Patterns of Carbon Sequestration in a Young Forest Ecosystem after Clear-Cutting

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Abstract: A large area of Estonian hemiboreal forest is recovering from clear-cut harvesting and changing carbon (C) balance of the stands. However, there is a lack of information about C- source/sink relationships during recovery of such stands. The eddy covariance technique was used to estimate C-status through net ecosystem exchange (NEE) of CO_2 in two stands of different development stages located in southeast Estonia in 2014. Measured summertime (June–September) mean CO_2 concentration was 337.75 ppm with mean NEE -1.72 µmol m^{-2} s^{-1}. June NEE was -4.60 µmol m^{-2} s^{-1}; July, August, and September NEE was -1.17, -0.77, and -0.25 µmol m^{-2} s^{-1}, respectively. The two stands had similar patterns of CO_2 exchange; measurement period temperature drove NEE. Our results show that after clear-cutting a 6-year-old forest ecosystem was a light C-sink and 8-year-old young stand demonstrated a stronger C-sink status during the measurement period.

Keywords: carbon flux; forest ecosystem; clear-cutting; disturbance; eddy covariance

1. Introduction

The important role of forests in the global carbon cycle is through relations between forest characteristics, climate conditions, and ecosystem functioning [1,2], which vary over time and stand age [3–5]. Most carbon balance estimations in European forest ecosystems have been measured in middle-aged stands [6], overlooking C-dynamics as stands age.

Disturbances play a key role in ecosystem carbon (C) dynamics [7–9]. Natural and anthropogenic disturbances in forest ecosystems significantly affect the C-balance [10–12], ecosystem functioning, and stand development [10,13–17]. Forest management, particularly clear-cut harvesting, alters C storage and fluxes, thereby increasing the chance that more carbon dioxide (CO_2) will be released into the atmosphere [10,18]. Conversely, photosynthesis in actively growing young forests removes CO_2 by uptake [19,20].

After significant stand-replacing disturbances, forest ecosystems generally act as C-sources, releasing more CO_2 than plants and soil microorganisms can absorb [19]. Nevertheless, carbon uptake quickly rises as forest biomass recovers with age, becoming C-sinks within about 10 years [7]. Middle-aged managed forests continue acting as C-sinks [6,18,21] until net ecosystem exchange (NEE) with the atmosphere declines with advancing age [4,6,22].

Eddy covariance (EC) is a micrometeorological method favored for estimating C-balance and NEE [9,16,23,24]. EC directly measures fluxes and assesses the carbon exchange of the whole forest ecosystem with the atmosphere above the canopy [9,10,21,23,24]. The widely used EC method

provides continuous measurement of carbon fluxes at the stand-level for studies of ecosystem physiology [6,8,23,25].

The main idea of NEE is to quantify C-uptake into ecosystems by taking into account several components of the carbon cycle [26,27]. A negative NEE means the atmosphere is losing carbon, while a positive NEE indicates that the atmosphere is absorbing carbon [5,18,28,29]. Duration and amount of carbon release depends on factors that affect C-stocks, including photosynthesis, vegetation and soil respiration, and weather [6,8,18–20,24,30,31]. Forest management affects C-source/sink strength. After clear-cutting, a forest ecosystem becomes a carbon source and usually soil C-storage decreases [6,9]. Using EC, we sought to identify current CO_2 levels and to quantify carbon dynamics in terms of C-sink or C-source status in two young stands that developed after clear-cutting. Our hypothesis is that the studied stands performed as weak C-sinks throughout the measurement period (June–September).

2. Materials and Methods

2.1. Site Description

The study site (58°16.890′ N, 27°18.315′ E) was located at the Järvselja Training and Experimental Forest Centre, Estonia, in the hemiboreal forest zone. The site is characterized by a continental climate, with warm summers and severe winters. In Estonia, the coldest month is February and the warmest is July. At the study site during the study period (May to September), monthly mean temperature was lowest in September (11.4 °C) and highest in July (18.5 °C), with a mean temperature of 15 °C. The soils of both stands are gleyic podzols soils and the *Oxalis-Vaccinium myrtillus* site type [32]. The stands are adjacent and before harvesting had similar growing conditions (Figure 1). Data for this study are from June to September 2014.
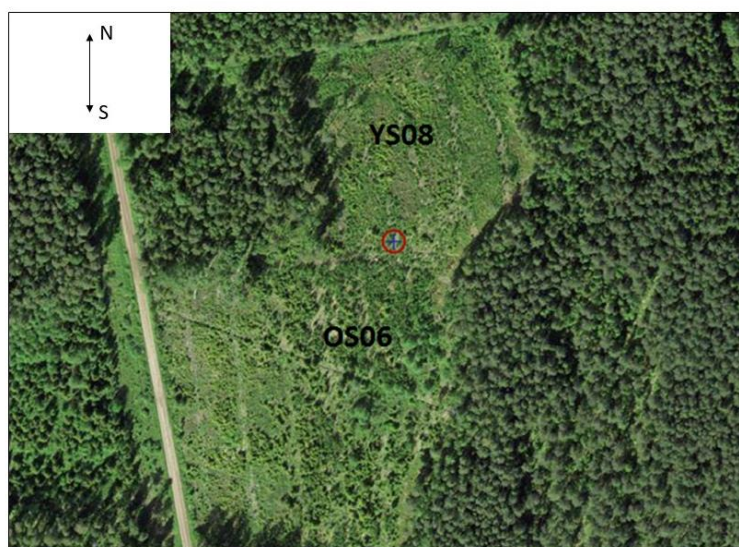
Figure 1. Location of the eddy flux tower (**red circle**) and the study stands (YS08, OS06).

The study area was divided into two parts according to harvest year; the younger stand was clear-cut in 2008 (YS08) and the older stand in 2006 (OS06) (Table 1). Before clear-cutting the dominant tree species in YS08 were Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth) and Norway spruce (*Picea abies* (L.) Karst). Scots pine was also the dominant tree species in OS06, but Norway spruce and silver birch were present. Understory vegetation was mainly rough small reed (*Calamagrostis arundinacea* (L.) Roth), sedges (*Carex spp.* L.), and lingonberry (*Vaccinium vitis-idaea* L.). Several years after clear-cutting, the dominant tree species at YS08 were silver birch and Norway spruce, with a minor component of Scots pine. Dominance at OS06 changed to Norway spruce and silver birch, with minor amounts of European aspen (*Populus tremula* L.) and Scots pine (Table 1).

Table 1. Characteristics of the stands at the Järvselja Training and Experimental Forest Centre, Estonia.

	YS08	OS06
Stand age (years since clear-cutting)	6	8
Trees average height (m)	1.3	2.1
Area of the stand (ha)	0.9	1.4
Open wind directions (°)	335–50	135–285
Growing season length (days)	121 (May–September)	121 (May–September)
Dominant tree species after harvest (percent):		
Silver birch (*Betula pendula*)	58	29
Norway spruce (*Picea abies*)	36	53
European aspen (*Populus tremula*)	0	12
Scots pine (*Pinus sylvestris*)	6	6

2.2. EC Measurements

An eddy covariance (EC) system [9,23] collected all data, including concentrations and fluxes of CO_2 and H_2O, and was installed at the study site in 2013. The EC system consists of a sonic anemometer (C-SAT 3, Campbell Scientific, Logan, UT, USA), and a closed-path infrared gas analyzer LI-7200 (LI-COR Biosciences, Lincoln, NE, USA). Temperature, and 3D wind speed and direction were measured using an anemometer. The instruments were mounted at 6 m above the ground, at the border between the two stands (Figure 1). Measurements for the two stands were differentiated by the intervals of main wind directions (Table 1). When wind direction was between 135 to 285 degrees, then EC was measured for the older stand and when wind direction was from 335 to 50 degrees, then it was younger stand.

The sampling line was 1 m (6 mm i.d.). Continuous high frequency (10 Hz) data, collected at half-hour intervals for calculating turbulent eddy fluxes, were saved automatically by datalogger (Campbell Scientific, USA) [23]. Measurements for this study began in 2014 after mounting and calibration. Data were available from June to September for the study sites. Flux data from the surrounding area (0–100 m) were taken also into account (Grace 2004). Carbon and water vapor fluxes data were converted from raw data to half-hourly mean values of micromole per square meter (μmol m^{-2} s^{-1}) and millimole per square meter (mmol m^{-2} s^{-1}). Mean values for days, months, and the entire measurement period were calculated from the processed data. Background information of precipitation levels came from a nearby weather station in the Järvselja Hunting Lodge (1.3 km distant) and used to validate other weather variables.

Net ecosystem CO_2 exchange (NEE) (μmol m^{-2} s^{-1}) was calculated as the sum of the measured eddy flux (F_c) [33] and storage flux (S_c) [15,16,25,29,34] according to the following equations:

$$NEE = F_c + S_c \tag{1}$$

$$F \approx \overline{P_a}\ \overline{w's'} \tag{2}$$

where

F = gas flow of eddy covariance (μmol m^{-2} s^{-1}),
P_a = air density
w' = vertical wind speed
s' = dry mole fraction, and

$$s_c = \int_0^{z_{ec}} \rho_a \frac{ds_c}{dt}\ dz \tag{3}$$

where,

Z_{ec} = height above ground level of EC measurements
ρ_a = molar density of dry air

S_c = CO$_2$ molar mixing ratio

2.3. Data Processing and Analysis

Quality assessment and control (QA/QC) included flux corrections and canopy storage calculations. The half-hour-average fluxes of CO$_2$ and water vapor were calculated using the EddyPro v6 software (LI-COR Biosciences, Lincoln, NE, USA). Data processing included raw data filtering and statistical tests, such as drop-outs and spike removals [29,35], block averaging, double rotation, time lag compensation, low and high frequency spectral correction [36]. Spike removals were needed to exceed quality control criteria and to ensure the reliability of high frequency data (10 Hz) [16,24], which may be affected by instrument or power failure [37]. Quality check flagging policy included flux quality flags classes from 1–9 according to the test for steady state conditions and developed turbulence following Foken et al. [38].

Further data processing and analysis was carried out in R-Statistics software. We used the method of Iglewicz and Hoaglin [39] to detect bad values in flux data with threshold value of 3.5. To avoid excluding true measurements we rounded up the allowable data region (200–700 ppm) for CO$_2$ concentration and ±100 μmol m^{-2} s^{-1} for CO$_2$ flux. The percentage of usable data after filtering was 89.5%.

Budget sums of forest ecosystem were estimated using the gap-filling method recommended by Jaksic et al. [37], performed as a combination of lookup tables [40] and the Reddy ProcWeb online tool (https://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWeb).

We evaluated the cumulative footprint at the clear-cut area every 30 min according to [41,42]. Measured fluxes were taken into account from 0° to 360°. The footprint area analysis showed that 90% of the cumulative footprint was located at 84.9 m distance as well showing the maximum extension of limits of clear-cut area from the tower. Cumulative footprints of 70%, 50%, 30%, and 10 % originated 31.3, 18.7, 11.7, and 5.3 m from the EC tower, respectively. Less than 1% of fluxes (0.5 m) showed offset from the tower. The footprint area completely covered the study and surrounding areas.

In this study, we examined effects of two binary factors (stand with levels "young" and "old" and light with levels "night" and "day") and several continuous variables like time (hours), air temperature, water vapor, etc., on NEE. We had no a priori reason to choose any particular parametric form for describing the shape of the relationship between NEE and the explanatory variables. In such cases, generalized additive models (GAMs) are useful. For data smoothing we used mgcv implementation of gam in R, contributed by Wood [43]. We selected the penalized cubic regression splines model for smoothing predictors. To study the effect of binary factors on NEE, one-way and two-way analysis of variance (ANOVA) was used as an option in GAM modelling procedure [43].

3. Results

Forest Ecosystem Carbon Balance

On a daily basis (24 h), the study site acted as a C-sink beginning about 07:00 in the morning and a C-source at night (Figure 2). Daytime average NEE was −3.398 μmol m^{-2} s^{-1}, varying between −96.793 μmol m^{-2} s^{-1} and 83.327 μmol m^{-2} s^{-1}. Around 20.00 h, NEE turned positive for the nighttime period, staying positive but near to neutral level (average 2.749 μmol m^{-2} s^{-1}).

Carbon fluxes were sensitive to temperature and precipitation over the study period. Temperatures stayed above 0 °C and NEE balance was negative (−1.72 μmol m^{-2} s^{-1}), indicating sink behavior (Figure 3). The beginning of June was cold and wet. Temperatures started rising later in the second half of the month. July was sunny and temperatures (average 18.5 °C) were the highest for the year. NEE showed higher uptake from the atmosphere in June. Fluxes acted as a C-sink between 08:00 and 21:00, between sunrise and sunset. C-uptake started in the mornings one hour after sunrise and respiration dominated in the nighttime one hour after sunset, similarly in every month.
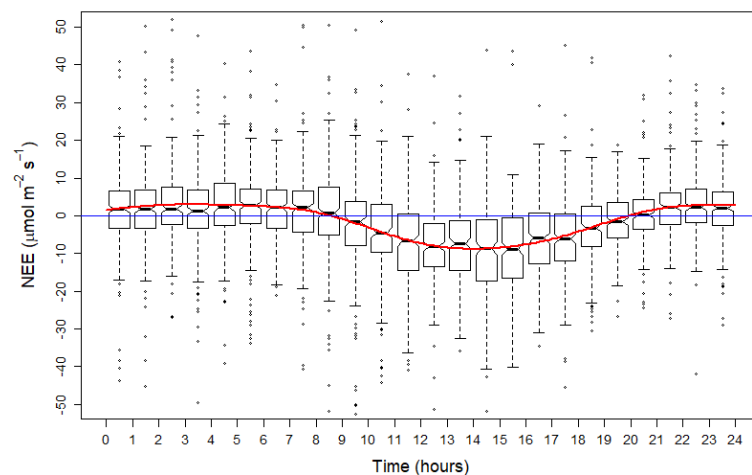
Figure 2. Values of net ecosystem exchange (NEE, μmol m^{-2} s^{-1}) over the study period (June to September, 2014) on a 24-h timescale. Red line describes smooth mean of the NEE.
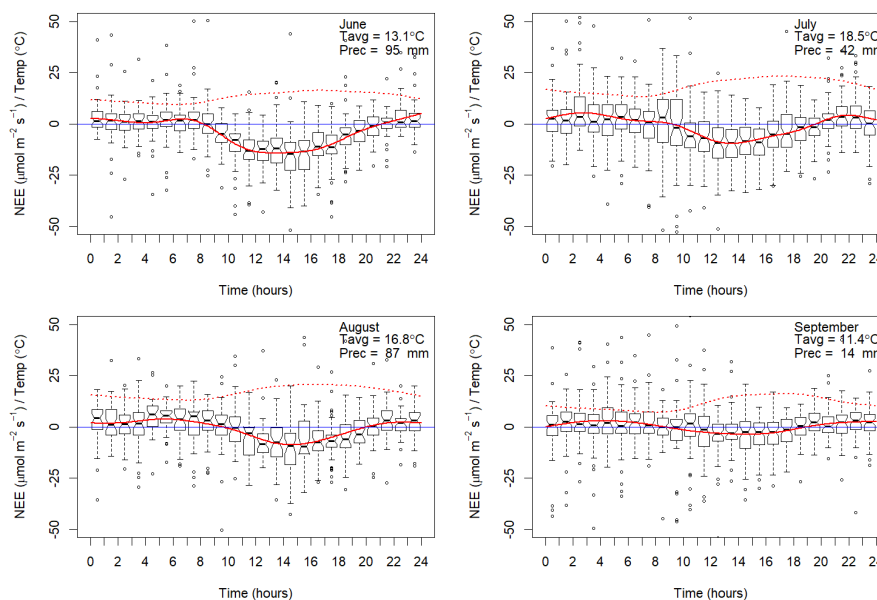
**Figure 3.** NEE (μmol m^{-2} s^{-1}) values per 24-h timescale and precipitation (mm) levels over the study period (June to September 2014). Dark red line describes smooth mean of the NEE, dotted red line illustrates average temperature.

June was the wettest month, followed by August. C-uptake increased with the higher precipitation values. September was sunny with low precipitation and NEE was C-neutral or showed slightly C-negative values.

Highest C-uptake occurred around 20 °C (between 15 to 25 °C) (Figure 4). More limited C-uptake occurred under lower temperature conditions and under extremely high temperatures and drought conditions.

The average NEE showed higher C-uptake in the older of the two stands (*p*-value = 0.001) (Table 2). Average CO$_2$ fluxes differed between nighttime and daytime in every month (Figure 4). The daytime NEE fluxes in the younger YS08 stand averaged −2.187 μmol m^{-2} s^{-1} and the average NEE for the older OS08 stand was −4.609 μmol m^{-2} s^{-1}. However, monthly results were more variable (Table 2). The median fluxes during daytime varied between −0.8913 μmol m^{-2} s^{-1} in September and −5.018 μmol m^{-2} s^{-1} in June (Figure 5). The sum of daytime average fluxes was −3.492 μmol m^{-2} s^{-1}.
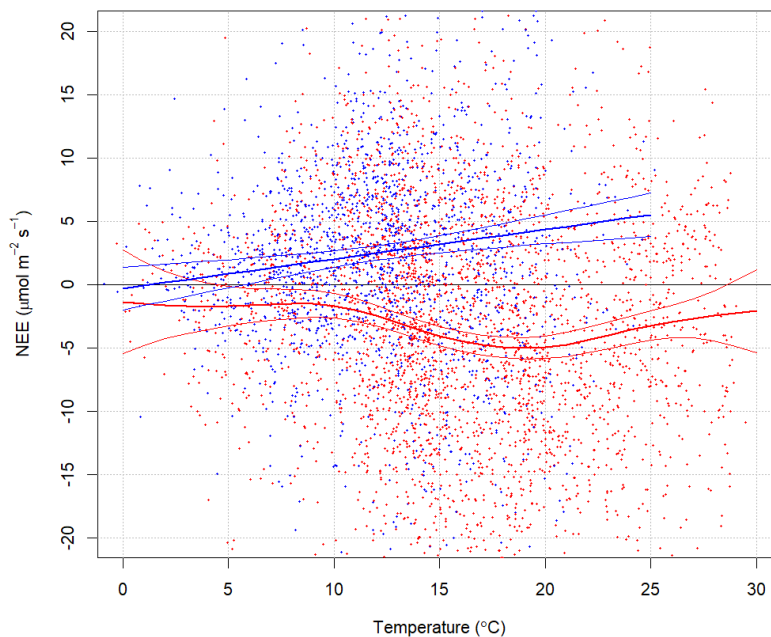
Figure 4. NEE (μmol m^{-2} s^{-1}) and temperature ($^{\circ}$C) over the study period (2014). Blue dots represent nighttime and red dots daytime eddy flux measurements. Lines represent GAM model predictions with confidence intervals.

Table 2. Average monthly and seasonal values of NEE (μmol m^{-2} s^{-1}), standard deviations (SD), and data points over the study period.

		YS08	OS06	Average *
June	NEE	−4.89	−4.45	−4.60
	SD	13.61	11.27	12.12
	Data points	372	708	
July	NEE	0.96	−3.55	−1.17
	SD	16.41	12.86	15.00
	Data points	613	547	
August	NEE	−0.66	−0.81	−0.77
	SD	12.96	10.62	11.27
	Data points	231	658	
September	NEE	0.23	−0.45	−0.25
	SD	13.15	12.37	12.60
	Data points	323	783	
Seasonal average	NEE	−0.85	−2.22	−1.72
	SD	14.78	11.90	13.04
Sum of data points		1539	2696	

* Average NEE level over 6- and 8-years-old stands.

Nighttime NEE fluxes in the younger stand averaged 2.509 μmol m^{-2} s^{-1}, similar to the older stand (average of 2.989 μmol m^{-2} s^{-1}). The median nighttime NEE fluxes in June, July, August, and September were 1.238, 2.083, 3.163, and 1.679 μmol m^{-2} s^{-1}, respectively. The sum of the stands' nighttime fluxes was 8.163 μmol m^{-2} s^{-1} and the monthly average was 2.555 μmol m^{-2} s^{-1}, peaking in August.

Local wind direction of fluxes generally was from the South, meaning that the wind mainly came from over the OS06 stand. Mean CO_2 concentration over YS08 was 339.7 ppm and NEE −0.85 μmol m^{-2} s^{-1}, however CO_2 concentration in the OS06 stand was 335.8 ppm and NEE was −2.22 μmol m^{-2} s^{-1}. The two stands had similar CO_2 concentrations; however, they had different monthly NEE values. Differences in NEE values may be caused by the observed severe summer drought event, resulting in differences in soil moisture conditions, which were moister in OS06 compared to YS08. Due to that, NEE results in July showed concrete differences between OS06 and YS08, where YS08 was a C-source and OS06 a C-sink (Table 2).
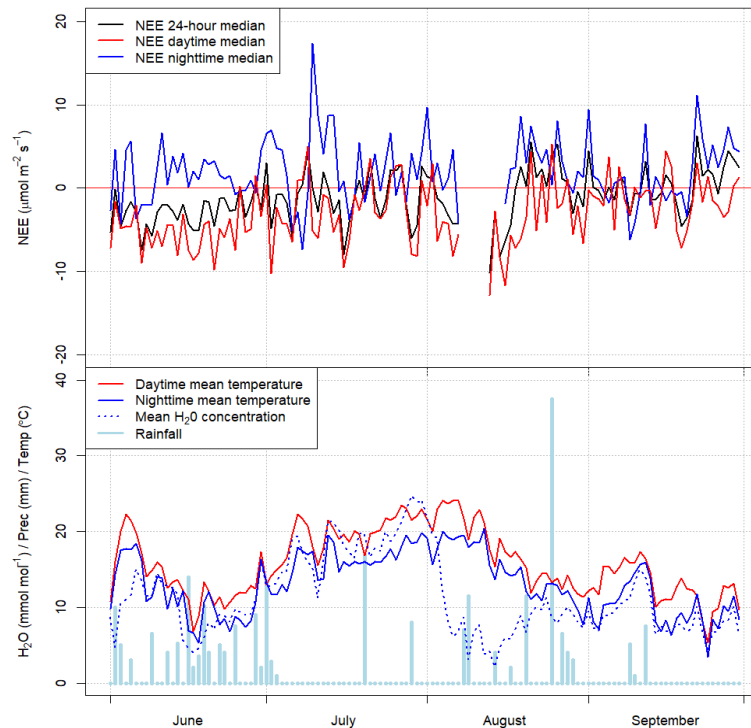
Figure 5. Daily NEE (μmol m^{-2} s^{-1}) values; nighttime flux (μmol m^{-2} s^{-1}), daytime flux (μmol m^{-2} s^{-1}), NEE average (μmol m^{-2} s^{-1}), temperature (C°), H_2O concentration (mmol mol^{-1}), and rainfall (mm) levels over the study period (2014).

4. Discussion

Stand-replacing disturbances have considerable impact on forest ecosystems' carbon dynamics, often turning ecosystems from C-sinks into C-sources [18,44]. Stands may require several years for recovery to C-sink status [45]. Even-aged management using clear-cutting is common in boreal and temperate forest biomes. This study in Estonia, in the hemiboreal transition between boreal and temperate biomes, presents carbon flux measurements using the eddy covariance technique after a stand-replacing disturbance. The EC method makes reliable and effective measurements of C-fluxes from canopy to atmosphere possible, even in complex terrain [18,25]. EC methods, however, do not provide individual tree flux measurements. Even though this affects dynamical measurements, all analysis and raw data depend more on site-specific conditions [25].

Measurements in two young stands six and eight years after clear-cutting provided estimates of NEE over the measurement period, illustrating monthly, daily, and diurnal variation in source-sink behavior. Over the measurement period (June to September), the two stands were slight C-sinks. In the daytime, the stands were C-sinks, turning to C-source behavior during the nighttime because of the connection with soil respiration, and to a lesser extent, with soil moisture [28,34]. As we hypothesized, the studied stands performed as weak C-sinks during the measurement period. Uri et al. [44] found

similar results in a 6-year-old Scots pine stand in Estonia, as did Aguilos et al. [16] with 7-year-old boreal mixed forest stand in Japan. A Canadian jack pine (*Pinus banksiana*) stand (7 and 8 years old) was almost C-neutral [46]. Taking only the snow free period into account, Payeur-Poirier et al. [47] found C-sink status by an 8-year-old spruce stand. Nevertheless, stands in other locations take longer to become C-sinks, up to 10 to 20 years in other boreal ecosystems [7,16,46,48,49].

Young forests (ages 0 to 10 years) have negative mean rates of net ecosystem production (NEP) because of high heterotrophic respiration [10,46,49,50]. Total ecosystem respiration is high when forests are young [4], but decreases as dead biomass that belonged to the previous forest rotation decomposes [51], although this may not be a monotonic decrease as early theory suggested and certainly depends upon the amount of legacy material left by a disturbance [52]. In boreal forests, it may take decades for NPP to exceed heterotrophic respiration [52,53]. Vigorously growing young stands, however, begin to offset respiration by photosynthetic activity. Temperature differences and variations directly affect both photosynthesis and respiration [17,33,54]. The NEE of forest stands combines the results of these two processes, depending on light, temperature, water vapor, and growing season length [28,49,55].

Photosynthesis and respiration strongly influence daytime NEE, attesting to the important role of photosynthetically active radiation [6,37,44]. Active daytime photosynthesis in our stands was evidenced by higher daytime CO_2 concentrations. Daily NEE was C-sink during the daytime and C-source during the night (Figure 5). Other studies in young stands have found similar results, for example, Kolari et al. [6] found nighttime fluxes in a 5-year-old Scots pine stand acting as a C-source (NEE was 3–6 μmol m^{-2} s^{-1}). During the daytime, the stand acted as a C-sink, but over the study period, the stand was a C-source [6]. Grant et al. [10] showed slight C-sink status on a daily basis from late May to June, similar to Rannik et al. [50] where a clear-cut (five years after disturbance) was a slight C-sink or neutral during the day in the summer.

Over the measurement period, monthly average NEE is sensitive to temperature; fluxes were greatest in June and decreased in September (Table 2). In slightly older logged Eurosiberian stands (7 and 13 years old), Schulze et al. [56] measured daily maximum ecosystem C flux in July between −7 and −4 μmol m^{-2} s^{-1}. Daytime NEE was close to the compensation point. Similarly, a young (<20 years) planted Norway spruce forest was a C sink; NEE was −10 to −5 g C m^{-2} d^{-1} [29]. During the winter season, daily respiration was close to zero so that C-flux was negative.

Carbon budget estimation of our clear-cut areas was −2.076 t C ha^{-1}—definite C-sink status. Despite the short measurement period in our study, our results compare well with other similar locations. Krasnova et al. [57] found annual results for NEE as −5.9 t C ha^{-1} yr^{-1}. Chi et al. [58] found NEE was 5–8 t C ha^{-1} yr^{-1} (500–800 g C m^{-2} yr^{-1}) six years after clear-cutting, similar to budget estimations in Aguilos et al. [16] and Kolari et al. [6] that found 12-year-old stand C budget is almost neutral.

Extreme precipitation alters CO_2 fluxes by influencing C-uptake during very wet conditions [54]. Different weather components, such as tropospheric ozone [59], including clouds [60], excessive rain, or drought, influence ecosystem functioning [17,18,22,54] and all may decrease C-uptake activity. Precipitation events often stimulate respiratory responses of microorganisms. Precipitation and higher humidity also affected C-cycling in our study. Similar results are found in other studies, where precipitation played a key role [5,61]. Wetter weather conditions generally promoted C-uptake (Figure 5). Also some other studies refer to similar results. Oishi et al. [61] found that in very warm and dry conditions, the ecosystem acted more as a weak C-sink, which confirm understanding of the current study. In our conditions, wet and dry weather was varying throughout study period. NEE showed higher uptake of C from the atmosphere in June, even though the temperature was lower at the beginning of the month.

Climate change influences C-cycling by modifying the C-uptake rate and period [7]. Generally, C-balance is sensitive to water availability, which may be important under wetter climate conditions in the future. In addition, drought events may be useful for C-uptake, excepting the extreme

drought conditions. On the one hand, the Estonian climate regime may shift to drought conditions, where warmer and drier summers may suppress higher photosynthesis in summertime and cause increases in ecosystem C-uptake [62–64] because of the decrease in July to September precipitation [62]. On the other hand, climate may become wetter over large areas of the boreal forest zone, leading to increased mineralization, higher plant productivity, and microbial activity in soils [17,51,65]. In this study, we experienced both warm and wet weather conditions over the summer. In August, there were quite high temperatures and precipitation levels, but low CO_2 levels. However, in July the higher peaks in CO_2 concentration coincided with average precipitation and high temperature. Some studies have shown that ecosystem respiration may be more variable than photosynthesis [54], thus fluxes may not correlate well with a single factor. Nevertheless, NEE is highly correlated with growing season length. Our results point to the need for greater attention to C-source and sink relationships during early stand development in order to better characterize C-dynamics.

5. Conclusions

Our main question was how much time was needed for recovery from clear-cutting and a return to a functioning ecosystem, in terms of becoming a C-sink. From our study, we can draw four conclusions: (1) Different weather conditions, especially precipitation and temperature, greatly affect forest C-balance; (2) after a stand-replacing disturbance, a 6-year-old forest ecosystem was a light C-sink during the measurement period; (3) an 8-year-old forest ecosystem demonstrated a stronger C-sink status; and (4) both young stands exhibit daytime C uptake and nighttime C losses.

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