

Dear Associate Editor Paul Stoy,

We are pleased to submit to Biogeosciences journal the revised version of the manuscript (bg-2016-265) “Species-specific temporal variation in photosynthesis as a moderator of peatland carbon sequestration” that was under review for the second time. We would like to thank the Editor and the reviewers for the valuable comments, which now have been incorporated to our manuscript. Below, each of the comments are addressed separately.

The largest revision suggested was to include uncertainty estimates to our eddy covariance –derived GPP and upscaled gross photosynthesis (P_G) estimate. We do agree with the reviewer that the uncertainty estimates would be very useful when comparing GPP and P_G , and the uncertainty estimate of GPP has now been added to our manuscript. Unfortunately, there are problems in calculating an uncertainty estimate for P_G , which was the reason why we originally decided to leave it out of our manuscript. We have below explained our reasoning behind that choice. Naturally, if requested by the Editor, we are prepared to try to find a way to calculate as good uncertainty estimate as possible, even though it would require quite much more modelling effort.

We would also like to point out that the order of second and third author has been switched in this version of the manuscript. This has been done with the acceptance of them both after reconsidering the weight of different methods for this work.

Associate Editor comments to the Author and our response:

Both referees find the manuscript publishable in Biogeosciences after minor revisions and I agree with their assessment. Please consider the remaining referee comments in a brief letter and improve the manuscript accordingly, and I will be happy to recommend it be published in Biogeosciences if the responses adequately account for the recommendations of the referees.

Sincerely,
Paul C. Stoy

We thank the Editor for offering us the change to resubmit our manuscript. Our detailed response to the specific comments is provided below.

Answer to the comments by Anonymous Referee #1

The authors have adequately addressed the details from earlier revision and the manuscript is nearly ready for publication in BG. I have only a few minor suggestions, mainly for improving the readability.

Page 3, line 2

Since climate is apparently warming it would be reasonable to give the actual 30 year period used for the 30 year averages.

We have added the years used for the 30 year averages.

Page 8, line 14

Use plural: The shapes of P_G and GPP development...

We have now used plural in this sentence.

Page 8, lines 16-19

Two complicated sentences. Could be rephrased, e.g.

The constant temperature, maintained in laboratory, allowed us to investigate how the changes in species photosynthetic parameters were affected by seasonal changes in moisture conditions in the field. Since measuring of species-specific temperature responses of PG was unachievable due to the large number of species, we instead chose to model the temperature dependence of EC-derived GPP (Eq. (4), Fig. 1a).

We have now reformulated the two sentences according to the suggestions of the reviewer.

Page 9, lines 3-4

A complicated sentence. Could be rephrased, e.g.

No inter-species differences in photosynthetic properties, either within vascular plants or Sphagna, could change this order.

We have reformulated the sentence as suggested by the reviewer.

Page 10, lines 27-29

Sentence “The diversity of vegetation... (Fig. 3a and b).”

may repeat what was already said on line 19-21. Please check.

This is true, thank you for noticing. We have modified the text to avoid repetition.

Answer to the comments by Anonymous Referee #2

I find the manuscript to be interesting and well written, but I struggled with the lack of uncertainty analyses about the eddy covariance and upscaled chamber-based observations, particularly when the model in equation 1 explicitly includes an uncertainty term. The discussion of potential sources of bias in the Discussion was nice, but uncertainty estimates should still be published. On the point of potential biases, I also find it important to include at least a mention to the notion that eddy covariance-based GPP estimates are likely overestimates due to recent findings that the Kok effect is likely larger than previously assumed (Wehr et al., 2016).

Wehr, R., Munger, J.W., McManus, J.B., Nelson, D.D., Zahniser, M.S., Davidson, E.A., Wofsy, S.C., Saleska, S.R., 2016. Seasonality of temperate forest photosynthesis and daytime respiration. *Nature* 534, 680–683.

We would like to thank the reviewer for the positive statement regarding our manuscript. We have now added the suggested reference to our manuscript on P9, L11-13 (page and row numbers refer to the revised version).

As stated above, we fully agree with the reviewer that the manuscript would benefit from including the uncertainty estimates. We have added a 95% confidence interval to our eddy covariance –derived GPP, P7, L26 and an explanation how it was calculated on P7, L10-13.

To calculate the uncertainty estimate of photosynthesis, we would have to take into account 1) the estimation errors of the fixed parameters, 2) the random effects of our mixed-effects models and 3) residual variance. For the second point we would need to have quantified the correlation of the random effects over time and between species. A proper model for such purpose would be a nonlinear models system that models correlated random effects and residual errors over time. However, model fitting procedures for such model are not available in the standard statistical software.

These problems are now explained in the manuscript on P5, L18-24. We tried to fit a less complicated model which assumed hierarchical nested random effects but we could not fit such a model due to estimation problems in the model fit. Modeling temporal and between-species correlation of random effects would be especially important for the uncertainty calculation, since almost all of our 87 models show that the random effects of the models account for several times more variation than the residual variation (Supplementary table 1). On the other hand, the large variation in the random effects compared with the residual variation supports our choice to use mixed-effects models, which takes into account the random variation between samples. Although the current modeling structure makes it difficult to calculate only one uncertainty estimate for the whole growing season, we sincerely believe this was the most accurate approach to estimate the light response parameters.

To put it short, calculating the uncertainty estimate of upscaled photosynthesis is quite complicated, and we are afraid such an estimate would very likely be erroneous. Therefore, we would prefer staying in our decision not to present it in the manuscript. Currently, the uncertainties of the 87 models are presented in the Supplement 1. However, we are willing to do our best to find a way to calculate an uncertainty estimate for the whole growing season, if requested by the Editor.

Species-specific temporal variation in photosynthesis as a moderator of peatland carbon sequestration

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Field Code Changed

15 **Abstract.** In boreal bogs plant species are low in number, but they differ greatly in their growth forms and photosynthetic properties. We assessed how ecosystem carbon (C) sink dynamics were affected by seasonal variations in photosynthetic rate and leaf area of different species. Photosynthetic properties (light-response parameters), leaf area development and areal cover (abundance) of the species were used to quantify species-specific net and gross photosynthesis rates (P_N and P_G , respectively), which were summed to express ecosystem-level P_N and P_G . The ecosystem-level P_G was compared with a gross primary production (GPP) estimate derived from eddy covariance measurements (EC).

20 Species areal cover, rather than differences in photosynthetic properties, determined the species with the highest P_G of both vascular plants and *Sphagna*. Species-specific contributions to the ecosystem P_G varied over the growing season, which, in turn, determined the seasonal variation in ecosystem P_G . The upscaled growing-season P_G estimate, 230 g C m^{-2} , agreed well with the GPP estimated by the EC, 243 g C m^{-2} .

25 *Sphagna* were superior to vascular plants in ecosystem-level P_G throughout the growing season, but had a lower P_N . P_N results indicated that areal cover of the species, together with their differences in photosynthetic parameters, shape the ecosystem-level C balance. Species with low areal cover but high photosynthetic efficiency, appear to be potentially important for the ecosystem C sink. Results imply that functional diversity, i.e. the presence of plant groups with different seasonal timing and efficiency of photosynthesis, may increase the stability of C sink of

30 **Key-words**

CO₂, ecosystem stability, insurance hypothesis, vascular plant, *Sphagnum*

1 Introduction

Northern peatlands are a globally important carbon (C) sink and storage of approximately 500 gigatons of C (Gorham, 1991; Yu et al., 2012) as a result of an imbalance between photosynthesis and decomposition. Boreal bogs are peatland ecosystems where photosynthetic productivity is limited by mid-summer dry periods, light induced stress and, in particular, low nutrient availability (Frolking et al., 1998; Moore et al., 2002). Due to the low rate of photosynthesis, the annual C sink of boreal bogs is weak and sensitive to changes; even a small change in the environmental conditions that regulate the C cycle can turn the ecosystem into a C source (Waddington and Roulet, 2000; Lund et al., 2012). The rate by which CO₂ enters the ecosystem through photosynthesis of all of the individual plants together is the definition of gross primary production (GPP). When ecosystem respiration (R_{eco}) is subtracted from GPP, the result is net ecosystem exchange (NEE) of CO₂ between the ecosystem and the atmosphere. On the scale of individual plants, the same processes are called gross photosynthesis (P_G), plant respiration (R) and net photosynthesis (P_N), respectively (Chapin et al. 2011).

Boreal bogs are ecosystems with low species diversity but high diversity of growth forms due to the large microtopographical variation and associated diversity of habitats along the water table gradient (Turetsky et al., 2012). Several studies (e.g. Weltzin et al., 2000; Moore et al., 2002; Leppälä et al., 2008) have reported that patterned bogs produce more biomass and have less variation in gross photosynthesis over the growing season than fens, which receive additional nutrients from the surrounding mineral soil and generally have more homogenous, sedge-dominated vegetation (Weltzin et al., 2000). Experimental studies have shown that bog plant growth forms have differential responses to warming and water table level manipulation, which can help to maintain the level of total ecosystem productivity under changing environmental conditions (Weltzin et al., 2000; Breeuwer et al., 2009). Short-term plant removal experiments have shown the differential roles of plant functional types for the peatland NEE and GPP (Ward et al., 2009; Kuiper et al., 2014; Robroek et al., 2015). Photosynthetic properties of bog plants are known to differ widely between species of the same functional type (Small, 1972) and between phases of growing season (Korrensalo et al., 2016). So far, the role of species-level differences in temporal variation of bog ecosystem photosynthesis has not been studied.

Here, we aim to solve the linkage between the temporal pattern of bog carbon balance and the development of species-specific potential photosynthesis and leaf area. For this purpose, we quantified the contribution of different plant species to ecosystem-level photosynthesis over a growing season. As species differ in their photosynthetic properties, and the properties vary over the growing season, we expect their importance for the ecosystem carbon sequestration also vary over the season. To reach our aim we estimate P_N and P_G for the whole study site based on the monthly species-level light response of photosynthesis and species-specific leaf area development over a growing season. To validate the upscaling approach, the sum of species-level P_G is compared to the GPP derived from eddy covariance (EC) measurements at the study site.

2 Methods

2.1 Study site

The study site (61° 50.179' N, 24° 10.145' E) is situated in an ombrotrophic bog, which is a part of the Siikaneva peatland complex in Southern Finland, located in the southern boreal vegetation zone. The annual temperature

sum in the area (base temperature 5 °C) is 1318 degree days, annual rainfall is 707 mm and the average annual, January and July temperatures are 4.2, -7.2 and 17.1 °C, respectively (30 year averages (years 1982–2011) from Juupajoki-Hyytiälä weather station). The study site has a surface topography typical of raised bogs that varies from open water pools and mud surfaces to hollows, lawns and hummocks. An EC flux tower is mounted on a raft in the center of the site.

The vegetation is mainly composed of 11 vascular plant and eight *Sphagnum* species (Table 1), the abundance of which varies markedly along the microtopographical gradient. A continuous *Sphagnum* carpet covers the surfaces from hummocks to hollows, although no *Sphagna* are present on the mud and water surfaces. *Sphagnum cuspidatum* and *S. majus* are dominant in hollows, *S. papillosum*, *S. rubellum*, *S. balticum* and *S. magellanicum* in lawns, and *S. fuscum*, *S. rubellum* and *S. angustifolium* cover the hummocks. Vascular plant species composition includes *Rhynchospora alba*, *Scheuchzeria palustris* and *Carex limosa* vegetation on mud and hollow surfaces, dwarf shrubs (*Andromeda polifolia*, *Vaccinium oxycoccos*) and *Eriophorum vaginatum* on lawn surfaces, and a thick shrub layer of *Calluna vulgaris*, *Betula nana*, *Empetrum nigrum*, and sedges *Eriophorum vaginatum* and *Trichophorum cespitosum* on hummocks.

2.2 Plant level photosynthesis measurements

To quantify the role of plant species in ecosystem-level photosynthesis over the growing season, we conducted net photosynthesis (P_N) measurements of 19 most common species at the study site. Over the growing season 2013, we measured CO_2 exchange of 3–5 samples of each species per month at three light levels with two open, flow-through gas exchange measurement devices (GFS-3000, Walz, Germany and LI-6400, LI-COR, USA). Samples were collected from several locations inside the study area a maximum of 30 hours prior to measurement; *Sphagna* were collected into small plastic bags and vascular plants into plastic boxes with an ample amount of roots and peat. These were kept moist until measured. Vascular plants were kept in shaded conditions and *Sphagna* were stored in the dark at 5 °C. The moss cuvettes were filled with *Sphagnum* capitula imitating their natural shoot density of each species in the field, resulting in a total number of 6–16 capitula inside a cuvette depending on the species. Before placing the capitula into the cuvettes, they were first wetted and then lightly dried of excess water with pulp paper. The cuvette was then placed under a photosynthetic photon flux density (PPFD) of approximately 1000 $\mu mol m^{-2} s^{-1}$ to acclimate to light for 20 min. The measured light levels were 2000, 25 and 0 $\mu mol m^{-2} s^{-1}$ for vascular plants and 2000, 35 and 0 $\mu mol m^{-2} s^{-1}$ for *Sphagna*. Light levels were designed to both catch the linear, light-limited beginning and the light-saturated maximum of the light response curve without causing photoinhibitory reduction of photosynthetic rate (Laine et al., 2015). Vascular plants were measured with a standard cuvette, but for *Sphagna* we used a moss cuvette of our own construction with internal dimensions of 3 × 2 × 1 cm (Hájek et al., 2009) with a net bottom to allow airflow above and below the sample reducing the aerodynamic resistance. After changing the light level, we waited for the P_N to reach steady state before recording the CO_2 exchange. Only PPFD was varied during the measurements, while we kept air temperature at constant 20 °C, the flow rate at 600 $\mu mol s^{-1}$ and the CO_2 concentration in the incoming air at 400 ppm to be able to compare the seasonal changes in photosynthetic potential among species. The relative humidity inside the cuvette was kept at 50% for the vascular plants and below 90% for the *Sphagna*. The measured P_N value of each sample at the three light levels was expressed per photosynthesizing leaf area ($mg CO_2 m^{-2} (LA) h^{-1}$), which was the leaf area inside the cuvette measured with a scanner for vascular plants and assumed to be the cuvette area for *Sphagna*. Two of

the species, namely *Rhynchospora alba* and *Rubus chamaemorus*, were not yet of measurable size in May; *R. alba* had already mostly senesced in September and therefore were not measured in those months. Altogether, the data consisted of 720 measurements.

2.3 Net photosynthesis model

5 To obtain a species-wise flux reconstruction of P_N and P_G , we fitted a nonlinear mixed-effects model separately for each combination of species and month. Mixed-effects modeling approach allowed us to take into account the variation between samples, of which each was measured at three light levels. We used the hyperbolic light saturation curve of P_N (Larcher, 2003):

$$PN_{si} = R_s + \frac{Pmax_s PPFDisi}{k_s + PPFDisi} + e_{si} \quad (1)$$

10 where PN_{si} is the observed net CO_2 exchange ($mg\ CO_2\ m^{-2}\ (LA\ h^{-1})$) and $PPFD_{si}$ is the photosynthetic photon flux density for measurement i of sample s . The three parameters to be estimated are the maximum rate of light-saturated net photosynthesis ($Pmax_s$), the PPFD level where half of $Pmax$ was reached (k_s) and respiration (R_s), and were assumed to be constant for each combination of species and month. e_{si} is the normally distributed residual variance of the model with a mean of zero. Normally distributed random effect of the sample was included in one to three of the parameters depending on the model. The random effect structure was selected based on the Akaike information criterion (AIC) values of the alternative models with random effects included in a different combination of parameters. The random effects for the sub-models of each nonlinear model form a vector of random effect with non-zero correlation. Parameter values for the 87 P_N models are presented in Supplementary information (Table S1). The separate fitting for each combination of species and month leads to models with similar asymptotic unbiasedness as a single model for complete data would do. However, separate models do not quantify the temporal and between-species correlation of random effects and residuals, and therefore do not provide a sufficiently detailed model for evaluating the prediction errors of upscaled estimates of net photosynthesis. A proper model for such purpose would model both temporal and between-species covariance of both random effects and residuals, but model fitting procedures for such model are not available in the standard statistical software. All models were fitted using the functions *nlme* of the R program package *nlme* (Pinheiro and
25 Bates, 2000).

Sphagna were not measured in June nor were vascular plants in July due to technical failures of the devices. Then, light response curves for these two months were fitted by combining data from the previous and following month for each species. In 5 of the 95 species-month combinations only one sample of the species had an acceptable measurement. The parameters for these months were estimated separately without the mixed model structure
30 (Supplementary information, Table S1).

2.4 Upscaling

To upscale species-level photosynthesis to the ecosystem level, the cover of each species was estimated within the study site with a systematic vegetation inventory conducted in July 2013. We estimated the relative cover of each plant species in 121 $0.071\ m^2$ plots (Table 1), which were arranged in a regular grid in a 30 m radius circle around
35 the EC tower. To link net photosynthesis measured per leaf area to species cover, we converted species cover in

the study area to leaf area index (LAI) using linear relationships between the two (Supplementary information, Table S2). Relationships were based on an inventory made in July 2012 over a 200 m radius circle where species cover was estimated, and then all living aboveground vegetation was harvested from 65 0.071 m² inventory plots for LAI measurements. The vascular plant LAI of these samples was measured in the laboratory.

5 We monitored LAI development of each vascular plant species over the growing season in 18 permanent sampling plots (0.36 m²) that represented all the vegetation communities (n=3 in each vegetation community) along the microtopographical gradient in the study site. LAI was estimated every third week according to method described by Wilson et al., (2007). Continuous LAI development of each species was then estimated by fitting a log-linear response to the observations. The shape of the log-linear LAI development was taken from this fitting and the
10 growing season LAI maximum for each species was taken from the converted average cover (Table 1). *Sphagnum* leaf area was assumed to stay constant over the whole growing season and was obtained using the average cover from the 2013 inventory.

Using the light response curves, estimated daily LAI, and half-hourly, above-canopy PPFD data from SMEAR II measurement station (61° 50.845' N, 24° 17.686' E), we calculated P_N and P_G for each half hour period (mg CO₂
15 m⁻² 30 min⁻¹) over the growing season (Julian days 121–273) with the species-wise and monthly light response curves. P_G was calculated with the same model without the R parameter, i.e. assuming that respiration is zero. Model predictions were not meaningfully changed by using marginal prediction, i.e. averaging the predictions over the distribution random effects (e.g. de-Miguel et al., 2012) and were therefore computed using the fixed part of the model only. Growing season P_N and P_G of the whole study site were calculated as a sum of their daily values.

20 **2.5 Ecosystem-level CO₂ exchange measurements and estimation of gross primary production**

To validate the measured levels of photosynthesis, the calculated values were compared with the GPP estimates obtained by EC measurements, which offer an independent estimate of the ecosystem-level CO₂ exchange measured directly as turbulent vertical fluxes (e.g. Baldocchi, 2003; Aubinet et al., 2012). The EC system comprised a 3-D ultrasonic anemometer (USA-1, METEK Meteorologische Messtechnik GmbH, Germany) and
25 an enclosed H₂O/CO₂ gas analyzer (LI-7200, LI-COR Biosciences, USA). The EC sensors were mounted on the mast 2.5 m above the peat surface. EddyUH software was used to process the raw data and produce the 30-min average fluxes of latent heat, sensible heat, and CO₂ (Mammarella et al., 2015). Standard EC data checks based on the widely accepted quality criteria (e.g. Aubinet et al., 2012) were applied partly automatically by the software and partly manually; the EC data at friction velocity (u*) less than 0.1 m s⁻¹ were rejected. The resulting EC fluxes
30 represent the exchange over a quasi-elliptical source area (footprint) located within about 30 m upwind of the EC mast, as suggested by footprint calculations using the model by Kormann and Meixner, (2001).

NEE measured by the EC method was then partitioned into ecosystem GPP and R_{eco}. The daytime R_{eco} estimates were obtained from the Q₁₀-type temperature response curve fitted to the nighttime EC data, when respiration is the only component of NEE. Nighttime was defined as all the periods when the sun elevation angle was lower than
35 5°. Peat temperature at 5cm depth was used as the driver of R_{eco}, in the following relationship:

$$R_{eco} = R_{ref} Q_{10}^{\left(\frac{T_p - T_{ref}}{10}\right)} \quad (2)$$

where T_p is the peat temperature at a 5cm depth ($^{\circ}\text{C}$) and T_{ref} is the peat reference temperature of 12°C . Parameters to be estimated from the fit of the model (Eq. (2)) to all available night time NEE data were R_{ref} , the reference respiration at the temperature of 12°C , and Q_{10} , the temperature sensitivity coefficient.

- 5 The GPP estimates were calculated by subtracting the modeled R_{eco} from the EC-derived NEE values. Finally, in order to gap-fill the GPP time series, a model using PPFD (from the SMEAR II measurement station) and the footprint-scale LAI was fitted to the data following:

$$GPP = \frac{Pmax \ PPFD}{k + PPFD} (LAI + b) \quad (3)$$

where GPP is expressed in $\text{mg} (\text{CO}_2) \text{m}^{-2} \text{h}^{-1}$. LAI is the modeled daily vascular leaf area index described above, while b represents the temporally constant contribution of the *Sphagnum* to total LAI.

- 10 One of the major sources of random uncertainty in cumulative GPP originates from the uncertainty in the R_{eco} and GPP model parameters. Random uncertainty was calculated as the 95% confidence interval of a set of 1000 cumulative GPP estimates obtained using R_{ref} , Q_{10} , P_{max} and k varied within their respective 95% confidence intervals.

- 15 Since laboratory measurements of P_G were conducted at a constant temperature of 20°C and EC measurements at the air temperatures present at the field site, the temperature limitation of GPP was studied by fitting to the GPP data a model similar to Eq. (3), but complemented with a Gaussian type temperature response (Maanaviija et al. 2011):

$$GPP = \frac{Pmax \ PPFD}{k + PPFD} (LAI + b) \exp\left(\frac{-0.5 (T_a - T_{opt})^2}{T_{tol}^2}\right) \quad (4)$$

- 20 where T_a is the air temperature, T_{opt} is the temperature optimum of GPP and T_{tol} is the temperature tolerance of GPP (deviation from the optimum at which GPP is 60% of the maximum). Using Eq. (4), GPP at 20°C and at ambient PAR and LAI was simulated for the study site over the growing season.

3 Results

3.1 Cumulative growing season gross photosynthesis

- 25 Fitting the temperature response curve of R_{eco} , Eq. (2) into the nighttime eddy covariance data yielded a reference respiration (R_{ref}) of $123 \text{ mg} (\text{CO}_2) \text{m}^{-2} \text{h}^{-1}$ and Q_{10} of 3.5. In the GPP model (Eq. (3)) fit, P_{max} was $1721.8 \text{ mg CO}_2 \text{m}^{-2} \text{h}^{-1}$, k was $128.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ and b was 0.08. After gap-filling the GPP data (Eq. (3)), the resulting cumulative growing season GPP estimate was 243 g C m^{-2} (95 % confidence interval: 220-265 g C m^{-2}). In the GPP model fit

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complemented with temperature response (Eq. (4)), P_{max} was 1852 mg (CO₂) m⁻² h⁻¹, k was 170.3 μmol m⁻² s⁻¹, b was 0.1, T_{opt} was 22.6 °C and T_{tol} was 20.9 °C.

Cumulative growing season P_G upscaled to the ecosystem level using the separate light response curves for species and months (Eq. (1)) was 230 g C m⁻² (Julian days 121–273). Daily P_G estimates were higher than GPP values from the EC tower in spring and lower in the middle of the summer (Fig. 1a). The GPP simulated at 20 °C, the same temperature as during the laboratory measurements, was similar than upscaled P_G in spring but closer to the measured GPP in the middle of the summer (Fig. 1a). In the autumn, all of the three estimates showed rather similar levels (Fig. 1a).

Sphagna at the study site had higher cumulative growing season P_G value (138 g C m⁻²) than vascular plants (92 g C m⁻²). *Sphagna* had higher daily P_G than vascular plants in spring and autumn, but were almost at the same level in the middle of the summer (Fig. 2). A small increase in *Sphagnum* photosynthesis was observed during May (Fig. 2 and 3b) due to increment of daily PPFD towards midsummer. Otherwise, *Sphagnum* P_G decreased steadily over the growing season (Fig. 2). Seasonal changes in vascular P_G showed similar patterns than vascular LAI development, although the maximum P_G was reached slightly earlier in the season than maximum LAI (Fig. 1a, 1c and 2).

The three vascular plant species having the highest P_G in the ecosystem were *C. vulgaris*, *R. alba* and *A. polifolia*. *A. polifolia* was the most productive species in May and September, *R. alba* in June and July and *C. vulgaris* in August (Fig. 3a and 4a). With 13% cover altogether (Table 1), they formed 22% of the seasonal ecosystem P_G and 56% of the vascular plant P_G (Fig. 4). The three *Sphagnum* species with highest P_G at the ecosystem level were *S. papillosum*, *S. fuscum* and *S. rubellum* (Fig. 3b and 4b). As with all of the *Sphagnum* species, their P_G per ground area decreased steadily over the growing season (Fig. 2 and 3b). With 42% cover altogether (Table 1), they formed 40% of the seasonal ecosystem P_G , 67% of the P_G of *Sphagnum* mosses (Fig. 4).

3.2 Cumulative growing season net photosynthesis

The aboveground vegetation of the study site was a carbon sink of 77 g C m⁻² over the growing season as estimated by P_N value upscaled to ecosystem level using the species- and month-wise light response curves. P_N results for *Sphagna* and vascular plants were reversed in comparison to P_G estimates; P_N of *Sphagna* was 20 g C m⁻² and vascular P_N was 57 g C m⁻².

The same vascular plant species had the highest growing season P_N and P_G ; *R. alba*, *C. vulgaris* and *A. polifolia* had the highest P_N estimates of 15.1, 9.1 and 8.4 g C m⁻², respectively (Table 1). These three species made up 57% of the total vascular P_N and 42% of the whole ecosystem-level P_N .

S. fuscum, *S. papillosum*, and *S. majus* had the highest seasonal P_N of *Sphagnum* species 7.4, 6.8 and 2.8 g C m⁻², respectively (Table 1). The P_N of these three species was 85% of the total *Sphagnum* P_N and 22% of the seasonal ecosystem P_N . Although having one of the highest coverage and P_G , *S. rubellum* was not among the three most productive species in terms of P_N .

4 Discussion

4.1 Comparison of upscaled gross photosynthesis values with eddy covariance gross primary production estimates

Accounting for the differences in photosynthetic parameters between species and between phases of the growing season appeared to accurately estimate ecosystem P_G when upscaling species level measurements. *Sphagnum* mosses especially showed a large seasonal variation in their photosynthetic light response, which could be accounted for in this upscaling approach. The similarity of the P_G estimates calculated with species-wise and monthly light response curves and GPP estimates derived from EC measurements (Fig. 1a), adds credibility to the methods used and indicates that the photosynthetic parameters measured under laboratory conditions are comparable with field measurements. Both methods carry their error sources. Annual CO_2 flux balances from EC measurements are prone to significant systematic bias, sometimes in excess of 30%, but usually between 10–30% of the cumulative flux (e.g. Baldocchi, 2003; Rannik et al., 2006). The underestimation of the EC fluxes implicit in the unclosed energy balance (70% for Siikaneva-1, unpublished data) might be partly compensated by the Kok effect that might be more significant than thought before, as indicated by Wehr et al. (2016). Our P_G estimates include errors related to the LAI development measurements, visual species cover estimation, the conversion from cover to LAI, and the laboratory measurements of photosynthetic parameters. Although the shading of the moss layer by vascular plants may figure as a potential error source of P_G , upscaled with PFD measured above the vegetation, it is not likely to be caused by the sparse cover of vascular plants at the site (Supplementary information, Fig. S3) with low seasonal maximum LAI (Fig. 1c). By taking into account the variation between samples in the 87 P_N models (Eq. (1)) we aimed at more accurate estimation of the light response parameters. Nevertheless, our ecosystem-level P_G estimate may contain bias caused by not accounting for the random effects of the 87 models in the upscaling procedure. The cumulative growing season P_G of 230 g C m^{-2} is very similar to the 205 g C m^{-2} obtained by Alm et al., (1999) at an ombrotrophic bog site under similar climatic conditions and comparable water levels, but where the exceptionally dry conditions during the measured season reduced photosynthetic capacity of many *Sphagnum* species. Our growing season P_G was considerably lower than the 500 g C m^{-2} obtained by Moore et al., (2002) and Roulet et al., (2007) at a temperate ombrotrophic bog with much lower water table levels. While our value only covers the period from May until September, it falls just below the large range of annual GPP values (250 to 900 g C m^{-2}) measured with the EC method from seven northern peatland sites (Lund et al., 2010).

The shapes of P_G and GPP development differed over the growing season, especially at the beginning of the summer, which is largely due to the constant temperature of $20 \text{ }^\circ\text{C}$ in our laboratory measurements (Fig. 1a). The constant temperature allowed us to investigate how the changes in species-specific photosynthetic parameters were of the species affected by the seasonal changes in moisture conditions in the field. Since the large number of species studied made it unachievable to measuring of species-specific temperature responses of species-specific- P_G was unachievable due to the large number of species, we instead chose to model the temperature dependence of EC-derived GPP (Eq. (4), Fig. 1a). Our upscaled P_G values were higher than GPP in May when vascular plants had a high capacity to use low light levels (low k value) and *Sphagna* had high P_{max} (Fig. 1a) (Supplementary information, Table S1), but this was the case when temperatures in the field remained mostly below $20 \text{ }^\circ\text{C}$ and limited the measured GPP (Fig. 1b). The temperature limitation of measured GPP is demonstrated by the lower spring-time measured GPP in comparison with GPP simulated at $20 \text{ }^\circ\text{C}$ (Eq. (4), Fig. 1a). Both

measured GPP and GPP simulated at 20 °C show higher levels than P_G in July and August (Fig. 1a), for which the reason remains partly unclear. Because the difference between GPP and P_G lasted for two months, the lack of vascular plant P_G measurements in July can only partly explain this midsummer deviation between the two methods. In September, when *Sphagnum* Pmax values and k values of both vascular plants and *Sphagnum* were at their lowest, P_G , measured GPP and GPP at 20 °C were all similar despite the difference between air and laboratory temperatures (Fig. 1a). According to our results peatland photosynthesis is temperature limited, especially in spring; *Sphagnum* had a high photosynthetic potential due to favourable moisture conditions at that time (Fig. 2), but the low field temperatures limited ecosystem-level GPP (Fig. 1a and b). Temperature limitation of spring-time photosynthesis is well known for boreal forests (Tanja et al., 2003; Ensminger et al., 2004), as well as for bog *Sphagnum* (Moore et al. 2006). Mean annual temperature together with PPFD during the growing season are the most important factors explaining *Sphagnum* productivity at the global scale (Gunnarsson, 2005; Loisel et al., 2012), and the temperature optimum of *Sphagnum* photosynthesis is known to change over the growing season (Gaberščik and Martinčič, 1987). However, the temperature dependence and acclimatization of species-level photosynthesis in peatlands has been studied only with a few *Sphagnum* species (Gaberščik and Martinčič, 1987; Robroek et al., 2007).

4.2 The contribution of plant species to ecosystem-level gross photosynthesis

Among both *Sphagnum* and vascular plants, the species with the highest seasonal upscaled P_G (g C per m⁻² of ground area) – and hence the most productive species at the ecosystem scale – were also the ones with the highest areal cover. ~~No inter-species differences in photosynthetic properties, either within vascular plants or *Sphagnum*, could change this order. Neither for vascular plants nor for *Sphagnum* could this order be changed by the differences in photosynthetic properties between species.~~ At the ecosystem scale, *Sphagnum* covering on average 63% of the ground area had higher upscaled daily P_G values for the whole summer than vascular plants covering only 24% despite the lower Pmax values of *Sphagnum* (Supplementary information, Table S1). In ombrotrophic bogs, *Sphagnum* are known to be the first group to start photosynthesizing in early spring (Moore et al., 2006), which was also evident at our site (Fig. 2). Combination of low Pmax values in July and September and high respiration rates in August and September (Supplementary information, Table S2) resulted in an almost linear decrease in ecosystem-scale *Sphagnum* P_G over the growing season (Fig. 2). The seasonally decreasing *Sphagnum* P_G is likely to reflect the change in the moisture conditions. Water table depth, which, together with precipitation, is known to be the most important moderator of *Sphagnum* photosynthesis (Hayward and Clymo 1983; Backéus 1988; Lindholm 1990; Nijp et al. 2014), decreased at the study site over the growing season (Fig. 1d).

Despite low Pmax values, *R. alba* was among the three vascular plant species with highest P_G at the ecosystem scale due to its high cover at the site (Table 1). It also had a very sharp but short-lived LAI and P_G peak at the end of June (Fig. 3a), which was largely the reason for the peak in vascular plant P_G (Fig. 2), occurring slightly earlier in the season than maximum vascular LAI (Fig. 1c). Evergreen shrubs have been observed to be the second group to start photosynthesizing after *Sphagnum* in spring (Moore et al., 2006). Similarly, the vascular plants with highest upscaled P_G in May were the evergreen shrubs *A. polifolia* and *C. vulgaris* (Fig. 3a). The contributions of different species to total *Sphagnum* P_G did not differ over the growing season (Fig. 4). Based on these observations, phenology and areal cover, rather than differences in photosynthetic parameters among species seems to be the key factor in determining the species with highest P_G of a bog ecosystem.

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4.3 Ecosystem-level net photosynthesis

The variation in photosynthetic properties changed the roles of the plant species in seasonal ecosystem-level carbon sink. Although *Sphagna* had more than twice the cover of vascular plants, seasonal P_N was much lower than vascular plants (Table 1). The seasonal P_N of *Sphagnum* species was not in relation with their areal cover; for example, the species with highest cover, *S. rubellum*, had a small seasonal P_N (Table 1). *S. rubellum* has earlier found to have lower light saturated photosynthesis and higher respiration than most of the other *Sphagnum* species (Supplementary information, Table S1, Korrensalo et al., 2016). The differences in photosynthetic parameters of *Sphagnum* species seem to become much more visible in ecosystem-level P_N than of vascular plant species, since the leaf area of *Sphagna* stays similar over the growing season. The vascular plants most important for the ecosystem-level P_N were the same as the species with greatest cover. However, *T. cespitosum* with only 1% of areal cover made up 12% of the seasonal vascular P_N .

Our results indicate that in addition to areal cover of the species, differences in photosynthetic parameters between species shape the ecosystem-level carbon sink of a bog. Species with low areal cover may be important for the ecosystem carbon sink because of their high photosynthetic efficiency. However, the P_N results have to be interpreted with care, since they contain the R parameter estimated based on respiration measurements done at 20 °C, which is higher than field temperature for most of the growing season. This general overestimation of respiration may be the reason behind slightly negative seasonal P_N of *S. balticum* (Table 1).

4.4 The role of functional diversity for peatland carbon sink

According to the insurance hypothesis, species diversity both enhances productivity and decreases the temporal variance of productivity of a plant community (Yachi and Loreau, 1999). This hypothesis has gained support from testing in several ecosystem types, especially in grasslands (Hector et al., 2010; Cardinale et al., 2011; Morin et al., 2014). In addition to species and genotype diversity (Hughes et al., 2008), the functional diversity, i.e. the presence of species and plant functional types with different physiology, morphology, resource requirements, seasonal growth patterns and life history may increase the productivity of an ecosystem (Tilman et al., 1997; Cadotte et al., 2008). Although this study did not directly test the insurance hypothesis, our results also indicate that functional diversity, especially in regard of differences in phenology and seasonal changes in photosynthetic parameters, decreased the temporal variation of ecosystem-level P_G and could therefore decrease the variation of the ecosystem C sink. Vascular plant species of different phenology had the highest ecosystem-level photosynthesis at distinct phases of the growing season (Fig. 3a). In addition, *Sphagna* and evergreen shrubs formed two stable baselines of ecosystem P_G , which was further increased by the mid-summer P_G peak of the sedge *R. alba* (Fig. 3 a and b). Especially ecosystem-level *Sphagnum* P_G was modified by the seasonal decrease in photosynthetic potential (Supplementary information, Table S1). This suggests that the growing season P_G of our study site is not only more stable, but it is also larger than it would be with a more functionally homogenous assemblage of species. Several studies have suggested that the C sink function of bogs is more stable over the growing season than that of fens, which have more homogenous and sedge dominated vegetation (Bubier et al., 1998; Leppälä et al., 2008). Hence, our results should be compared with the patterns of photosynthetic productivity of a peatland site with a more homogenous plant assemblage.

Based on small-scale experimental studies, bog species and growth forms are known to vary in terms of their contribution to ecosystem productivity and to differ in their responses to manipulations of environmental conditions (Weltzin et al., 2000; Ward et al., 2009; Kuiper et al., 2014). In this study, the laboratory measurements of species photosynthetic parameters were for the first time upscaled to ecosystem level over a whole growing season and verified by the comparison with EC measurements. ~~The diversity of vegetation was found to make the photosynthetic productivity of a boreal bog species more stable over a growing season as seen by the differences within species were found to differ~~ in the timing of their maximum P_G over a growing season (Fig. 3a and b). Diversity in species responses to environmental factors is hypothesized to make a plant community more resilient towards changing conditions (Yachi and Loreau, 1999; Gunderson, 2000). In addition to species diversity, plant community diversity within an ecosystem has been shown to increase ecosystem stability during a severe drought in grasslands (Frank and McNaughton, 1991). In boreal bogs, *Sphagnum* mosses create microtopographic variations that – according to model simulations – increase resilience towards environmental perturbations both through the diversity of growth forms it supports and by variation in physical properties between microforms (Turetsky et al., 2012). To find out about the effect of bog spatial heterogeneity on ecosystem resilience, studies extending over several growing seasons are needed. As demonstrated in an arctic sedge fen, the impact of extreme weather conditions on ecosystem C sink may occur with a lag of one growing season (Zona et al., 2014). Our study provides tools to empirically study the role of species and community diversity at the ecosystem scale. The combination of laboratory measurements of photosynthetic parameters, phenological monitoring and EC measurements opens up the possibility of long-term and experimental ecosystem-level studies on the effect of functional diversity on the peatland ecosystem carbon sink. The long-term measurements would permit the inclusion of a wider range of environmental conditions. In particular, the EC method would allow for a comparison of the effect of diversity at sites with different plant assemblages.

4.5 Conclusions

The areal cover of the species determined the species with the highest gross photosynthesis while phenology in leaf area and photosynthetic activity drove the variation in ecosystem-level gross photosynthesis. In spring, potential ecosystem-level gross photosynthesis was much higher than measured gross primary production, which appeared to be due to temperature limitation of photosynthesis. Ecosystem-level net photosynthesis was more of a combination of the differences in (i) photosynthetic parameters, which were important in *Sphagna*, (ii) phenology, which largely defined vascular productivity, and (iii) areal coverage, which acted in both vascular plants and *Sphagna*.

The different growth strategies of the plant species present at our study site appeared to increase the ecosystem-level photosynthesis and decrease its variation within a growing season. We are looking forward for the future studies finding out, if the diversity of growth forms has the same stabilizing effect on the interannual variation of ecosystem-level photosynthesis.

35 Data availability

The data associated with the manuscript will be published in PANGAEA repository. Upon request, the data can also be obtained from the corresponding author.

Author contribution

EST formulated the idea. AK, TH and EST designed the measurements, which were done by AK and TH. AK, TH and EST were responsible for the primary photosynthesis data processing. Eddy covariance data collection and analysis was done by PA, JR, TV and IM. The mixed-effects models were developed by LM and AK. AK, PA and EST wrote the manuscript, which was commented by all the other authors.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Tables

Table 1 Average projection cover of the most common plant species at the study site, maximum leaf area index (LAI) values, and cumulative seasonal gross and net photosynthesis (P_G , P_N) of the species measured in this study. The cover values are based on a vegetation inventory conducted in 2013 at the study site within the 30 m radius footprint of the eddy covariance tower (N=121). LAI values of vascular plants are seasonal maxima of each species calculated by converting the cover values into LAI using species-wise linear relationships (Supplementary information, Table S2). *Sphagnum* LAI is assumed to stay similar over the growing season and is simply the coverage expressed as LAI. *Sphagnum* and vascular species nomenclature according to Laine et al., (2009) and Hämet-Ahti (1998), respectively.

Species	Cover mean \pm S.E. (%)	LAI ($m^2 m^{-2}$)	Seasonal P_G (g C m^{-2})	Seasonal P_N (g C m^{-2})
Vascular total	24.2 \pm 1.9	0.29	92.2	57.3
<i>Rhynchospora alba</i>	6.9 \pm 0.8	0.10	23.3	15.1
<i>Andromeda polifolia</i>	3.7 \pm 0.4	0.03	14.4	8.4
<i>Calluna vulgaris</i>	2.8 \pm 0.9	0.04	13.8	9.1
<i>Rubus chamaemorus</i>	2.5 \pm 0.6	0.03	6.9	4.5
<i>Eriophorum vaginatum</i>	1.5 \pm 0.3	0.02	6.0	3.8
<i>Vaccinium oxycoccos</i>	1.2 \pm 0.2	0.01	5.3	3.2
<i>Drosera rotundifolia</i>	1.1 \pm 0.1			
<i>Empetrum nigrum</i>	1.0 \pm 0.5	0.01	2.3	1.2
<i>Trichophorum cespitosum</i>	1.0 \pm 0.5	0.02	11.5	6.7
<i>Drosera longifolia</i>	0.8 \pm 0.4			
<i>Scheuchzeria palustris</i>	0.8 \pm 0.1	0.02	5.1	3.0
<i>Betula nana</i>	0.4 \pm 0.2	0.004	1.1	0.5
<i>Carex limosa</i>	0.4 \pm 0.1	0.005	2.4	1.8
<i>Sphagnum</i> total	63.8 \pm 3.7	0.65	137.8	19.9
<i>Sphagnum rubellum</i>	18.3 \pm 2.6	0.18	30.7	0.8
<i>S. papillosum</i>	12.9 \pm 2.3	0.13	33.9	6.8
<i>S. fuscum</i>	11.0 \pm 2.3	0.11	27.1	7.4
<i>S. balticum</i>	8.3 \pm 1.5	0.08	15.7	-0.5
<i>S. cuspidatum</i>	4.8 \pm 1.3	0.05	13.4	1.7
<i>S. majus</i>	4.7 \pm 1.2	0.05	12.7	2.8
<i>S. angustifolium</i>	1.3 \pm 0.5	0.01	3.6	0.6
<i>S. lindbergii</i>	0.8 \pm 0.8			
<i>S. magellanicum</i>	0.3 \pm 0.1	0.003	0.7	0.1
Other mosses and lichens				
<i>Pleurozium schreberi</i>	0.8 \pm 0.5			
<i>Mylia anomala</i>	0.2 \pm 0.1			
<i>Cladina rangiferina</i>	0.4 \pm 0.2			

Figures

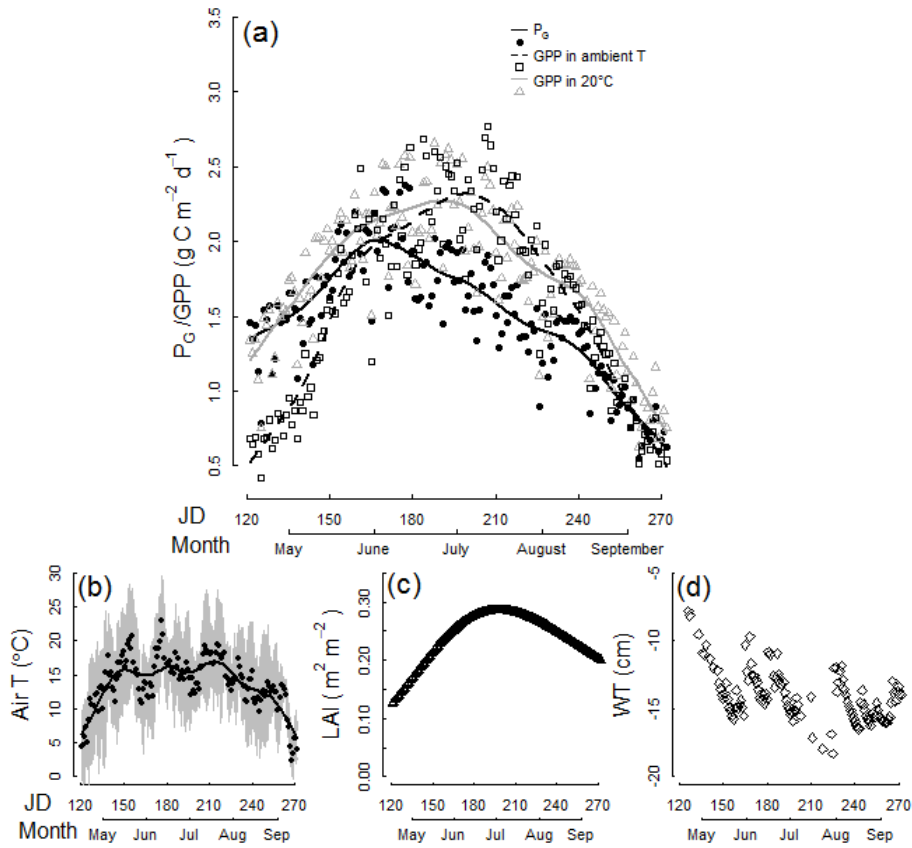


Figure 1: a) Comparison of total daily ecosystem-level gross photosynthesis estimate of all plants (P_G) derived from laboratory measurements with GPP estimates derived directly from the eddy covariance measurements and with GPP simulated at constant temperature of 20°C. The temperature in laboratory photosynthesis measurements was kept constant at 20 °C during the whole growing season. b) Daily mean air temperature (in black) and daily temperature variation (in grey fill) (Hyytiälä Forest Research Station 10 km from the study site, Finnish Meteorological Institute, 2016), c) sum of modeled vascular leaf area during the growing season 2013 and d) average daily lawn (i.e. intermediate) surface water table (WT) at the study site. Lines represent locally weighted scatterplot smoothing (Loess, smoothing parameter=0.25) curves.

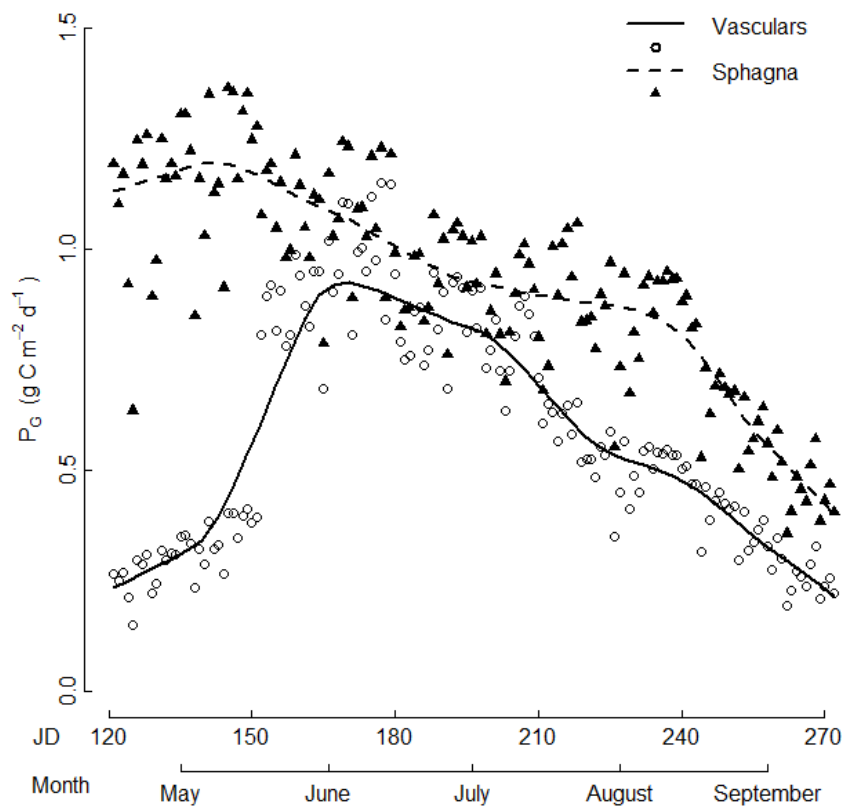


Figure 2: Daily gross photosynthesis estimates ($\text{g C m}^{-2} \text{d}^{-1}$) of vascular plants and *Sphagna* upscaled to ecosystem-level using the species-specific, monthly light response curves derived from laboratory measurements. Lines represent Loess averaging (smoothing parameter=0.25)

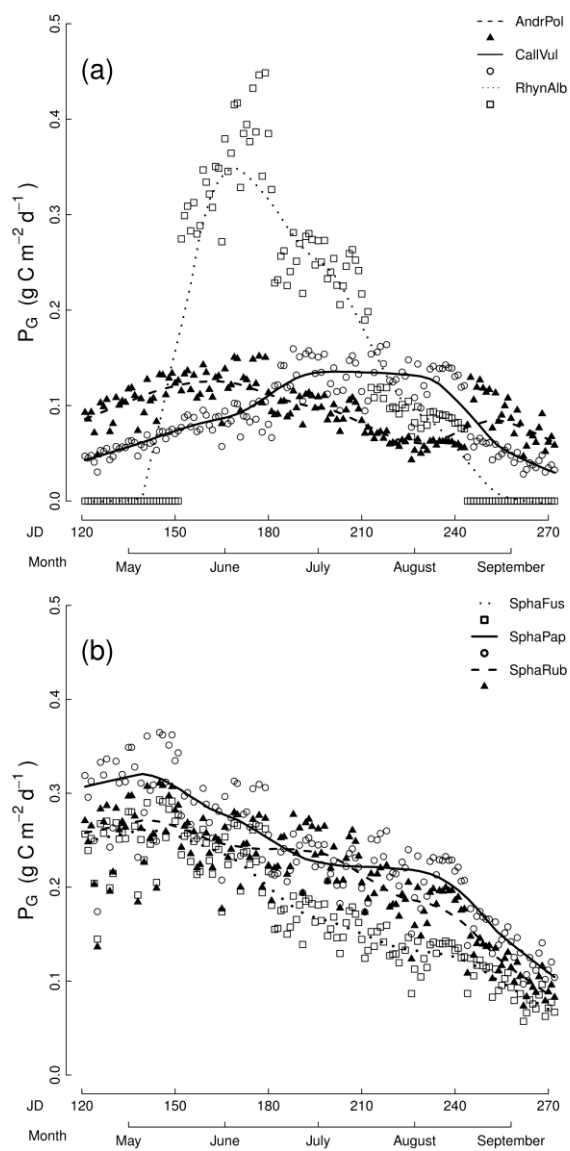


Figure 3: Daily gross photosynthesis estimates ($\text{g C m}^{-2} \text{d}^{-1}$) of the three most productive a) vascular and b) *Sphagnum* species upscaled to ecosystem-level using the species-specific, monthly light response curves derived from laboratory measurements. Lines represent Loess averaging (smoothing parameter=0.25). The species cover within the study site (EC footprint) is given in Table 1. Abbreviations of the species' names are: *AndrPol*=*Andromeda polifolia*, *CallVul*=*Calluna vulgaris*, *RhynAlb*=*Rhynchospora alba*, *SphaFusc*=*Sphagnum fuscum*, *SphaPapi*=*Sphagnum papillosum*, *SphaRube*=*Sphagnum rubellum*.

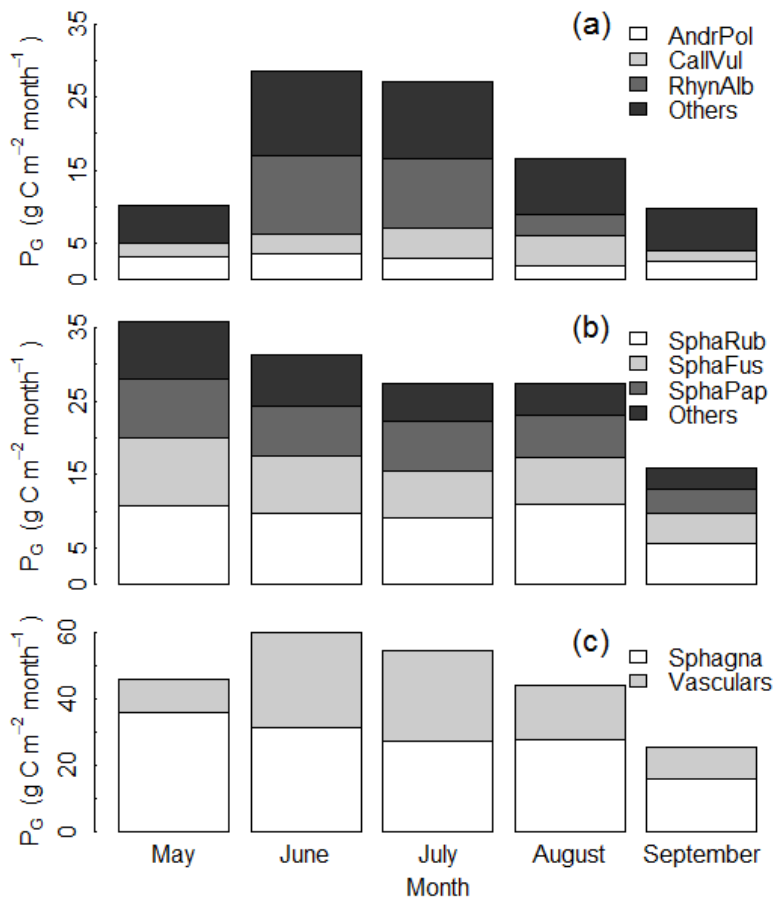


Figure 4: Species' proportions of monthly ecosystem-scale gross photosynthesis (P_G) of a) vascular plants, b) *Sphagnum* mosses and c) the contribution of those two groups to total monthly ecosystem scale P_G . Ecosystem-level P_G was calculated using the species-specific, monthly light response curves derived from laboratory measurements. For abbreviations of the species' names see Figure 3.