

Carbon balance of a cutover bog in the Jura mountains at different stages of regeneration

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Introduction

In many climatic areas of the world, peat bogs are widespread ecosystems. Those of northern countries store about one quarter of the world's pool of soil organic carbon (Gorham, 1991). Since the middle of the last century, the human impact on wetlands has been very strong, especially with the human exploitation of peat for horticulture and energy. Harvested bogs lose their carbon sink capacity (Silvola *et al.*, 1996), which is an important property in the present issue of climate change expected over the coming years due to the increase of atmospheric greenhouse gases. In this context, their rehabilitation as a carbon sink is a considerable asset. For example, it has already been shown that the re-establishment of specific bog vegetation – particularly the keystone *Sphagnum* moss (Rydin & McDonald, 1985; Gerdol *et al.*, 1996) – is essential for accumulating organic matter (Chapman *et al.*, 2003). In order to quantify what happens in a cutover bog during regeneration in terms of carbon balance, the modelling of carbon fluxes is an essential step. Our work took place in the Jura mountains, where most of the bogs have been at least partly harvested. In this part of western Europe, the regeneration and the re-establishment of the typical bog vegetation had already been studied (Grosvernier *et al.*, 1995) but no information was available on the carbon fluxes. The aim of our study was to derive an empirical model of CO₂ fluxes in a cutover bog with contrasted stages of regeneration in order to reconstruct its carbon balance. To reach our goal, we made regular monitoring of the CO₂ fluxes with parallel measurement of all the biotic and abiotic variables.

Material and methods

The study site, one of the sites of the European project RECIPE (Reconciling commercial exploitation of peat with biodiversity in peatland ecosystems) is a French bog of 27 ha in the Jura mountains (Sur les seignes, Frambouhans-Les Ecorces; 47°18'N, 6°79'E) at an altitude of 867m. The exploitation of the peat for horticultural purposes was finished in 1984 and the harvested site covers 2 ha. The lower part has been named 'Recent Regeneration' and for 20 years the

spontaneous recolonisation was made by mostly cottongrass (*Eriophorum angustifolium* and some tussocks of *Eriophorum vaginatum*) and in the latter years a few *Sphagnum fallax*, *S. magellanicum* and *S. rubellum* and some *Polytrichum strictum* have grown under the cottongrass. Some bare peat surfaces are left and represent the 'Bare peat' location. In the named 'Advanced Regeneration' location, there had been drainage and some clearing but vegetation had not been completely removed. Hence there is a net break in the profile with, in the lower part, a highly decomposed peat and on the upper 20 cm a yellowish young peat. *Sphagnum fallax* is the dominant species with *Polytrichum strictum*, *Eriophorum vaginatum*, *Carex nigra*, *Calluna vulgaris*, *Vaccinium oxycoccos* as companion plants.

Eleven stainless steel collars of 30cm diameter and with 10cm inserted into the peat for the gas fluxes measurements were established on different surfaces, which were representative of the contrasted situations of vegetation in the study site: four collars per each recent and advanced regeneration, and three collar on the bare peat station. Flux measurements were started in November 2003 and stopped in November 2005, with breaks during the snow periods. CO₂ fluxes were measured, except when the weather was too cloudy, once a week in 2004, on 26 sunny days and every 3 weeks, on 8 sunny days, in 2005.

CO₂ fluxes for the net CO₂ exchange of the ecosystem ($EE_{N_{sat}}$) under saturating PPFD (photosynthetic photon flux density) were measured under a PPFD higher than 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Light response curves showed that light saturation was reached at PPFD around 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$. A transparent chamber (surface area = 0.071 m²) was used, coupled with a portable infrared gas analyser, functioning in an open mode (CIRAS1, PP systems, Herts, U.K.). Then the chamber was darkened by an aluminium bag and, after a 2-min lag time, data recorded during the next 3 min were averaged to estimate ecosystem respiration (R_E). Gross photosynthesis under saturating photon flux density ($P_{G_{sat}}$) was calculated as the sum of $EE_{N_{sat}}$ and R_E . On the bare peat station, microbial CO₂ uptake was negligible. Net ecosystem exchange (EE_N) without light saturation were obtained using artificial shading made with frames supporting plastic fly net. Depending on the number of net layers, 5 different PPFD values below the 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ threshold were obtained. The EE_N measurements were made on different collars and at different seasons in 2005.

Methane fluxes (F_{CH_4}) were measured on the same collars as those used for CO₂ measurements at 7 occasions in 2004 and 2005. Vented closed chambers darkened with an aluminium cover preventing temperature increase were used. A septum on the top centre of the chambers enabled gas sampling with a syringe. The gas sample was immediately put into a 20 ml vacuum tube with a septum and

stored in a cold and dark chamber for less than one week until it was analysed by gas chromatography (CP 4900, Varian, USA). Three samples were taken after 15 min, 45 min and 75 min. The CH₄ fluxes were calculated from the slope of the linear increase of CH₄ concentration with time, knowing the chamber volume and the covered area.

The desiccation state of the *Sphagnum* carpet in each collar was characterized using a visual index that has been established on *Sphagnum fallax* during the very dry summer 2003 on the same site. The desiccation index (DI) was based on the colour of the first four cm of *Sphagnum* plants, which is related to their water content. This relationship was statistically validated by measuring the water content of twenty plants of *S. fallax* collected randomly within each class of desiccation.

During the CO₂ fluxes measurements, PPF inside the chamber was measured with a quantum sensor and air temperature (T_A) inside the chamber was measured with a thermocouple. In addition, soil temperature (T_S) at the depths of 5 cm, 10 cm and 50 cm was recorded in the vicinity of each collar during CO₂ and CH₄ flux measurements. Depth of water table (WT) in perforated tubes located close to each collar was noted at the same time. In addition, air and soil temperature, rain events (P) and global radiation (R_g) were permanently recorded on the site over the whole period of two years. Air temperature was measured every 10 min and averaged for half an hour. Peat temperature at 5 cm and 30 cm were measured every hour (Hobo H8 pro series, Onset computer corporation, Bourne, MA, USA). Global radiation was measured every 30s using 33 cm-long linear radiometers (INRA Versailles, France) and averaged for half an hour (CR510 datalogger, Campbell Scientific, Courtaboeuf, France).

The bryophyte index (BI) in each collar was obtained by summing the product of covered area on a relative scale by the density of each species (recorded in three subplots with a total surface of 50.1 cm² per collar) relative to the highest density observed. Leaf area index (LAI) in each collar was calculated by summing the leaf areas of the main vascular plant species (*Eriophorum angustifolium*, *E. vaginatum*, *Carex nigra* and *Vaccinium oxycoccos* present in two collars). For each collar, a vegetation index (VI) ranging from 0 to 1 was calculated as follows:

$$VI = \frac{\left(LAI + BI * \left(\frac{DI}{DI_{max}} \right) \right)}{(LAI_{max} + BI_{max})} \quad [1]$$

with LAI, the leaf area index, BI, the bryophyte index and DI, the desiccation index. LAI_{max} was set at 1.4 m² m⁻², a value just above the highest leaf area index recorded on all the collars; BI_{max} was set at 1 (BI is a relative value) and DI_{max} was set at 6, the highest value of the desiccation index (see Table 1).

Relationships between carbon fluxes and biotic and abiotic variables were fitted for each group of collars within each kind of vegetation using non linear regression curves (Sigmaplot 3.0, SPSS Inc., IL, USA) for CO₂ fluxes and linear regression curves (Jmpin 3.2.1., SAS Institute Inc, NC, USA) for CH₄ fluxes. Criteria for a valid model were a minimum root mean squared errors (rmse) and no bias in the distribution of the residuals. The annual carbon balance was built for each collar by summing EE_N calculated every half hour using half hour values of temperature and global radiation, the daily values of the depth of the water table. LAI, BI and DI were linearly interpolated between each date of measurements. These materials and methods are detailed in (Bortoluzzi *et al.*, 2006)

Results and discussion

CO₂ fluxes

R_E increased with increasing temperature. The best fit was obtained using a power function with air temperature as the driving variable. Temperature was the first factor which explained most of R_E variations as underlined by Lafleur *et al.* (2005). On bare peat plots, the residuals of the power function were linearly related to the level of the water table:

$$R_E = \left(a * \frac{WT}{WT_{ref}} + c \right) * \left(\frac{(T_A - T_{min})}{(T_{ref} - T_{min})} \right)^b \quad [2]$$

WT_{ref}, the reference depth for water table, was set at -0.4 m, a value just under the lowest observed water table. T_{min}, the minimum temperature at which a positive respiration occurred, was set at -5°C. T_{ref}, the reference air temperature was set at 15°C. Coefficient *b* accounts for the temperature sensitivity of R_E. Coefficients *a* and *c* are two fitted empirical parameters.

On the bare peat station, R_E had very low values, the highest ones were 1.45 μmol CO₂ m⁻² s⁻¹ on day 178, whereas R_E reached during summer 2005 the values of 6.7 ± 1.7 μmol CO₂ m⁻² s⁻¹ in advanced regeneration and 5.4 ± 0.8 μmol CO₂ m⁻² s⁻¹ in recent regeneration. In this location without vegetation, the water table level was high all over the year and it probably restricted carbon mineralization. Water table fluctuation has an influence on ecosystem respiration as already described by Alm *et al.* (1999).

On vegetated plots, residuals of the power function increased with increasing vegetation index. 35-90% of the ecosystem respiration in organic soils is known to be produced by plant respiration (Silvola *et al.*, 1996; Johnson *et al.*, 2000). Moreover, bryophytes desiccation was a key factor for gross photosynthesis under saturating photosynthetic photon flux density (P_{gsat}). Our vegetation

index took into account the two types of vegetation with relative variations in leaf area of vascular plants (LAI) in moss density and covered area (BI), and the desiccation of bryophytes (DI). This is well-adapted to the patchy situations encountered in our site, to the micro-heterogeneity inside a collar and to their potential impact in case of drought.

CH₄ fluxes

Over the two years, the CH₄ fluxes measured were very low, with the greatest fluxes found in May 2005 with a mean value of 30.5 ± 31.4 nmol CH₄ m⁻² s⁻¹ for the recent regeneration, 8.7 ± 5.8 nmol CH₄ m⁻² s⁻¹ for the advanced regeneration and 2.1 ± 1.7 nmol CH₄ m⁻² s⁻¹ for the bare peat plots. There was a high intra-site variability.

In vegetated areas, CH₄ fluxes were related to the leaf area index of vascular plants. This is consistent with previous studies showing that CH₄ fluxes were in correlation with the number of vascular plants (Öquist & Svensson, 2002). Two types of interaction could be possible, with vascular plants acting as methane duct and or increasing the availability of organic carbon (Mikkela *et al.*, 1995). Low CH₄ fluxes in our site where the peat was highly decomposed were in agreement with previous findings of Glatzel *et al.*, (2004). For the bare peat plots, CH₄ fluxes increased with the decreasing depth of the water table. Seasonal fluctuations of the water table can be a confounding factor that would affect the relationship between peat temperature and methane production.

Carbon balance

Daily simulated values of EE_N, excepting winter fluxes, were largely positive for the vegetated locations. Some negative values were found at spring's beginning and autumn's end, with a weaker vegetation index, and during summer with hot but cloudy days, so giving high R_E but low P_G. The high daily EE_N fluctuations were linked to the variations of air temperature. Considering the net carbon exchange, bare peat was a weak carbon source (between -19 and -32 g C m⁻² y⁻¹) mainly due to its high water table level all over the year. During 2004 and 2005, the two vegetated locations acted as carbon sinks. The recent regeneration was slightly less efficient (between 67 and 166 g C m⁻² y⁻¹) than the advanced regeneration (between 93 and 183 g C m⁻² y⁻¹) (Table 1). The increase of the bare peat respiration with the lowered water table had a negative impact on the carbon balance. This balance depended also on the relative quantity of bryophytes (which lose their sink capacity in case of drought) and of vascular plants (which facilitate CH₄ efflux)

Table 1. Compartments of the annual carbon budget and carbon balance estimated ($\text{g C m}^{-2} \text{y}^{-1}$) for the year 2004 (a) and for the year 2005 (b) for four collars of the advanced regeneration and of the recent regeneration, and for three collars of the bare peat location.

(a) Compartments – year 2004	Bare peat location	Recent regeneration	Advanced regeneration
G_P		197 ~ 306	284 ~ 474
R_E	- 22	-121 ~ -207	-186 ~ -297
EE_N	- 22	68 ~ 120	94 ~ 176
F_{CH_4}	- 0.4	-1.5 ~ -2.8	-0.7 ~ -2.3
Balance	-22	67 ~ 118	93 ~ 175
(b) Compartments – year 2005	Bare peat location	Recent regeneration	Advanced regeneration
G_P	-	279 ~ 379	359 ~ 525
R_E	-19 ~ -31	-199 ~ -214	-233 ~ -340
EE_N	-19 ~ -31	80 ~ 169	122 ~ 185
F_{CH_4}	-0.2 ~ -0.6	-1.8 ~ -3.9	-0.5 ~ -2.7
Balance	-19 ~ -32	78 ~ 166	122 ~ 183

Conclusion and perspectives

Whereas the high decomposed bare peat location was a weak carbon source, 20 years after exploitation, the recovery of vegetation in the two other locations allowed them to become carbon sinks again. The advanced regeneration, dominated by *Sphagnum*, is slightly more efficient but more sensitive to drought impact than the recent regeneration, dominated by vascular plants, but which can release more methane.

These two distinct stages of regeneration have a closed carbon balance but with different processes, which could evolve in several ways in the case of climate change. A composite vegetation would be better adapted to these climate changes in term of carbon balance and hence a mixed vegetation should be favoured in the restoration plans of harvested bogs. A better comprehension of physiological processes of the different key vegetal species and of micro organisms should allow

the construction of more mechanistic models and subsequent scenario testing of climate change or of restoration management options.

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