“Guidelines for cutover peatland restoration”
Insights from the EU-project RECIPE

Scientific context

Since the submission of project RECIPE several publications have been released on the topic of peatland regeneration. Thus the most useful contribution may not be yet another similar approach but rather an analysis of some specific case studies of cutover peatland regeneration: the five study peatlands of the RECIPE project. By this approch we can use the results of RECIPE to test the limits of the general restoration guidelines and to identify research areas that might deserve further attention. We based our analysis on the recently completed BRIDGE project and the guidelines resulting from it (Blankenburg and Tonnis, 2004). An additional rationale for this approach is that both projects were funded by the EU and were based on European peatlands. The summary descriptions of the five peatlands studied in detail in the RECIPE project, their starting condition, categories and end-point options according to BRIDGE and conflict or subjects requiring further research are summarized in Table 1.

Classification of the five RECIPE peatlands according to the BRIDGE categories and likely end-point options

1. Aitoneva, Finland

The peat deposits of Aitoneva were surveyed in 1942. Originally the site had been a treeless bog with an average peat depth of 2.9 m. In the mire centre the highest peat depth was 6.6 m (Stén and Toivonen, 1990). Peat harvesting in the area was started soon after the survey in 1942 and in some areas is still ongoing.

In the first years, the harvesting method used was block cutting, which created several 3 to 4 meter deep trenches, surrounded by ca. 5-meter-wide dry baulks of peat. The drainage system was fairly inefficient and the trenches started to regenerate spontaneously soon after the harvesting had ceased in 1948. The microtopography of the regenerated trenches is fairly even and the vegetation consists mainly of hollow and lawn vegetation. *Carex lasiocarpa* Ehrh., *C. rostrata* and *Eriophorum vaginatum* are the dominant vascular plants in the field layer. *Sphagnum pulchrum* (Braithw.) Warnst. and to lesser extent *S. lindbergii* Schimp. ex Lindb. dominate the hollows and *S. papillosum* Lindb. the lawns in the bottom layer (Yli-Petäys et al., 2007). The initial starting conditions for regeneration may be classified as type D. After five decades of succession, the site is now a type 3 poor fen–transition mire.

In the 1960´s, more efficient peat milling became the dominant harvesting method, and today the general topography of harvested surfaces in Aitoneva is fairly even. Due to the large area of the original mire complex (>1000 ha), starting conditions for regeneration vary quite much but generally the cut-away surfaces can be classified as types A, Bi or D.

The major, and most of the minor, drainage ditches in the area are still maintained, and restoration measures always include blocking of the drainage system. Apart from restoration, other after use options, such as afforestation, are also being considered. This requires careful planning of the restoration activities so that no economic losses will be caused for the other land users. The restoration of the milled surfaces will likely result mostly in the end-point options 1, 2 and 7 but in some places woodland restoration will be the best alternative.

End-point options: 1, 2 or 7, unless hydrology is unfavourable.

2. Middlemuir, Scotland

A peat survey of Scotland dating from 1961 describes the peat depth at Middlemuir as ranging from 1 (at the fringes) to 5 metres. Mechanical peat extraction started shortly after this, although localised manual peat extraction at the site by the local community is documented throughout the last 2 centuries. Peat was harvested in baulks and trenches approximately 100 metres in width until extraction was phased out around 1993. As a consequence, the topography is rather heterogeneous due to the uneven peat extraction intensity. Therefore the starting conditions for regeneration may range from category A (deep *Sphagnum* peat >100 cm, ombrotrophic, very acidic, raised surface, etc.), to Bi (thin *Sphagnum* peat <100cm, very acidic, raised surface, etc.) where extraction has nearly exhausted the depth of remaining peat. In various parts of the peatland there are still deposits exceeding 2 metres in depth of highly humified and relatively impermeable peat.

The minor drainage ditches were not maintained after cessation of peat extraction and some peat vegetation has spontaneously recolonised these sites. However, the main ring-drain surrounding the peatland is still being maintained, thus resulting in drainage losses along the periphery of the peatland. The main species recolonising the raised, drier, strips of peat (Site A) are isolated patches of *Eriophorum vaginatum* and *Campylopus introflexus.* In the lower strips (Sites B/C), the vascular plant cover is more complete and diverse and species of *Sphagnum* are beginning to recolonise areas between the vascular plants. Site D, as a consequence of the thin remaining depth of ombrotrophic peat and its location close to the edge of the peatland, is colonised by vegetation that includes species more indicative of wet heathlands (e.g. *Deschampsia flexuosa*).

In all these cases, according the BRIDGE guidelines, the end-point options for restoration are either "dryland restoration to heathland, scrub and woodland with wet niches" if seepage losses are prohibitively high owing to the topography and resulting hydrology and this cannot be solved logistically, or end-point options 1 (emergent acidic bog) or 2 (floating acidic bog) if seepage losses are lower or can be reduced through appropriate management. These latter options would have greater conservation value as heathland and scrub are well-represented in the area while acidic bog is a diminishing resource. We are not sure if floating acidic bog would ever be a major component of Middlemuir, but perhaps is possible for a few smaller areas within this peatland. Recontouring and bunding of the peat surface, along with a review of the drainage regime, should be considered as potential restoration measures as the current surface topography is encouraging lateral seepage losses.

End-point options: 1 or 2(?), unless hydrology is unfavourable.

3. La Chaux d'Abel, Switzerland

This site in the Jura Mountains was abandoned after active peat cutting ceased in 1963 with only a small area remaining intact. Subsequently, spontaneous regeneration took place and communities dominated by *Sphagnum* spp., *Polytrichum strictum, P.commune, Eriophorum vaginatum,* and *E. angustifolium* with stands of *Betula* *pubescens* and *Picea abies* have developed for variable lengths of time on different parts of the site.

Three secondary sites were selected in La Chaux d'Abel: "early regeneration" (A), "intermediate regeneration" (B), and "late regeneration" (C). Detailed analyses of the peat revealed that the stages A and B developed on fen peat and thus indeed shared the same or very similar starting conditions, while in stage C some bog peat remained at the surface when peat extraction was ended. Site A is dominated by *Sphagnum* spp., *E. vaginatum*, *Comarum palustris* and *Carex nigra* with variable coverage of *C. vulgaris*, *Betula nana*, *Anthroxanthum odaratum* and *Potentilla erecta*. Site B is mainly *Sphagnum* spp. and *E. vaginatum*. Site C also has *Sphagnum* spp. and *E. vaginatum* with variable cover of *P. erecta* and *Vaccinium oxycoccus*.

End-point options: 1, 2, 3 or 6.

4. Le Russey, France

Le Russey and La Chaux d'Abel peatlands are similar in many ways. The two areas are only about 15km distant and developed in a comparable geological setting (calcareous Jura Mountains). The peat harvesting in both peatlands was rather unplanned resulting in a complex topography and hydrological condition.

The total surface of the bog covers ca. 27 ha, of which much is now wooded bog. Active peat cutting started in 1968 and was stopped in 1984, leaving at least 1–2 m bog peat. Subsequently, spontaneous regeneration has resulted in communities dominated by *Sphagnum* spp., *Polytrichum strictum*, *Eriophorum vaginatum* and *E. angustifolium*. Three secondary sites were selected for study: Site A, bare peat; Site B, dominated by *E. angustifoliuum* and *P. strictum*, and with variable coverage of *Calluna vulgaris*, *S. fallax* and *S. rubellum*; Site C, dominated by *S. fallax*, *S. rubellum* and *E. vaginatum* with lesser coverage of *C. vulgaris*, *Carex nigra*, *Vaccinium oxycoccus* and *P. strictum*.

End-point options: 1 or 2, unless hydrology is unfavourable.

5. Baupte, France

Baupte is different from the other four sites in its developmental history. It is one of the most important peat deposit in France and has been intensively harvested since the end of the Second World War. The peatland is only a few meters above sea level and developed over littoral sediments over a succession of marine regressions and transgressions. From the Boreal period (9000 years BP), 4 stages were considered: a marsh (1); an aquatic stage (2) developed at the transition Boreal-Atlantic phase; after a sedge-fen state (3); the first occurence of *Sphagnum* during the Subboreal indicated that an ombrotrophic and ombrogenous system (4) had started to develop. At the end of the 19th century, *Drosera longifolia, Andromeda polifolia* and *Oxycoccos palustris* were not rare in the peatland. However, *Andromeda polifolia* disappeared in 1965 (always absent in 2006) while today no *Sphagnum* carpets remain.

The peat thickness ranged from 1 to 8 m (12 m in places). Peat deposit lays on faluns and clay and was harvested over large surfaces as milled peat. Only a relatively shallow depth of fen peat remains at the study site. The overlying peat is very decomposed and the cellulose content is very low (14.8±3.1 mg g^{-1}). The mean pH is equal to 5.5 ± 0.4 and the peat C:N ratio 21±2 while organic S content reached 0.500±0.053 %, the highest value of the 5 peatlands. The most completely extracted parts, where harvest stopped in 1995, were artificially flooded. This flooding has created some large shallow pools. In the oldest harvested parts, some *Phragmites* developed as fens with active C-sequestration and functioning as “sinks”. In other places, vegetation such as *Eleocharis palustris, Agrostis stolonifera* or *Carex* spp. has colonized the banks of pools but *Phragmites* is expected to invade. *Eriophorum angustifolium* colonized locally bare peat sites but never developed as well as the reeds.

Milled-peat harvesting stopped in 2005 but the local company wishes to continue peat harvesting with a new technical process (peat harvesting under water). The company also proposed to take into account the environmental problems by re-flooding the abandoned sites in order to re-create some good hydrological conditions and re-wetting of the remaining peat. The objectives of the whole project (not yet accepted by the authorities) are to increase plant diversity, to maintain the exceptional bird richness resulting from artificial flooding (especially of over-wintering species) and to favour C-sequestration. With the same kind of philosophy, they have authorized peatland access for scientific research (both at the national and international levels). If this project is accepted, a scientific committee would monitor the success of the re-habilitation options.

Starting conditions would be Fi/Fii (but not high pH, see above) and the remaining peat thickness would depend on the extracted peat areas. Sometimes, the depth is <0.5 m and we have seen clay showing at the surface (but not a dominant feature).

Deep inundation in the large milled-peat areas is the major situation now observed in Baupte with the current water management. In some cases, ancient pools are now completely recolonized by *Phragmites* and this plant is developing more and more. *Eriophorum angustifolium* colonized the bare peat areas early in the succession but did not develop very much (probably due to the substrate quality which is meso-eutrophic). As there is no development of significant vegetation rafts, the protection of edges was one of the main recommendations of “Recréer la Nature”, a national research programme of the French Ministry of the Environment (1998–2000) whose main aim was to carry out experimental rehabilitations of a set of disturbed ecosystems across France. In this framework, the effects of artificial flooding of cutover peatlands have been tested in Baupte. Wave action seems to be strong in the created Baupte pools. One suggestion would be the creation of dams with vegetation to reduce the surface area of the lakes.

Plant introduction would be a good strategy but this could only be carried out on with a good knowledge of the peat quality in order to locate the the poorest (mesotrophic) areas, especially for *Eriophorum* species. We observed some good growth of *Eriophorum angustifolium* and *E. vaginatum* two years after introduction of plants (RECIPE-WPII) but the death rate remained high, probably in relation to the peat properties. All introduced *Sphagnum* decreased quickly. This information could be helpful in reaching end-point 3.

In the oldest areas, *Salix* spp. developed well. This seems to correspond to a stage of wet woodland (end-point 8), or to a late-successional stage succeeding to tall herbaceous fen (end-point 6). Maintaining the two situations could be possible but this would require prevention of *Salix* spp. extension (by harvesting?).

The Baupte site and its large havested peat areas are of interest for testing different ways of rehabilitation and the long-term of restoration of peatland. It would be easy to develop patches of different vegetation types but the possible experimental manipulations are now dependent on the response of the authorities to the proposed extraction under water. It seems that the chances will be "fifty-fifty" (right of extraction= management of water regime; no right = nothing will be done!).

End-point options: 3, 4, (5), 6 or (8).

Contribution of RECIPE results to the improvement of management guidelines and general knowledge on peatland restoration

Land-uses of peatlands, biodiversity and C-sequestration

Mires have been used for a large range of activities and as a consequence the peatland regeneration potential is very much site dependent. Some activities have strongly modified the structure and the functioning of the ecosystem, especially in terms of biodiversity and C-sequestration in peat. On the other hand, some practices have had a rather positive effect, as they lead to regeneration processes. Partly on the basis of the socio-economic studies within RECIPE, it is possible to summarize the framework showing the main anthropic effects on peatland dynamics (Figure 1).

Change in ecosystem function in relation to regeneration

It is generally assumed that the restoration of a *Sphagnum* cover suffices to restore the carbon sequestration function. Indeed, we have seen the reestablishment of C sink function in both *Sphagnum*-dominated and *Eriophorum*-dominated cutover bog within 20 years (Bortoluzzi et al., 2006). However this is clearly not always the case. Secondary cutover bogs may function as C sinks, but usually not in the very early stages. Furthermore, the C-sequestration function may peak at an intermediate stage in the regeneration sequence and then lessen (Kivimäki et al., 2007). Thus the high C sequestration rates observed in some secondary sites may only be transient. Similarly, higher potential microbial activities (by peat incubation) were measured for the intermediate regeneration stage (20-30 years, Francez et al., 2007).

It is often stated that emissions of methane could be reduced by keeping the peatland water tables so low that most of the CH_4 would be oxidised to CO_2 before entering the atmosphere. In contrast, plant carbon sequestration is known the reach the optimum at high water levels. Thus, there is a trade off between these two variables but so far the effect of the water level on the peatland´s total carbon budget has not been studied in detail. Recent results from RECIPE (Yli-Petäys & Vasander, unpublished) imply that water levels as low as -20 cm below the surface are enough for maintaining a carbon sink for the three sedge species investigated (*C. rostrata, E. vaginatum, E. angustifolium*). In the same experiment, *Sphagnum fallax* and bare peat surfaces acted as weak sources of carbon (Figure 2). However, since methane is 21 times stronger as a greenhouse gas compared to CO_2, very high water levels ranging from -10 to -6 cm were needed for a net cooling effect. On the basis of our results, maintaining stable water levels near the peatland surface is essential for effective carbon accumulation.

These considerations would indicate that peatland managers need to maintain ongoing monitoring of the C sequestration status of restored sites (taking this to be one aim of peatland restoration). One cannot assume that the presence of *Sphagnum,* or even the accumulation of a new peat layer, is necessarily indicative of C accumulation, as any C fixed may be balanced or exceeded by C mineralisation from deeper horizons. However, once the new acrotelm has reached 20–30 cms we can be reasonably confident of net accumulation.

Bioindication

Results from RECIPE show that peat organic matter, peat botanical composition, and microbial indicators validate the evolution inferred from surface vegetation and microtopography (Laggoun-Défarge et al., 2007).

Changes in microbial communities across the regeneration sequences are related to differences in organic matter properties such as C/N ratio, total C content, soluble and total N and the presence of certain plant species. These results confirm the important role of labile carbon in determining the composition and activity of the microbial communities (Artz et al., 2007; Francez et al., 2007).

Microbial biomass dynamics over the 55 year chronosequence (considering all RECIPE sites) illustrated the poor conditions of bare peat recolonization, despite the re-wetting of abandoned sites. We observed a lag time of ca. 10 years in the early stages of succession. The registered microbial biomass values are among the lowest recorded in peatlands. Vegetation colonization and increasing plant diversity have positive effects on the development of the microbial pools which significantly increase at the intermediate stages (from 10 to ca. 40 years after abandonment). In artificially revegetated mined peatlands as in the Bois-des-Bel site (Québec, Canada), the recovery of the microbial biomass C started sooner and very quickly with the development of plants, especially *Sphagnum* (Andersen et al., 2006). Only 5 years after the re-introduction of propagules and the growth of plants, the microbial biomass C reached 2310 ± 220µg g DP^{-1}, a value that we only registered in RECIPE around 20 years after abandonment (Figure 3).

These results further suggest that microorganisms and peat organic matter properties can be used as bioindicators for ecosystem regeneration and ecosystem function (carbon cycling and pore water methane concentrations, Siegenthaler et al., 2007).

Impact of global change on peatland regeneration

At the Swiss site, after less than 50 years, spontaneous secondary succession has led to a poor fen strongly dominated by *Sphagnum fallax*. It appears very likely that this process will lead to a true raised bog community. However, succession, and therefore the possible evolution from poor-fen to a true bog community may depend on climate. The potential to sequester C in the intermediate stages of succession may be adversely affected by global warming but longer-term regeneration sites (>50 years) may be more resilient (Samaritani et al., 2007).

Influence of socio-economic context on peatland regeneration

The RECIPE project has highlighted the fact that across Europe there are very varying attitudes to the exploitation, conservation and rehabilitation of peatlands. In many areas exploitation continues to be a source of a valuable raw commodity and of income for rural communities. However, the tendency to conserve and rehabilitate rather than exploit varies inversely with the absolute area of peatland within each region though other cultural values also play a role and there is increasing pressure in many regions to promote peatland conservation (Schwarz et al., 2007).

Summary

1. Almost every cutover peatland is unique in its properties and each needs to be dealt with on its individual merits.
2. Even within a single peatland variation will occur which may demand different approaches.
3. Hydrological condition is the main, though not the sole, driver for the course of regeneration within a cutover peatland.
4. Regrowth of *Sphagnum* mosses is not necessarily an indicator of restoration of the C sink function of peatlands.
5. Sedge species may be more effective in achieving a net sink function compared with Sphagna.
6. The C sink function may be greatest during intermediate stages of succession.
7. Optimum water table level to maximize the net global cooling of peatlands is probably just below the surface (-10 to -6 cms).
8. Recovery of the microbial activity lags behind vegetative cover but, together with changes in organic matter properties, can be an indicator of the reestablishment of ecosystem function, particularly C cycling.
9. Global warming may impact on the success of rehabilitation, particularly in the intermediate stages of succession.
10. Reuse options will also be guided by the socio-economic contex of the peatland in question.

Table 1. Summary description of the five studied cutover peatlands, correspondence with the BRIDGE project starting condition categories, supposed end-point options according to BRIDGE and points of conflict or those needing further attention.

Peatland location	Location (Lat., Long., elevation)	Site code	Dominant plants	Time since abandonment (y)	Starting conditions according to BRIDGE typology	Notes on starting conditions	End-point options according to BRIDGE	Notes on succession from BRIDGE	Additional points from RECIPE
Aitoneva, Finland	62°12'N, 23°18'E, 156m	A	*Eriophorum vaginatum* wet	10	Fii		1, 2 or 7 unless hydrology unfavourable		C-sequestration function may decline with time
		B	*Eriophorum vaginatum* dry	10	A		ditto		
		C	*Carex rostrata*	10	Fii		ditto		
		D	*Sphagnum. fallax*	10	Fii		ditto		
		E	Bare peat, no vegetation	10	Fii (or Bii?)		ditto		
Middlemuir Moss, Scotland, United Kingdom	57°36'N, 2°9'W, 110m	A	Mostly bare, isolated *E. vaginatum, C. introflexus*	<5	A		1 or 2(?), unless hydrology unfavourable		Spontaneous colonization has followed abandonment but *Sphagnum* has only grown in lower (wetter) areas and when preceded by 'nurse' species, mainly *Eriophorum*. New peat has formed at 50 year site but C sequestration status is equivocal.
		B	*S. cuspidatum, S. auriculatum, E. vaginatum*	5-10	A		ditto		
		C	*E. angustifolium, S. auriculatum, S. cuspidatum*	5-10	A		ditto		
		D	*Sphagnum spp, C. vulgaris, Deschampsia flexuosa*	>50	Bi		ditto		
Chaux d' Abel, Jura Mountains, Switzerland	47°10'N, 6°57'E, 1040m	A	*S. fallax, P. strictum, P. commune, Eriophorum* spp	29+	C, or Fii	(or Bii if bog peat remained)	3 or 6 (1 or 2 if starting condition was Bii)	From point 3 (poor fen) slow evolution towards ombrotrophy	After less than 50 years, spontaneous secondary succession has led to a poor fen strongly dominated by *Sphagnum fallax*. It appears

		B	Same species, intermediate between A and C	42-43				possible if left unchecked	very likely that this process will lead to a true raised bog community. However, succession, and therefore the possible evolution of point 3 (poor-fen) to 1 or 2 (true bog community) may depend on climate. Peat OM and botanical composition, and microbial indicators validate the evolution inferred from surface vegetation and microtopography.
		C	*S. fallax, P. strictum, E. vaginatum, Vaccinium* spp.	52-58	Bii (or Bi)	Microscopic analysis of peat revealed that the old peat in site C was bog peat	1 or 2		
Le Russey, Jura Mountains, France	47°10'N, 6°47'E, 867m	A	Bare peat	4	A		1 or 2, unless hydrology unfavourable		
		B	*Sphagnum fallax, S. rubellum, E. angustifolium and C. vulgaris (variable)*	22	A		ditto		
		C	*S. fallax, S. rubellum, E. vaginatum, Calluna vulgaris*	28-40	A		ditto		
Baupte, France	49°17'N, 1°21'E, 20m	A	Bare peat, no vegetation	5-10	Fii	In this case topography would suggest starting condition Fii	3, 4, (5), 6, (8)	Depending of the peat quality and the degree of disturbance (drainage, compaction effects) and the location on morphology of pools	Baupte peatland has been strongly exploited as milled peat. Harvesting stopped in 2005. Large areas of bare peat are flooded and watering is managed. *Eriophorum angustifolium* colonized the bare peat sporadically early after cessation of harvest, but reeds *(Phragmites)* now colonize more and more of the pool edges.
		B	*E. angustifolium* , *Hypnacaea*	5-10	Fii	ditto	mainly 3, 5		

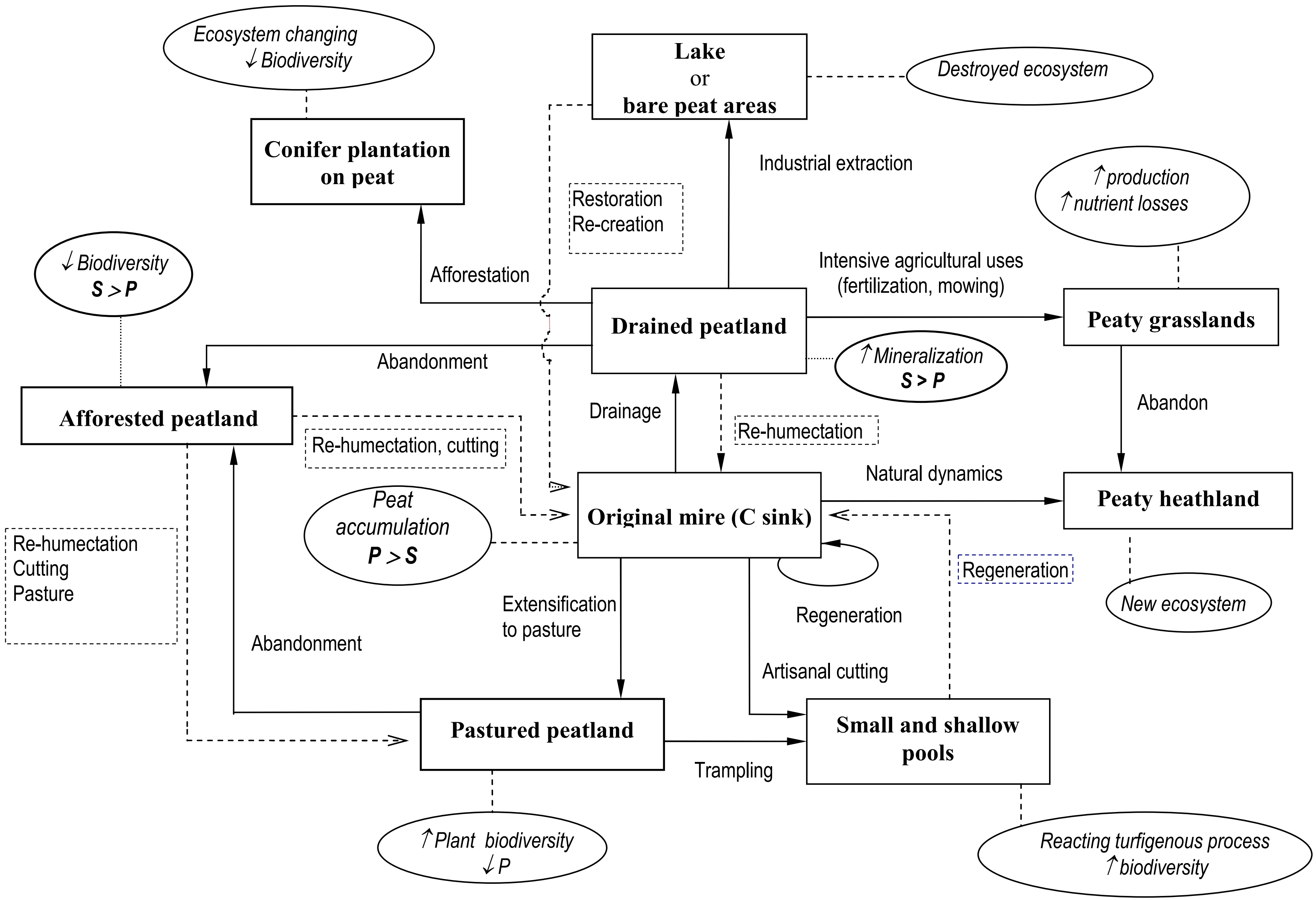

Figure 1. Main effects of land-use changes on the C sink-source function of European peatlands (S=source, P=sink; ↑and ↓=increasing and decreasing process or property) (after Francez, 2000 modified ; Schwarz et al., 2007).

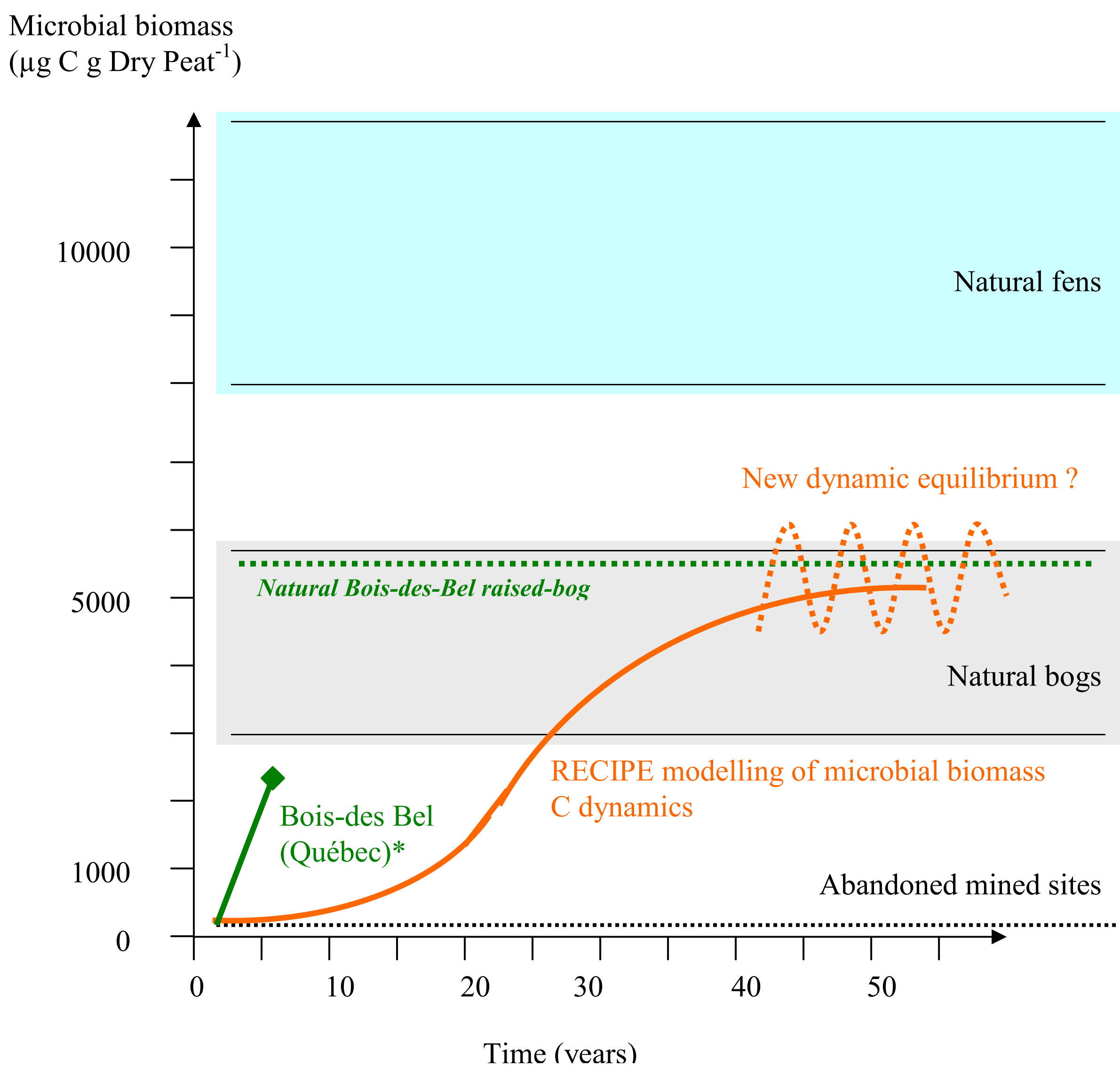

Figure 2. Dynamics of microbial biomass C over a 55-year chronosequence of peatland regeneration. Ranges of microbial biomass C in natural mires (fens and bogs), extracted from literature data, are reported as colour surfaces. These could serve as reference points or objectives in the monitoring of peatland regeneration with or without management interventions. * In Bois-des-Bel, the mean microbial biomass carbon in the natural peatland (reference site) was 5780±260 µg C g DP^{-1} in the surface peat; it attained 2310 µg C g DP^{-1} only a few years after reintroduction of plant propagules spread on the surface of the abandoned mined peatland.

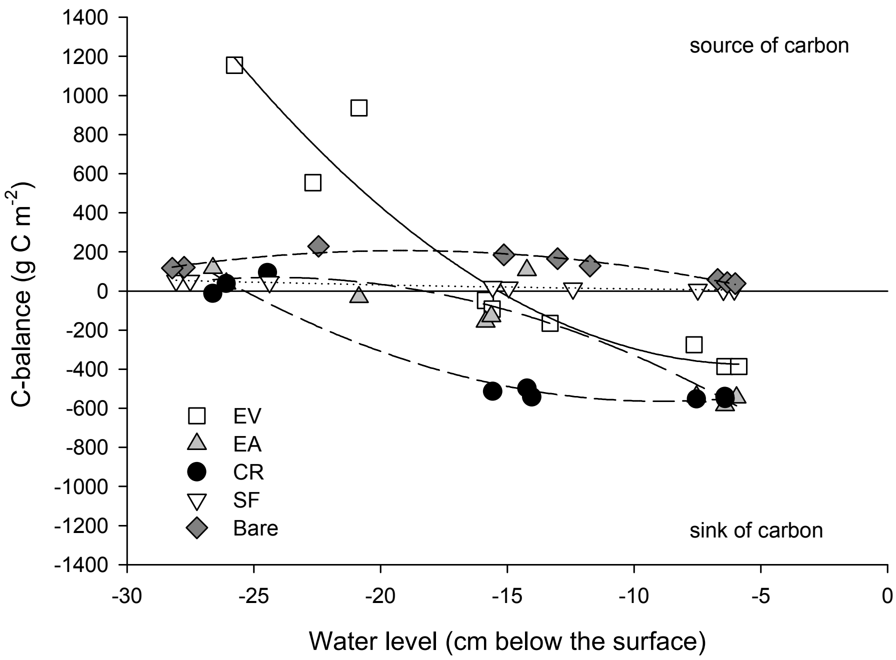

Figure 3. Seasonal carbon balance (June-September) of three sedge species, *Sphagnum* mosses and bare peat surfaces at different water levels. The acronyms for species are: *EV*, *Eriophorum vaginatum*; *EA*, *Eriophorum angustifolium*; *CR*, *Carex rostrata*; *SF*, *Sphagnum fallax*; *Bare*, bare peat.

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