

# Swift recovery of *Sphagnum* carpet and carbon sequestration after shallow *Sphagnum* biomass harvesting

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## SUMMARY

White horticultural peat is a microbiologically active growing medium which binds significant quantities of nutrients and water due to its favourable cation exchange capacity and porosity. Unfortunately, horticultural peat is only very slowly renewable, and good quality horticultural peat is not common even in peatland-rich countries. Therefore, good-quality and simultaneously renewable alternative growing media are needed. A new growing medium based on *Sphagnum* moss biomass is introduced in this study. According to our results, harvesting of *Sphagnum* biomass to a depth of no more than 30 cm will have a relatively short-term effect on *Sphagnum* carpet coverage and carbon sequestration, allowing a harvesting cycle of ~30 years to be achieved. Therefore, the average harvesting depth will be 30 cm. Only half of the mire surface on each harvesting area will be utilised, the other half being kept intact for transportation routes. This will also secure a reserve of *Sphagnum* mosses for reseeding and recovery. The end product - *Sphagnum* biomass based growing medium - will be truly renewable, and environmental effects will be negligible compared with conventional extraction of white horticultural peat. Therefore, *Sphagnum* biomass harvesting is more comparable with sustainable forestry management than with the production of white peat, which causes drastic and long-term alterations of the mire ecosystem.

**KEY WORDS:** carbon sequestration, renewable growing medium, *Sphagnum* biomass harvesting

## INTRODUCTION

The two primary growing media used in greenhouse cultivation nowadays are rockwool and white horticultural peat (formed from *Sphagnum* mosses). Of these, white *Sphagnum* peat is by far the more widely used around the world (Reinikainen & Picken 2008, Schmilewski 2008). Weakly decomposed *Sphagnum* peat is highly porous because the tissue structure of the *Sphagnum* mosses in the peat is practically undecomposed (Puustjärvi 1977, Amha *et al.* 2010). It also has a large specific surface (up to 200 m<sup>2</sup> g<sup>-1</sup>), ensuring high cation exchange capacity (Puustjärvi 1977, Amha *et al.* 2010). Because of its structure, *Sphagnum* peat has a high water retention capacity: one cubic metre (1000 litres) of such peat can absorb up to 600–800 litres of water (Reinikainen & Picken 2008). The absorption capacity of peat depends on its degree of decomposition and, in general, the lower the degree of decomposition the more suitable it is as a growing medium constituent (Puustjärvi 1977, Amha *et al.* 2010).

Horticultural peat is only very slowly renewable and, consequently, the availability of good-quality horticultural peat is diminishing even in peatland-rich countries. Therefore, good-quality and simultaneously renewable alternative growing media

are needed. A novel growing medium introduced in this study is based on harvested living *Sphagnum* moss biomass, which is expected to regrow within around 30 years on the same peatland site (Reinikainen *et al.* 2012, Silvan *et al.* 2012). *Sphagnum* biomass is harvested from the mire surface down to a maximum depth of 30 cm (Reinikainen *et al.* 2012, Silvan *et al.* 2012). This is approximately the depth of the ‘one spade-prick trenches’ that were excavated throughout Europe to obtain peat litter for animal bedding during past decades (Gerding *et al.* 2015). Studies of spontaneously regenerated trenches on peatlands such as Thorne Waste in England (Smart *et al.* 1989) and Isosuo in Southern Finland (Roderfeld *et al.* 1996) showed that average biomass accumulation rates on the harvested areas corresponded rather well with those of geologically young nutrient-poor pristine mires (Tolonen & Turunen 1996), giving good indications for recovery of the mire vegetation and carbon balance over a few decades after peat litter collection. Thus, keeping the harvesting depth shallow enough will probably ensure the recovery of both *Sphagnum* mosses and the carbon dynamics of the harvesting area.

*Sphagnum* biomass harvesting for horticultural purposes has been carried out at moderate industrial scale in North America (Elling & Knighton 1984),

Australia (Whinam & Buxton 1997, Whinam *et al.* 2003) and Chile (Diaz *et al.* 2012) for many decades, with promising recovery rates. It has been conducted both under winter snow and frost conditions (in North America e.g. Elling & Knighton 1984, Quilty & Rochefort 2003) and in summer (in Australia e.g. Whinam & Buxton 1997, Whinam *et al.* 2003). During summertime, machinery used for *Sphagnum* biomass harvesting must be equipped with extremely broad tracks ( $\geq 140$  cm), and the normal tractor-pulled carts cannot generally be used for *Sphagnum* biomass transportation. Instead, caterpillar type transport machinery is required (Silvan *et al.* 2012, Näkkilä *et al.* 2015). Despite the challenges, *Sphagnum* biomass harvesting is likely to be carried out successfully (with appropriate machinery) in summer as well as in winter.

For growing medium purposes, hummock-forming and some lawn species (for instance *Sphagnum fuscum*, *S. rubellum*, *S. magellanicum* and *S. papillosum*) are the most applicable (Gaudig & Joosten 2002). The most successful habitats for these species are pristine nutrient-poor treeless or sparsely wooded bogs (Laine *et al.* 2012). There are also adequate amounts of *Sphagnum* for harvesting purposes on many nutrient-poor and unprofitable peatlands which have been drained for forestry (Laine *et al.* 2012). Due to public opinion, *Sphagnum* biomass harvesting should be directed onto these drained peatland areas, for which there may be no other profitable land-use options. This is a significant opportunity for Finland, where approximately one million hectares of unprofitable drained peatland with low forest growth remain out of wood production. It is estimated that some 300,000 ha of the one million hectares could be utilised for *Sphagnum* biomass harvesting (Näkkilä *et al.* 2015).

The aims of this study were to:

- 1) confirm the recovery of *Sphagnum* mosses and other mire vegetation; and
- 2) quantify the short-term effects of *Sphagnum* biomass harvesting on carbon sequestration.

We hypothesised that:

- 1) *Sphagnum* mosses and other mire vegetation will recolonise the harvested area rather rapidly, in under five years; and
- 2) the recolonisation of *Sphagnum* mosses and other mire vegetation will reinstate carbon sequestration after harvesting.

The destructive effects of *Sphagnum* biomass harvesting on mire biodiversity and carbon sequestration will, therefore, remain relatively small and short-term.

## METHODS

### Study site

The study was carried out over the growing seasons of 2013 and 2014 at Palloneva (62° 47' N, 22° 54' E) in central Finland. The site was a nutrient-poor forestry drained peatland extending to approximately six hectares, which was the country's first operational-scale demonstration area for *Sphagnum* biomass harvesting, with around 12,000 m<sup>3</sup> of *Sphagnum* harvested. Part (approximately 2 ha) of the area was preserved as an intact control and the remainder was harvested. The Palloneva demonstration area was preceded by two small-scale (0.3–1 ha) pilot harvesting areas in central Finland, namely Keisarinneva (62° 12' N, 23° 18' E) and Tunkiosalonneva (62° 11' N, 22° 48' E) (Silvan *et al.* 2012). The ditch network at Palloneva was sparse and had partly degraded, allowing the water table to rise and thus favouring the recovery of *Sphagnum* mosses. The original mire site type of the study site was low sedge bog (Laine *et al.* 2012). The long-term annual mean temperature is around 3.8 °C, the annual mean precipitation is approximately 540 mm, and the accumulated temperature (+5 °C) is around 1,150 degree-days.

### *Sphagnum* biomass harvesting method

*Sphagnum* biomass was harvested in January 2012 from the mire surface down to a maximum depth of 30 cm (Silvan *et al.* 2012, Reinikainen *et al.* 2012). Under normal weather conditions the best harvesting period in central Finland has been shown to be during early winter, when the depth of soil frost is approximately equal to the harvesting depth (Silvan *et al.* 2012, Reinikainen *et al.* 2012). Wintertime harvesting is “tidy” and economical because the normal excavator with tractor-pulled cart, without special modifications, is suitable for *Sphagnum* biomass harvesting and transportation at that time of year (Silvan *et al.* 2012, Reinikainen *et al.* 2012).

### *Sphagnum* carpet recovery and length increment monitoring

The recovery of *Sphagnum* carpet was monitored in late August (2013 and 2014) by counting the density of *Sphagnum* capitula (the tops of the shoots). For *Sphagnum* cover monitoring, 20 systematic monitoring plots of 0.07 m<sup>2</sup> were established on the *Sphagnum* biomass harvesting area, and for comparison ten monitoring plots were set up on the intact area.

To determine the length increment rate of *Sphagnum* mosses we used an adaptation of the cranked wire method (Clymo 1970). Crank-shaped

steel wires (~30 cm long) were placed in the moss carpet after harvesting with the horizontal part of the crank coincident with and parallel to the surface, and *Sphagnum* moss length increment was determined by measuring from the moss surface to the top of the crank at later dates. The *Sphagnum* species observed in this study were *Sphagnum magellanicum*, *S. balticum*, *S. fuscum* and *S. rubellum*, which are the most common species at the Palloneva site. *Sphagnum* length increment measurements were made on ten individual stems of each studied *Sphagnum* species. The cranked steel wires were inserted in August 2013 and *Sphagnum* length increments were measured in August 2014. Statistical analyses of the recovery and length increment rates of *Sphagnum* mosses were carried out using parametric one-way ANOVA (SPSS 22.0, SPSS Inc.).

### ***Sphagnum* yield measurements by CO<sub>2</sub> exchange method**

For both intact and harvested surfaces, CO<sub>2</sub> exchange measurements were made approximately biweekly during the growing seasons (May–October) of 2013 and 2014 using the closed chamber technique (Alm *et al.* 2007). Three CO<sub>2</sub> exchange measurement plots in the intact control area and six in the harvested area were selected to represent the typical average composition of surface vegetation. Prior to the measurements, a permanent aluminum collar (60 × 60 cm) was inserted to 30 cm depth in each plot. Dying dwarf shrub roots are known to cause a small CO<sub>2</sub> pulse during the first years after collar insertion (Minkinen *et al.* 2007), but the effect was regarded as equal in each plot.

Each collar was surrounded with a water groove that allowed chamber placement and airtight sealing of the measurement system. Instantaneous net ecosystem CO<sub>2</sub> exchange (NEE) in each plot was measured with a transparent plastic chamber and a portable infra-red gas analyser (EGM-4, PP Systems, UK). Measurements lasting 90–180 s were carried out in full light and under an artificial shade that reduced the amount of incoming light by 40–60 %. During the measurements, CO<sub>2</sub> concentration in the chamber headspace, photosynthetically active radiation (PAR) under the chamber roof, and chamber temperature were recorded at intervals of 15 s. After the measurements in light, the chamber was covered with an opaque hood and ecosystem respiration (RE) in the dark was measured. Simultaneously with the CO<sub>2</sub> exchange measurements, water table level in a perforated tube next to each plot and peat temperature 5 cm below the moss or peat surface were measured, in order to

relate the fluxes to the prevailing environmental conditions.

NEE and RE were calculated as rates of change in CO<sub>2</sub> concentration by fitting linear regression lines. Gross photosynthesis (PG) was estimated as the sum of the (negative) NEE rate in the light and the succeeding RE measurement in the dark. Both PG and RE values are stated as positive.

### **Vegetation monitoring**

A leaf area index (LAI) estimation was employed to relate CO<sub>2</sub> fluxes to spatial and temporal variations in vegetation. For vascular plants, species-specific LAIs in each sample plot were estimated three times during each growing season as the product of the number of leaves and the average leaf size (Wilson *et al.* 2007). The number of green leaves of each species was estimated by counting the number of leaves in five permanent sub-sample plots within each sample plot that accounted for approximately 10 % of the total area of the plot.

For each sample plot, the species-specific LAIs on the measurement days were summed up to the total leaf area of all vascular plants. To describe LAI development during the growing seasons, a Gaussian curve was fitted for each group according to the equation

$$LAI = a * x^{[-0.5 * (\frac{x-x_0}{b})^2]} \quad [1]$$

where LAI (m<sup>2</sup> m<sup>-2</sup>) is the total LAI of vascular plants, parameter *a* denotes the maximum LAI during the season (LAI<sub>max</sub>), *x* denotes Julian day (days of a year numbered from 1 to 365) and parameter *b* denotes the timing of LAI<sub>max</sub>. Parametric one-way ANOVA (SPSS 22.0, SPSS Inc.) was used for statistical analyses of the LAIs.

### **CO<sub>2</sub> exchange models**

We constructed CO<sub>2</sub> exchange models to analyse the controls on CO<sub>2</sub> exchange and to simulate CO<sub>2</sub> exchange over the growing season May–October. PG and RE were modelled separately, using multivariate non-linear regression models. The forms of response functions (modifications from Tuittila *et al.* 2004) are ecologically meaningful and interpretable. Modelling was performed using the SigmaPlot 11.0 software package (SPSS Inc.). We combined the photosynthetic response to PAR and LAI into a PG model, in which the response of PG to PAR is saturating, as follows:

$$PG = y_0 + a * \frac{x}{(b+x)} * (c + d * LAI) \quad [2]$$

where  $x$  is PAR (photon flux  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and  $y_0$ ,  $a$ ,  $b$ ,  $c$  and  $d$  are model parameters (Table 1).

In the RE model (Lloyd & Taylor 1994) (Equation 3), we used the exponential relationship of respiration to peat temperature 5 cm below the moss or peat surface ( $T_5$ ).

$$R_{tot} = a * x^{(b * \left( \left( \frac{1}{(10+46.02)^x} \right) - \left( \frac{1}{(x+46.02)^x} \right) \right))} \quad [3]$$

In Equation 3,  $x$  is  $T_5$ , the numbers 10 and 46.02 are constants, and  $a$  and  $b$  are model parameters (Table 2).

### Reconstructed CO<sub>2</sub> exchange

To derive seasonal estimates, we reconstructed plot-wise PG and RE with the models for six months from May to October over the two growing seasons 2013–2014. We parameterised PG and RE models

separately for each sample plot to improve the sensitivity of the models to environmental variables (Tables 1 and 2). Bihourly reconstructed NEE was calculated as the difference between PG and RE. Positive NEE values represented net uptake of CO<sub>2</sub> by the ecosystem and negative values reflected net loss of CO<sub>2</sub> to the atmosphere. For seasonal temperature and PAR derived model simulations, continuous soil temperature and PAR data were obtained from weather stations close to the site and from miniature temperature data loggers (i-button, Dallas Semiconductor Corp.) on the measurement plots. For the PG simulations, daily plant LAI was derived by calculating the average LAI of plants from the plot-wise LAI models. Parametric one-way ANOVA (SPSS 22.0, SPSS Inc.) was used for the statistical analyses of the reconstructed carbon balances.

Table 1. Parameters for the PG models during 2013–2014.

2013	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>y0</i>
Intact 1	71.6	1584	12.4	53.7	33.2
Intact 2	725	35580	21.7	32.9	14.8
Intact 3	4432	3505000	463	503	70.4
Harvested 1	44.9	3517	7.26	104	22.3
Harvested 2	228	11870	2.63	97.0	43.2
Harvested 3	250	5239000	618	3796	92.2
Harvested 4	180	130000	71.8	2056	33.3
Harvested 5	9154	4046000	157	-289	29.4
2014	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>y0</i>
Intact 1	92.8	26060	-66.3	649	135
Intact 2	604	2632000	896	5951	58.2
Intact 3	67.7	2707	-7.65	142	124
Harvested 1	1064	9169000	579	-59.0	38.7
Harvested 2	6.81	810	-20.1	940	39.4
Harvested 3	936	12870	-0.20	34.4	85.2
Harvested 4	648	1129000	-116	6328	100
Harvested 5	24.5	2310	13.9	737	17.5

Table 2. Parameters for the RE models during 2013–2014.

	2013		2014	
	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
Intact 1	188	313	152	389
Intact 2	108	493	156	294
Intact 3	181	409	247	325
Harvested 1	56.3	183	67.5	148
Harvested 2	70.5	332	87.5	242
Harvested 3	80.7	183	132	239
Harvested 4	113	206	149	270
Harvested 5	113	189	140	326

**RESULTS**

**Weather conditions during the study period**

The thermal growing season started in early May and lasted until the end of October in both study years (2013 and 2014) (Figure 1). The mean seasonal (May–October) temperatures at Palloneva in the two study years (12.2 °C and 11.7 °C, respectively) were only slightly higher than the 1984–2014 long-term average (10.8 °C). However, the temperature in July 2014 was clearly higher than the 1984–2014 long-term average (Figure 1). The cumulative precipitation during May–October was slightly higher in 2013 (413 mm) and slightly lower in 2014 (301 mm) than the 1984–2014 long-term average (346 mm). The peak season precipitation in June–July was clearly higher than the 1984–2014 long-term average in 2013, but clearly lower than the 1984–2014 long-term average in 2014 (Figure 1).

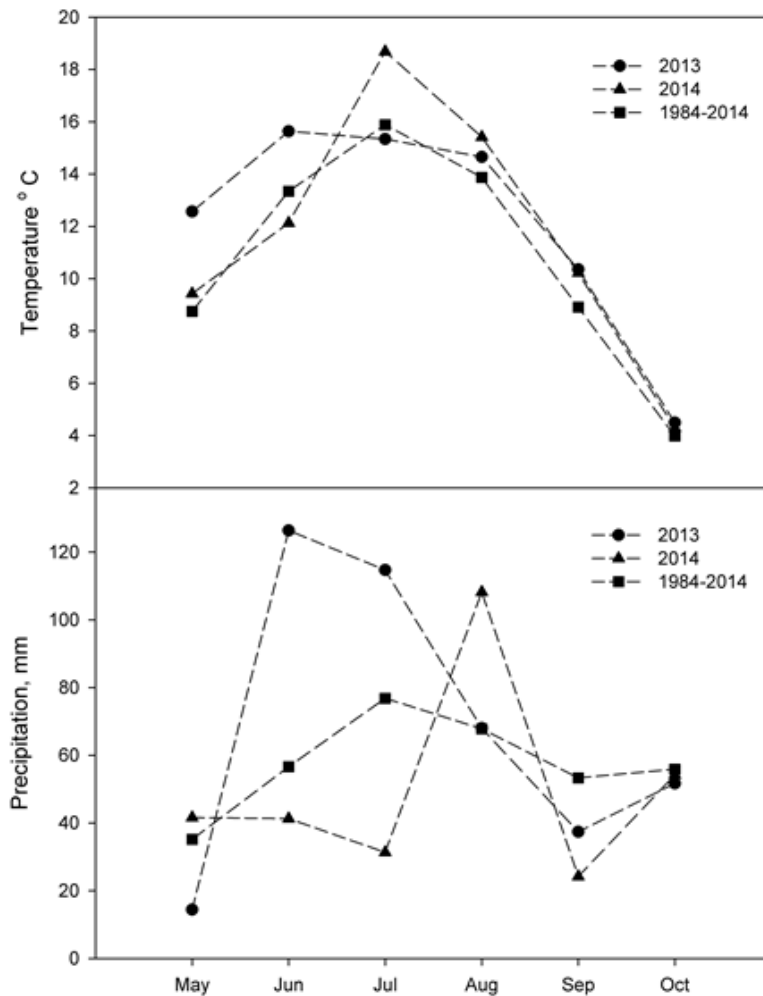


Figure 1. Mean air temperature and monthly precipitation at Palloneva from May to October in 2013, 2014 and as 30-year average 1984–2014.

Water table levels were approximately 15–25 cm and 30–40 cm below the soil surface for intact and harvested surfaces, respectively (Figure 2). However, during the dry and hot weather of July 2014, water table levels were 40 cm and >50 cm below the soil surface for intact and harvested surfaces, respectively (Figure 2). The highest PAR values measured under the chamber roofs ranged from ~400  $\mu\text{mol m}^{-2} \text{s}^{-1}$  during late season in October to 1600  $\mu\text{mol m}^{-2} \text{s}^{-1}$  during peak season in July (Figure 3).

### Vegetation recovery

According to our results, the *Sphagnum* carpet of the harvested surface regrew rapidly. The most active *Sphagnum* coloniser was *S. balticum*, especially at the beginning of the succession, although *S. fuscum* and *S. magellanicum* also reclaimed the free area during succession. On the intact area, almost the same average density of *Sphagnum* capitula was observed in both study years. The densities of

*Sphagnum* capitula on intact and harvested surfaces (20,584 versus 9,634 capitula  $\text{m}^{-2}$ ) differed significantly ( $F=19.61$ ,  $p<0.05$ ) in 2013 but not in 2014, which was the third year after *Sphagnum* biomass harvesting (20,372 versus 16,446 capitula  $\text{m}^{-2}$ ) (Figure 4).

The annual mean length increments of *Sphagnum* mosses on the intact area during the period August 2013 to August 2014 were 2.0 cm, 1.1 cm, 0.9 cm and 0.8 cm for *Sphagnum magellanicum*, *S. fuscum*, *S. rubellum* and *S. balticum*, respectively. On the harvested area the corresponding mean length increment values were 2.7 cm, 1.5 cm, 1.1 cm and 0.9 cm for the same species (Table 3). The mean length increments for all studied *Sphagnum* species combined were 1.2 cm for the intact area and 1.5 cm for the harvested area. The mean length increments of *Sphagnum* mosses were slightly higher on the harvested area, but the differences between the areas were not significant.

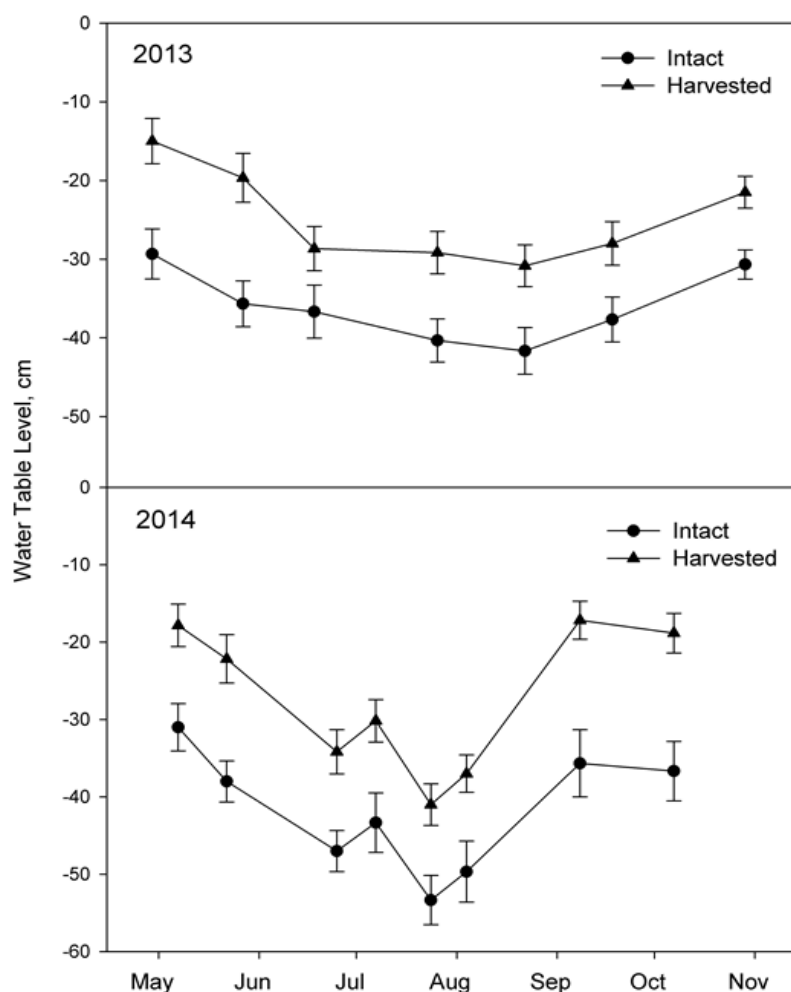


Figure 2. Water table levels at Palloneva from May to October in 2013 and 2014. Vertical bars are SE for means.

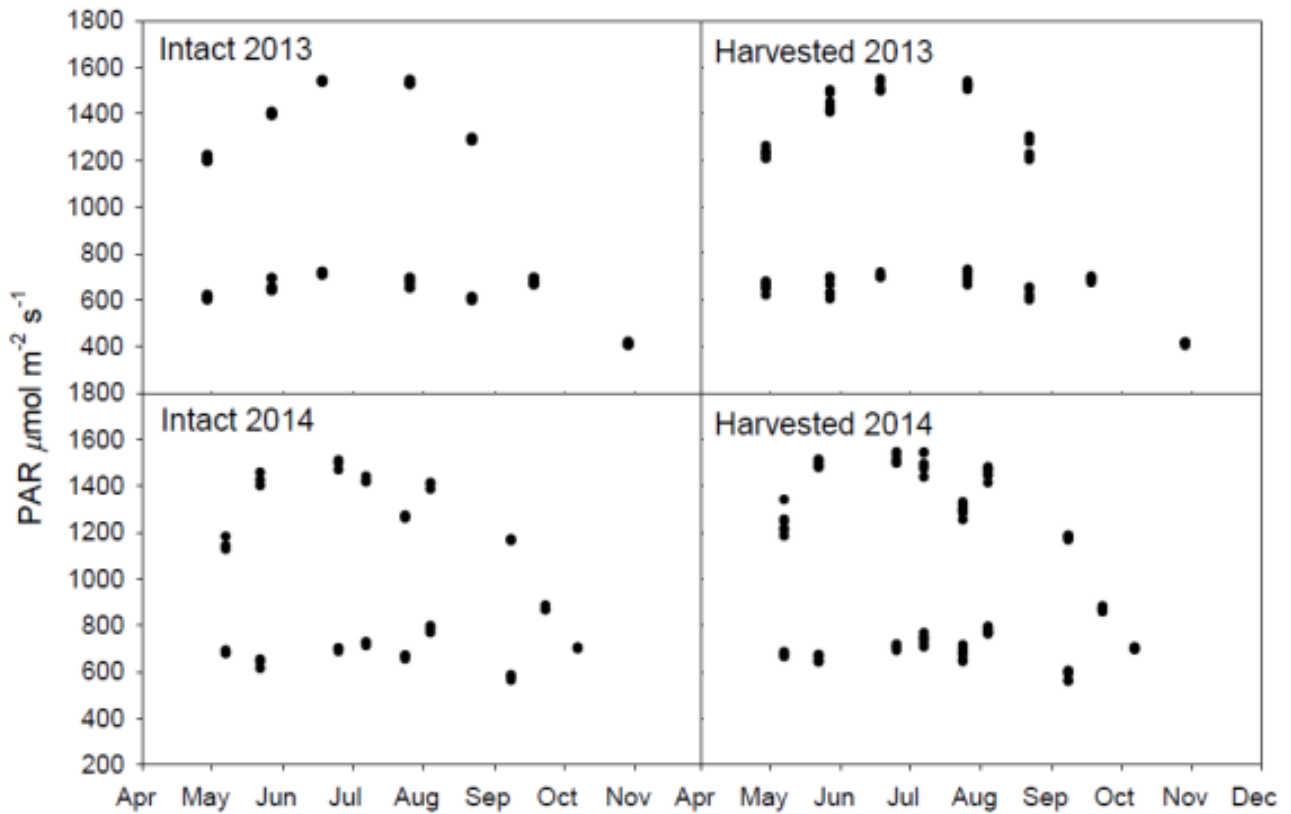


Figure 3. Measured photosynthetically active radiations (PAR) at Palloneva in 2013 and 2014. PAR values are based on manual measurements made in conjunction with CO<sub>2</sub> exchange measurements. Some of the measurements were done under an artificial shade reducing the ambient light by 40–60 % resulting the rather large variation in PARs.

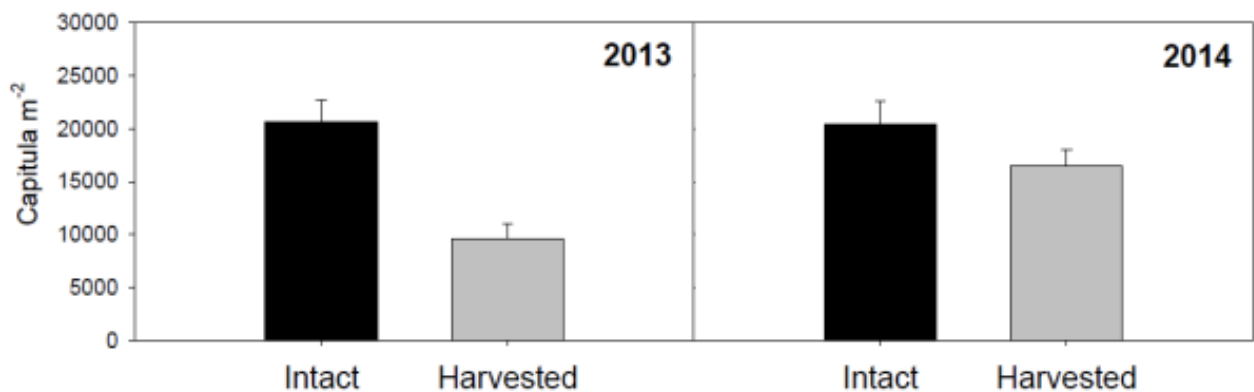


Figure 4. The number of *Sphagnum* capitula on the intact and harvested surfaces in 2013 and 2014. Vertical bars are SE for means.

Table 3. The mean length increments (cm) of *S. magellanicum* (*S. mag*), *S. balticum* (*S. bal*), *S. fuscum* (*S. fus*) and *S. rubellum* (*S. rub*) on the intact and harvested surfaces during 2013–2014.

	<i>S. mag</i>	<i>S. bal</i>	<i>S. fus</i>	<i>S. rub</i>
Intact	2.0±0.3	0.8±0.1	1.1±0.2	0.9±0.1
Harvested	2.7±0.4	0.9±0.1	1.5±0.1	1.1±0.1

The maximum LAI of vascular plants (measured in early August) was generally very low at Palloneva. On the intact plots the mean LAI was similar (~0.35 m<sup>2</sup> m<sup>-2</sup>) in both study years. The LAI was higher in 2014 (0.10 m<sup>2</sup> m<sup>-2</sup>) than in 2013 (0.07 m<sup>2</sup> m<sup>-2</sup>) on the harvested plots, although the difference between the two years was not significant. The dominant vascular plants observed at Palloneva were *Andromeda polifolia*, *Empetrum nigrum*, *Vaccinium microcarpon* and *Rubus chamaemorus* on the intact plots, and *Eriophorum vaginatum* and *Vaccinium microcarpon* on the harvested plots.

### Seasonal carbon balance

The mean seasonal NEE, as C, for intact and harvested surfaces during 2013–2014 was, respectively, 97 and 66 mg m<sup>-2</sup> h<sup>-1</sup>. RE (as C, in the dark) was 275 and 121 mg m<sup>-2</sup> h<sup>-1</sup> (Figure 5). Both fluxes were generally higher in 2014 (Figure 5).

Based on reconstructions with models and weather data for both years, the intact surface showed a positive seasonal net CO<sub>2</sub> balance, with net CO<sub>2</sub>-C fluxes of 39.0 and 19.2 g m<sup>-2</sup> season<sup>-1</sup>, respectively. In other words, intact surface was acting as a sink for CO<sub>2</sub>-C (Figure 6). Harvested surface showed a very small negative seasonal net CO<sub>2</sub>-C balance in 2013 (-1.7 g m<sup>-2</sup> season<sup>-1</sup>) and a positive net balance in 2014 (11.1 g m<sup>-2</sup> season<sup>-1</sup>) (Figure 6). The difference between the CO<sub>2</sub> balances of intact and harvested surfaces was significant (F=7.95, p<0.05) in 2013 but not in 2014. Both surfaces showed relatively large differences between the two years, but neither year was more favourable for both surfaces (Figure 6). The seasonal carbon sequestration of intact surface was clearly lower in 2014 than in 2013 (Figure 6). Conversely, the seasonal carbon sequestration of harvested surface was clearly higher in 2014 than in 2013 (Figure 6).

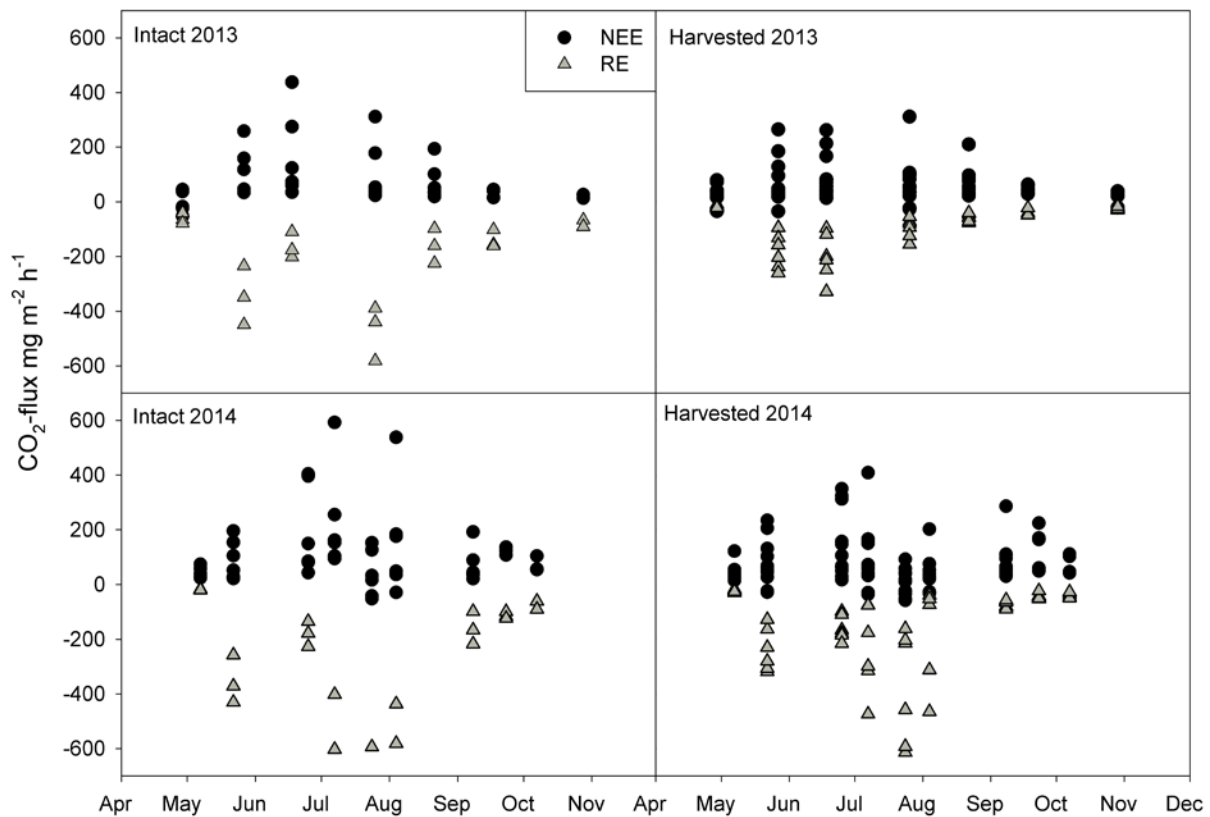


Figure 5. Measured instantaneous CO<sub>2</sub> exchange (NEE and RE) of the intact and harvested surfaces in 2013 and 2014. Positive values are sinks and negative values are sources of atmospheric CO<sub>2</sub>.



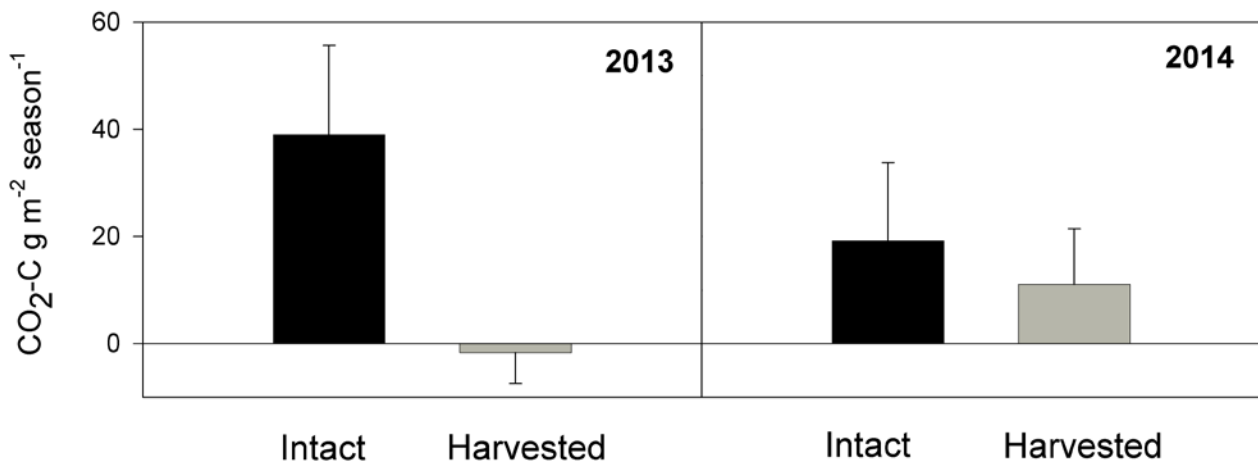


Figure 6. Simulated seasonal CO<sub>2</sub>-C balance of the intact and harvested surfaces in 2013 and 2014. Vertical bars are SE for means. Positive values are sinks of atmospheric CO<sub>2</sub> and negative values are sources.

## DISCUSSION

Although the long-term prognosis for recovery and productivity of harvested *Sphagnum* mosses under the conditions at Palloneva is still unknown, areas from which *Sphagnum* had been removed regained significant parts their function as carbon sinks within three years after harvesting in our study. According to our results, *Sphagnum* biomass harvesting extending down to a depth of no more than 30 cm will have a rather short-term (less than five years) effect on *Sphagnum* carpet coverage and carbon sequestration.

There are very few available studies about industrial-scale harvesting of *Sphagnum* biomass for use as a constituent of growing media (Elling & Knighton 1984, Whinam *et al.* 2003), and perhaps even fewer about *Sphagnum* moss yields and recovery on the harvested areas (Elling & Knighton 1984, Whinam & Buxton 1997). The short-term *Sphagnum* yields measured during our study are clearly smaller than those measured in studies carried out in east-central Minnesota (North America), where approximately 20 cm of frozen *Sphagnum* carpet was removed during winter and an active *Sphagnum* carpet regrew in less than five years with yields of 7.63 t ha<sup>-1</sup> (i.e. 1.53 t ha<sup>-1</sup> y<sup>-1</sup>) as measured by the biomass harvesting method (Elling & Knighton 1984). Lainevesi (1990) reported very similar *Sphagnum* yield results (1.48 t ha<sup>-1</sup> y<sup>-1</sup>) as a 40-year average for a naturally regenerated cutaway peatland in central Finland.

In our study, the net CO<sub>2</sub>-C balance was 11.1 g m<sup>-2</sup> in the third year after harvesting. Assuming that the C content of dry *Sphagnum* biomass is 50 %, this converts to a *Sphagnum* biomass yield of 0.22 t ha<sup>-1</sup> y<sup>-1</sup>. However, our estimate of *Sphagnum*

biomass yield was derived by different methods than in earlier studies, during a very early phase of recovery and the relatively unfavourable growing season of 2014. Additionally, this value included a small amount of carbon fixed by vascular plants. There is some evidence that the cranked wire and biomass harvesting methods may over-estimate the growth rates of *Sphagnum* by as much as three-fold compared to the CO<sub>2</sub>-exchange method (McNeil & Waddington 2003). Thus, it is probable that a much larger *Sphagnum* biomass yield will be accumulated in the coming years. Elling & Knighton (1984) estimated that almost total recovery of the 72 t ha<sup>-1</sup> of *Sphagnum* biomass that was present prior to harvesting would require 20 years, so maximum *Sphagnum* yields could be expected from a 20-year (minimum) harvest cycle.

The mean length increments of *Sphagnum* mosses (1.5 cm y<sup>-1</sup>) measured in this study were also rather small compared to values obtained in other studies, for example 0.9–10.0 cm y<sup>-1</sup> in Australia (Whinam & Buxton 1997) and around 2.0 cm y<sup>-1</sup> in The Netherlands (Limpens & Berendse 2003). On the other hand, the mean length increments of *Sphagnum* mosses observed in our study aligned rather well with those observed by Jauhiainen *et al.* (1998) in Finland, where *Sphagnum* length increments ranged from ~0.3 cm over 71 days (*S. angustifolium*) to ~0.5 cm over 98 days (*S. warnstorffii*). The densities of *Sphagnum* capitula on the intact area at Palloneva (around 20,000 capitula m<sup>-2</sup>) agreed with results obtained by Jauhiainen *et al.* (1998), who recorded densities close to 20,000 capitula m<sup>-2</sup> for *S. angustifolium* and *S. warnstorffii*, but were much lower than those reported by Gunnarsson & Rydin (2000) who found densities of up to 70,000–90,000 capitula m<sup>-2</sup> for *S. fuscum* and *S. rubellum*.

Because of the short-term nature of our study, it is uncertain what timespan will be needed for full recovery of *Sphagnum* carpet to a condition corresponding to that before harvesting. Additionally, if harvesting is extended to depths exceeding 30 cm, there is a possibility that the *Sphagnum*-dominated vegetation will be replaced by sedge-like species (Silvan *et al.* 2012), for example by *Eriophorum vaginatum*, which may enhance methane emissions (Tuittila *et al.* 2000). Aesthetic (scenery) disadvantages will also increase as the depth of harvesting increases.

Although the peat reserves in Finland are very large, under high demand conditions a shortage of good-quality horticultural peat may arise in the near future. The best areas for extraction of good-quality horticultural peat are large pristine raised bogs, which are also very valuable as nature sanctuaries. In southern Finland and, especially, in central Europe, the pristine mires that are large enough for extraction of horticultural peat are protected for nature conservation. *Sphagnum* biomass harvesting provides a renewable alternative constituent for growing media with negligible environmental effects in comparison to conventional production of horticultural white peat. There will be appropriate peatlands for *Sphagnum* biomass harvesting (in contrast to white peat production) since, with a rotation time of ~30 years, the peatland area needed to meet the demand for horticultural peat in Finland (approximately  $10^6 \text{ m}^3 \text{ y}^{-1}$ ) is around 20,000 ha (Näkkilä *et al.* 2015). This can be achieved with an average harvesting depth of 30 cm and 50 % of the mire surface on each harvesting area remaining intact for transportation routes as well as to ensure a reserve of *Sphagnum* mosses for reseeding and recovery (Whinam *et al.* 2003, Näkkilä *et al.* 2015). The one million hectares of peatland in Finland could also accommodate much larger production volumes in the case of significant worldwide demand for growing media based on *Sphagnum* biomass. Additionally, the establishment of *Sphagnum* biomass harvesting areas would not require costly ditching, preparation of harvesting fields or road construction. For the most part, *Sphagnum* biomass harvesting is more closely comparable with sustainable forestry than with white peat production, which causes drastic and long-term alterations of the mire ecosystem.

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