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CarbonSink+ — Accounting for multiple climate feedbacks from forests

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Forests cool the climate system by acting as a sink for carbon dioxide (CO_2) and by enhancing the atmospheric aerosol load, whereas the simultaneous decrease of the surface albedo tends to have a warming effect. Here, we present the concept of CarbonSink+, which considers these combined effects. Using the boreal forest environment as an illustrative example, we estimated that accounting for the CarbonSink+ enhances the forest CO_2 uptake by 10–50% due to the combined effects of CO_2 fertilization and aerosol-induced diffuse radiation enhancement on photosynthesis. We further estimated that with afforestation or reforestation, i.e., replacing grasslands with forests in a boreal environment, the radiative cooling due to forest aerosols cancels most of the radiative warming due to decreased surface albedos. These two forcing components have, however, relatively large uncertainty ranges, resulting in large uncertainties in the overall effect of CarbonSink+. We discuss shortly the potential future changes in the strength of CarbonSink+ in the boreal region, resulting from changes in atmospheric composition and climate.

Introduction

It has been recognized for decades that the biosphere plays an important role in the Earth's climate system (IPCC 1996), affecting the regional water cycle and energy balance, and storing carbon in biomass and soils (e.g. Freedman and Fitzjarrald 2001, Barth *et al.* 2005, Ellison *et al.* 2017, Teuling *et al.* 2017, Bennett and Barton, 2018). Globally, land ecosystems, including forests, mires and agricultural lands, sequester about 30% of anthropogenic carbon dioxide (CO_2) emissions (Houghton *et al.* 2012, Giglio *et al.* 2013, Le Quéré *et al.* 2015, Fernandez-Martinez *et al.* 2017).

Forests have great potential for climate change mitigation. In addition to substituting fossil fuels via the use of bioenergy and less carbon intensive materials, forests act as a carbon sink (e.g. Bonan 2008) and a source of

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aerosol particles (e.g. Tunved *et al.* 2006, Kerminen *et al.* 2018). The climatic effects of forest management on the carbon balance are supplemented by changes in the surface albedo, evapotranspiration and the release of volatile organic compounds (VOCs) (Pielke *et al.* 2002, Bonan 2008, Jackson *et al.* 2008, Ellison *et al.* 2017, Arvesen *et al.* 2018). These biogenic VOCs are oxidized into condensable vapors in the forest atmosphere, increasing the number and mass concentrations of aerosol particles (Kulmala *et al.* 1998, Tunved *et al.* 2006, Ehn *et al.* 2014, Lehtipalo *et al.* 2018). The additional aerosol loading due to forest emissions influences cloud properties and photosynthesis (e.g. Kerminen *et al.* 2012, Ezhova *et al.* 2018, Petäjä *et al.* 2020), enhancing both carbon uptake and radiative cooling in forest ecosystems. In addition to influencing atmospheric aerosol loads and carbon uptake, biogenic VOCs emitted by forests alter atmospheric concentrations of methane and ozone (Unger 2014, Scott *et al.* 2008a), two globally very important greenhouse gases.

Recently, Koch *et al.* (2019) showed an example on how historical reforestation has caused a cooling effect on climate. They investigated the climate effect and Earth system impacts of the European arrival and the Great Dying in the Americas after 1492 by combined multiple methods in estimating pre-Columbian population numbers. According to their estimate, the European arrival in 1492 lead to 56 million deaths by 1600. The large population reduction led to a reforestation of 55.8 Mha and an additional uptake of 7.4 Pg C. Accordingly, by 1610 this depopulation of the Americas was estimated to explain a large fraction of the atmospheric CO_2 concentration decrease of 7–10 ppm within 100 years and a temperature decrease of 0.15°C. This demonstrates how humans have contributed to Earth system changes already before the Industrial Revolution.

To make the scientific basis of climate change mitigation based on afforestation/reforestation activities more complete, we introduce here the concept of CarbonSink+. It includes the combined effects of CO_2 fertilization and aerosol-induced diffuse radiation enhancement on photosynthesis, and thereby on the forest carbon uptake, as well as changes in surface and cloud albedos as a result of reforestation or afforestation. In general, the CarbonSink+ analysis will provide tools to: 1) optimize afforestation and reforestation activities, and 2) analyze the net climate impact of these activities, and this way enhance tackling of the increasing greenhouse gas concentration due to anthropogenic emissions, and the consequent warming. We focus our analysis on the boreal forest environment, keeping in mind that the general idea of CarbonSink+ is in principle applicable to other forest ecosystems as well.

Different components of CarbonSink+

Forest ecoystem-based climate mitigation has usually been thought to take place through conserving and enhancing the carbon sink and through reducing greenhouse gas emissions from deforestation (e.g. Grassi *et al.* 2017). CarbonSink+ builds on this idea and extends it in two ways. First, CarbonSink+ attempts to take into account the influences of changing atmospheric composition on the forest carbon uptake over the time scales relevant for afforestation/reforestation activities. This is motivated by the notable changes in the global terrestrial carbon sink observed during the recent decades (Sarmiento *et al.* 2010, Ballantyne *et al.* 2012, Campbell *et al.* 2017, Ciais *et al.* 2019). Second, CarbonSink+ considers the facts that in addition to acting as a carbon sink, forests perturb the climate system by changing the surface albedo and atmospheric aerosol loading (e.g. Kulmala *et al.* 2004, 2013, Makkonen *et al.* 2012, Favero *et al.* 2018). In the following, we look at these components in more detail individually, and then combine them using the radiative forcing concept. We do not consider the potential influences of afforestation/reforestation activities on atmospheric methane or ozone budgets, not the resulting radiative forcing. Based on our current understanding, this appears justified for the boreal forest environment, but the situation might be totally different for temperate and tropical forests (Scott *et al.* 2018b).

Enhanced carbon uptake through fertilization by CO_2 and diffuse radiation

Forest ecosystems are globally an efficient carbon sink (e.g. Pan *et al.* 2011). Forests remove CO_2 from the atmosphere via photosynthesis (gross primary productivity, GPP) and consequent net ecosystem production (NEP). Although the basic mechanisms of GPP and NEP are well understood, there are still uncertainties in accounting for all biogeochemical and biophysical feedback mechanisms affecting the overall strength of the carbon sink (e.g. Hyvönen *et al.* 2007, Norby and Zak 2011, Jiang *et al.* 2020).

Among the factors influencing historical changes in terrestrial photosynthesis, CO_2 fertilization caused by increasing atmospheric CO_2 levels has usually been identified as the main contributing factor (Fernandez-Martinez *et al.* 2017, Liu *et al.* 2019, Tharammal *et al.* 2019). Fernandez-Martinez *et al.* (2017) estimated the relative importance of CO_2 fertilization, sulfur and nitrogen deposition, atmospheric temperature change and other possible contributing factors on observed GPP increases at 23 temperate and boreal forest sites over the period from 1995–2011. They found CO_2 fertilization to be the dominant contributor and estimated that, averaged across all the sites, it increased the GPP by 4.49 ± 0.75 g C m^{-2} $year^{-1}$ for each ppm increase of the atmospheric CO_2 concentration. Since the CO_2 concentration increase was 2.04 ppm $year^{-1}$ during the same period (Fernandez-Martinez *et al.* 2017), the annual increase of GPP due to CO_2 fertilization was equal to 9.16 ± 1.53 g C m^{-2} $year^{-1}$.

Atmospheric aerosol particles enhance the diffuse component of incoming solar radiation and boost photosynthesis via diffuse radiation fertilization (Gu *et al.* 2002, Niyogi *et al.* 2004, Mercado *et al.* 2009, Cirino *et al.* 2014, O'Sullivan *et al.* 2016, Strada and Unger 2016, Ezhova *et al.* 2018, Xie *et al.* 2020). This leads to a positive feedback on the forest carbon uptake. In order to estimate the enhancement of carbon uptake via the combined effect of CO_2 fertilization and aerosol-induced changes in diffuse radiation, we employed the classical feedback–amplifier analysis for photosynthesis, GPP (Fig. 1). In this approach, GPP_{in} represents

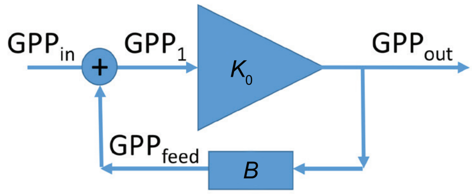

Fig 1. Schematic picture of a nonlinear amplifier with feedback (see, e.g. Coleman 2004), as applied here for photosynthesis, GPP. See text for the definition of the terms in this figure.

photosynthesis in the absence of any amplifying factor or feedback, K_0 is the amplifying factor for GPP due to CO_2 fertilization, B is the fraction of photosynthesis caused by the aerosol-induced diffuse radiation on GPP (GPP_{feed}), and GPP_{out} represents photosynthesis after including both these effects. Noting that these quantities are connected to each other via (Fig. 1):

$$GPP_{feed} = B \times GPP_{out},$$
$$GPP_1 = GPP_{in} + GPP_{feed},$$
$$GPP_{out} = K_0 \times GPP_1,$$

we obtain the overall enhancement factor for photosynthesis:

$$K_{GPP} = GPP_{out} / GPP_{in} = K_0 / (1 - B \times K_0). \quad (1)$$

The net ecosystem production (NEP) is equal to the difference between the carbon uptake in photosynthesis (GPP) and the total ecosystem respiration (R_C),

$$NEP = GPP - R_C, \quad (2)$$

and in analogy to Eq. 1, we can define the enhancement factor for NEP as:

$$K_{NEP} = NEP_{out} / NEP_{in}. \quad (3)$$

Although R_C is known to be sensitive to climate variables, especially the temperature (e.g. Goodwin *et al.* 2019, Williams *et al.* 2019), we next assume that R_C is affected by neither CO_2 fertilization nor aerosol-induced changes in diffuse radiation. As an independent justification for this approximation, we refer to Fernandez-Martinez *et al.* (2017), who observed that

NEP and GPP had very similar trends during 1995–2011 when averaged over 23 forest sites in Europe and USA, while the corresponding R_C showed practically no trend. This situation may, however, change in the future, as discussed later in this paper. By combining all of the above together, we finally obtain:

$$K_{NEP} = (GPP_{out} - R_c) / (GPP_{in} - R_c)$$
$$= [K_{GPP} - (R_c / GPP_{in})] / [1 - (R_c / GPP_{in})]. \quad (4)$$

K_{NEP} can be interpreted as the overall enhancement factor for the net forest carbon uptake caused by the combined effect of CO_2 fertilization and aerosol-induced changes in diffuse radiation.

Forcing associated with surface albedo changes

One of the main criticisms against addressing climate change mitigation by afforestation and reforestation, especially in boreal environments, is directed to albedo changes associated with changing land area from open vegetation to forest (Betts 2000, Canadell and Raupach 2008, Jackson *et al.* 2008, Arora and Montenegro 2011, Favero *et al.* 2018, Luyssaert *et al.* 2018). It is true that increased (dark) evergreen forest cover decreases the surface albedo and therefore has a warming effect compared with many other land cover types. However, estimated albedo effects over boreal forests vary widely in the literature (Betts 2000, Bright *et al.* 2014, Alkama and Cescatti 2016), reflecting spatio-temporal differences in forest properties and associated uncertainties in empirical data. As an example, two studies that both derived albedo values from MODIS satellite produced different surface albedo changes when comparing forest and non-forest patches images (O'Halloran *et al.* 2012, Kuusinen *et al.* 2014). This difference was largest in mature forests during the snow-cover period in winter and spring.

We estimated the shortwave surface albedo of a boreal environment based on typical seasonal conditions at the SMEAR II (Station for

Table 1. Summary of the values used in surface albedo calculations, and the resulting total albedos. The baseline values of the boreal forest albedo (0.3–3 µm) are based on the work by Kuusinen *et al.* (2012, 2014) and those of the bare and snow-covered grassland are taken from Briegleb and Ramanathan (1982), Briegleb *et al.* (1986) and Gardner and Sharp (2010). The majority of clouds are considered to be low-level clouds, for which the cloud albedo lies in the range of 0.4–0.7 depending on the cloud thickness (Sena *et al.* 2016). We assumed a cloud albedo of 0.7. The length of day is assumed to be 7 h, 12 h and 17 h in winter, transitional periods and summer, respectively. Cloud cover data are based on observations at the SMEAR II station.

	Albedo without clouds	Cloud cover	Total albedo
Forest, baseline			
summer	0.13	0.55	0.44
transitional	0.22	0.70	0.56
winter	0.30	0.80	0.62
Average over the year			0.50
Grassland, baseline			
summer	0.21	0.55	0.48
transitional	0.44	0.70	0.62
winter (snow)	0.66	0.80	0.69
Average over the year			0.55
Grassland, 10% cloud cover reduction in summer			
summer	0.21	0.50	0.46
transitional	0.44	0.70	0.62
winter (snow)	0.66	0.80	0.69
Average over the year			0.54

Measuring Forest Ecosystem–Atmosphere Relations) station and compared it to an albedo corresponding grassland environment (Table 1). For this purpose, we considered separately the summer period (May– September), winter period (November–February) and transitional periods (October, March and April), and took into account the variability in the length of day over the year. We found that under current cloud cover conditions, the difference in the annual-average albedo between the boreal forest and grassland is 0.05. Betts (2000) argued that the mean annual albedo difference between the boreal forest and cropland is in the range of 0.1–0.3. This, considerably larger albedo difference compared with our estimate is at least partly due to the following reasons. First, Betts (2000) used an upper limit of 0.78 for the snow albedo, representing deep snow, whereas the average snow albedo of 0.66 (e.g. Gardner and Sharp 2010) was adopted here. Second, Betts (2000) considered a dense coniferous forest with a small winter albedo of 0.26, although the average managed boreal forest is not necessarily dense but rather has an open canopy structure. We assumed a winter forest albedo of 0.3 based on the observations done at the SMEAR II station (Table 1 in Kuusinen *et al.* 2014). Third, the percentage of cloud cover in winter is very high (80%) at the SMEAR II station, making the annual-average albedo only weakly sensitive to the albedo of the underlying surface in winter. Based on the daytime cloud climatology in winter (Eastman *et al.*: Climatic Atlas of Clouds Over Land and Ocean; https://atmos.uw.edu/CloudMap/index.html; last visited: 27 Oct. 2020), this result can be generalized to Northern Europe and Northern European Russia to Ural Mountains (longitudes 0–60°E).

Compared with non-forested areas, there are strong indications that the presence of forests enhances the regional cloud cover (Heiblum *et al.* 2014, Teuling *et al.* 2017, Bosman *et al.* 2019, Pearce 2020). We explored this possibility by assuming that, compared with a boreal forest environment, a grassland has 10% lower cloud cover during the summer period. This results in an annual-average albedo difference of 0.03 between a boreal forest and grassland (Table 1). We stress that any cloud cover changes associated with transitions between forested and non-forested areas depends in a complicated way on water and energy exchange between the surface and atmosphere (e.g. Jackson *et al.* 2008, Bosman *et al.* 2019, Petäjä *et al.* 2020).

In order to convert the surface albedo difference (range: 0.04–0.05) into radiative forcing, we used a value of 200 W m^{-2} for the annual-average short-wave radiation intensity on the top of atmosphere representative of the SMEAR II station. The resulting radiative forcing difference between a boreal forest and grassland is therefore in the range of 8–10 W m^{-2}.

Forcing associated with forest aerosols

In addition to increasing the amount of diffuse radiation in the air, and especially inside a forest canopy, aerosol particles produced from biogenic VOC emissions are capable of enhancing cloud albedos, and thereby decreasing the intensity of solar radiation reaching the Earth's surface (Kulmala *et al.* 2004, Spracklen *et al.* 2008, Makkonen *et al.* 2012, Scott *et al.* 2018b). Spracklen *et al.* (2008) investigated the local cloud albedo forcing over a boreal forest using a global model and estimated its annually-averaged value to be in the range from –1.6 W m^{-2} to –6.7 W m^{-2}. Kurten *et al.* (2003) used observations made in Hyytiälä, Finland, and estimated this forcing to lie between –1.0 W m^{-2} and –12 W m^{-2} (best estimate: –5.4 W m^{-2}) when assuming that all particles larger than 80 nm in diameter act as CCN. This 80-nm threshold is consistent with cloud microphysical observations made at the northern edge of a boreal forest zone (Komppula *et al.* 2005).

The forcing estimates discussed above include only the cloud albedo effect. Mülmenstädt *et al.* (2019) separated radiative forcing by aerosol-cloud interactions and cloud adjustments from climate model simulations, and estimated that compared with the cloud albedo forcing in the global atmosphere, the forcing by the cloud liquid water path adjustment is equally strong and that by cloud-fraction adjustment is somewhat weaker. This result is inconsistent with observations made downwind from volcanic and various anthropogenic aerosol sources, showing only weak responses of the cloud liquid water path to aerosol perturbations (Malavelle *et al.* 2017, Toll *et al.* 2019). Finally, besides its influences on warm clouds via biogenic VOC emissions, forest vegetation is also a source of primary biological aerosol particles (PBAP) capable of acting as ice nuclei (Morris *et al.* 2014). The magnitude of PBAP sources and their impacts on ice or mixed-phase clouds are poorly quantified (Tegen and Schepanski 2018), so no radiative forcing estimate by this aerosol type over the boreal forests can be made at the moment.

In addition to the cloud albedo effect, forest aerosols cause a direct radiative effect by scattering a fraction of incoming solar radiation back to space. Lihavainen *et al.* (2009) used atmospheric observations to derive the direct radiative forcing by the boreal forest aerosol and estimated it to be about an order of magnitude lower than the corresponding cloud albedo forcing. Paasonen *et al.* (2013) and Sporre *et al.* (2019) ended up with the same conclusion when estimating the global radiative forcing by biogenic secondary organic aerosol using atmospheric observations and global model simulations, respectively.

The overall effect of CarbonSink+

In order to combine the climatic effects due to CO_2 and the warming-induced enhanced forest carbon uptake and aerosol-cloud interactions related to the forest aerosols (CarbonSink+), we use radiative forcing as a common metric. Then we compared them with the corresponding surface albedo effect.

The radiative forcing due to carbon uptake changes and accumulates over time, being dependent on the time-integrated value of NEP when taking into account the CO_2 lifetime in the atmosphere (Frolking and Roulet 2007, Lohila *et al.* 2010, Neubauer and Megonigal 2015). A commonly used approach is to assume four separate atmospheric CO_2 pools that have lifetimes of τ_i = 4.30, 36.5, 394 and ∞ years and corresponding fractions f_i = 0.276, 0.282, 0.224 and 0.217 of the total atmospheric CO_2 concentration (Joos *et al.* 2013). Each of these pools gives the following contribution to the global radiative forcing at time *t* after the beginning of carbon uptake (e.g. Frolking and Roulet 2007):

$$F_i(t) = \mathrm{A} \times f_i \times \int_0^t \mathrm{NEP}(t') \times \exp[(t'-t)/\tau_i]dt', \tag{5}$$

where A = 1.77×10^{-15} W m^{-2} (kg CO_2)$^{-1}$ ≈ 5.31×10^{-18} W m^{-2} (g C)$^{-1}$ is the radiative efficiency of CO_2 (Joos *et al.* 2013). The total radiative forcing at time *t*, $F(t)$, due to the cumulative carbon uptake is the sum of these four pools.

With NEP typically given as g C m^{-2} per some time unit, F (W m^{-2} m^{-2}) represents the global radiative forcing due to the carbon uptake, caused by one square meter of forest. The global radiative forcing of the whole forest would thus be equal to F times the total forest area A_{for}. The radiative forcing due to forest aerosol-cloud interactions (F_{AER}) and surface albedo changes associated with reforestation/afforestation (F_{SUR}) are local, so the corresponding global forcings would be equal to F_{AER} (or F_{SUR}) times A_{for}/A_{tot}, where A_{tot} = 5.1×10^{14} m^2 is the total surface area of the Earth. The global values of the three forcings are thus equal to $F \times A_{for}$, $F_{AER} \times A_{for}/A_{tot}$ and $F_{SUR} \times A_{for}/A_{tot}$. While global forcings are needed in simulating the Earth' radiation budget, for the purposes of this paper we only need to compare the relative magnitudes of the forcings. To get rid of the unknown forest size, we therefore multiply the three global forcing values with the ratio A_{tot}/A_{for}, which results in the following three quantities: $F \times A_{tot}$, F_{AER} and F_{SUR}. Essentially, this procedure turns the radiative forcing by forest carbon uptake to the same framework as the two local forcings, F_{AER} and F_{SUR}.

Let us denote the radiative forcing due to the enhanced forest carbon uptake (NEP$_{out}$) by F_{C+} (= $F \times A_{tot}$) and the radiative forcing due to the forest carbon uptake without CO_2 fertilization and aerosol-induced changes in diffuse radiation (NEP$_{in}$) by F_C. With the help of Eq. 3 and approximate linearity between the carbon uptake (NEP) and associated forcing (Eq. 5), the enhancement factor for the negative radiative forcing due to CarbonSink+ is then equal to:

$$\begin{aligned} K_{F,C+} &= \left(F_{C+} + F_{AER} + F_{SUR}\right)/F_C \\ &= \left(F_{C+}/F_C\right)\times\left(F_{C+} + F_{AER} + F_{SUR}\right)/F_{C+} \\ &\approx K_{NEP}\left(1 + F_{AER}/F_{C+} + F_{SUR}/F_{C+}\right). \end{aligned} \tag{6}$$

In addition to $F_{C+} + F_{AER} + F_{SUR}$, Eq. 6 could easily be extended to include any other forcing mechanism caused by changes in the forest cover.

CarbonSink+ and boreal forests

Preliminary estimate on the current strength of CarbonSink+

We take the boreal forest environment as an example to illustrate the potential strength of CarbonSink+. As many of the quantities needed in calculating the values of K_{NEP} or $K_{F,C+}$ cannot be quantified over the whole boreal forest area, we focus on data representative of the region around the SMEAR II station in Hyytiälä, Southern Finland (Hari and Kulmala 2005). The SMEAR II station is located in a rather homogenous Scots pine (*Pinus sylvestris*) stand on a flat terrain at Hyytiälä Forestry Field Station of the University of Helsinki (61°51'N, 24°17'E, 181 m above sea level) 220 km north from Helsinki. The annual long-term average temperature in the area is +3.5°C, with February being the coldest month (–7.7°C) and July being the warmest month (+16°C). The mean annual precipitation from 1981 to 2010 was 711 mm. The managed stand was established in 1962 by sowing after the area had first been treated with prescribed burning and light soil preparation. The soil type is Haplic podzol formed in a glacial till, with the average thickness of the soil being 50–150 cm, and the ground vegetation mainly consists of bilberry-lingonberry-mosses. The canopy height is about 20 m, with an average tree density of 1370 stems (diameter at breast height > 5 cm) per hectare (Ilvesniemi *et al.* 2009) and the average all-sided leaf area index 8.0 m^2 m^{-2} (Hari *et al.* 2013). Due to recent thinning operations, the current values for these two variables are 1232 stems per hectare and 7.8 m^2 m^{-2}.

We start from the enhanced forest carbon uptake, K_{NEP}, associated with CarbonSink+. For this purpose, we need to estimate K_0, B and the ratio between R_C and GPP_{in}. When it comes to the value of K_0, responses of the plants to the increased CO_2 concentration are controversial (e.g. Medlyn *et al.* 2013), and typically the CO_2 fertilization effect on GPP is the strongest in stands with a low leaf area index when the light-limitation of photosynthesis is infrequent. To minimize the large uncertainties related to the strength of CO_2 fertilization at any individual site, we take all the 23 forest sites by Fernandez-Martinez *et al.* (2017) into the consideration. By comparing the site-average, annual increase of GPP ascribed to the CO_2 fertilization effect (9.16 ± 1.53 g C m^{-2} $year^{-1}$) to the corresponding absolute value of GPP (1400 g C m^{-2} $year^{-1}$) by Fernandez-Martinez *et al.* (2017), we obtain $K_0 = 1.0065 \pm 0.0010$. In case of B, it is very difficult to provide the best estimate on this quantity or its uncertainty range based on the available data. Ezhova *et al.* (2018) determined the effect of aerosol particles on radiation and GPP at five boreal and hemiboreal forest sites. In the absence of clouds, they estimated that aerosol particles caused a maximum increase of 6% in GPP at the SMEAR II station, and the corresponding increases were 13% in northern Finland and 14% in Estonia. Strada and Unger (2016) simulated changes in GPP due to pollution aerosols using an Earth system model and obtained annually-average increases of 5–8% over both Eurasia and eastern North America. In the following calculation, we select $B = 0.04$ (range: 0.02–0.08), keeping in mind that these values are not based on any statistical analyses. To get some estimate on the ratio R_C / GPP, we use 18 years of data (2001–2019) from the SMEAR II station, which gives R_C / GPP = 0.79. By combining all these values, we obtain $K_{NEP} = 1.23$ (range: 1.12–1.46).

In order to determine the overall strength of CarbonSink+, we need to estimate the values of F_{C+}, F_{AER} and F_{SUR} in Eq. (6). As discussed earlier, F_{AER} is likely to be dominated by the cloud albedo effect in a boreal forest environment. Here, we adopt the best estimate of –5.4 W m^{-2} by Kurten *et al.* (2003) with the large associated uncertainty range from –1.0 W m^{-2} to –12.3 W m^{-2}. For F_{SUR}, we assume the range of 8–10 W m^{-2} obtained earlier for the conditions representative of those at the SMEAR II station. The observed value of NEP at the SMEAR II station, measured with the eddy covariance method, has increased from about 187 ± 35 g C m^{-2} $year^{-1}$ during 2001–2005 to about 274 ± 26 g C m^{-2} $year^{-1}$ during 2015–2019 (https://avaa.tdata.fi/web/smart, https://etsin.fairdata.fi/dataset/b478533f-cc86-4ac1-ad2a-3941c6dd4f00; last visited: 27 Oct. 2020). The pine stand around the SMEAR II station has been recovering from the thinning made in 2012, so the increasing biomass may explain a significant fraction of this increased NEP (Grönholm *et al.* 2018).

According to Eq. (5), the radiative forcing of the forest carbon uptake increases with time. For simplicity, we assume here the NEP to be in the range of 200–300 g C m^{-2} year^{-1} and consider the forcing after 20–60 years of carbon uptake. This results in F_{C+} in the range of about –8 W m^{-2} to –24 W m^{-2}. By selecting the middle point of this range as the best estimate, we finally get $K_{F,C+}$ = 1.0 (range: 0–1.9) as also summarized in Table 2. The large uncertainty range of this estimate is mainly due to uncertainties in the ratio F_{AER} / F_{C+} in Eq. (6).

CarbonSink+ in changing atmospheric conditions

Over the time scales of tens of years, relevant for climate mitigation by afforestation/reforestation activities, changes in atmospheric composition and climate are likely to influence the different components dictating the strength of CarbonSink+. Here we discuss shortly this issue, noting that the complexity of atmosphere-biosphere interactions and feedbacks prevents us from making quantitative estimates on these future changes.

Carbon-cycle feedbacks operating in the climate system influence the carbon sink, and hence K_{NEP} in Eq. (4), through either GPP or R_C (e.g. Williams *et al.* 2019). While there is a good scientific basis for enhanced carbon uptake due to CO_2 fertilization during the recent decades (Keenan *et al.* 2016, Fernandez-Martinez *et al.* 2017, Liu *et al.* 2019, Tharammal *et al.* 2019), concerns have been raised whether this effect would not be sustained at increasing atmospheric CO_2 concentration levels (e.g. Hyvönen *et al.* 2007, Norby and Zak 2011, Kalliokoski *et al.* 2018, Tharammal *et al.* 2019, Jiang *et al.* 2020). Our estimate on the strength of CarbonSink+ did not consider potential changes in R_C. Trends of R_C change have differed from those of GPP during last decades and include large uncertainties (e.g. Li *et al.* 2018), although the increase in global soil respiration has been well constrained (Jian *et al.* 2018). However, there are strong indications that R_C will increase in the future, mainly as a response of elevated ambient temperatures but also due to higher carbon uptake at elevated CO_2 concentrations (e.g. Tharammal *et al.* 2019, Williams *et al.* 2019, Jiang *et al.* 2020)

Contrary to carbon-cycle feedbacks that may decrease the strength of CarbonSink+ in the future, aerosol-related feedbacks tend to increase it (Kulmala *et al.* 2013, Fig. 2). In boreal and temperate zones, increasing ambient temperatures increase GPP, VOC emissions from the trees and aerosol formation (Kulmala *et al.* 2004, Makkonen *et al.* 2012, Grote *et al.* 2013, Liao *et al.* 2014), and this chain of processes constitutes a negative feedback loop for global warming. Based on temperature-dependent changes in observed particle number size distributions, Paasonen *et al.* (2013) estimated the magnitude of this feedback for 11 continental sites and found it to be largest in the boreal forest environment, with growing-season mean values ranging

Table 2. Estimates of radiative forcing due to forest-related phenomena.

Phenomenon	Min. benefit	Best guess	Max. benefit
ACI effect on SW radiation, F_{AER}	–1 W / m^2	–5.4 W / m^2	–12.3 W / m^2
Surface albedo, F_{SUR}	10 W / m^2	9 W / m^2	8 W / m^2
Forest carbon sink accounting for diffuse radiation and CO_2 fertilization, F_{C+}	–8 W / m^2	–16 W / m^2	–24 W / m^2
Forest carbon sink not accounting for diffuse radiation and CO_2 fertilization, F_C	–6.5 W / m^2	–13 W / m^2	–19.5 W / m^2
Total increase, coefficient, $K_{F,C+}$	0	1	1.9

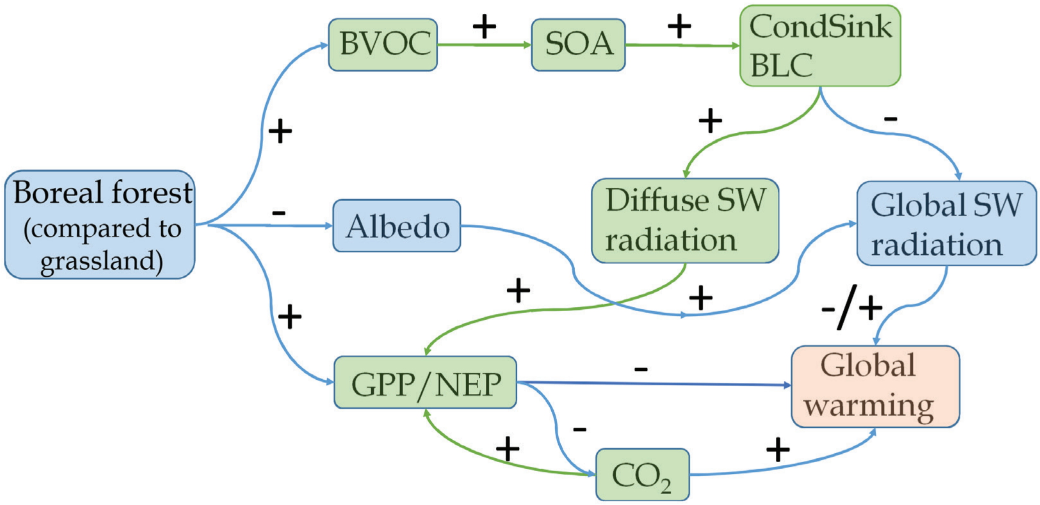

Fig 2. Schematic of the boreal forest effect on warming illustrating CarbonSink+ concept. GPP refers to the gross primary production, NEP to net ecosystem production, BVOC to biogenic volatile organic compounds, SOA to secondary organic aerosol, CondSink to condensation sink, BLC to boundary layer clouds, SW to shortwave radiation. Plus (minus) means a positive (negative) response between the two quantities linked by an arrow. Green arrows correspond to enhancing interactions in CarbonSink+.

between about –0.4 W m^{-2} K^{-1} and –0.7 W m^{-2} K^{-1} among four boreal forest sites. By using the same data set, Paasonen *et al.* (2013) estimated the global cloud albedo feedback due to biogenic secondary organic aerosol. The resulting value of about –0.01 W m^{-2} K^{-1} is close to that (–0.013 W m^{-2} K^{-1}) obtained later by Scott *et al.* (2018b) using global model simulations. Considering plausible future temperature increases, this feedback cannot be neglected when considering future changes in CarbonSink+.

Future changes in the aerosol-induced diffuse radiation effect on photosynthesis are tied to increasing atmospheric CO_2 concentrations and temperatures (Fig. 2), and to changes in anthropogenic emissions of aerosol particles or their precursors. Kulmala *et al.* (2014) made the first attempt to isolate the role of the CO_2 concentration increase in this regard at a boreal forest site. They reported a potentially large feedback, however with a large uncertainty range. In a boreal forest environment, increasing atmospheric CO_2 concentrations and temperatures are expected to act together in favor of increased aerosol concentrations, thereby enhancing carbon uptake via diffuse radiation fertilization. Model simulations indicate potentially large effects of anthropogenic aerosols on photosynthesis via diffuse radiation (Strada and Unger 2006), as well as considerable geographical differences in how this effect has changed during the recent past (O'Sullivan *et al.* 2016). In the future, anthropogenic aerosol concentrations are expected to decrease practically everywhere as a result of tightening air quality regulations (Smith *et al.* 2016, Gidden *et al.* 2019). This would decrease the strength of forest carbon uptake, however to very different degrees in different parts of the world.

In addition to feedbacks discussed above, the changing climatic conditions will cause other phenomena that will influence one or several components of CarbonSink+. These include changes in the occurrence and severity of forest fires (Rogers *et al.* 2015, Liu *et al.* 2016, Veira *et al.* 2016, Walker *et al.* 2019), in forest growth and mortality (Allen *et al.* 2010, Searle and Chen 2018, Babst *et al.* 2019) and in stress-related biogenic VOC from the forest biosphere (Toome *et al.* 2010, Noe and Niinemets 2020), as well as influences of climate extremes on the carbon cycle (e.g. Reichstein *et al.* 2013). Furthermore, the dependency of albedo effect on snow cover in conifer forest canopy is strongly dependent on the winter precipitation, and in case it is not coming as snow, this may change the magnitude of albedo effect.

Conclusions and outlook

We introduced CarbonSink+, which is a new concept to describe the integrative importance of forest ecosystems in mitigating future climate change. CarbonSink+ includes the combined effects of CO_2 fertilization and aerosol-induced diffuse radiation enhancement on photosynthesis, and thereby on the forest carbon uptake, as well as changes in surface and cloud albedos as a result of reforestation or afforestation activities. In addition to describing the theoretical framework of CarbonSink+, we performed an order-of-magnitude estimation of its strength in a boreal forest environment and discussed relevant issues likely influencing the future strength of Carbonsink+.

We estimated that the current forest carbon uptake is likely to be enhanced by 10–50% due to the combined effects of CO_2 fertilization and aerosol-induced diffuse radiation enhancement on photosynthesis in boreal forests. While the CO_2 fertilization effect has been extensively studied, the aerosol-induced diffuse radiation effect has remained poorly quantified despite its potentially large impacts on the forest carbon uptake. Replacing non-forested areas with forests decreases the surface albedo, causing a warming effect, whereas aerosol particles originating from forest VOC emissions cause an opposite, cooling effect via aerosol-cloud interactions. We estimated that the radiative cooling due to forest aerosols cancels most of the radiative warming due to the surface albedo effect in the boreal environment, however large uncertainties remain in the relative strengths of these opposite effects. Based on available literature data, it seems likely that the radiative effects of aerosol-cloud interactions are dominated by the cloud albedo effect over a boreal forest environment, but the situation might be different in other forest ecosystems. Furthermore, based on our current understanding, cloud cover changes associated with increasing forest areas are beneficial for climate change mitigation, but quantifying this effect requires further investigations.

Compared with the current situation, future changes in atmospheric composition and climate conditions are expected to influence all the components of CarbonSink+. We discussed briefly the plausible implications of such changes.

Our preliminary analysis conducted here indicates that regional-scale afforestation and reforestation activities would have larger climate benefits than usually thought, making such efforts an important tool to mitigate climate change through increased biosphere carbon sinks and storages in a sustainable manner. Most importantly, such actions could give mankind more time to significantly reduce fossil carbon emissions and further to control the carbon balance of the atmosphere-to-Earth surface continuum. However, considering the large uncertainties involved, we would need to perform observations all around the world and different ecosystems to be able to find out how important CarbonSink+ would be globally. This will be a crucial part of the Global SMEAR activity (Kulmala 2018).

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