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Suivi à long terme de la dynamique de la végétation pour évaluer le succès de la restauration d'une tourbière exploitée (Québec, Canada). *Résumé*

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Nous présentons les résultats d'un suivi de la dynamique de reconstitution de la végétation sur une période de 7 ans depuis la restauration d'une tourbière anciennement exploitée. Le but de l'étude est 1) d'estimer le succès de la restauration par une approche de ''paludification''; 2) de suivre l'évolution de la végétation en terme de recouvrement et de diversité. La tourbière a été exploitée sur 11,4 ha et laissée à l'abandon à partir de 1980. La restauration a été effectuée en 1999 sur 8,5 ha, par réintroduction de diaspores de sphaignes prélevées dans une tourbière naturelle, l'ajout d'un paillage, le blocage des canaux de drainage et une légère fertilisation phosphorée. La végétation a ensuite été suivie par deux méthodes : tous les deux ans (de 1999 à 2005) par des relevés de type points-contacts, avec au maximum 6900 points répartis systématiquement sur le site, et toutes les années par des relevés dans des parcelles permanentes. La dynamique de la végétation sur le site restauré a été comparée avec la partie non restaurée du site et des tourbières naturelles de référence. En 2005, le degré de couverture des sphaignes était 50 fois plus important sur le site restauré que sur le site non restauré. La diversité des sphaignes a atteint 12 espèces. Le recouvrement des autres mousses tel que le Polytric (*Polytrichum strictum*) était deux fois plus élevé en 2003 dans le site restauré que dans les tourbières de référence, mais a commencé à diminuer par la suite. La strate herbacée était également beaucoup plus présente, avec 55 espèces au maximum, mais on s'attend à une diminution de l'espèce principale *Eriophorum vaginatum* avec le temps. La méthode de restauration s'avère globalement efficace pour rétablir un couvert végétal diversifié sur des tourbières anciennement exploitées. Les différences de résultats entre les deux méthodes de suivi seront également discutées pour les strates et les espèces.

Long-term vegetation monitoring to assess the restoration success of a vacuum-mined peatland (Québec, Canada).

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Introduction

Peatlands cover approximately 9 to 12% of the Quebec's landscape (Tarnocai et al 2000; Zoltai & Pollet 1983) but most of the degradations are concentrated in the southern part of the country, through agriculture development, drainage, urbanization, water management projects, and peat harvesting (Zoltai & Pollet 1983). The peat is mainly harvested for the needs of agriculture and horticulture. The block-cut technique has been the principal mean of peat extraction before the 1970s, but nowadays peatlands are exploited by milling machines and vacuum harvesters. Once the exploitation has ceased, the peatland is abandoned and can be recolonized by vegetation. However, the slowness of the natural regeneration is well documented and is particularly evident for vacuum-mined peatlands (Campbell & Rochefort 2003; Poulin et al 2005; Price & Whitehead 2004). Soil surfaces of vacuum-mined peatlands can remain bare or scarcely vegetated 10 years after abandonment (Lavoie & Rochefort 1996). More specifically, numerous studies have shown that the spontaneous re-colonization by *Sphagnum* mosses on vacuum-mined peatlands is infrequent (Poulin et al 2005). Consequently, the *Peatland Ecology Research Group* with numerous partners have developed and applied restoration techniques for revegetate degraded and abandoned peatlands (Quinty & Rochefort 2003).
Here, we use the term restoration in its broad sense, defined by the SER (Society for Ecological Restoration, policy working group 2004; chap. 16) as the process of assisting the recovery of an ecosystem that has been damaged, degraded or destroyed. That implies to restore ecosystem structure with a sufficient level of biodiversity, ecosystem functioning, resilience and sustainability. In the particular case of vacuum peatlands, the goal of restoration is to re-establish a typical hydrological regime and a plant cover largely dominated by *Sphagnum* (or brown mosses) for favoring plant and animal diversity, peat formation and carbon accumulation (Rochefort 2000).
The main restoration steps consist in introducing *Sphagnum* fragments on bare peat, with other plant diaspores and straw mulch thereafter to block the drainage ditches for rewetting the site (Rochefort et al 1997). A light fertilisation in phosphorus is sometimes applied.

In this paper, we present the evolution of the vegetation from the year prior to and up to six 6 years after the restoration of the Bois-des-Bel peatland. We assessed the restoration success of the whole site by answering the following questions: does the restoration procedure lead back to 1) a *Sphagnum* carpet and a production of a new moss carpet; 2) a recovery by plant; 3) a level of plant diversity, all comparable to natural reference peatlands?

Material and Methods

The site

The Bois-des-Bel peatland is located 200-km north-east of Québec City, on the south shore of the St Laurent river (Fig.1; 47°58' N, 69°26' W). The mean annual temperature is 4.2°C and mean annual precipitation is 930 mm.

Peat was exploited on a section of 11.5 ha with was part of a larger peatland of 189 ha. Peat milling was stopped in 1980, leaving a peat deposit of approximately 2 m. In 1999, the PERG has initiated a restoration project on 8.4 ha of the mined section. A zone of 3.1 ha was not restored. This zone was characterized by three peat fields, one serving as a buffer zone between the rewetted and the non-rewetted zone.

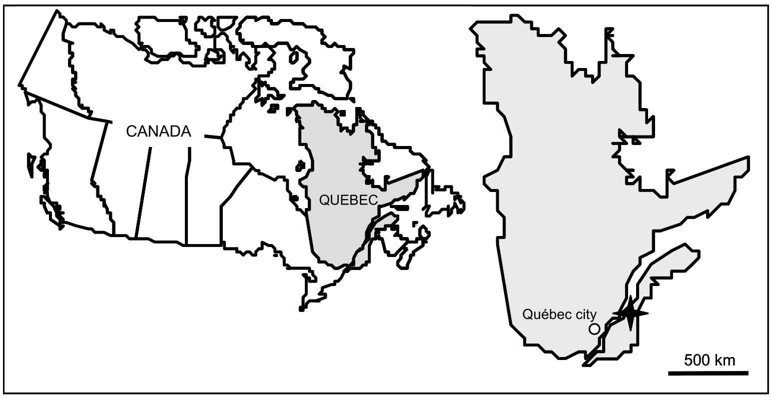

Fig.1. Location of the study site: Bois-des-Bel peatland (Québec, Canada).

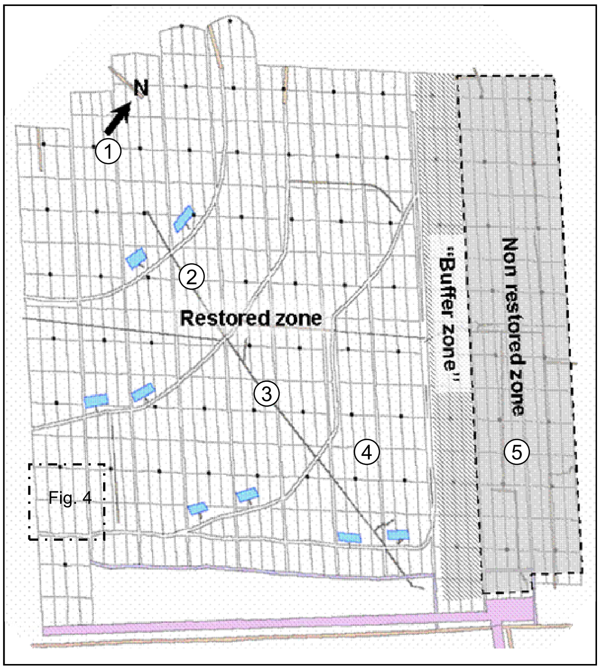

Fig.2. Map and GIS grid of the study site (see fig. 4 for a zoom in a section). Curved grey lines that cross the site are embankments established during restoration for distributing water over the site. Grey rectangles represent created pools. Numbers in circles indicate terraces created by embankments.

Restoration procedure on the site

The restoration work had started in the fall 1999, and was completed in the fall 2000 for terrace number one. The restoration work was planned and performed with the collaboration of peat industrials.

The restoration procedure included six major steps:

1- Surface preparation: in order to level the peat fields, and also to break it up the soil surface crust, for improving contact between soil and plant diaspores contacts. Trees and shrubs were removed from the peat fields (fig. 3a).
2- Construction of embankments along topographical levels to create terraces (fig.3b); this aimed at reprofiling the slope to favour a better water distribution (Bugnon et al 1997);
3- Reintroduction of plant diaspores including *Sphagnum* collected in a proximate natural peatland, the donor site. The collection consisted in uprooting and collecting the first 10 cm of the vegetation (fig.3c).
4- Spreading of straw mulch (fig.3d) with a box manure spreader. As far as possible it is preferable to use light manure spreader to avoid the formation of deep tracks in the peat that could be a hindrance for *Sphagnum* regeneration (Price et al 1998);
5- Blocking of drainage ditches (fig.3e): this operation completed the straw application, and allowed to retain water within the site;
6- Fertilization, the following summer, (Ferland & Rochefort 1997) (fig.3f)

a. Site preparation

b. Embankment

c. Diaspore collection and…

…diaspore spreading

d. Straw mulch application

e. Ditch blocking

f. Fertilization

Fig.3. The six steps used for the restoration of the Bois-des-Bel mined peatland (Québec, Canada; photographs from *Peatland Ecology Research Group*).

Moss carpet thickness

We measured the newly formed moss carpet on the restored and non restored zone. The thickness was measured from the top of the residual peat layer to the top of *Sphagnum* capitulum or of other moss species when dominated at the point of measure. Measures were taken in the centre of each 20 x 7m cell (see fig.4) on every peat fields (750 measurements) in 2003, 2005 and 2007. We calculated the mean thickness of moss carpet by terraces; five terraces including the non-restored zone (fig. 4) and 112, 117, 193, 88 and 136 measurements for the terraces 1 to 5 respectively.

Vegetation survey

We used the point-intercept method (Bonham 1989) to collect cover data for the vascular and non-vascular strata. A vertical rod was displaced each 3.3 m along a 30 m long transect, i.e. at 10 equidistant points. Transects were shifted every 5 m from the beginning of the peat field (fig. 4). All plant species intercepted by the rod were recorded. If the rod intercepted no plant, the ground surface was recorded as bare peat or litter. The survey was conducted prior to (1999) and after restoration (2001, 2003 and 2005).

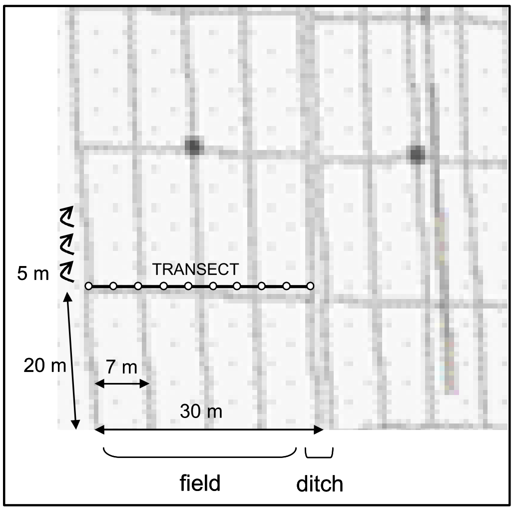

Fig. 4. Zoom in a section of the site showing the cells (20x7m) and the transects used for the point intercept method.

Data treatment
Using this point intercept method, total cover can be calculated as the percentage of hits, relative to the total number of points sampled, here around 4510 points for the restored zone and 1260 for the non-restored zone. By the same way, estimation of individual species cover can also be estimated by recording the plant species when intercepted by the rod for each point. Cover of bare peat and litter was also estimated.

We divided the plant species in 6 groups or strata:

1- *Sphagnum* strata, including the different species of *Sphagnum*;
2- Bryophytes, including mosses (other than *Sphagnum*), liverworts and hornworts;
3- Lichen, exclusively the species which grow on soil surface;
4- Ericaceae, herbaceous, shrubs or sub-shrubs pertaining to this family;
5- Shrubs (other than Ericaceae);
6- Herbs.

Plant recovery for each of these strata was compared with cover estimations in natural peatlands or "reference sites". We used vegetation dataset of seven natural peatlands investigated in the region surrounding the study site (Pouliot et al. unpublished data). The design involved ten 1-m² circular samples along 1-km transects crossing each natural peatland. In this case, replications allow us to calculate the cover ranges of the different plant groups. We calculated the first quartile (x.25), the median (x.50) and the third quartile (x.75).

Results and Discussion

Even though standard deviations are large, mean moss carpet thickness on the site (fig. 5) increased from 2003 to 2007. Considering all terraces, the moss carpet was three-times thicker in 2007 than in 2003. The lowest thickness was found on the non-restored zone, which stayed very thin, below 1cm-thick, and every year. In the restored zone, the moss carpet increased at the same rate for all terraces. The large variation of thicknesses is mainly due to: (1) the natural heterogeneity i.e. the hummock-hollow gradient that progressively takes place on the restored zone; (2) the variations of hydrology on the whole site; (3) and whether the moss carpet is dominated by *Sphagnum* species or by *Polytrichum strictum*. The term acrotelm can not be applied strictly to the moss carpet that has grown since the restoration. The acrotelm consists of the living parts of mosses, also with dead and poorly decomposed plant material. This part is submitted both to fluctuation of the water table and aerobic conditions. In this restored peatland the moss carpet is growing directly on a compacted residual peat layer. The hydrologic conditions in the moss carpet are different of a real acrotelm.

Percent cover of bare peat and percent cover of litter (fig. 6 & 7) decreased from 1999 (the year of restoration) until 2005. However, bare peat cover in the non-restored zone was stable except the slight decrease between 2003 and 2005. The decrease of bare peat was marked in the restored zone especially the first years, but this is a result of the diaspore spreading (fragmented moss carpet, patches of vegetation, fragment of plants). Nevertheless, bare peat and litter cover are two indirect parameters of vegetation recovery. The bare peat cover was less than 10 % in 2005, meaning that all vegetation strata combined have reached 90% cover (fig.6). Litter cover reflected both vegetation recovery and concomitant deposition of dead plant materials, and process of organic matter decomposition. Values differed between the restored and non-restored zones of the site (fig. 7). The income of organic matter seems to be more important in the non-restored zone than in the restored zone which means decomposition rate is lower in the non-restored zone.

The establishment of *Sphagnum* diaspores was remarkable over the years and clearly higher in the restored zone in comparison with the non-restored (fig. 8a). *Sphagnum* cover in the non-restored zone reached a maximum of 0.25 % in 2005 while it attained 60% the same year in the restored zone. This value is close to the range of *Sphagnum* cover found in the natural sites. Indeed, fifty percent of *Sphagnum* cover values in natural sites ranged between 80% and 86%. The highest outlier observation was close to 100% cover whereas the smallest was 45% cover. In the restored zone, the cover of *Sphagnum* was essentially composed of *Sphagnum rubellum* (fig.9) which accounted for nearly three-quarter of the total species composition. This species was the dominant *Sphagnum* species in the donor site. Moreover, *Sphagnum rubellum* has shown a high growth rate and abilities to regenerate (Joosten 1995; Robroek et al 2006). This species is also abundant in the landscape, in the surrounding natural peatlands, and was found as a component of the flora at the beginning of bog succession (Robert et al 1999). The common habitat of *Sph. rubellum* in the bog of eastern Canada is in the lawns. As the typical hummock-hollow gradient of is not yet well-developed in the restored zone, consequently most of the peatland surface could be associated with lawn habitats. *Sphagnum magellanicum* was the second most abundant species with 10% (2003) and 15% (2005) of the *Sphagnum* composition. Among the minor species, *Sphagnum angustifolium, Sph. fallax* and *Sph. cuspidatum* were observed the most. Surprisingly *Sphagnum fuscum* was one of the most abundant species in 2003 but was a minor species in 2005. In 2003 the *Sphagnum* individuals were still small and made the identification difficult. Therefore, it is possible that *Sph. fuscum* was misidentified and overestimated that year. Also, *Sphagnum rubellum* was maybe able to outcompete *Sph. fuscum* reducing its density. Maybe it has suffered from frost injuries or desiccation, or a combination of all of the above factors.

The cover of bryophytes, mostly mosses and liverworts, strongly increased just after the restoration and was particularly high (fig. 8b); it reached 70% but has started to decrease after 2003. Cover values in the non-restored zone were closer to the natural peatlands where the maximum cover value not exceeded 11% cover. The moss cover was dominated by *Polytrichum strictum* Brid. and *Pohlia nutans* (Hedw.) Lindb. The most common liverworts pertain to the families of *Cephaloziaceae* and the *Jungermanniaceae*, especially *Mylia anomala* (Hook.) Gray.

Percent covers of lichens were generally low and under 15% (fig. 8c). The highest values have been found in the non-restored zone where the cover of lichen increased gradually since 1999. In 2005 the cover was 10 times higher in this zone than in the restored zone. Along the years, the cover values of lichen in the non-restored zone were in the range of what it was found in the natural peatlands, principally because of the large variation of the cover values. Dryer conditions on newly formed hummocks could explain the presence of lichens in the restored zone. Lichens were more abundant in the non-restored zone because they are organisms which successfully grow under harsh conditions such as bare peat, heat, dryness. The most common species belong to the *Cladoniaceae* family (*Cladonia spp.*, *Cladina spp.*).

The cover of ericaceous species (fig. 8d) strongly rose after 2001 in the restored zone. It rose over the cover of Ericaceae in the non-restored part. Here again, the range of Ericaceae cover in the natural peatlands shows large variation, with a minimum of 8% to a maximum of 68%. Twelve species were found in the restored zone and ten in the non-restored zone. Both in the natural peatlands and in the restored peatland, the dominant species were *Chamaedaphne calyculata* (L.) Moench, *Rhododendron groenlandicum* (Oeder) Kron & Judd, *Vaccinium angustifolium* Ait., *Kalmia angustifolia* L..

The establishment of shrubs was slow both in the restored and non-restored zone (fig. 8e), even though the cover was higher every year in the non-restored zone. Values in the restored zone were comparable to those observed in the natural peatlands. Among the 18 species recorded in the restored zone, the dominant ones were: *Spiraea alba var. latifolia* Du Roi (Ait.) Dippel, *Salix spp.*, *Aronia melanocarpa* (Michx.) Ell., *Rubus idaeus* L.

Herbs, including species of grasses, sedges, forbs and legumes, were very abundant in the restored zone (fig. 8f). The cover was almost multiplied by 5 between 2001 and 2003 and reached a peak in 2005. Covers especially in the restored zone were clearly higher than the range of the cover values observed in the natural peatlands. There was a maximum of 55 species of herbaceous plants in 2003 in the restored zone, but the most abundant species was the cotton-grass *Eriophorum vaginatum L.* which represented 32% and 29% of the species in 2003 and 2005 respectively. This range of cover is particularly high for a peatland. The role of the cotton-grass in the restoration process is not clearly defined (Lavoie et al 2005). Some studies have shown negative impacts when cotton-grass invaded a peatland and intercepts precipitation (Lavoie et al 2005; Marcoux 2000), but others shown that it can also act as a nursing plant, protecting mosses and *Sphagnum* against desiccation (Boudreau & Rochefort 1999; Tuittila et al 2000). However, the cover of *E. vaginatum* tends to decrease slightly since 2003 and thereafter, following a typical succession of post-harvested peatland (Robert et al 1999).

Conclusion

The restoration techniques that have been used in 1999 seem very effective for restoring the vacuum mined peatland in its whole. (1) The *Sphagnum* carpet is well established and dominated by *Sph. rubellum*. Moreover, a new moss layer has been developed with the creation of small hummocks and hollows. (2) Both non-vascular and vascular plants cover all the peat surfaces of the site. (3) Fifteen species of *Sphagnum* are present in the restored section, as well as different species of mosses and liverworts (16), *Ericaceae* (20), other shrubs (18) and herbs (55). The restoration procedure should drive this vacuum-mined peatland towards a functional and "typical" peatland ecosystem.

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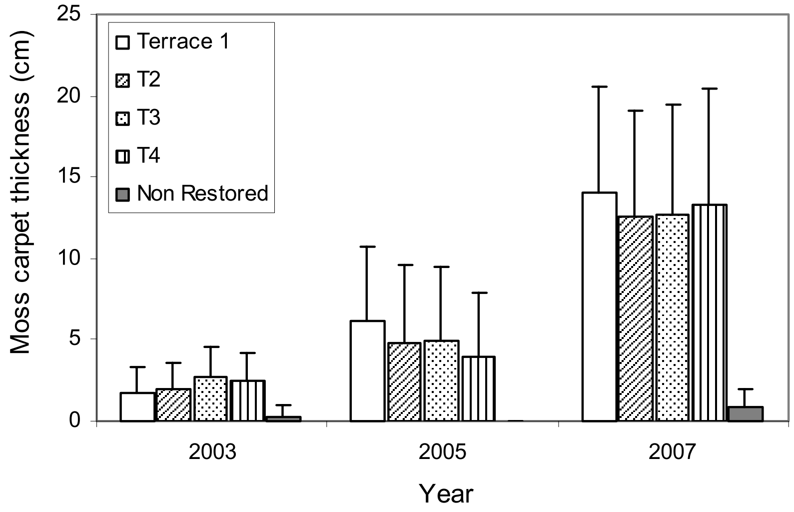


Fig.5. Evolution of moss carpet thickness over the the Bois-des-Bel peatland.
Measurements were taken on each terrace; bars are mean thickness (± SD).

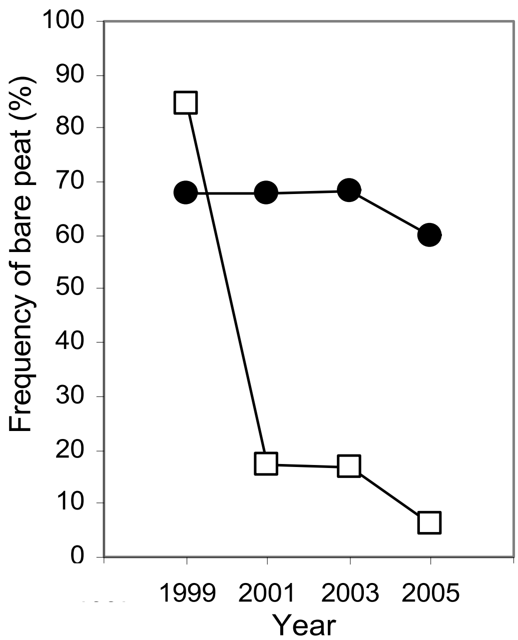


Fig.6. Variation of bare peat cover frequency since 1999 in the restored (□) and non-restored zone (□).

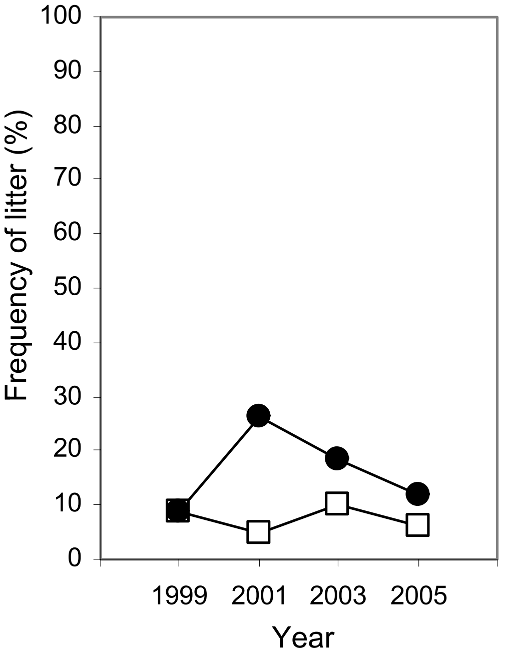
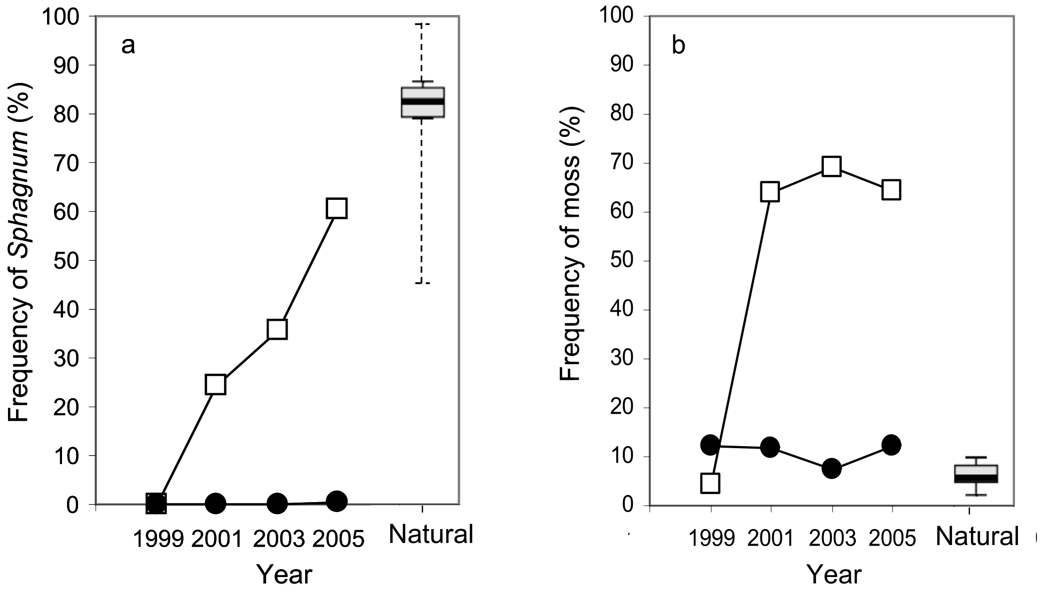


Fig. 7. Variation of litter cover frequency since 1999 in the restored (□) and non-restored zone (●).



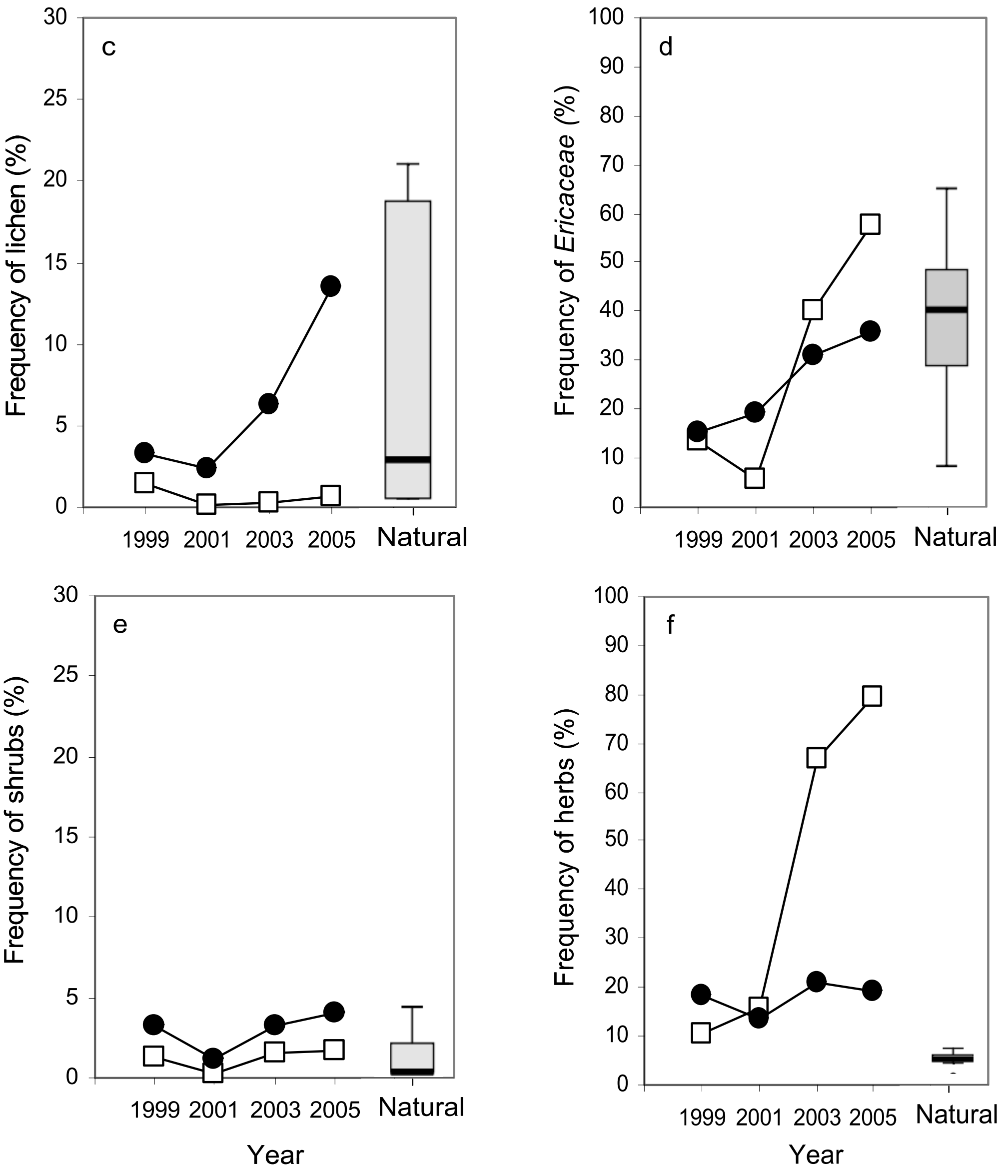


Fig.8. Variation of the different plant groups since 1999 and comparison with natural sites. Values are total percentages of the plant group considered in the restored (□) or in the non-restored zone (●). The box-plots represent the range of vegetation covers observed in natural peatlands with first quartile, median (black trait), third quartile, smallest non-outlier observation (down "whisker") and largest non-outlier observation (up "whisker").

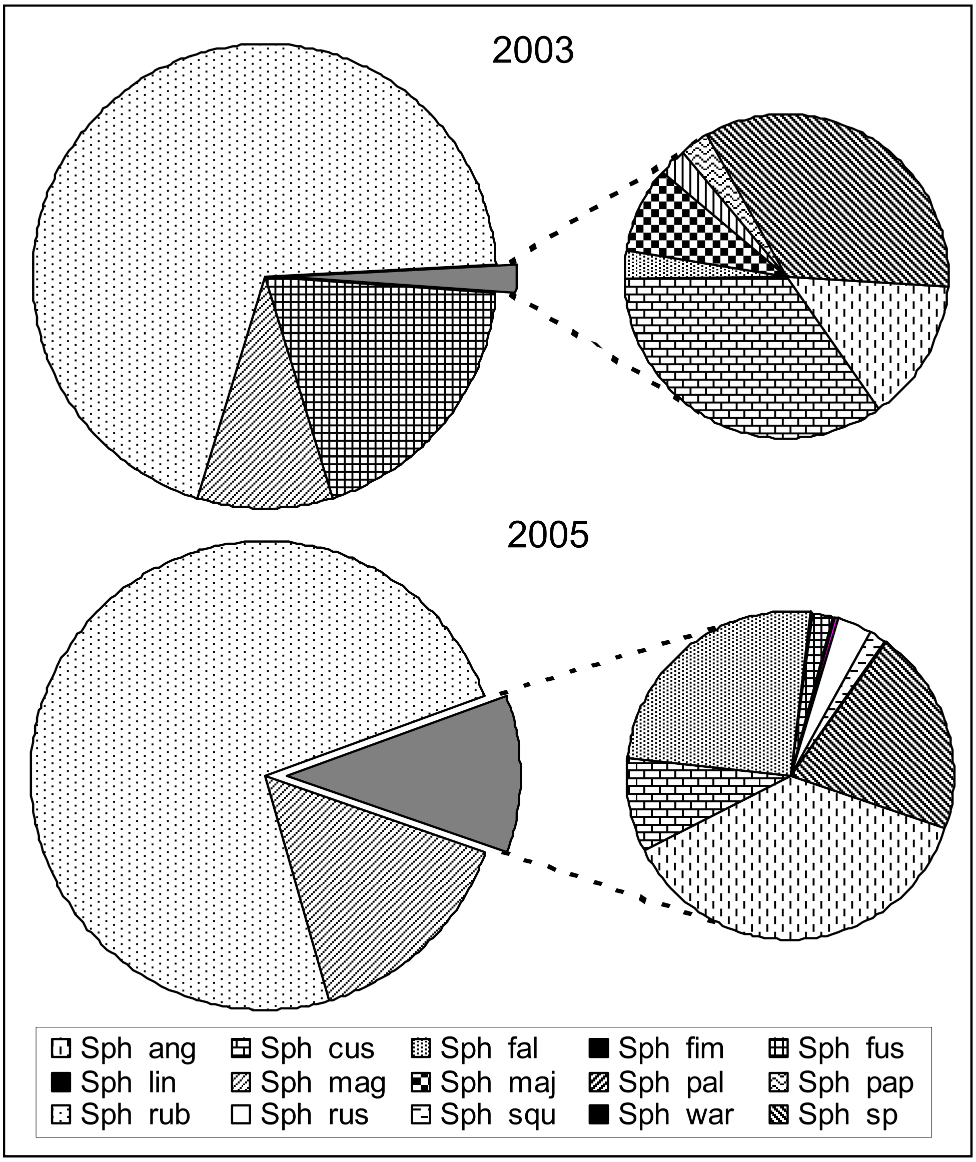


Fig.9. Proportion of the different *Sphagnum* species after the restoration. Percentages below 0.05 appear in black.