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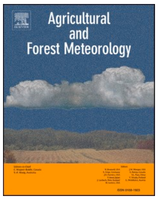

From source to sink – recovery of the carbon balance in young forests

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ABSTRACT

We analyzed ecosystem carbon fluxes from eddy-covariance measurements in five young forests in southern Sweden where the previous stand had been harvested by clear-cutting or wind-felled: three stands with Norway spruce (*Picea abies* (L.) Karst.), one with Scots pine (*Pinus sylvestris*) and one with Larch (*Larix x eurolepis* A. Henry). One of the spruce stands had the stumps harvested, one was fertilized and one without any special treatments. These stands returned from positive (sources) to negative (sinks) annual carbon fluxes 8–13 years after disturbance, depending on site productivity and management. This corresponds to approximately 15% of the rotation periods at these sites. Extrapolation in combination with chronosequence data suggests that conventionally regenerated stands reach a neutral carbon balance after approximately 30% of the rotation period. The lowest carbon emissions and shortest recovery time was observed in a stand where the stumps of the trees, in addition to the stems and logging residues, were removed after harvest. This stand not only returned to a carbon sink within this time period but the total carbon gains since disturbance also equaled the total losses after only 11 years. These results stress that production stands in southern Sweden are carbon sources during a relatively small part of the rotation period, and that this part can be considerably shortened by measures that increase productivity or reduce the amount of woody debris left after disturbance.

1. Introduction

A large share of the world's forest is located in the boreal and northern temperate areas (Melillo et al., 1993; Bartholomé and Belward, 2005; FAO, 2014). These northern forests are characterized by high soil carbon storage because of low rates of turnover due to low temperatures, despite that the net primary production commonly is low (Anderson, 1991; Goulden et al., 1998). Northern forests are to an increasing extent utilized for forest biomass production and are, especially in the boreal biome, continuously converted to artificially regenerated production forests (FAO, 2014). This process may be further accelerated by climate change as productivity may increase (Bergh et al., 1998; Gonsamo et al., 2017), and the vast extent of these forests together with their high carbon storage makes them a crucial component of the global carbon cycle. Hence, it is of utmost importance that management systems applied here are evaluated in the climate change context (Canadell and Raupach, 2008).

Northern forests are commonly managed by clear-cutting, or harvest with a varying degree of green (live) tree retention and/or seed trees, followed by natural or artificial regeneration of the next forest generation (Mårald et al., 2016). Also contemporary Swedish forestry is reliant on these management systems, often with planting of coniferous trees in monocultures, and rotation periods of 60–120 years, usually with several thinnings. This type of forestry is today conducted on >80% of the Swedish productive forest land, and about 90% of the annual growth (120 million m^3) is extracted each year (Swedish Forest Agency, 2016). The efficiency of this forest management system is reflected in an increase of productivity by 80% since 1920 (SLU, 2015).

Although this management system has several weaknesses from a sustainability point of view (e.g. negative effects on biodiversity and water quality; Lindenmayer and Franklin 2002; Felton et al., 2016), it has advantages in the viewpoint of high biomass production and operational efficiency (Sedjo, 2010). The high biomass production may be vital to climate change mitigation strategies (fossil fuel substitution and carbon storage) as tree growth provides means of removing carbon dioxide from the atmosphere (Sathre et al., 2010). Adding complexity, the large soil carbon pool in northern forests is partly mobilized by harvest operations, causing carbon emissions to the atmosphere and thereby reducing the efficiency of both substitution and storage (in products) strategies. Hence, there is a scientific challenge to understand how

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different forest management options can best contribute to climate change adaptation and mitigation (cf. Canadell and Raupach 2008).

The carbon losses that occur after clear-cutting (Malhi et al., 1999) have been intensively debated during the last decades (Lacroix et al., 2016) and it has been suggested to take a long time before the forest system has re-absorbed the amounts of carbon dioxide lost during the clear-cut phase (Lindroth et al., 2010, 2012; Rebane et al., 2019). The amounts of carbon lost and time of recovery is crucial for our understanding of different mitigation strategies and how forest management can contribute to these. Hence, one specific challenge is to understand how the carbon balance of a managed forest subjected to clear-cutting changes during the rotation period. In principle, from emitting carbon dioxide (source) during the early phase after clear-cutting, it reaches a maximum uptake of carbon dioxide (sink) when the biomass production peaks, and finally in a late-maturity phase the carbon uptake potentially decreases. This involves the transition from source to sink, and the juncture for net uptake of a forest generation, which currently is poorly understood. But it is also of great interest to determine how different levels of productivity and biomass extraction affect the overall carbon balance. Extraction of logging residues and stumps for biofuel purposes has, for example, the potential to substitute fossil fuels in a "carbon neutral" manner in case no more carbon dioxide is emitted by harvest and combustion than would have been emitted by decomposition of the extracted biomass. Tree stump harvest, however, causes a significant disturbance of the soil and there have been concerns that this disturbance could result in a net carbon dioxide efflux from increased decomposition of the organic soil layer (Swedish Forest Agency, 2009; Walmsley and Godbold, 2010; Persson, 2013). Based on some recent studies however, neither mechanical site preparation nor stump harvest affect forest carbon balance adversely neither during the first years, nor long term (Grelle et al., 2012; Strömgren et al., 2013, 2017; Mjöfors et al., 2015; Jurevics et al., 2016; Persson and Egnell, 2018; Ranius et al., 2018).

A key measure that quantifies the source- or sink-strength of managed ecosystems, and thereby determines their climate impact, is the net ecosystem exchange (NEE) of carbon dioxide between the ecosystem and the atmosphere. In the global carbon cycle, this net balance between photosynthesis and respiration of terrestrial ecosystems offsets about a quarter of all anthropogenic emissions (Tharammal et al., 2019). At a forest stand scale, it can be determined by eddy covariance, a micrometeorological measurement technique with high temporal resolution for fluxes at ecosystem level (e.g., Aubinet et al., 2000). This technique provides opportunities to compare instant fluxes as well as annual carbon budgets from different ecosystems, and to study responses on, e.g., weather, soil and growth conditions at time scales from minutes to years.

The strength of this method is the accuracy associated with measuring net fluxes instead of determining the small difference between large gross fluxes, which may imply large uncertainties and biased estimates. A potential drawback is high requirements to the ecosystem's spatial size, homogeneity and topography.

In this study we used the eddy-covariance technique to estimate the amount of carbon lost through emission of carbon dioxide during the regeneration phase after clear cutting. Specifically, we aimed to determine the juncture when a stand shifts from emitting to absorbing carbon dioxide, and to estimate the rate of recovery of the carbon balance in five differently disturbed and reforested clear-felled areas and young forest stands with different productivity in southern (four sites) and south-central (one site) Sweden, respectively. In particular, the impact of site productivity, coarse woody debris removal, and N-fertilization on the recovery of the carbon balance after clear cutting was to be studied. This yields more solid estimates of recovery times in different parts of Sweden and provides a basis for silviculture recommendations to increase long-term carbon uptake by forests managed through stand replacing forestry.

2. Material and methods

2.1. Site description

We used five eddy-covariance systems of which four were located on experimental sites at the Toftaholm estate in southern Sweden (57°0'N; 14°3'E), and one system at the Skyttorp site (Fluxnet SE-Sk1, fluxnet.ornl.gov) in south-central Sweden (60°7'N; 17°55'E). For this study, data from the start of the respective measurement period until 2018 (Southwest) and 2021 (south-central) were used. The soil conditions were similar at all sites. The Skyttorp site was however less productive than the Toftaholm sites mainly due to colder climate (Table 1), while the tree species composition and management varied between the sites (see below).

The climate at all sites is humid continental and the mean annual temperature at Toftaholm (Skyttorp in brackets) is 6.3 °C (5.5 °C) with 766 mm (527 mm) mean annual precipitation. The monthly mean temperatures vary from -2.6 °C (-4.4 °C) in January to 15.6 °C (16.3 °C) in July and the monthly precipitation fluctuates from 41.5 mm (27.6 mm) in February to 83.7 mm (69.1 mm) in July (SMHI 2016; average 1961–1990). Both study areas are dominated by mesic sandy moraines with smaller wetter areas with a thin peat layer. The bedrock in the areas is mainly acid granite. The terrains are level with only small variations in elevation (SI, Figs. 2 and 3).

At Toftaholm, large forest areas dominated by the evergreen coniferous tree species Norway spruce (*Picea abies* (L.) Karst.) were wind-felled by a hurricane (also named Gudrun) in January 2005, resulting in clear-cut areas of several hundred hectares after salvage logging. The land was reforested by planting after soil scarification. In the western part of the area, larch (*Larix* x *eurolepis* A. Henry) was planted, referred to as the *Larix* site (L). Here, flux- and climate measurements started during summer 2005. In 2007 (year 3 after the hurricane), adjacent to the larch stand the tree stumps were harvested to be used as bioenergy, and Norway spruce was planted, referred to as the *Picea* Stump Harvest site (PSH). The stump harvest followed general recommendations in Sweden (Swedish Forest Agency, 2009), which implies that ca. 80% of the stumps were extracted. Here, measurements started immediately after the stump harvest.

In the eastern part of the wind-felled area, two areas have been reforested by planting of Norway spruce, referred to as the *Picea* South 1 (PS1) and the *Picea* South 2 (PS2) site, respectively. At these two sites, flux measurements started in 2013. The PS1 site was planted in 2006, one year later than PS2. Furthermore, PS1 was fertilized by N (150 kg ha^{-1}) and P (150 kg ha^{-1}) in 2014, and N (150 kg ha^{-1}), P (19.6 kg), K (52.2 kg) in 2016 and 2018.

All four southern sites were subject to pre-commercial thinning (PCT) during winter 2016/2017, i.e. 12 years after the hurricane.

A measurement system was placed in the center of each site. The distances between the four sites at Toftaholm range between 0.7 and 2.8 km (SI Fig. 2). The site surface areas and the minimum distances between the measurement system and the site edge (fetch) are shown in Table 1.

At Skyttorp (referred to as the *Pinus* North site (PN), (SI Fig. 3)), a mature stand of Norway spruce was harvested during the winter 2000-2001. The area was reforested by planting of Scots pine (*Pinus sylvestris*) after soil scarification in spring 2003. Here, flux measurements started in 2001 (year 1 after the disturbance).

2.2. Flux measurements

Exchange of carbon dioxide, water vapor, heat and momentum between ecosystems and the atmosphere can be determined by simultaneous measurements of turbulent wind components and the respective scalar quantities. In principle, relating instantaneous air movements to current air properties yields net fluxes of any property or quantity that is transported by turbulence.

Table 1

Description of the southern (Toftaholm) and northern (Skyttorp) sites where flux measurements were performed. Means ± SE are based on tree measurements in the 21 or 22 plots surrounding the PS1 and PS2 sites. Tree measurements were performed during winter between year 10 and 11 after the disturbance (2014/2015) in the PS1 and PS2 sites, in autumn of year 12 (2016, PSH and L) and in autumn of year 17 (2017, PN).

	PS1	PS2	PSH	L	PN
Study location	Toftaholm	Toftaholm	Toftaholm	Toftaholm	Skyttorp
Site area (ha)	14	34	12	15	15
Year of disturbance/soil preparation/re-generation	2005/2006/2006	2005/2005/2005	2005	2005	2000-2001/2003/2003
Year of fertilization/stump harvest	2014, 2016, 2018 (fertilization)	-	2007 (stump harvest)	-	-
Years of measurements	2013-2018	2013-2018	2007-2018	2005-2018	2001-2021
Minimum fetch (m)	150	170	120	160	130
Species planted	*Picea abies*	*Picea abies*	*Picea abies*	*Larix* x *eurolepis*	*Pinus sylvestris*
Tree biomass (Mg ha-1)	16.3±1.5	19.6±2.0	13.6	30.6	46.1
Broadleaves biomass share (%)	61	67	66	49	18
Basal area (m^2 ha^{-1})	3.8±0.3	4.2±0.4	3.0	6.7	8.0
Broadleaves basal area share (%)	58	66	34	54	21
Norway spruce basal area share (%)	42	34	66	13	20
Scots pine basal area share (%)	0	0	0	0	59
Larch basal area share (%)	0	0	0	33	0
Number of stems (stems ha-1)	4538±478	6795±1248	4810	4848	3569
Site index (m)	33±0.3	33±0.5	32	38	29
Logging fallow period (years)	1	2	2	1	2
Common rotation period (years)	60	60	60	not yet known	90

Measurements were done at 10 Hz and fluxes were calculated as 30 min average values. Overall calculation and correction of fluxes followed the EUROFLUX methodology (Aubinet et al., 2000; Lee et al., 2004). Since this study is a compilation of different independent research projects, three different types of measurement systems were used (an extended description of the flux measurements can be found in the supplementary information). This was justified by intercomparison experiments at an agricultural field site in Harbo, Sweden, and at Toftaholm. Here, a closed-path system was considered as reference and the agreement between the systems was expressed as the correlation between half-hourly flux data from the other systems with concurrent data from the closed path system after appliance of all relevant corrections (SI Table 2).

2.2.1. *Integrated system (sites PS1 and PS2)*

The integrated measuring systems consisted of an ultrasonic anemometer with an integrated open path gas analyzer (IRGASON, Campbell Scientific, Logan, USA). The integrated design reduces the number of required corrections. The systems were mounted on expandable telescopic masts (CM5705, Fireco, Gussago, Italy) that allow continuous adaptation of measurement height to stand height.

2.2.2. *Open path system (sites PSH and L)*

The open path systems contained a Solent R3 sonic anemometer (Gill Instruments, Lymington, UK) and an LI-7500 open path gas analyzer (LI-COR inc., Lincoln, Nebraska, USA), mounted on telescopic tripods, and the measurement height was periodically adapted to stand height.

2.2.3. *Closed path system (site PN)*

Similar to the open path system, the closed path system (In Situ Instrument AB, Ockelbo, Sweden) consisted basically of a Solent R3 sonic anemometer (Gill Instruments, Lymington, UK), here in combination with a closed path infrared gas analyzer (IRGA) LI-6262 (LI-COR inc., Lincoln, Nebraska, USA) as described by Grelle and Lindroth (1996) and Grelle et al., (2007). Anemometer and air inlet were mounted on a telescopic tripod, and the measurement height was periodically adapted to stand height. When the measurement height exceeded 5 m, the tripod was extended by an adjustable ladder. The air inlet was placed 10 cm below the sampling volume of the sonic anemometer. Air was drawn from the inlet through a 6 mm diameter, 6 m long high-density polyethylene tube to the IRGA that was mounted in a heated, ventilated, and insulated enclosure. The air flow-rate was 12 NL min^{-1} (liter at 0 °C, 1013 hPa), measured and controlled by a mass flow regulator (Brooks Instrument, Hatfield, PA, USA

2.2.4. *Decomposition into gross components*

To analyze the effect of stump harvesting at the PSH site, net fluxes from PSH and L were decomposed into gross components. This was done by means of temperature response functions of dark respiration R_d in the form

$$R_d = a + b\cdot e^{c\cdot T} \tag{1}$$

where T is air temperature, which yielded a higher correlation coefficient than soil temperature. The response functions were fitted to night-time fluxes during conditions of sufficient turbulent mixing ($u_* > 0.1$ m s^{-1}) and parameters a, b, c were determined for each site on a seasonal basis. Total ecosystem respiration (R) was estimated by extrapolation of the temperature response functions to daytime. Subtracting R from the net flux (NEE) yields gross uptake (GPP).

2.3. *Biometric measurements*

Detailed inventories of trees and soil were done in an area of 12.6 ha (Ø of 400 m) around each eddy-covariance tower at the PS1 and PS2 sites during the winter 2014/2015. This was considered to be the main flux source area of the eddy-covariance systems (cf. Supplementary information). Tree biomass was estimated in circular plots (5.64 m radius). These plots were laid out in a grid with a random starting point and 75 m intervals resulting in 21 plots around the PS1 tower and 22 plots around the PS2 tower. Height and diameter at breast height (1.3 m) were measured on all trees on the plots. Biomass functions were then used to calculate the tree biomass divided into stem, branches (Marklund, 1988; Petersson et al., 2012) and roots >2 mm (Petersson and Ståhl, 2006). Site indices were calculated according to Elfving (2003) as the potential height at the stand age of 100 years (H100).

The PS1 and the PS2 sites were very similar in many aspects such as productivity (site index) (Table 1). The PS2 site was regenerated in 2005, while the Norway spruce seedlings in the PS1 site were planted in 2006. This difference could be one explanation why the tree biomass tended, although not significantly, to be higher at the PS2 site. Natural regeneration led to a co-dominance of deciduous broadleaves, mainly birch species (*Betula* spp.), ten years after regeneration (winter 2014/2015). This share was somewhat higher at the PS2 site which can also have contributed to the higher biomass here since birch is a pioneer species with high growth rates at early successional stages.

At the other sites the basal area of the trees was estimated in late summer and autumn 2016 (PSH and L) and 2017 (PN). This was done by measuring the diameter at breast height of all trees taller than 1.3 m in 10 (16 at PN) systematically distributed circular plots (5.64 m radius) at each site. Site indices were calculated in the same way as for PS1 and PS2.

3. Results

3.1. Norway spruce sites (PS1 and PS2)

Measurements at the two southern sites, PS1 and PS2, started in July 2013, year 9 after the hurricane. A full year of measurements was accomplished in 2014 and at this stage both sites had already turned into net carbon sinks on an annual basis (Fig. 1). The net annual sink strength on both sites was about 5 Mg ha^{-1} yr^{-1}. The cumulative curves are characterized by small carbon losses during wintertime and substantial uptake during summer. Since cumulative fluxes before 2013 are unavailable and thus the ordinate value for the starting point is unknown, we placed the starting point of the PS1 and the PS2 curves onto the *Larix* (L) line (Fig. 1). This is equivalent to assuming that PS1 and PS2 had the same cumulative carbon budget as L during the first 8 years after disturbance, which is probably an overestimation. The conditions on both sites were very similar to L shortly after the hurricane, but it is likely that their C-budget peaked 1-2 years earlier, since both stands already were rather large carbon sinks when the measurements started. Thus, the absolute values are uncertain, and the vertical positions of the curves are likely to represent an upper limit.

Curves from both sites (PS1 and PS2) have very similar dynamics, but PS2 consistently took up more carbon than PS1 during the first two years of measurements. This is likely to reflect the head start in planting and the higher stand density of PS2 (Table 1). During the third year, the carbon uptake of PS1 surpasses PS2, resulting in a slightly larger carbon uptake of PS1 for the entire observation period despite the delay in planting and the lower stand density. This is likely to be an effect of the fertilization of PS1.

3.2. Stump harvest site

Flux measurements at the stump harvested site (PSH) started during year 3 after the hurricane, immediately after stump harvesting had been applied. During the first four months of the experiment the fluxes were very alike those from the L site. Therefore, we assumed that they have been similar since the hurricane as well, and we assigned the same values to the cumulative carbon fluxes of the L and PSH sites to the time period before stump harvest took place. The conditions on both sites were very similar shortly after the hurricane, and the similarity of the fluxes during the first four months suggest that this was a more realistic method for gap-filling than a modeling approach. Nevertheless, there is a remaining uncertainty in the ordinate level of the cumulative PSH curve, which does not affect the dynamics of the measured time series though.

During late summer of year 3, the cumulative carbon fluxes from the PSH site started to deviate from the L site towards smaller carbon losses. During year 4 and 5, the net losses were comparable with those from the PN site (Fig. 1). To analyze the deviation from the L site, we decomposed the net fluxes from the L and the PSH site into their gross components. Fig. 2 shows gross carbon dioxide fluxes from both sites during year 3–13 after the disturbance. On average, gross uptake (GPP) was 7% higher and gross respiration (R) was 10% lower at PSH than at L. While R was consistently lower at PSH throughout the period, there was a transient increase in GPP during year 9, six years after stump harvesting. Later in year 12, GPP decreased again and became smaller at PSH than at L (Fig. 3). This coincides with PCT that was applied at both PSH and L during year 12, when even gross respiration R increased slightly at both sites.

This indicates that the deviation of the NEE curve of PSH was caused by reduced respiration and, to a lesser extent, by temporarily enhanced photosynthesis. The exact quantity of harvested stumps is unknown, but by ocular and photographic inspection of the harvested volume and comparison with other sites (e.g. Strömgren et al., 2012; Grelle et al., 2012) we estimated the corresponding carbon pool to 20 Mg ha^{-1}. According to the model by Melin et al. (2009), stump decomposition has thus contributed with 9.5 Mg C ha^{-1} to ecosystem respiration R during the observation period, while the difference in R between the PSH and the L site was 12 Mg C ha^{-1}. The remaining of 2.5 Mg C ha^{-1} were probably attributed to decomposition of logging residues at L. The accuracy of these numbers is relatively low, since they are based on a rather coarse estimate of harvested stump biomass.

The net carbon emissions from the PSH site peaked after eight years already, turning the site into a carbon sink again. The sink strength during subsequent years was about 5 Mg C ha^{-1} yr^{-1}, i.e., similar to PS1 and PS2. During year 11 after the hurricane, the cumulative curve

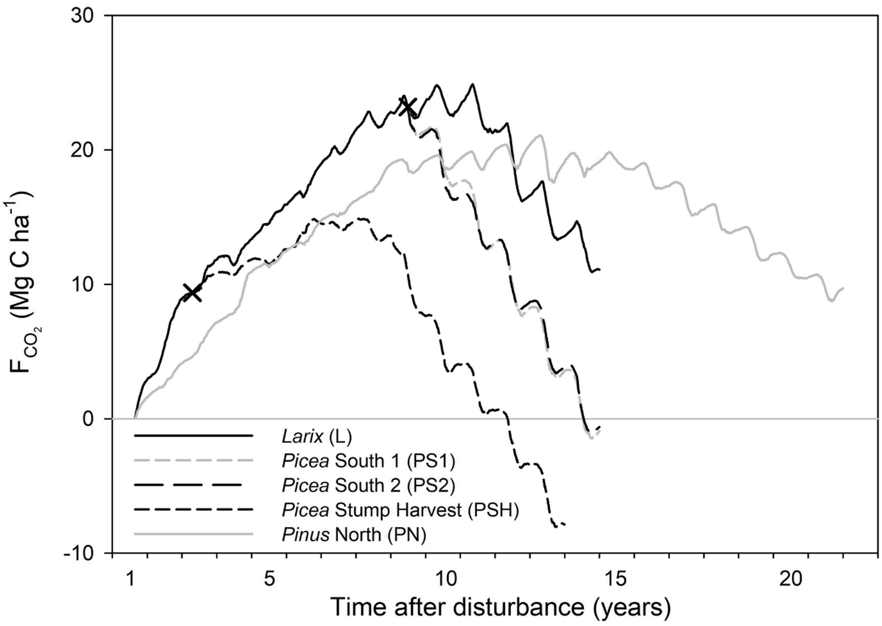

Fig. 1. Cumulative carbon dioxide fluxes (converted to mass units of carbon) from forests reforested after disturbance. The x-axis denotes years after disturbance. PN is a *Pinus sylvestris* stand at Skyttorp in south-central Sweden, while PS1 and PS2 are *Picea abies* stands at Toftaholm in southern Sweden. L means *Larix* x *eurolepis* stand and PSH is *Picea abies* stand with stump harvest, both at Toftaholm in southern Sweden. Measurements at PS1, PS2 and PSH started some years after the disturbance (starting points marked by crosses), and similarity with L was assumed during the first, missing years.

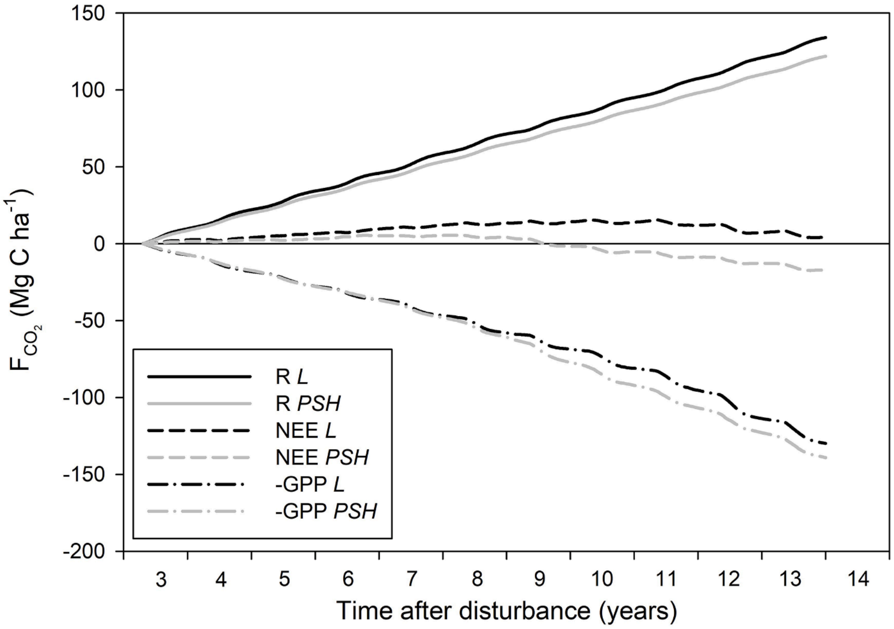

Fig. 2. Cumulative gross carbon dioxide fluxes in mass units of carbon of the larch site (L) and the stump-harvested site (PSH). R = ecosystem respiration, NEE = net ecosystem exchange, GPP = gross primary productivity.

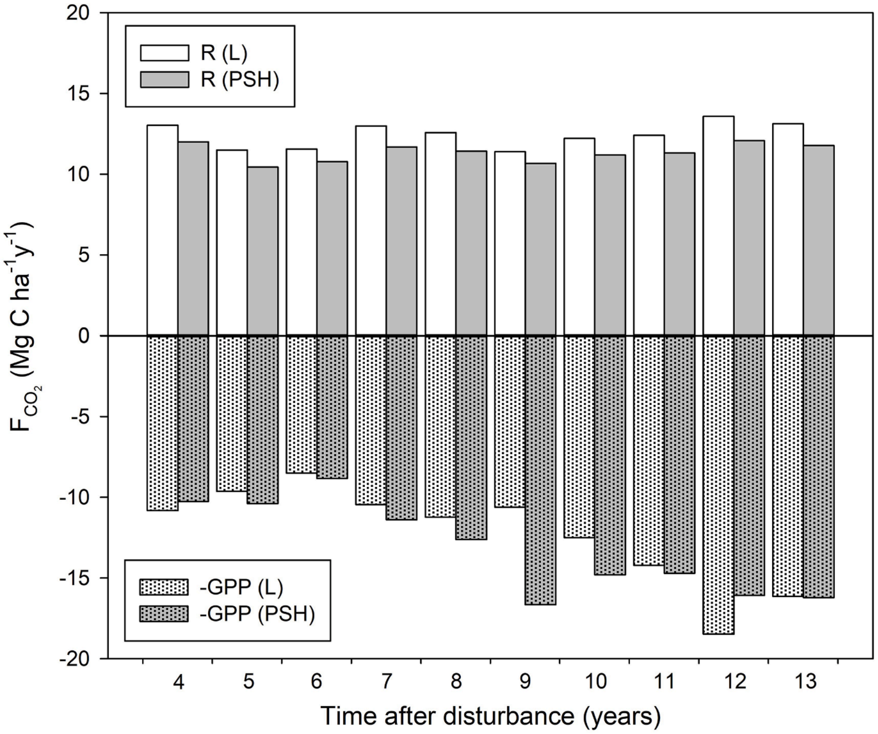

Fig. 3. Annual sums of gross ecosystem carbon dioxide fluxes from sites PSH and L.

intersected the zero line (Fig. 1), indicating that the emissions after the disturbance had been compensated by subsequent uptake, and the site's carbon budget was thus restored to the state before the disturbance (disregarding the loss of biomass and a change in current sink strength).

3.3. Larch site

The initial carbon fluxes from the larch stand (L) were also characterized by small carbon losses during wintertime and larger losses during summer. Annual losses of carbon were more than 5 Mg C ha^{-1} y^{-1} during the first years (Fig. 1). From the third year after the hurricane, these losses declined relatively quickly, and during the 6th year the canopy was so dense that considerable summertime-uptake of carbon was observed. After 10 years, the emissions leveled off and the stand turned into a carbon sink again on an annual basis. During the observed period of emissions, the ecosystem has lost 25 Mg C ha^{-1} to the atmosphere.

3.4. Northern pine site (PN)

The PN site was harvested four years before the harvest at the other sites. The time base for evaluation of fluxes from all sites starts with the respective disturbance. Since no climatic extremes occurred during the experiment period and inter-annual weather variations are likely to cancel out in the multi-annual time series without affecting our results, the time series from PN is shifted in time and directly compared with the other sites.

The cumulative carbon fluxes from the PN site showed consistent carbon losses from the ecosystem to the atmosphere during the first years after harvest (Fig. 1). During wintertime, carbon losses were small, resulting in flatter slopes of the cumulative carbon fluxes, while the carbon losses and corresponding slopes were generally larger during summertime. During the entire experiment, carbon losses from PN were significantly lower than from L, with only half of their magnitude during the first years. During the fourth year after harvest, i.e. the summer after soil scarification, carbon losses were significantly larger than during preceding and subsequent years. Nine years after harvest and at a tree height of ca. 4 m, the carbon fluxes were characterized by distinct uptake during the summer months. 13 years after harvest, the cumulative carbon fluxes peaked and turned downward again, i.e. the stand had turned from a carbon source into a carbon sink on an annual basis. In total, 23.5 Mg C ha^{-1} were lost from the ecosystem before it turned into a carbon sink again. This was slightly less than the losses from the L site (25 Mg C ha^{-1}) despite the longer emission period. In comparison with the southern sites the fluxes from the PN site were characterized by lower rates of emission and uptake, lower “peak emissions” (i.e. the culmination point of the cumulative carbon dioxide fluxes) and a slower recovery. That means that although less carbon was temporarily lost from the clear-cut, it takes more time to compensate for these losses than it takes for the southern sites to compensate for their respective losses. The cumulative carbon fluxes of PN and L intersect during year 12 after the disturbance. That means that, despite the large initial losses, the southern L site has lost less carbon than the northern PN site at a timescale longer than 12 years.

3.4.1. Rotation period perspective

Chronosequence data provide an excellent base to filter out the effect of stand age when other factors affecting carbon fluxes are to be assessed (Magnani et al., 2007), and facilitate extrapolation and interpolation in time. In particular, the carbon balance of forests throughout the rotation period can be approximated by chronosequences, while direct quantifications are impossible so far. Adding annual carbon budgets from stands in this study to the Skyttorp chronosequence that was established previously (Magnani et al., 2007) provides a base for a curve fit that resembles curves of periodic annual increment (PAI), but with the important distinction that also ecosystem respiration is included here (Fig. 4). To account for geographic differences, annual NEE was normalized by maximum NEE during the rotation. Here, the Skyttorp chronosequence was used as reference and scaled by site productivity (SLU, 2015) to match the southern sites. In accordance with Lindroth et al. (2009) the stand age was normalized by rotation period. To confine the analysis to conventional regeneration, the fertilized and the stump-harvested sites (PS2 and PSH) were excluded.

A logarithmic fit explained 72% of the variation (solid line in Fig. 4). The zero intercept indicates the transition from carbon source to sink after 15% of the rotation period, which confirms the number found by Lindroth et al. (2009) for European chronosequences. The minimum of the logarithmic fit (solid line in Fig. 4) indicates culmination of the periodic NEE at a stand age of 44% of the rotation period. The initial rise of the curve may indicate colonization of substrate by decomposers (cf. Harmon et al., 1986). In analogy with mean annual increment (MAI), integration of the curve and division by stand age yields the mean annual fraction of NEE, where ecosystem respiration is included. The intercept of the lines of periodic NEE fraction and mean annual NEE fraction after 82% of the rotation period indicates the point where harvest and regeneration would yield maximum long-term carbon uptake. The mean annual NEE at the intercept corresponds to 52% of the peak periodic NEE, which highlights the relative impact of the carbon losses during the clear-cut phase and illustrates the importance of assessing forest carbon balances in the perspective of entire rotation periods. Furthermore, the zero intercept of the mean annual NEE fraction (dashed line in Fig. 4) indicates the time when the emissions are balanced by subsequent uptake and the carbon balance is restored to the

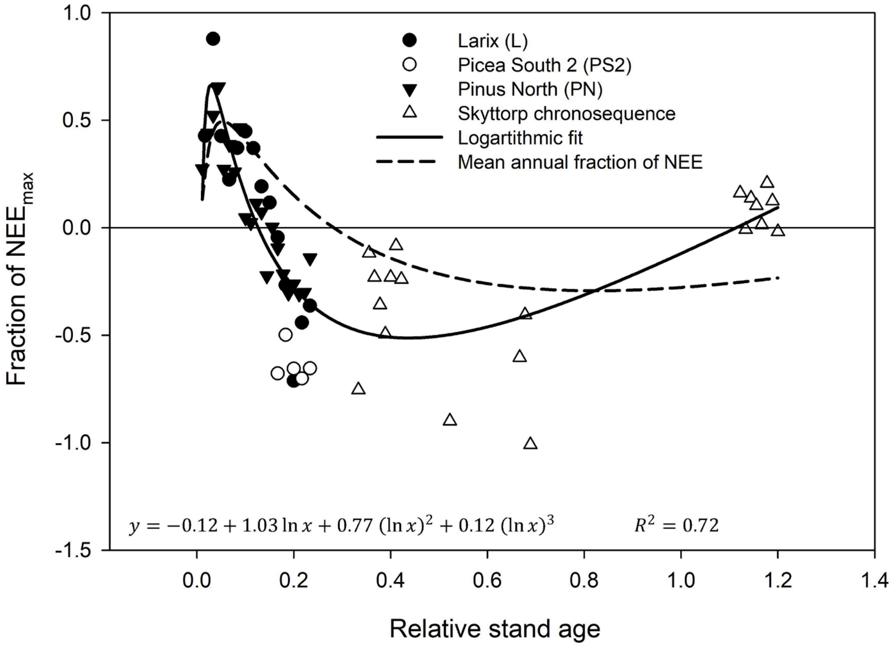

Fig. 4. Normalized relationship between stand age and net ecosystem exchange (NEE). The equation is valid for the solid line. The stand age is normalized with rotation period and NEE is normalized with the maximum NEE during the rotation. The intersection of the solid and the dashed line denotes the point where harvest yields maximum mean annual NEE.

state before the disturbance (disregarding the loss of biomass and a change in current sink strength). Here, that state is reached after 29% of the rotation period.

This model, however, relies on rather few data points at high age with positive or close to neutral NEE. Old-growth forests may be carbon sinks (Luyssaert et al., 2008), and a slightly more negative NEE at this end of the gradient would push the culmination point forward. Therefore, additional data from annual carbon budgets of different mature forests would refine the result.

4. Discussion

4.1. Recovery of the carbon balance

This study shows by a unique compilation of data from intermediate to long-term carbon flux measurements at different sites in Sweden that young forest stands may return to act as carbon sinks as early as eight years after harvest and regeneration with planting of tree seedlings. The observed differences between our southern stands that grow under similar climate- and soil conditions suggest that the emission period may be shortened considerably by adjustments to the management system.

Three sites at Toftaholm (PS1, PS2, PSH) in southern Sweden turned to carbon sinks 8-9 years after disturbance (harvest/hurricane-felling), compared with 13 years at the more northern site (PN). These results are in the lower end of the variation in age when compared to studies in similar forest systems in North America and Europe (Amiro et al., 2010; Rebane et al., 2019). These ages correspond to approximately 15% of the common rotation periods at both locations (Roberge et al., 2016). If we were to extrapolate these results to northern Sweden with common rotation periods of 120 years (Roberge et al., 2016), there the transition from source to sink would take place 18 years after harvest. Most likely the difference between Toftaholm (PS1, PS2, PSH, L) and Skyttorp (PN) is an effect of both higher site productivity (Table 1) and longer growing season at Toftaholm. On average, the growing season was 156 days at Skyttorp and 175 days at Toftaholm, as derived by mean daily air temperature, in line with Bergh et al. (1999, 2005). This promotes faster development of leaf area and increases photosynthesis at the stand level.

Another potentially contributing reason might be increased mineralization caused by soil disturbances associated with detached root systems, which might discriminate the windthrow from a conventional clear-cut. However, since generally not even stump harvest enhances mineralization (Kaarakka et al., 2016), the relatively moderate soil disturbance caused by detached roots most likely did not enhance it either. On the other hand, it is reasonable to assume that higher temperatures and higher soil carbon content at Toftaholm (SLU, 2015) have caused higher soil respiration than at the PN site. This explains the stronger carbon source during the first years, which is subsequently counteracted by higher site productivity and longer growing season, highlighting the importance of forest productivity for the carbon balance of a forest stand. Forest management possesses several tools to improve forest growth and carbon sequestration, and thereby affect the carbon balance (Poudel et al., 2012), including the use of genetically improved seedling material and scarification methods at stand establishment, and later-rotation measures such as fertilization (Hedwall et al., 2014).

The juncture for the stump harvested spruce site (PSH), when the stand shifted from emitting to absorbing carbon dioxode, was clearly earlier compared with the *Larix* site (L). This is likely an effect of reduced amount of decomposable substrate on the stump harvested site, which lowered the emissions of carbon dioxide ("direct effect" of stump harvest, Grelle et al., 2012). The intersection of the cumulative flux curve with the zero line, i.e., the point in time when emissions were balanced by subsequent uptake, is to some extent depending on the starting point of the cumulative curve. Our assumption that the fluxes from the PSH site equaled the fluxes from the L site during the first year thereby introduces some uncertainty which may shift the intersection to either side. The time of culmination, i.e., the turn from a carbon source into a carbon sink, is however not affected by this uncertainty.

It has earlier been a concern that soil disturbance from stump harvest may cause an increased decomposition and therefore higher emissions (Swedish Forest Agency, 2009; Walmsley and Godbold, 2010; Persson, 2013). However, more recent results from a soil disturbance study do not support this (Mjöfors et al., 2015). Although the carbon dioxide emissions may increase during the first two weeks after a soil disturbance such as stump harvest (Strömgren et al., 2012), the effect seems to be transient and more than 15 different site preparation and stump harvest experiments show no significant difference in carbon dioxide emissions after stump harvest in comparison to conventional site preparation during the first years after the disturbance (Strömgren et al., 2012, 2013, 2017). The absent effects of stump harvest on soil respiration in these studies lead us to believe that the large differences between the sites in our study is mainly an effect of lower stump and coarse root biomass decomposition.

The soil disturbance caused by stump harvest may also promote regeneration and establishment of young tree seedlings and thereby carbon uptake (Saksa, 2013; Johansson et al., 2013; Mjöfors et al., 2017). Hence, another contributing reason might be a faster stand development caused by stump harvest due to increased natural regeneration of seedlings (Saksa, 2013). The transient increase in GPP six years after stump harvest (Figs. 2 and 3) indeed suggests an association to vegetation establishment. During the first years the vegetation was dominated by shrubs and grasses, while increasing needle biomass of re-growing trees governed the carbon uptake after six years. However, in the end of the period the PSH site had the lowest basal area of trees of all sites at the southern location, and GPP had decreased to the same level as at the L site (Figs. 1 and 2). This is probably a consequence of PCT which aims to promote a set number of main stems per hectare, and thus equals out initial differences between stands.

4.1.1. Pre-commercial thinning and effects of tree species

Coniferous tree species were the target for forest management at all sites included in this study. Especially Norway spruce is a late successional species and thus a slow starter with comparably lower growth at young stages than many early successional tree species. In Sweden, although artificial regeneration with conifers after clear-cut of the old stand is the most common management system, an abundant natural regeneration of broadleaved tree species (especially birch, *Betula* sp.) is common. This was also the case at our sites where birch was the most, or second most, common species. Birch is an early successional species with a fast growth during the sapling stage and a large share of this species may shorten the time from clear-cut until the transition from carbon source to sink. At the PSH site, high abundance of birch probably explains the increase in GPP that ceased with PCT during year 12 after the hurricane.

A larger share of birch may also, together with a larger tree biomass, explain the greater initial sink strength of PS2 than PS1 despite the fertilization of PS1. This highlights the importance of PCT for the carbon balance. Postponing PCT measures or omitting them and performing an early thinning of broadleaved trees instead may increase the forest's carbon uptake. But so far, little is known about the relative importance of early broadleaved tree species for the boreal forest carbon balance.

Even beyond PCT there is a likely effect of tree species on the carbon balance. In this study, the Norway spruce sites (PS1 and PS2) turned to a sink earlier than the larch site (L), despite the higher basal area at the latter site. By the end of the period the magnitude of the sink strength was also considerably higher for the spruce stands compared with L. One potential reason for this may be the phenological differences between the two species and the turnover of foliage. While Norway spruce exchange the whole foliage over a time period of several years (Muukkonen and Lehtonen, 2004) and continuously increase the foliage mass at this development stage, larch replace the entire foliage annually and the foliage litter is partly decomposed during the following autumn and winter. At the same time, specific leaf area is usually twice as large for larch as for spruce (Fellner et al., 2016; Hager, 2011). However, the foliage biomass of Norway spruce even can exceed the stem biomass at this stage (Albaugh et al., 2009), and constitutes a considerable carbon sink and intermediate-term (5–10 years) carbon storage.

4.1.2. Landscape perspective

Comprehensive systems analyzes are needed to identify sustainable long-term approaches to carbon management through land-use (Lundmark et al., 2013) and such analyzes are largely dependent on the geographical scale applied. In Sweden, as in large parts of the rest of the boreal and temperate regions, landscapes with a high forest cover are managed as forestry systems, where the management activities in stands are coordinated. While a steady flow of harvested wood may not be possible from an individual stand, it can be provided from a forest system managed at the landscape-scale. Just like concerning wood flow, carbon balances are also highly scale-dependent; while the carbon balance in a forest stand may switch dramatically from uptake to loss at final felling, the carbon stock in forest landscapes fluctuates around a trend line. This trend can be changing or roughly stable since carbon gains in some stands counteract carbon losses in other stands (McKinley et al., 2011). However, to adequately address issues concerning the effects of forest management on the carbon balance in forest landscapes, detailed knowledge from the stand level, like in this study, is needed. Additionally, data covering the full rotation period in managed forests is crucial for upscaling to landscape level carbon balances but, unfortunately, very scarce.

5. Concluding remarks

This study refines our understanding of forest carbon balance recovery after clear cutting. Recovery time appears to be related to site productivity, and thereby to the rotation period, and for southern Sweden it is shorter than previously assumed, despite higher initial emissions than further north. Going beyond interpolated annual carbon budgets in chronosequence studies, continuous single-stand flux measurements during a rotation period not only reveal the transition from carbon source to sink with higher accuracy, but also allow to follow the dynamics of the fluxes and to estimate the total quantities of carbon that are released and absorbed. Thus, the restoration time of the carbon budget to the state before the disturbance can be determined, and it varies with rotation period and management.

Seedlings establishment, stand productivity, and biomass removal are key parameters that affect the recovery of the carbon balance. Thus, site preparation, fertilization, choice of tree species, biofuel extraction, and appropriate timing of measures such as PCT are forestry options that can promote the transition from carbon source to sink after disturbances and thereby increase the overall carbon sequestration by forests.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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