* (*Caro verticillati-Juncetum acutiflori* (Korn. 62) Oberd. 1993, *Juncion acutiflori* Br.-Bl. *in* Br.-Bl. et Tüxen 1952) associated with *Sphagnum* and *Menyanthes trifoliata* (*Carici curtae-Menyanthetum trifoliatae* Thébaud *et al.* 2012, *Caricion lasiocarpae* Vanden Berghen 1949), a typical association of floating carpets and flooded hollows. The peat depth can be anything up to 3 m. Accumulation of the peat wedges on these sites started between the middle of the Sub-Boreal period (around 4100 cal. BP) and the 15th century AD (Cubizolle *et al.* 2004). In the example illustrated in Figure 2, the dam is a low wall some 20 m in length and about one metre high that denotes the boundary of a parcel of land. The area of the mire is 300 m² and the maximum peat depth is 1.05 m. The oldest date obtained from the base of the peat places the onset of peat accumulation at the end of the Roman period.

The second type is represented by Le Jas, which is a fen situated in a depression of about 1000 m² dug out by humans during the High Middle Ages (the period from the 5th to the 11th century AD) (Figure 3). A medieval settlement has been recorded by archaeologists on the slope 100 m from the mire. Here, the thickness of peat reaches 2.91 m. From top to bottom, the stratigraphy shows a horizon of decomposed fibrous *Sphagnum* sp. peat overlying mesic peat that is often sandy. Plant communities are dominated by oligo-mesotrophic rush communities (*Caro verticillati-Juncetum acutiflori* (Korn. 62) Oberd. 1993, *Juncion acutiflori* Br.-Bl. *in* Br.-Bl. et Tüxen 1952). Only two species, *Sphagnum teres* and *Aulacomnium palustre*, are clearly identified as peat-forming plants. We observed several other plant species, including *Climatium dendroïdes* in hydromorphic meadows that are evolving towards alder forest, and *Pedicularis sylvatica* whose presence reflects the impact of grazing by cattle that do not roam widely. Finally, *Carex panicea* and *Caltha palustris* are very common in this wetland type.

Altitude 1100–1250 m

At altitudes between 1100 m and 1250 m, within a median mountain zone that is currently densely covered by acidophilous pines, *Abies alba* and *Vaccinium myrtillus* on a brown podzolic soil, some very varied and typologically complex mire

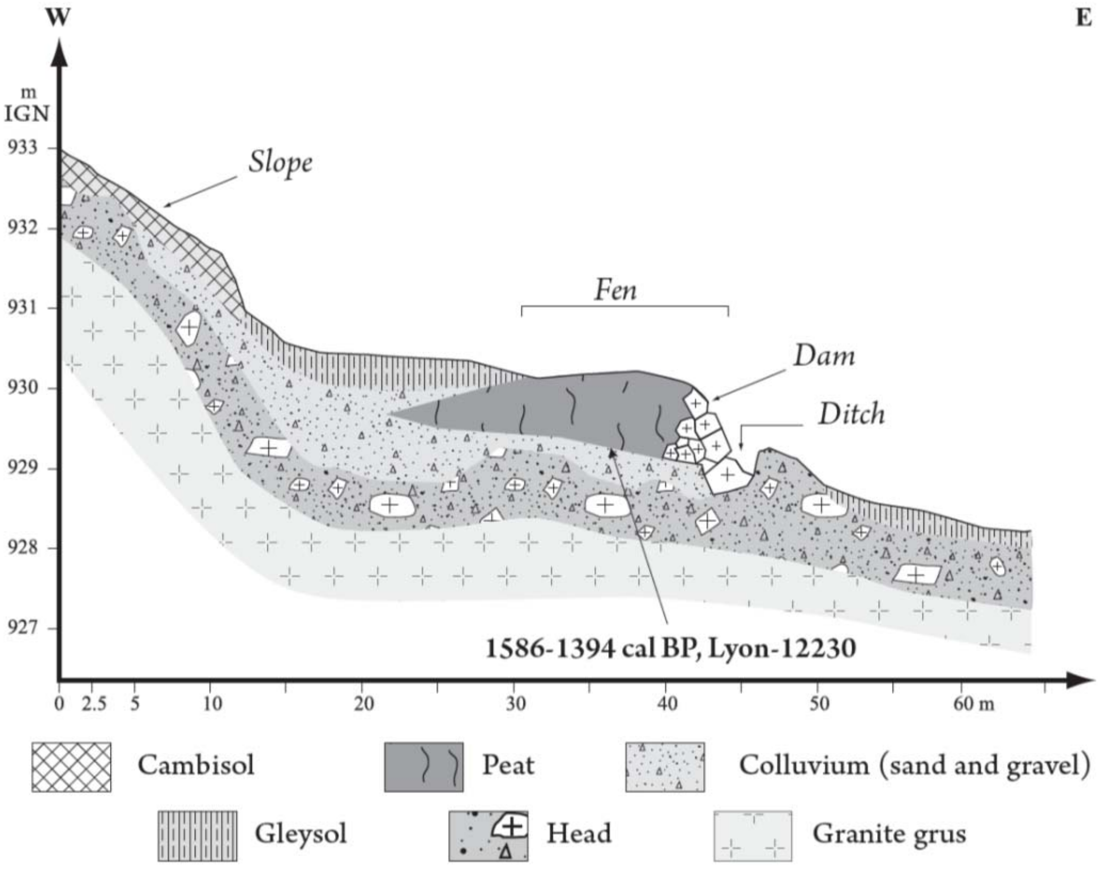

Figure 2. An example of an anthropogenic fen in a small valley: the fen of Souvazoux (altitude 930 m).

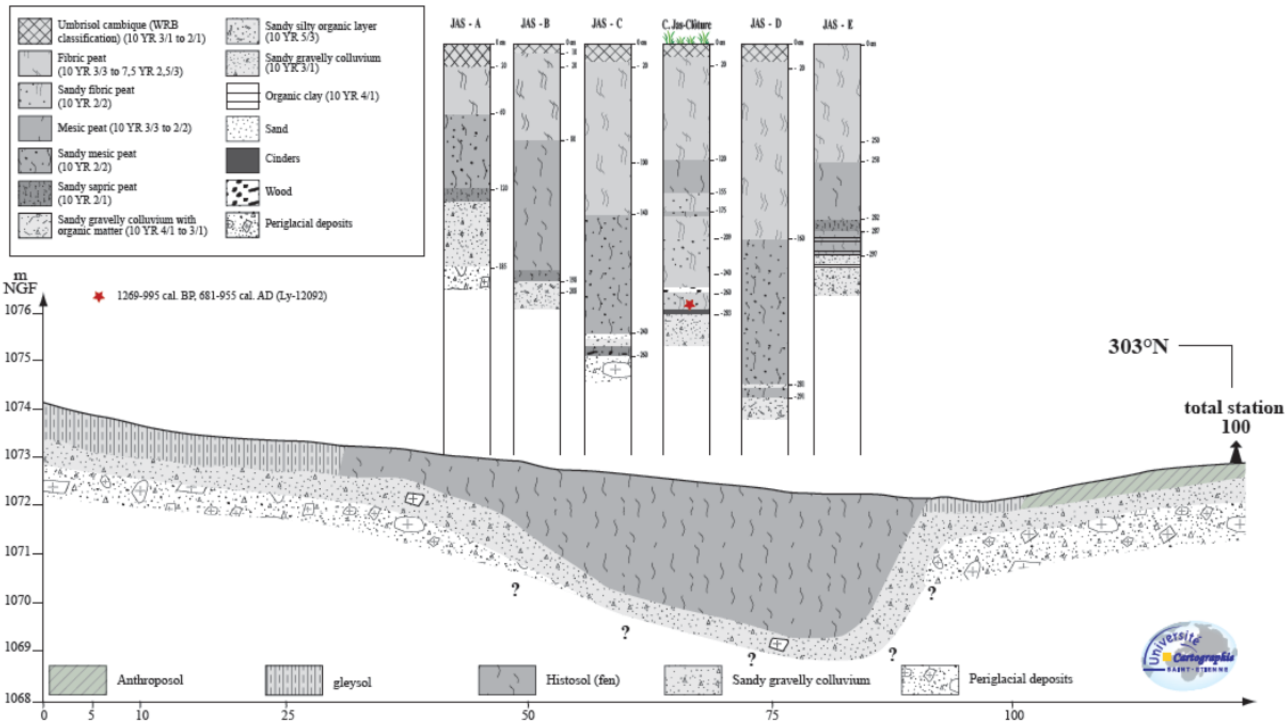

Figure 3. An example of a basin fen in a very small valley: the fen of Le Jas (altitude 1075 m).

ecosystems have developed. These have established in the bottoms of valleys, often in headwater catchments where they constitute more or less wooded clearings of area 3–20 hectares with pines at the centre. From a phytoecological point of view, we observed a mosaic of ombotrophic and minerotrophic *Sphagnum* mires (Figure 4). Ombrotrophic communities belong to the *Sphagnion magellanici* Kästner & Flössner 1933, a phytosociological alliance of medio-european raised bogs. Two main associations are common: firstly, *Sphagnetum magellanici* Kästner & Flössner *ex.* Steiner 1992 which corresponds to a young ombrotrophic stage and, secondly, *Eriophoro vaginati-Vaccinietum uliginosi* de Foucault 1999, which encompasses ombrotrophic medium-dry and humicolous communities invaded by trees and shrubs. These bogs are more or less eroded and often wooded with *Pinus sylvestris* and *Betula pubescens* (*Betulion pubescentis* Lohmeyer & Tüxen, alliance) (Figure 4). Minerotrophic communities are represented by several associations:

- sub-Atlantic montane rush communities dominated by *Juncus acutiflorus* and *Molinia caerulea* (*Selino pyrenaei-Juncetum acutiflori* Julve 1983, *Juncion acutiflori* Br.-Bl. *in* Br.-Bl. & Tüxen 1952);
- oligotrophic small-sedge communities (*Epikeros pyrenaei-Caricetum nigrae* (Issler) Oberdorfer 1957, *Caricion fuscae* alliance Koch 1926 *em.* Klika 1934); and
- communities of floating carpets and flooded hollows (*Carici curtae-Menyanthetum trifoliatae* Thébaud *et al.*, alliance du *Caricion lasiocarpae* Vanden Berghen 1949).

These fens generally evolve towards *Pinus sylvestris* and *Betula pubescens* minerotrophic peat-forests (*Betulion pubescentis* Lohmeyer & Tüxen, alliance). On certain sites we noted an evolution to peaty fir and birch woods (*Betulo pubescentis-Abietetum albae* Lemée *ex* Thébaud 2006). The datings showed varying ages for the basal layers of these mires: the oldest dates are 12100–10200 Cal. BP, during the Younger Dryas and the Pre-Boreal, whereas the most recent originated in the middle of the Sub-Boreal period, around 4500 Cal. BP (Cubizolle *et al.* 2003, 2012).

Altitude 1250–1450 m

Within the upper mountain levels (1250–1450 m), where the ground is covered by an anthropic heathland which has been slowly overgrown by trees due to the decline of grazing since the middle of the 20th century, there are large ombotrophic (convex) raised bogs with *Sphagnum magellanicum*,

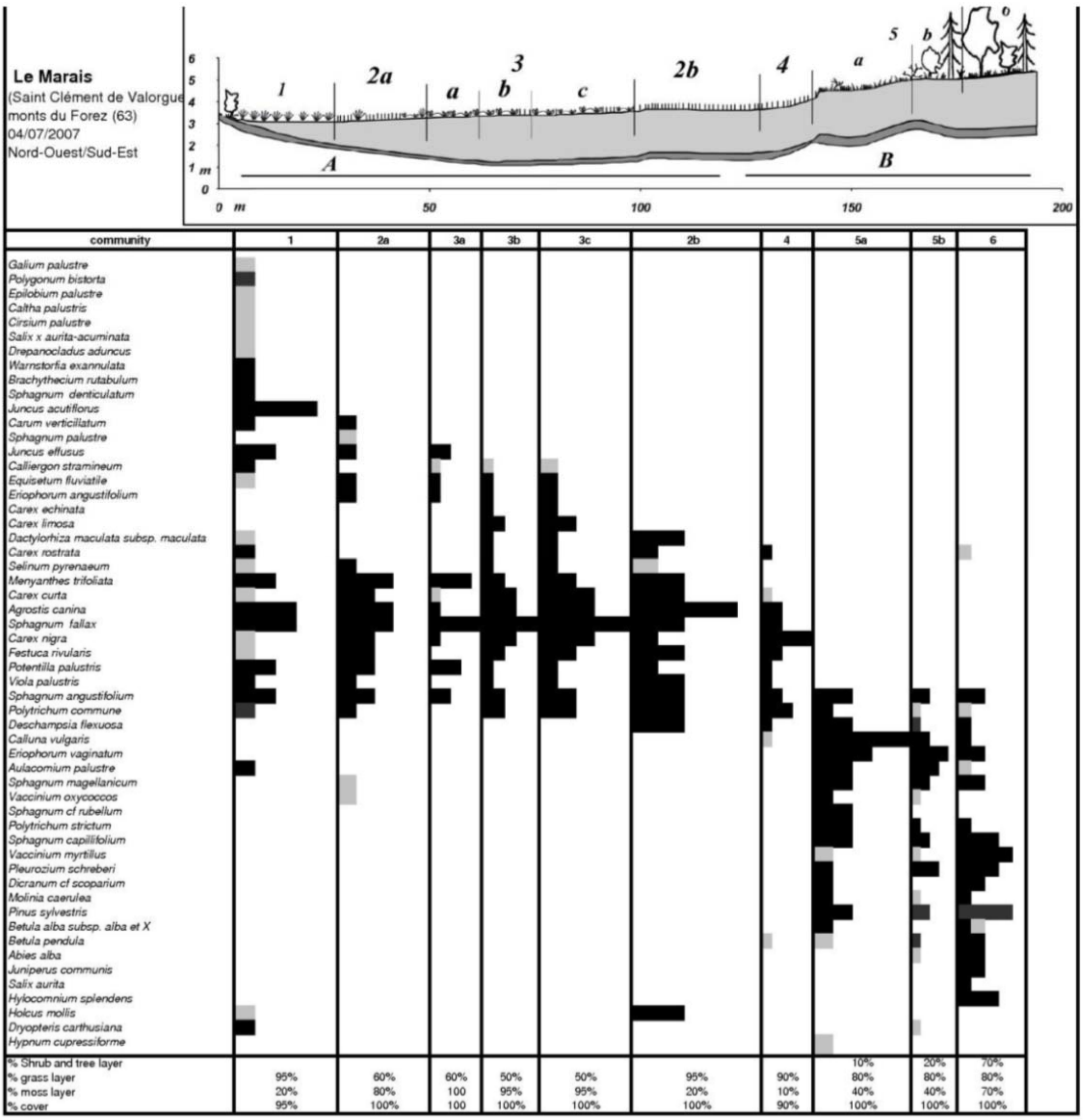

Figure 4. A socio-ecological toposequence of communities described from Le Marais (altitude 1190 m), an ombro-minerotrophic mire within the highest altitudinal belt in the south of Les Monts du Forez mountain range (adapted from Thébaud *et al.* 2012). The light grey shading in the profile diagram indicates peat, and the dark grey shading below the peat indicates organo-mineral soil. A: marginal and central area of the mire, depending on soligenous water table; B: internal area depending on ombrogenous water. The communities are as follows: (1): rushes (*Selino pyrenaei-Juncetum acutiflori* Julve 1983) on the flooded mesotrophic margins of the mire; (2a): small-sedge communities (*Epikero pyrenaei-Caricetum nigrae* (Issler) Oberdorfer 1957) on the flooded oligo-mesotrophic margin of the mire; (3a, 3b, 3c): central hollows with *Menyanthes trifoliata* and *Carex limosa* (*Carici curtae-Menyanthetum trifoliatae typicum* Thébaud *et al*. 2012); (2b): small-sedge communities (*Epikero pyrenaei-Caricetum nigrae* (Issler) Oberdorfer 1957) in the oligotrophic, elevated central area; (4): drier, impoverished small-sedge communities (*Caricetum nigrae* Braun 1915) edging the ombrotrophic raised bog; (5a) and (5b): ombrotrophic raised bog with medium-dry communities invaded by phanerophytes (*Eriophoro vaginati-Vaccinietum uliginosi* de Foucault 1999); and (6): peat forests (*Vaccinio uliginosi-Pinetum sylvestris* Dziubaltowski 1928). The width of each column is determined by the transect distance occupied by the corresponding community/relevé (1–6), and the lengths of the bars are proportional to the cover values for individual species. Grey bars indicate the Braun-Blanquet cover value '+' and darker bars indicate Braun-Blanquet values greater than '+' (1–5).

S. rubellum and *S. capillifolium*; also with *S. fuscum* on examples situated in the north of the Massif. These are often associated with minerotrophic mires extending along river valley corridors to form extensive peatland systems of several hundred hectares. The bogs are situated at the heads of the valleys and many are associated with glacial relief (glacial cirques and moraine dams), but also with firn cirques. They form pronounced rounded domes and the thickness of the peat ranges from 3 m to 6.5 m (Figure 5). The plant communities of these mires belong mainly to the medio-european active bog alliance *Sphagnion magellanici*, which is represented by several associations: *Sphagnetum magellanici* Kästner & Flössner *ex* Steiner 1992 in initial active stages of hummocks; *Eriophoro vaginati*-*Vaccinietum uliginosi* de Foucault 1999 on drier stages of hummocks; and *Sphagno tenelli-Trichophoretum cespitosi* Osvald *ex* Thébaud & Pétel 2008 in hollows. In the lagg, acidophilic small sedge communities represented by the *Caricion fuscae* alliance dominate, with *Epikero pyrenaei-Caricetum nigrae* (Issler) Oberdorfer 1957 on the minerotrophic margin of the mire; and *Caricetum nigrae* Braun 1915 occurs in the most oligotrophic sectors at the edges of the ombrotrophic raised bog. Finally, communities of floating carpets and flooded hollows are composed of *Carici curtae-Menyanthetum trifoliatae* Thébaud *et al.* 2012 (*Caricion lasiocarpae* alliance Vanden Berghen 1949). They are surrounded by heathlands with *Calluna vulgaris* and *Vaccinium myrtillus*, and beech groves, pines or groups of *Sorbus aria* or *Sorbus acuparia*. Almost all of these mires began to form in the first half of the Holocene epoch, mainly in the Boreal and old Atlantic periods, between 10200 and 6800 Cal. BP (Cubizolle *et al.* 2012).

Above 1450 m altitude

Above 1450 m is a lower sub-alpine level where only small (< 2 ha) mires can be found scattered amongst heathlands. Their characteristic species are *Vaccinium uliginosum*, *Calluna vulgaris*, *Alchemilla saxatilis*, *Trifolium alpinum*, *Festuca nigrescens* and *Sorbus chamaemespilus* (Thébaud 1990). Mires are not very numerous, but have established in small firn cirques and nivation cirques up to an altitude of 1570 m, some 60 m below the summit (Figure 6). Here, there are as many ombrotrophic as minerotrophic mires, and a maximum peat thickness of one metre is occasionally achieved. We mainly observed the *Sphagnetum magellanici*, a typical association of young stages of ombrotrophic bog, and small-sedge subalpine communities of flooded hollows with *Carex nigra*, *Juncus filiformis* and *Warnstorfia exannulata* (*Junco filiformis-Caricetum*

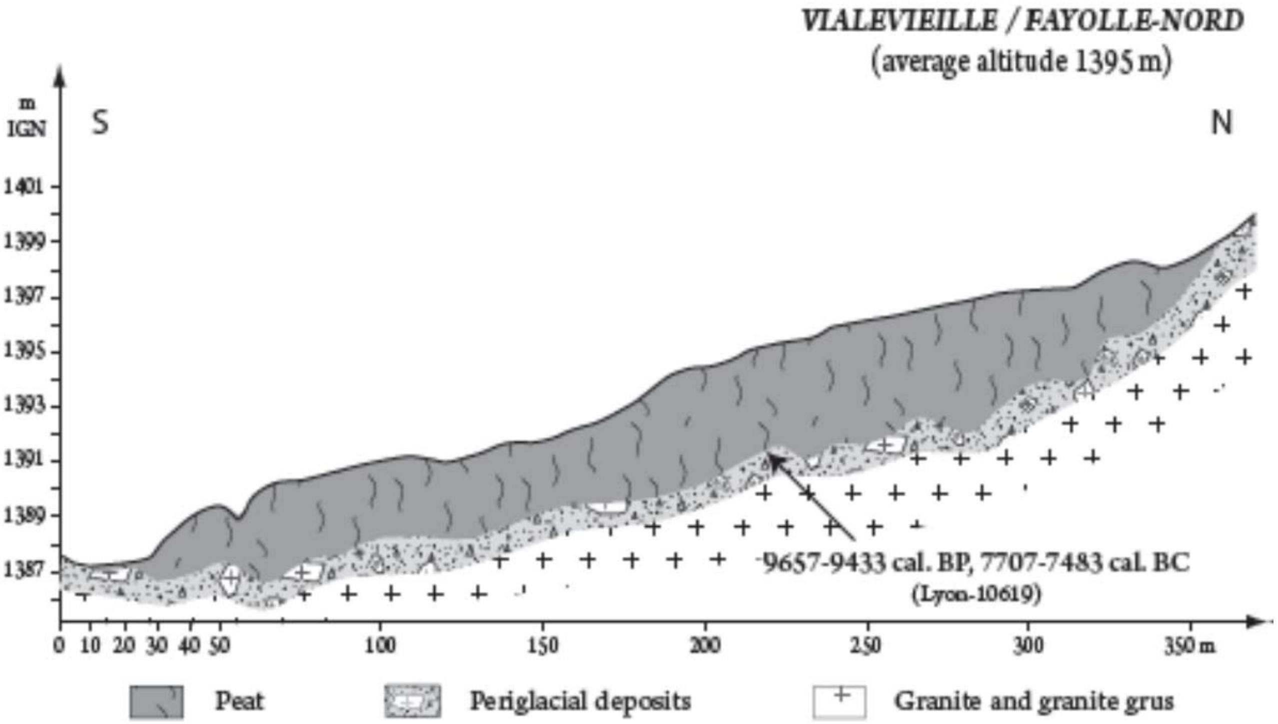

Figure 5. The raised bog of Vialevieille (altitude 1395 m), in the south of Les Monts du Forez mountain range.

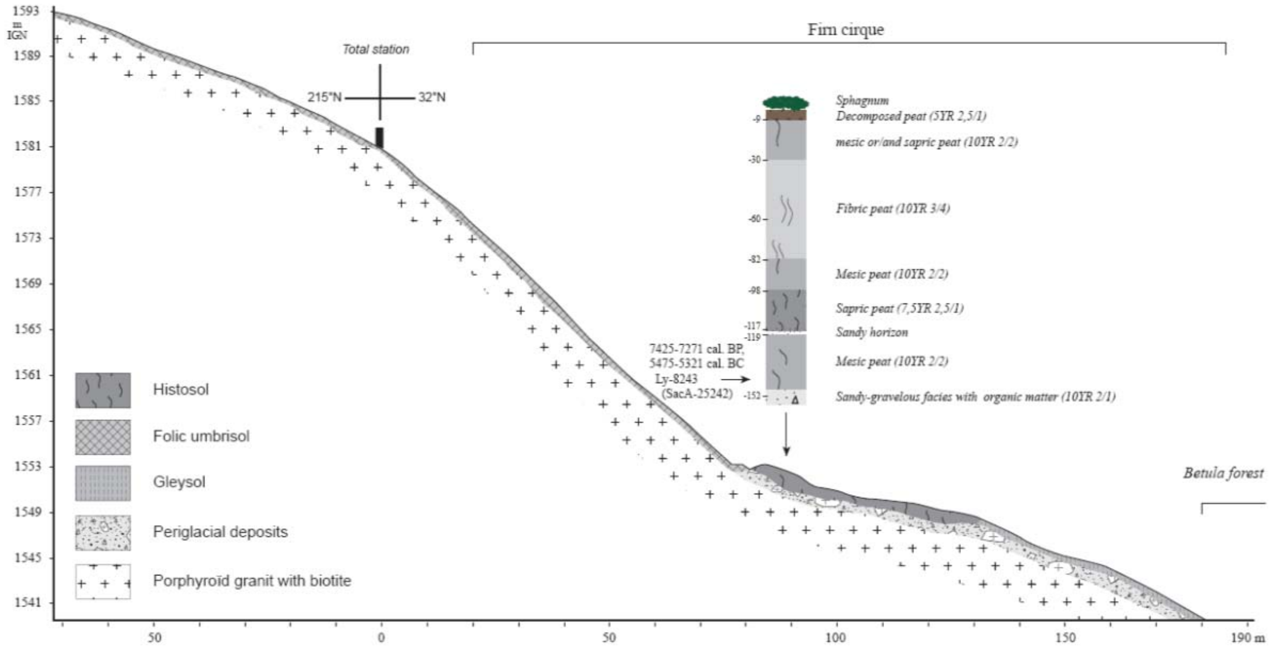

Figure 6. Corniche en Coeur Mire, in a firn cirque located at 1540 m in Les Monts du Forez mountain range.

nigrae (Oberdorfer 1957) Rivaz-Martinez & Gehu 1978, *Caricion nigrae* alliance Koch 1928 *em*. Klika 1934). However, their specificity lies in the occurrence of spring mire plant communities supplied by water from melted snow. Some of these are interesting subalpine indicators like *Sphagno auriculati-Trichophoretum cespitosi* Thébaud *et al*., 2012 and *Nardietum compressae* Guessler 1976. The datings obtained showed that they are mostly of Sub-Atlantic origin, occasionally Sub-Boreal and very rarely Atlantic, as shown in Figure 6 (Cubizolle *et al.* 2012).

Overview of results

In summary, we recorded: an absence of mires at foothill levels; a huge diversity of mires at mountain levels, which host the largest area of mires; and few mires of very small area on the highest ground at sub-alpine levels (Figure 7).

DISCUSSION

The geographical distribution of mires at regional scale is explained by a large number of factors that operate at different spatial scales. We shall again consider these mires in order, from lower to upper altitudes.

The absence of mires in the foothills below 850 m altitude can be explained mostly by the unfavourable climatic conditions: average annual rainfall 600–900 mm; average annual temperature ranging from 12 °C below 500 m altitude to 8 °C at 850 m; and maximum temperatures in excess of 17 °C. Thus, evaporation is important for several months of the year and this is revealed by a notable degradation of the humiferous layers from June to October. The other unfavourable factors are hydrology and geomorphology. Superficial displaced periglacial slope deposits are absent and the Tertiary grus have a very discontinuous distribution (Cubizolle *et al.* 2013a). Thus, the only aquifer is the fissured rock layer, in which the groundwater level is generally low except from time to time during winter and spring. Finally, it is highly probable that a few small peat accumulations had developed in the bottoms of valleys but were subsequently destroyed by agricultural drainage, as most of the land at this level was used as farmland and meadows for several centuries up to 1950.

The fens and buried Histosols at the lower mountain levels between 850 m and 1100 m altitude are characteristic of an area that was historically dedicated to ploughing and pasture land. Hence, some human responsibility can be invoked for both the establishment of mires and the presence of fossil Histosols. The mires behind dams are of anthropic origin, owing their existence to historical human activities that blocked the flow of water along the valley bottoms, causing a dramatic change from

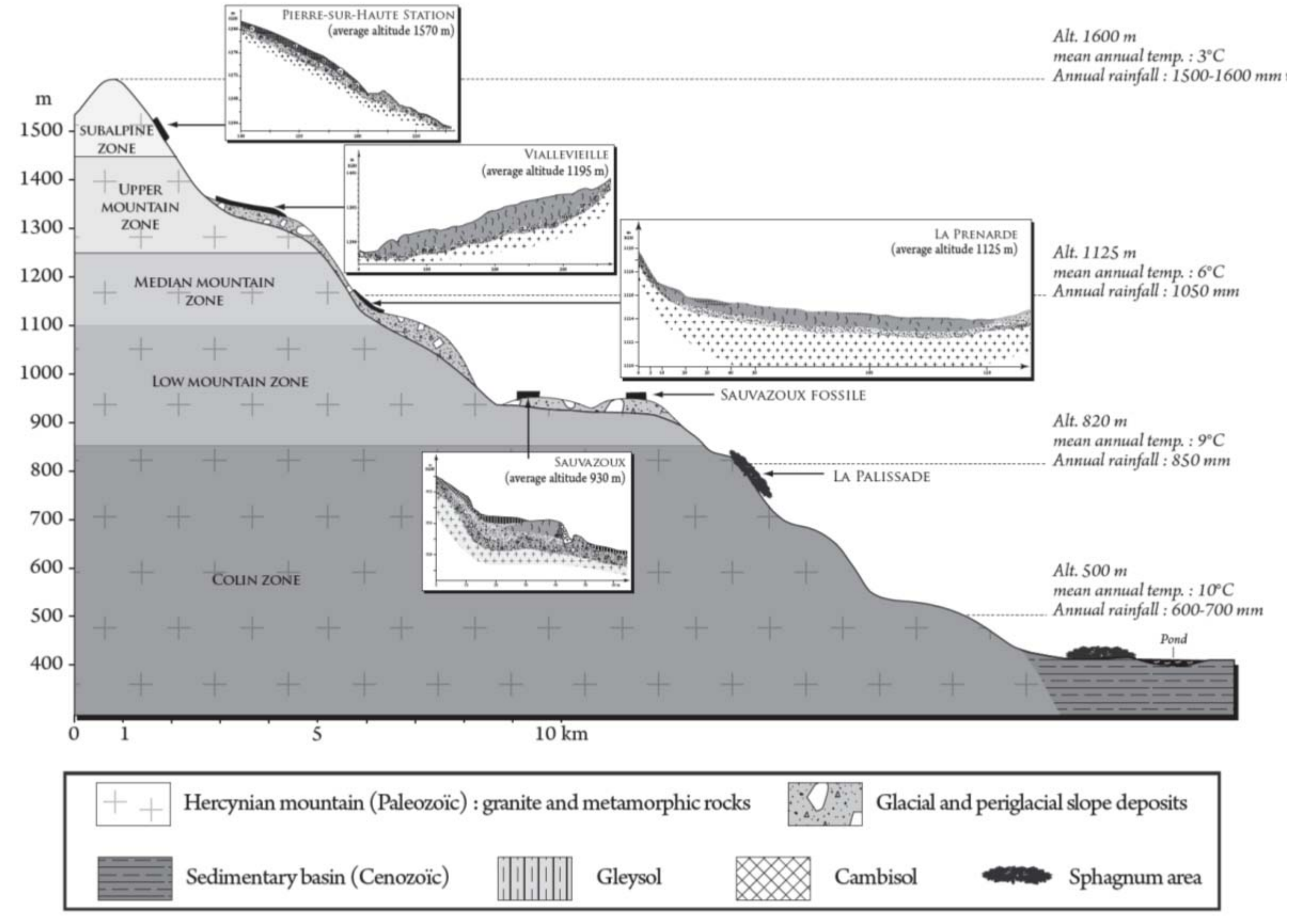

Figure 7. Overview of the altitudinal zonation of mires on the eastern slopes of Les Monts du Forez mountain range.

negative to positive water balance (Cubizolle *et al.* 2004). The fossil Histosols arise because peat accumulation was arrested when the water supplying the peat bog system was drained or diverted so as to lower the water table for a large part of the year; and the degree of ancient human intervention—or its more or less substantial effect—explains the presence of a thick mineral soil on top of the peat, which gives a thin and very humid organo-mineral horizon. The origin of the fossil Histosols is still a matter for discussion. Some are associated with ancient peat dams. Others could be natural because the climatic conditions at these altitudes are more favourable for peat formation, with annual rainfall in the range 1000–1100 mm combined with lower (especially summer) temperatures. Otherwise, the presence of grus (*in situ* or bedded grus, formed by disintegration of granitic rocks) and the abundance of surface undulations are favourable geomorphological factors. However, much of the peat in this altitude zone is assumed to be of anthropic origin according to an example proposed by Anglo-Saxon authors (Caseldine & Hatton 1993, Moore 1993). In fact, these mires appeared during the last 4500 years (Cubizolle *et al.* 2012), during which period there was rapid development of agricultural activities at altitude (de Beaulieu *et al*. 1987, Janssen 1990, Argant & Cubizolle 2005, Cubizolle *et al.* 2013b). The effects of deforestation by fire and farming pressure have combined to reduce the water deficit in the hydromorphic valley bottoms where trees have been felled, and thus to activate the peat accumulation process (Cubizolle *et al.* 2012).

The median mountain level between 1100 m and 1250 m, which has been densely forested since the 1950s, offers a slightly different context. The land here was ploughed and grazed until the Second World War. However, the intensity of tillage and grazing was highly variable depending on the area, and this appears to explain part of the peat diversity that we observed. Certain areas were grazed intensively, and others much less. Also, drainage of some sites had been attempted and, in all probability, this affected peat accumulation. Although the oldest mires are unquestionably natural in origin, the ones that appeared from the Sub-Boreal period could find their origins, like those of the lower mountain levels, in the agricultural and grazing activity from the end of the Neolithic period (Cubizolle *et al.* 2003, Argant & Cubizolle 2005, Cubizolle *et al.* 2005, Cubizolle *et al.* 2012). In fact, there is irrefutable palaeo-ecological evidence of a significant human influence on the natural environment of the Massif Central during the Sub-Boreal period (de Beaulieu de *et al.* 1987, Cubizolle *et al.* 2004, Cubizolle 2005, Cubizolle *et al.* 2013b, Cubizolle *et al.* in press).

Between altitudes of 1250 m and 1450 m, the presence of large raised bogs is fundamentally explained by the combination of favourable climatic, geomorphological and topographical conditions. The climate at these altitudes has a distinctive mountain character, with rainfall spread throughout the year and totalling on average 1200–1400 mm per year. Snow cover is also more abundant and more persistent than at lower altitudes, blocking the ground and superficial relief until the beginning of summer in the 1970s and until the middle of spring at the beginning of the 1980s (Etlicher 1986). The topography of these plateaux explains the numerous gently sloping surfaces and the patterns of glacial and periglacial hollows such as valley heads, glacial cirques, firn cirques, small nivation cirques and small moraine dams. The origins of the mires, which appeared in the first half of the Holocene epoch, are incontestably related to the postglacial climate (Cubizolle *et al.* 2003). The influence of man in initiating the peat formation process is excluded here; neither archaeology nor palaeoecology has been able to show that Mesolithic and Neolithic man played any role in modifying the evolution of these ecosystems.

In spite of frequent rainfall totalling 1500–1600 mm per year, the climatic conditions above 1450 m altitude appear less favourable for peat accumulation, on the one hand owing to the considerable shortening of the growing season, which limits biomass production, and on the other hand because of the rarity of gently sloping surfaces and concave landforms. In fact, the massif of Pierre-sur-Haute, which essentially encompasses all of the areas concerned, emerged at the Würm ice cap with the result that it was not affected by periglacial processes. The only favourable landforms suitable for peat development are found on its eastern flank; for example, firn and small nivation cirques like the example at “Corniche en Coeur", which is a firn cirque bog located at 1553 m (Figure 6).

Nevertheless, the recent age (up to 4500 years) of the majority of mires in this sector suggests that their establishment could have been linked to human activities on high ground from the middle of the Sub-Boreal period to the beginning of the Sub-Atlantic period. The palaeoecological data confirm that the modern treeless landscape above 1350–1400 m in Les Monts du Forez results from the expansion of pre-existing non-forested summit ‘islands’ from the middle of the Sub-Boreal period (Janssen 1990, Cubizolle *et al.* in press) which is also apparent in results obtained at the scale of the Massif Central as a whole (de Beaulieu *et al.* 1987).

Finally, at the scale of an 1800 km² mountain massif such as Les Monts du Forez, the combination of climate, hydrological, geomorphological and human factors can explain in detail the locations of mires on slopes and the changes in their characteristics with altitude (Figure 7). We note, on the other hand, the fundamental importance of human factors in the areas affected by agriculture and grazing over several millennia. The role of man is evident in a number of mires, but is not considered in the literature except in work on mires in the United Kingdom (e.g. Chambers & Daniell 2011). In contrast to the situation in north-western Europe, the anthropically initiated mires in this part of the Massif Central are small, minerotrophic and young because the majority of them date back only to the Sub-Atlantic period, since around 2750 cal. BP according to Cubizolle *et al.* 2012. However, they are still of interest because of their geographical position near the southern limit of the distribution of peat bogs in the northern hemisphere (Lappalainen 1996). They also contribute to the biodiversity of these south European regions, and elsewhere play a conservative role for the natural historical archives of landscapes and of the human societies that created them.

A major consequence in terms of conservation management is the multiplicity of factors that appear to be involved in determining the distribution of mires, and the numerous and often insidious persistent threats to these ecosystems. We can distinguish three types of threat:

- those that are well known, such as drainage or peat extraction;
- those that are strongly suspected but still badly characterised, such as ongoing climate change, and whose impacts on west European mires are highly variable depending on the context; and
- the lack of understanding that land management factors, such as the appropriately planned abandonment of agricultural land in mountains, could generate favourable hydrological conditions for the initiation of a number of small anthropic mires.

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REFERENCES

Andreyko, M.J., Fiene, F. & Cohen, A.D. (1983) Comparison of ashing techniques for determination of the inorganic content of peats. In: Jarett, P.M. (ed.) *Testing of Peats and Organic Soils*, ASTM STP 820, American Society for Testing and Materials, 5–20.

Argant, A. & Cubizolle, H. (2005) L'évolution holocène de la végétation des Monts de la Madeleine, du Forez, du Livradois et du Pilat (Massif Central oriental, France): l'apport d'une nouvelle série d'analyses palynologiques (The Holocene vegetation development of the Monts de la Madeleine, Forez, Livradois and Pilat (eastern Massif Central, France): the addition of a new series of palynological analyses. *Quaternaire*, 16(2), 119–142 (in French).

Bardat, J., Bioret, F., Botineau, M., Boullet, V., Delpech, R., Gehu, J.-M., Haury, J., Lacoste, A., Rameau, J.-C., Royer, J.-M., Roux, G. & Touffet, J. (2004) *Prodrome des végétations de France* (*Prodromus of the Vegetation of France*). Museum National d'Histoire Naturelle, Paris, 171 pp. (in French).

Botch, M.S. & Masing, V.V. (1979) Regionality in mire typology in the USSR. In: Kivinen, E., Heikurainen, L. & Pakarinen, P. (eds.) *Classification of Peat and Peatlands*, Proceedings of the International Symposium, International Peat Society, Hyytiälä, Finland, 1–11.

Braun-Blanquet, J. (1964) Pflanzensoziologie: Grundzüge der Vegetationskunde (*Phytosociology: Principles of Vegetation Science*). Third Edition, Volume 1, Springer, Vienna, 865 pp. (in German).

BRGM (2009) *Silures Limousin – Module 1. Silures Bases de Données, Recueil des Données, Interprétations et Bilans* (*Silures Limousin – Module 1. Silures Database, Interpretation and Balance Sheets*). Final Report, Bureau des Recherches Géologiques et Minières, BRGM/RP-57901-FR, 365 pp. (in French).

Caseldine, C. & Hatton, J. (1993) The development of high moor land on Dartmoor: fire and the influence of Mesolithic activity on vegetation change. In: Chambers, F.M. (ed.) *Climate Change and Human Impact on Landscape*, Chapman & Hall, London, 119–131.

Chambers, F.M. (1981) Date of blanket peat initiation in upland South Wales. *Quaternary Newsletter*, 35, 24–29.

Chambers, F.M. & Daniell, J.R.G. (2011) Conservation and habitat restoration of moorland and bog in the UK uplands: A regional, paleoecological perspective. *PAGES Newsletter*, 19(2), 45–47. Online at: http://www.pages-igbp.org/download/docs/newsletter/2011-2/Chambers&Daniell_2011-2(45-47).pdf, accessed 20 December 2013.

Charman, D. (2002) *Peatlands and Environmental Change*. Wiley, Chichester, England, 301 pp.

Coronato, A., Roig, C., Collado, L. & Roig, F. (2006) Geomorphologic emplacement and vegetation characteristics of Fuegian peatlands, southernmost Argentina, South-America. In: Martini, I.P., Cortizas, A.M. & Chesworth, W. (eds.) *Peatlands: Evolution and Records of Environmental and Climate Changes*, Elsevier, Amsterdam, 111–128.

Cubizolle, H. (1997) *La Dore et sa Vallée. Approche Géohistorique des Relations Homme/Milieu Fluvial* (*La Dore and its Valley. A Geo-historical Approach to Human–Fluvial Relationships*). Publications de l'Université de Saint-Etienne, Clermont-Ferrand, France, 389 pp. (in French).

Cubizolle, H. (2005) *Paléoenvironnements et Turfigenèse. L'apport de L'étude des Tourbières à la Connaissance de L'évolution Holocène des Milieux Montagnards du Massif Central Oriental Granitique* (*Palaeoenvironments and Peat Genesis. The Contribution of a Study of Peatlands to Our Understanding of the Holocene Evolution of Mountain Environments in the Granitic Massif Central*). Habilitation à Diriger des Recherches, Université de Limoges, 750 pp. (in French).

Cubizolle, H., Argant, J., Latour-Argant, C. & Fassion, F. (in press) La réponse de la végétation aux changements climatiques et à l'évolution de l'emprise humaine depuis la fin du Tardiglaciaire dans le Massif Central oriental (France) (Vegetation response to climate changes and human expansion at the end of the Late Glacial in the Eastern Massif Central (France)). *Quaternaire* (in French).

Cubizolle, H., Bonnel, P., Oberlin, C., Tourman, A. & Porteret, J. (2007) Advantages and limits of radiocarbon dating applied to peat inception since the end of the Late Glacial: the example of mires in the eastern Massif Central (France).

Quaternaire, 18(2), 187–206.

Cubizolle, H., Etlicher, B. & Porteret, J. (2013a) Modélisation de la répartition géographique des tourbières à partir des données géologiques, topographiques et géomorphologiques: application au Massif Central oriental (France) (Modelling of the geographical distribution of mires from geological, topographical and geomorphological data: the example of the eastern part of French Massif Central). *Géomorphologie, Relief, Processus, Environnement*, 2, 55–70 (in French).

Cubizolle, H., Fassion, F., Argant, J., Latour-Argant, C., Galet, P. & Oberlin, C. (2012) Mire initiation, climatic change and agricultural expansion over the course of the Late-Holocene in the Massif Central mountain range (France): what are the causal links and what are the implications for mire conservation? *Quaternary International*, 251, 77–96.

Cubizolle, H., Georges, V., Latour, C., Argant, J. & Serieyssol, K. (2004) La turfigenèse à la fin du Subboréal et au Subatlantique dans les tourbières basses du Massif Central oriental granitique (France): une manifestation de l'action humaine? (Peat inception in fens, at the end of the Subboreal and during the Subatlantic, in the granitic eastern Massif Central (France): a manifestation of human activities?). *Quaternaire*, 15(4), 343–359 (in French).

Cubizolle, H., Haas, J.N., Bielowski, W., Dietre, B., Chatelard, S., Argant, J., Latour-Argant, C. & Oberlin, C. (2013b) Palaeopaludification and environmental changes during the mid and late Holocene in Western Europe: the example of la Prenarde-Pifoy mire in French Massif Central. *Quaternaire*, 24(4) (419–442).

Cubizolle, H., Serieyssol, K. & Argant, J. (2005) Holocene vegetation dynamics and human impact on the peatland of Virennes (French Massif Central). *Diatoms Research*, 20(2), 257–273.

Cubizolle, H., Tourman, A., Argant, J., Porteret, J., Oberlin, C. & Serieyssol, K. (2003) Origins of European biodiversity: palaeo-geographic signification of peat inception during the Holocene in the granitic eastern Massif Central (France). *Landscape Ecology*, 18, 227–238.

Damman, A.W.H. (1979) Geographic patterns in peat bog development in eastern North America. In: Kivenin, E., Heikurainen, L. & Pakarinen, P. (eds.) *Classification of Peat and Peatlands*, Proceedings of the International Symposium, International Peat Society, Hyytiälä, Finland, 42–57.

Damon, M. (1972) *Les Jasseries des Monts du Forez. Sociologie de la Vie Pastorale* (*The Jasseries of Les Monts du Forez. The Sociology of Pastoral Life*). Thèse de troisième cycle, Faculté des Lettres et Sciences Humaines, Université de Lyon, 260 pp. (in French).

de Beaulieu, J-L., Pons, A. & Reille, M. (1987) History of vegetation, climate and human action in the French Massif Central over the last 15,000 years. In: Digerfeldt, G. (ed.) *Palaeohydrological Changes in the Temperate Zone in the Last 15,000 Years*, Symposium at Hoor, Sweden, 18–26 May 1987, IGCP 158, Lundqua Report 26, 207–211.

de Foucault, B. (1986) La Phytosociologie Sigmatiste: une Morphophysique (Sigmatist Phytosoioclogy: a "Morphophysic"). Mémoire Université de Lille, 147 pp. (in French).

Degorce, J.N., (1995) *Les Milieux Humides de la Loire* (*The Wetlands of the Loire*). Centre d'Etudes Foréziennes, Publications de l'Université de Saint-Etienne, France, 377 pp. (in French).

De Vleeschower, F., Chambers, F.M. & Swindles, G.T. (2010) Coring and sub-sampling of peatlands for palaeoenvironmental research. *Mires and Peat*, 7(01), 1–10.

Dewandel, B., Lachassagne, P., Wyns, R., Marechal, J.C. & Krishnamurthy, N.S. (2006) A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. *Journal of Hydrology*, 330, 260–284.

Etlicher, B. (1986) *Les Massifs du Forez, du Pilat et du Vivarais, Régionalisation et Dynamique des Héritages Glaciaires et Périglaciaires en Moyenne Montagne Cristalline* (*Forez, Pilat and Vivarrais Mountain Ranges, Distribution and Dynamics of Periglacial and Glacial Inheritances in Crystalline Mountains*). Thèse de Doctorat d'Etat, Lyon 2 University, 687 pp. (in French).

Etlicher, B. (2005) French and Belgian uplands. In: Koster, E.A. (ed.) *The Physical Geography of Western Europe*, Oxford Regional Environments, Oxford University Press, 231–250.

Eurola, S. (1962) Über die regionale Einteilung des Südfinnischen Moore (On the regional division of south Finnish mires). *Annales Botanici Societatis 'Vanamo'*, 33(2), 1–243 (in German).

Fel, A. (1962) *Les Hautes Terres du Massif Central. Tradition Paysanne et Économie Agricole* (*The Highlands of the Massif Central. Peasant Tradition and Agricultural Economy*). Publications de la Faculté des Lettres et Sciences Humaines, Institut de Géographie, Université de Clermont-Ferrand, France, 340 pp. (in French).

Gehu, J.M. & Rivas-Martinez, S. (1981) Notions fondamentales de phytosociologie (Fundamental notions of phytosociology). In: Dierschke, H. (ed.) *Syntaxonomie. Bericht International Symposium IV–V*, Cramer, Vaduz, 5–33.

Georges, V. (2007) *Le Forez du 6ème Millénaire au 1er Millénaire Avant J-C. Territoires, Identités et Stratégies des Sociétés Humaines du Massif Central dans le Bassin Amont de la Loire (France)* (*Le Forez From the 6th to the First Millennium B.C. Territories, Identities and Strategies of Human Societies of the Massif Central in the Upstream Basin of the Loire, (France)*). PhD thesis (Archaeology), Bourgogne University, Dijon, 435 pp. (in French).

Gobat, J.M., Grosvernier, P. & Matthey, W. (1991) Un triangle granulométrique pour les tourbes: analyses semi-automatique et représentation graphique (A granulometric triangle for peats: semi-automatic analysis and graphical representation). *Science du Sol*, 29(1), 23–35 (in French).

Gorham, E., Lehman, C., Dyke, A., Janssen, J. & Dyke, L. (2007) Temporal and spatial aspects of peatland initiation following deglaciation in North America. *Quaternary Sciences Reviews*, 26, 300–311.

Graniero, P.A. & Price, J.S. (1999) The importance of topographic factors on the distribution of bog and heath in a Newfoundland blanket bog complex. *Catena*, 36, 233–254.

Grosvernier, P., Matthey, Y. & Buttler, A. (1995) Microclimate and physical properties of peat: new clues to the understanding of bog restoration processes. In: Wheeler, B.D., Shaw, S.C., Fojt, W.J. & Robertson, R.A. (eds.) *Restoration of Temperate Wetlands*, John Wiley & Sons Ltd, Chichester, 435–450.

Heiri, O., Lotter, A.F. & Lemcke, G. (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparison of results. *Journal of Paleolimnology*, 25**,** 101–110.

Janssen, C.R. (1990) Histoire de la végétation des Monts du Forez (Vegetation history of Les Monts du Forez). In: Centre d'Études Foréziennes (ed.) *Les Monts du Forez, le Milieu et les Hommes (Les Monts du Forez, Environment and People)*, Jean Monnet University, Saint-Etienne, France, 65–79 (in French).

Jolly, M-C. & Lecompte, M. (1988) L'origine de l'asylvatisme d'altitude en Auvergne, une question contoversée: l'exemple du Cantal (The origin of treelessness at altitude in the Auvergne, a controversial question: the example of Cantal. *Documents de Cartographie Écologique*, 31, 49–60 (in French). Online at: http://ecologie-alpine.ujf-grenoble.fr/articles/DCE_1988__31__49_0.pdf, accessed 19 October 2013.

Joosten, H. & Clarke, D. (2002) *Wise Use of Mires and Peatlands - Background and Principles Including a Framework for Decision-making*. International Mire Conservation Group and International Peat Society, 304 pp.

Korhola, A. (1992) Mire induction, ecosystem dynamics and lateral extension on raised bogs in the southern coastal area of Finland. *Fennia*, 170, 25–94.

Korhola, A., (1995) Holocene climatic variations in southern Finland reconstructed from peat-initiation data. *The Holocene*, 5, 43–58.

Lappalainen, E. (1996) General review on world peat bog and peat resources. In: Lappalainen, E. (ed.) *Global Peat Resources*, International Peat Society, Finland, 53–56.

Levesque, M. & Dinel, H. (1977) Fiber content, particle-size distribution and some related properties of four peat materials in Eastern Canada. *Canadian Journal of Soil Science*, 57, 187–195.

Levesque, M.P. & Dinel, H. (1982) Some morphological and chemical aspects of peats applied to the characterisation of histosols. *Soil Science*, 5, 324–332.

MacDonald, G.M., Beilman, D.W., Krementski, K., Sheng, Y., Smith, L.C. & Velichko, A.A. (2006) Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science*, 314, 285–288.

Mitchell, G.F. (1972) Soil deterioration associated with prehistoric agriculture in Ireland. *Proceedings of the 24th International Geological Congress, Montréal, Canada, Symposium 1: Earth Sciences and the Quality of Life*, 59–68.

Moore, P.D. (1975) Origin of blanket mires. *Nature*, 256, 267–269.

Moore, P.D. (1993) The origin of blanket mire, revisited. In: Chambers, F.M. (ed.) *Climate Change and Human Impact on Landscape*, Chapman & Hall, London, 217–224.

Moore, P.D., Merryfield, L. & Price, M.D.R. (1984) The vegetation and development of blanket mires. In: Moore, P.D. (ed.) *European Mires*, Academic Press, London, 203–235.

Osvald, H. (1925) Die Hochmoortypen Europas (The Bog Types of Europe). *Veröffentlichungen des Geobotanischen Institütes, Stiftung Rübel, Zürich*, 3, 707–723 (in German).

Ozenda, P. (1985) *La Végétation de la Chaîne Alpine* (*The Vegetation of the Alpine Chain*). Masson, Paris, 330 pp. (in French).

Pajunen, H. (2005) Mires. In: Seppälä, M. (ed.) *The Physical Geography of Fennoscandia*, Oxford Regional Environments, Oxford University Press, 77–95.

Payette, S. & Rochefort, L (2001) *L'écologie des Tourbières du Québec-Labrador* (*The Ecology of Peatlands in Quebec-Labrador*). Les Presses Universitaire de Laval, Québec, Canada, 619 pp. (in French).

Pennington, W. (1975) The effect of Neolithic man on the environment in North West England : the use of absolute pollen diagrams. In: Evans, J.G., Limbrey, S. & Cleere, H. (eds.) *The Effect of Man on the Landscape : the Highlands Zone*, CBA Research Report 11, Council for British Archaeology, London, 74–86.

Piotroswka, N., Blaauw, M., Mauquoy, D. & Chambers, F.M. (2011) Constructing deposition chronologies for peat deposits using radiocarbon dating. *Mires and Peat*, 7(10), 1–14.

Reimer, P.J., Baillie M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J. & Weyhenmeyer, C.E. (2009) INTCAL09 and Marine09 radiocarbon age calibration curves, 0–50,000 years Cal BP. *Radiocarbon*, 51(4), 1111–1150.

Rieley, J.O., Sieffermann, R.G. & Page, S.E. (1992) The origin, development, present status and importance of the lowland peat swamp forests of Borneo. *Suo*, 43(4–5), 241–244.

Rivas-Martinez S. & Gehu, J.-M. (1978) Observation syntaxonomiques sur quelques végétations du Valais Suisse. Compte-rendu de l'excursion de l'Association Amicale Francophone de Phytosociologie dans les Alpes Suisses de 1976 (Syntaxonomical observation on some vegetation of the Swiss Valais. Account of the 1976 tour of the Francophone Phyto-sociological Friendly Association in the Swiss Alps). *Document Phytosociologiques*, 3, 371–423 (in French).

Ruuhijärvi, R. (1960) Über die regionale Einteilung der nordfinnischen Moore (On the regional division of north Finnish mires). *Annales Botanici Societatis 'Vanamo'*, 31, 1–360 (in German).

Sjörs, H. (1950) Regional studies in north Swedish mire vegetation. *Botaniska Notiser*, 103, 173–222.

Smith, A.G. (1970) The influence of Mesolithic and Neolithic man on British vegetation. In: Walker, D. & West, R.G. (eds.) *Studies in the Vegetational History of the British Isles*, Cambridge University Press, 81–96.

Smith, L.C., MacDoland, G.M., Velichko, A.A., Beilman, D.W., Borisova, O.K., Frey, K.E., Kremenetski, K.V. & Sheng, Y. (2004) Siberian peatlands a net sink and global methane source since the early Holocene. *Science*, 303, 353–356.

Stanek, W. (1977) Classification of muskeg. In: Radforth, N.W. & Brawner, C.O. (eds.) *Muskeg and the Northern Environment in Canada*, Proceedings of the 15th Research Conference (Edmonton, Alberta, 1973), University of Toronto Press, Toronto and Buffalo, Canada, 31–62.

Succow, M. & Lange, E. (1984) The mire types of the German Democratic Republic. In: Moore, P.D. (ed.) *European Mires*, Academic Press, London, 149–175.

Tallis, J.H. (1964) The pre-peat vegetation of the southern Pennines. *New Phytologist*, 63, 363–373.

Thébaud, G. (1990) La végétation du Haut-Forez (The vegetation of the High Forez). In: Centre d'Études Foréziennes (ed.) *Les Monts du Forez, le Milieu et les Hommes* (*Les Monts du Forez, Environment and People*), Jean Monnet University, Saint-Etienne, France, 37–63 (in French).

Thébaud, G., Goubet, P., Skrzypczak, R. & Sourp, E. (2009) Communautés végétales des tourbières ombrotrophes du Massif Central oriental (Bog plant communities of the eastern Massif Central). *Acta Botanica Gallica*, 156(3), 341–377 (in French).

Thébaud, G. & Petel, G. (2008) Contribution à une révision des végétations tourbeuses ombrotrophes et ombrominérotrophes médio-européennes (Contribution to a revision of ombrotrophic and ombro-minerotrophic mire vegetation in central Europe). *Phytocoenologia*, 38(4), 287–304 (in French).

Thébaud, G., Roux, C., Delcoigne, A. & Petel, G. (2012) Contribution à une révision des bas-marais acides d'Europe tempérée occidentale (Contribution to a revision of the acid fens of temperate western Europe). *Phytocoenologia*, 42(1–2), 67–98 (in French).

Vitt, D.H., Halsey, L.A. & Zoltai, S.C. (1994) The bog landforms of continental western Canada relative to climate and permafrost patterns. *Arctic and Alpine Research*, 26, 1–13.

von Kaule, G. (1976) Begriffsbestimmungen anhand der Moortypen Mitteleuropas (Definitions of the mire types in central Europe). In: Göttlich, K.

(ed.) *Moor and Torfkunde*, E.Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1–21 (in German).

von Post, L. & Grandlung, E (1926) Södra Sveriges Torvtillgångar I (Peat resources in southern Sweden I). *Sveriges Geologiska Undersökning, Series C*, 335 (= Årsbok 19:2), Stockholm, 127 pp. (in Swedish).

Walker, D. (1956) A site at Stump Cross, near Grassington, Yorkshire, and the age of the Pennine microlith industry. In: Clark, J.G.D., Oakley, K.P. & Piggott, S. (eds.) *Proceedings of the Prehistoric Society, New Series*, 22, 23–28.

Weber, H.E., Moravec, J. & Theurillat, J.-P. (2000) International code of phytosociological nomenclature, 3rd edition. *Journal of Vegetation Science*, 11, 739–768.

WRB (2006) *World Soil Resources Report 103*. World Reference Base for Soil Resources, UN Food and Agriculture Organization (FAO), Rome, 128 pp.

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