Eesti Maaülikool
Estonian University of Life Sciences

EVALUTION OF FOREST MANAGEMENT IN THE CONTEXT OF CARBON FLUXES: EDDY-COVARIANCE METHOD

METSADE MAJANDAMISE MÕJU HINDAMINE SÜSINIKU KONTEKSTIS: TURBULENTSE KOVARIATSIOONI MEETOD

SILLE REBANE

A Thesis
for applying for the degree of Doctor of Philosophy in Forestry

Väitekiri
filosoofiadoktori kraadi taotlemiseks metsanduse erialal

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According to verdict No 6-14/10-2, 19th of June, 2020, the Defence Board of PhD theses in Forestry of the Estonian University of Life Sciences has accepted the thesis for the defence of the degree of Doctor of Philosophy in Forestry.

Opponent: **Professor Urban Nilsson, PhD**
Centre of Southern Swedish Forest Research
Swedish University of Agricultural Sciences

Supervisors: **Research Professor Kalev Jõgiste, PhD**
Institute of Forestry and Rural Engineering
Estonian University of Life Sciences

Senior Researcher Marek Metslaid, PhD
Institute of Forestry and Rural Engineering
Estonian University of Life Sciences

Defence of the thesis:
Estonian University of Life Sciences, room 2A1, Kreutzwaldi 5, Tartu, on October 9th, 2020, at 11:00.

The English language was edited by Visiting Prof. John A. Stanturf and Estonian by Urve Ansip.

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following three papers (I–III). The original publications are referred to in the text by their Roman numerals.

I   **Rebane, S.**, Jõgiste, K., Põldveer, E., Stanturf, J.A., Metslaid, M. 2019. Direct measurements of carbon exchange at forest disturbance sites: A review of results with the eddy covariance method. Scandinavian Journal of Forest Research, 34(7), 585–597.

II   **Rebane, S.**, Jõgiste, K., Kiviste, A., Stanturf, J.A., Metslaid, M. 2020. Patterns of carbon sequestration in a young forest ecosystem after clear-cutting. Forests, 11(2), 216.

III   **Rebane, S.**, Jõgiste, K., Kiviste, A., Stanturf, J.A., Kangur, A., Metslaid, M. 2020. C-exchange and balance following clear-cutting in hemiboreal forest ecosystem under summer drought. Forest Ecology and Management, 472, 118249.

The contributions of the authors to the papers were as follows:

	I	II	III
Original idea	**SR**, KJ, MM	**SR**, MM, KJ	**SR**, MM, KJ
Study design	**SR**, MM, KJ	**SR**, KJ, MM,	**SR**, KJ, MM
Data collection	**SR**, MM, EP	**SR**, KJ	**SR**, KJ, AKa
Data analysis	**SR**, EP	**SR**, AK	**SR**, AK
Manuscript preparation	**SR**, MM, KJ, EP, JAS	**SR**, MM, KJ, AK, JAS	**SR**, MM, KJ, AK, JAS, AKa

SR – Sille Rebane; KJ – Kalev Jõgiste; MM – Marek Metslaid; AK – Andres Kiviste; JAS – John A. Stanturf; EP – Eneli Põldveer; AKa – Ahto Kangur.

ABBREVIATIONS

P_a	Air density
ρ_a	Molar density of dry air
C	Carbon
CO_2	Carbon dioxide
DOY	Day of year
EC	Eddy covariance
F	Gas flow of eddy covariance
F_c	Eddy flux
GPP	Gross primary production
H_2O	Water vapour
LAI	Leaf area index
NEE	Net ecosystem exchange
RE	Respiration
S_c	CO_2 molar mixing ratio
S_c	Storage flux
Z_{ec}	Height above ground level
s'	Dry mole fraction
w'	Vertical wind speed

1. INTRODUCTION

One of the important tasks of ecological research is the monitoring of climate change and response of ecosystems to such a change. It has become rather urgent during recent decades as altered environment threatens societal expectations for ecosystem services. Global warming and increasing carbon dioxide (CO_2) concentration as a reason for such a process are the main factors on which to focus scientific interest because of their direct impact on primary production (Liu *et al.*, 2006; Jaagus & Mändla, 2014, Jaagus *et al.*, 2017). Results based on models show, that temperature is expected to increase (Thom & Seidl, 2016) from 1.4 to 3.8 °C by year 2100 (Schneider, 2009). How global warming affects the forest is not well studied.

Boreal forest, being a widely distributed vegetation type as well being a substantial part of the global carbon (C) cycle, must be addressed to understand the consequences of climate change (Schulze *et al.*, 1999; Kolari, 2010). Forest ecosystems are part of the biosphere as a whole and have a global role in maintaining equilibrium of whole living world (Noe *et al.*, 2011). Also, forest ecosystems have the ability to regulate Earth´s climate and energy fluxes. The forests, including boreal and hemiboreal forests, can absorb CO_2 from the atmosphere and store carbon in biomass (Froelich *et al.*, 2015). C is released to the atmosphere through respiration processes, e.g., from living tissues of vegetation, soil and decaying wood.

Another urgent question is how different disturbances, such as fire, insects, wind and clear-cutting, affect forest ecosystems during temperature rise (I) (Lindroth *et al.*, 1998; Bronson *et al.*, 2009; Froelich *et al.*, 2015). Different disturbances have great influence on forest growth and productivity, mortality, vitality, decomposition and C-cycling (Vesala *et al.*, 2005; Köster *et al.*, 2009; Laarmann *et al.*, 2009; Froelich *et al.*, 2015). Some disturbances have a stronger effect on forest ecosystems than others (Schulze *et al.*, 1999). In the future, windstorms, fires and insect outbreaks are expected to increase (Seidl *et al.*, 2014; Thom & Seidl, 2016; Seidl *et al.*, 2020). According to Seidl *et al.* (2014) windstorms and insects outbreaks do not show clear patterns during the stand development stages. Wildfires are comparable with clear-cutting by affecting C-cycle during forest stand development (**I**).

After a clear-cutting disturbance the forest ecosystem C-balance is totally changed (Schulze *et al.*, 1999). Clearcut harvesting is a common practice in Estonian forest management. After a clearcut a considerable amount of residues (branches, stumps, roots etc.) stays in the harvested area (Zha *et al.*, 2009; Aguilos *et al.*, 2014). It changes site balance by active photosynthesis with increased autotrophic and heterotrophic respiration (Kowalski *et al.*, 2004; Urbanski *et al.*, 2007; Aguilos *et al.*, 2014). Net content of the CO_2 in the air is affected by two processes: photosynthesis and respiration. It is assumed that immediately after a clearcut, a huge amount of C is released, which make a forest stand act as a C-source (Kolari *et al.*, 2004; Humphreys *et al.*, 2005, 2006; Zha *et al.*, 2009; Amiro *et al.*, 2010; Noormets *et al.*, 2012; Paul-Limoges *et al.*, 2015). However, several years after disturbance a forest ecosystem is able to sequestrate C as the trees are growing and ageing (Valentini *et al.*, 2000; Kowalski *et al.*, 2004; Aguilos *et al.*, 2014). This kind of forest recovery results in C-sink status with higher C-uptake (Kowalski *et al.*, 2004). How quickly and intensively a forest can absorb C and attain the compensation point (moment when C emission is exceeded by C-uptake) depends on different aspects (Rannik *et al.*, 2002; Zha *et al.*, 2009; Froelich *et al.*, 2015).

The main drivers of recovery are growing season length and vegetation growth, which helps to achieve C-balance (Vesala *et al.*, 2005; Oishi *et al.*, 2018). If vegetation recovery is quick, then C-uptake of the forest ecosystem is more intensive. Another set of impact factors are meteorological conditions, where all components, such as temperature, water vapor, and humidity are playing key roles in photosynthesis and C-cycling (Kowalski *et al.*, 2004; Zha *et al.*, 2009; Kupper *et al.*, 2011). However, we have to pay attention to radiation by determining daytime and nighttime, which helps to indentify the active photosynthetic period in 24-hours.

As forests are regulating Earth´s energy fluxes it is important to understand how forest ecosystems are reacting to environmental factors, they are at the same time a complex biome (Suffling, 1995; Bergeron *et al.*, 2008; Noe *et al.*, 2011). To fully understand the energy exchange, there is the basic model of net ecosystem exchange: GPP=NEE - RE (Urbanski *et al.*, 2007; Jensen *et al.*, 2017). It means that gross primary production (GPP) = net ecosystem exchange (NEE) - ecosystem respiration (RE), where NEE is actually a combination of two different fluxes (storage

flux and C-flux) (Zha *et al.*, 2009). If RE exceeds GPP then NEE is positive, which means that the ecosystem is a C-source. If RE is lower than GPP, then we can attribute C-sink status to the forest ecosystem (Urbanski *et al.*, 2007). This kind of ecosystem study is monitored by the widely used eddy covariance method (EC). It is the most adequate way to measure NEE between ground and atmosphere (Burba *et al.*, 2013). EC is a direct micrometeorological measurement method for identifying C-fluxes in forest ecosystems (Amiro *et al.*, 2006; Rannik *et al.,* 2020).

This thesis is a synthesis of three original papers. Paper **I** focuses on disturbances, such as forest fires, storm and wind damages, insect attacks and clear-cuttings in the boreal zone including some relevant temperate zone studies. The main focus besides disturbances is on ecosystem C-balance and possible affecting factors. Also paper **I** is a synthesis of different studies and provides an overview of the literature; Papers **II** and **III** present measured C-flux results in young forest stands. All papers (**I**, **II**, **III**) show how active forest management, such as clearcut harvesting, can affect the forest ecosystem C-cycle and help to understand how long it could take for stands to recover after stand-replacing disturbance and achieve a C-sink status.

2. REVIEW OF THE LITERATURE

Disturbances play a key role in carbon dynamics of forest ecosystems, where disturbance size, type, frequency and intensity determine stand C-exchange (Gromtsev, 2002; Thom & Seidl, 2016; Seidl *et al.*, 2020). Patterns of C-exchange in boreal and temperate forests can be quite similar (Seidl *et al.*, 2020). The literature of C-balance affected by natural disturbances and active forest management (e.g., clear-cutting) is reviewed in paper (I) that gives an overview of different studies and results in the boreal zone and some of the more important temperate zone studies.

Management and planning of boreal forests are significant for C-dynamics (Amiro *et al.*, 2006). Disturbances, natural and anthropogenic, can switch forest stands from C-sinks to C-sources (Kuuluvainen & Aakala, 2011; Thom & Seidl, 2016; Mamkin *et al.*, 2019). Generally, after disturbance the amount of decaying biomass increases and productivity of the stand temporarily decreases as vegetation recovers. Extreme climate events, which are caused by global warming, can increase and higher temperature may double disturbance frequency (Amiro *et al.*, 2006).

Managing forests sustainably challenges forest managers, owners and policymakers to balance between traditional forest management objectives and global warming mitigation (Amiro *et al.*, 2006). After a stand-replacing disturbance, such as clear-cutting, monitoring stand development helps to better understand the processes of forest ecosystem recovery (Uri *et al.*, 2019). Many studies globally of C-dynamics after disturbance have used the eddy covariance method. In particular, Canadian studies have contributed significantly to our understanding (Mkhabela *et al.*, 2009; Amiro *et al.*, 2010; Grant *et al.*, 2010; Coursolle *et al.*, 2012; Rebane *et al.*, 2019). Also, some studies have been done in China, Russia and Europe: France, Great Britain, Germany, Finland and Estonia (Rannik *et al.*, 2002; Kolari *et al.*, 2004; Kowalski *et al.*, 2004; Zha *et al.*, 2009; Krasnova *et al.*, 2019; Mamkin *et al.*, 2019; Uri *et al.*, 2019).

Immediately after clear-cutting most stands act as C-sources. For example in Russia, a fresh clear-cut that regenerated with spruce acted as a C-source (Mamkin *et al.*, 2019). Similar results in other studies of recent clearcuts showed C-source status for several years (Amiro 2001;

Kowalski *et al.*, 2003; Kolari *et al.*, 2004; Giasson *et al.*, 2006; Humpreys *et al.*, 2006; Williams *et al.*, 2014; Paul-Limoges *et al.*, 2015; Mamkin *et al.*, 2019).

A critical factor is determining the compensation point when a recovering stand becomes C-neutral or turns into a C-sink. C-neutral status may take more than two or three years depending on site conditions. Most studies show variations how long it takes to reach the point when forest ecosystem C-balance is almost zero, that is by stand age (Amiro *et al.,* 2006; Zha *et al.*, 2009; Coursolle *et al.,* 2012). For example, a 7-year-old jack pine (*Pinus banksiana*) stand in Canada was almost C-neutral (Amiro *et al.*, 2006) and remained so a year later. Very similar results (near-neutrality) were found in Canada two years after clear-cutting (Giasson *et al.*, 2006; Zha *et al.*, 2009; Coursolle *et al.*, 2012).

Recovery to C-neutrality could take longer than two or three years. In Japan Aguilos *et al.* (2014) found a 4-year-old stand was C-neutral during the whole measured year and achieved C-sink status by the age of 7. Similarly, it took 7 years for black spruce (*Picea mariana*) to become C-neutral (Grant *et al.*, 2010; Coursolle *et al.*, 2012). These results, as well as Amiro *et al.* (2006), leads to the understanding that 7-years after clear-cutting are required for forest stands to recover neutrality and possibly at least 11 years to become a C-sink (e.g., Mkhabela *et al.*, 2009).

Generally, one clear trend could be distinguished: after clear-cutting the forest ecosystem turns into a C-source. Studies from Estonia and Finland show that recovery may take place much earlier, after 10 years (Kolari *et al.*, 2004) and in some cases even as few as 7 years after clear-cutting (Krasnova *et al.*, 2019; Uri *et al.*, 2019). Studies in Japan and Canada confirm these results (Amiro *et al.*, 2006; Aguilos *et al.*, 2014). Nevertheless, according to most of the Canadian examples it can take up to 20 years for forest stands to recover and acquire a C-sink status (Bergeron *et al.*, 2008; Amiro *et al.*, 2010).

Finding a compensation point in ecosystem C-exchange, and reconciling the varied results, depends on different environmental factors (Amiro *et al.*, 2010; Niu *et al.*, 2017). Precipitation can strongly affect the C-cycle by influencing the variability of NEE and ecosystem respiration (Amiro *et al.*, 2006). Substantial rainfall may positively stimulate plant growth and C-uptake (Niu *et al.*, 2017). Extreme conditions, however, of drought

or wet weather are two drastic situations where C-uptake shuts down (Jaksic *et al.*, 2006; Oishi *et al.*, 2018).

There are many factors other than precipitation that influence C-dynamics, such as radiation, forest site type, etc. making for complex processes that are difficult to understand (Jaksic *et al.*, 2006). Temperature effects can be described through ecosystem processes such as respiration and photosynthesis (Frank *et al.*, 2015). Increasing temperature may extend growing season length and shift levels of nutrient, water and vegetation growth (Amiro *et al.*, 2006; Frank *et al.*, 2015).

2.1. Research needs

The eddy covariance method has been used in many studies of disturbances that have focused on forest fires and clearcut harvesting. Eddy covariance studies of other disturbances such as windstorms and insect outbreaks are mostly missing. The available studies are primarily restricted to two or three locations and best represented by studies of different disturbances that have measured NEE in forest ecosystems in North America. For a better understanding of global patterns of disturbance effects on the global C-cycle, we need to improve the spatial and temporal scales of studies. Geographically more research is needed at sites in Europe, Russia and Asia that represent different site types. To get a complete overview of forest ecosystem processes and C dynamics, it is important to monitor different disturbances over a long time scale. Additionally, short-term dynamics of post-disturbance effects are knowledge gaps that need to be addressed.

Estimates of disturbance effects on the forest ecosystem C-cycle are needed for improving climate change adaptation and mitigation strategies. Increasing disturbance frequency is predicted that will affect C-uptake process and release more C than forests can absorb. Forest practitioners need a better understanding of the effects of management practices such as clear-cutting on C-dynamics in order to mitigate and adapt to climate change (Jandl *et al.*, 2007; Mayer *et al.*, 2020). Although increasing CO_2 in the future may increase productivity (Frank *et al.*, 2015), choice of regeneration method will affect the C-recovery period.

Data from studies using the EC technique, combined with inventory-based methods and modelling are needed in forest practice for

management decisions. In Estonia clearcut areas are mostly regenerated artificially, usually by planting or sowing, but sometimes natural regeneration is more reasonable, depending on site and location. Proper regeneration method may shorten the recovery period and help to accelerate C-uptake. There is a difference in time scale as well: natural regeneration usually takes more time than artificial regeneration.

Researchers and practicing foresters need to cooperate to find solutions for how to manage forests under climate change. Foresters need new research knowledge on which forest management actions are adaptive to altered disturbance regimes and ecosystem responses under climate change. The important question remains: How long does it takes to recover from stand-replacing disturbance, especially regeneration after clear-cutting?

3. AIMS OF THE STUDY

The general aim of the present thesis was to investigate patterns of CO_2 exchange and interactions between mixed forest ecosystems and environmental changes. For this, forest ecosystem C-balance during the measurement period was quantified.

The specific aims of this doctoral thesis were:

1. To review selected literature about the relationships between different processes that influence C-uptake in forest ecosystems (**I−III**);

2. To examine how long it takes for a forest ecosystem to recover from different disturbances and become C-neutral or achieve a C-sink status, focusing on long-term studies (**I**);

3. To quantify dynamics of C-fluxes after a stand-replacing disturbance, such as clear-cutting (**II−III**);

4. To determine C-exchange under summer drought conditions after clear-cutting during the measurement period (**III**);

5. To examine the time needed for a young forest ecosystem to turn into a C-sink after successful regeneration (**II−III**).

4. MATERIALS AND METHODS

4.1. Study area

The study was carried out in south-eastern part of Estonia (**II−III**), in Järvselja Training and Experimental Forest Centre which belongs to the hemiboreal forest zone (Figure 1). The climate is characterized by warm summers and cold winters with average annual temperature of +5 °C. Average precipitation in Estonia is 550–800 mm.
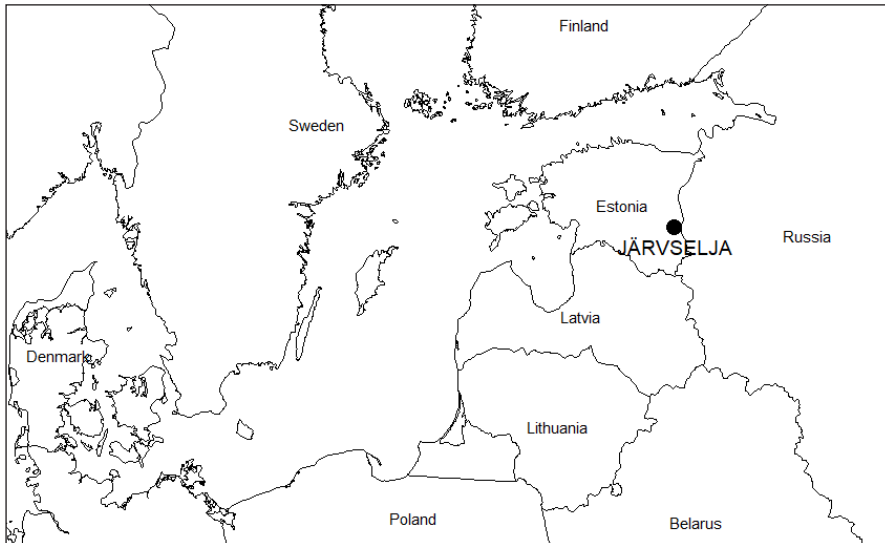
Figure 1. Location of the Järvselja study site.

The field measurements of this thesis were done in two different locations. The first study site is located in compartment JS223, where two subcompartments (2 and 6) are included (**II**). Subcompartments 2 (0.9 ha) and 6 (1.4 ha) were clearcut harvested in 2008 and 2006, respectively. Before clear-cutting subcompartments 2 and 6 had very similar growing conditions with *Oxalis-Vaccinium myrtillus* site type (Lõhmus, 1984) and the site index was 1. Growing stock in subcompartment 2 was 333 m^3 ha^{-1} and in subcompartment 6 was 352 m^3 ha^{-1}. Before clear-cutting the dominant tree species in subcompartment 2 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

subcompartment 6, where Norway spruce and silver birch were present. Understory vegetation was mainly rough small reed (*Calamagrostis arundinacea* (L.) Roth), sedges (*Carex* spp.), lingonberry (*Vaccinium vitis-idaea* L.) and European blueberry (*Vaccinium myrtillus* L.).

Six years after clear-cutting the dominant regenerating tree species in subcompartment 2 were birch (*Betula* spp.) and Norway spruce with a minor component of Scots pine. Dominance in subcompartment 6 changed after 8 years to Norway spruce and silver birch, with minor amounts of European aspen (*Populus tremula*) and Scots pine (Table 1). Average stand height 6-years after clear-cutting was 1.3 m and 8-years after clear-cutting in site 6 it was 2.1 m.

Another study site was located in compartment JS338, subcompartment 8 (0.7 ha), which was clearcut harvested in 2013 (III). Soil scarification and planting with Norway spruce was carried out in 2013 and 2014. The site type is *Oxalis-Vaccinium myrtillus* (Lõhmus, 1984) and the site index is 1. Before clear-cutting the site was dominated by birch (*Betula* spp.); there were also spruce (*Picea abies*) and European aspen, with growing stock 322 m^3 ha^{-1}. Vegetation in the understory included European blueberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-idaea*) and some bryophytes. Bryophytes were represented by red-stemmed feathermoss (*Pleurozium schreberi*), glittering woodmoss (*Hylocomium splendens*), broom forkmoss (*Dicranum scoparium*) and common haircap (*Polytrichum commune*).

Five-years after clear-cutting the study site was dominated by Norway spruce (*Picea abies*) and birch (*Betula* spp.) (Table 1). Understory vegetation consisted mainly of the same bryophytes as before clear-cutting. Average stand height was 1.43 m.

Table 1. Dominant tree species after harvest (percent) and trees per hectare of the stands JS223 (2006, 2008) and JS338 (2013) at the Järvselja Training and Experimental Forest Centre, Estonia.

Year	Dominant tree species after harvest (percent) / trees per hectare			
	Silver birch (*Betula* spp.)	Norway spruce (*Picea abies*)	European aspen (*Populus tremula*)	Scots pine (*Pinus sylvestris*)
2006	29	53	12	6
	700	1300	300	150
2008	58	36		6
	1780	1100		200
2013	47	47		6
	2100	2100		200

4.2. Eddy covariance measurements

Eddy covariance is a method for measuring gas exchange between the terrestrial ecosystem and the atmosphere. It is a direct way to measure whole net ecosystem exchange (NEE).

NEE measurements started in the different study sites in 2014 and are still running. The two towers were mounted in the study sites. In the first study site (JS223) (**II**) the tower was located on the border between two clearcut areas; in another site (JS338) (**III**) the tower was located in the middle of the subcompartment. The eddy covariance equipment was installed on the tower at a height of 6 m in the JS223 site. In the other site, JS338, EC equipment was mounted 3.8 m above ground. The eddy covariance installation includes a 3D sonic anemometer (C-SAT 3, Campbell Scientific, USA) and closed-path infrared gas analyzer LI-7200 (LI-COR Biosciences, Lincoln, NE, USA). The sonic anemometer is used to measure wind 3D components and temperature, with an infrared gas analyzer to measure surrounding air CO_2 and H_2O concentrations.

The measurements in 2014 was carried out from June to September (**II**) and measurement in 2018 was carried out from May to August (**III**). Measurements are saved automatically to a data logger in a high sampling frequency (10 Hz). All data were converted into Excel format by using the EddyPro software (LI-COR Biosciences, Lincoln, NE, USA).

The NEE, which is detected by EC, was estimated every 30 minutes and is a sum of two different fluxes: eddy flux (F_c) and storage flux (S_c) according to general NEE and eddy flux 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 ($\mu mol\ m^{-2}\ s^{-1}$),
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

These flux components are combined with C-uptake of all vegetation layers and C release according to respiration processes, being the major fluxes in eddy covariance raw data.

4.3. Statistical analysis

Data processing included filtering of raw data and statistical screening, drop-outs and despiking, double rotation, block averaging, time lag compensation and spectral correction of low and high frequency (Vickers & Mahrt, 1997). Despiking was needed for quality control to ensure reliability of high frequency data. For that we used a steady-state and the developed turbulence tests combined with a quality control flag system, where classes were from 1 to 9 (Foken *et al.*, 2004).

For further data processing and analysis, final calculations and figures used R software (R Core Team 2019). In this study the method of Iglewicz and Hoaglin (1993) was used with a threshold value of 3.5 (abs(x – me(x))/mad(x) > 3.5) where me(x) was the median and mad(x) the median absolute deviation to detect bad values. Single outstanding

and physically impossible fluxes were eliminated $\pm$ 100 µmol m^{-2} s^{-1} (**II**) and $\pm$30 µmol m^{-2} s^{-1} (**III**) for CO_2 flux.

This study 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 (**II**). For data smoothing the gam function implemented in R was used, in the mgcv package contributed by Wood (2006). The penalized cubic regression splines model was selected 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 the GAM modelling procedure.

The gap-filling method of Reichstein *et al.* (2005) was used for NEE budget estimations (**II**−**III**), which is performed using lookup tables and the Reddy online tool (https://www.bgcjena.mpg.de/bgi/index.php/ Services/REddyProcWeb). Using the online tool method is required for gap-filling in order to represent different variables, such as radiation, vapor pressure deficit, temperature. This method takes into account similar NEE values and conditions to calculate and fill NEE gaps. Gap-filled data was used only for budget estimations.

Meteorological data for gap-filling (gaps in recorded eddy-covariance measurement) were filled with data that came from the Järvselja Hunting Lodge weather station. The weather station site is located 1.3 km (**II**) and 2 km (**III**) from study site.

The cumulative footprint at the clearcut sites (**II**−**III**) was evaluated following the method of Kljun *et al.* (2004) for footprint analyses. Fluxes are taken into account (0° to 360°).

5. RESULTS

5.1. Carbon balance in forest ecosystems

Measurements of C-balance at the global scale have shown large variations (**I**). Different disturbances have affected forest ecosystems and turned them into C releasing environments. Insect outbreaks, especially bark beetles, cause damage to whole ecosystems (Kurz & Apps, 1999; Dale *et al.*, 2001; Edburg *et al.*, 2012; Seidl *et al.*, 2014; Valeria *et al.*, 2016). After beetle attack in lodgepole pine (*Pinus contorta* Douglas) stands, the forest ecosystem is a strong C-source during the growing season for 1 to 2 years. After a 3-year-long bark beetle attack, the stand may turn into a C-sink with NEE of -4 gC m^{-2} y^{-1}. However it depends on forest recovery dynamics; in some cases C-sink and C-source can reverse from one year to another year (Brown *et al.*, 2010, 2012).

Forest ecosystems that have experienced stand-replacing disturbance, such as windstorm damage, turn into huge C-sources with 575 gC m^{-2} y^{-1}, decreasing during subsequent years. After windstorm a 4-year old spruce forest in Poland demonstrated C emissions as high as 250 gC m^{-2} y^{-1} during the measurement period (March to September) (Ziemblinska *et al.*, 2018).

Forest ecosystems became C-sources immediately after fire disturbance (Dore *et al.*, 2008). Different jack pine (*Pinus banksiana* Lamb) stands had great variation, such as a 6-year-old stand that acted as a C-sink -3 gC m^{-2} y^{-1}, however one year later it turned into a C-source with 43 gC m^{-2} y^{-1}. At age 15, a jack pine stand achieved C-sink status for two years (-115 gC m^{-2} y^{-1}). Variations continued after every ten or twenty years, changing into a C-source and C-sink; for example at the age of 76, the forest stand was a C-sink -36 gC m^{-2} y^{-1}; however, a 15-year-old stand was absorbing C more than a 76-year-old stand (Mkhabela *et al.*, 2009). Also black spruce (*Picea mariana* (Mill.) BSP) stands (160−169 years old) showed C-sink status from -7 to -58 gC m^{-2} y^{-1} after fire disturbance (Dunn *et al.*, 2007), but still did not exceed the absorbing ability of a 15-year-old jack pine stand (Mkhabela *et al.*, 2009). From age 10 to 15-years-old, stands presented both source and sink statuses depending on quick vegetation growth and increased leaf area index (LAI).

Most studies of clear-cutting have been carried out in Canada. Different studies showed that it takes several years to become a C-sink after large-scale disturbance in forest ecosystems. Recovery may take approximately 20 years, however in some cases it is shorter, for example an 11-year-old Jack pine stands behaved as a C-sink with -34 gC m^{-2} y^{-1} (Mkhabela *et al.*, 2009). Similar results were found by Kolari *et al.* (2004) in Finland, where a 12-year-old Scots pine stand was a C-sink (-24 gC m^{-2} y^{-1}). Other studies demonstrated C-sink status 17 years after clear-cutting with -20 gC m^{-2} y^{-1} and C-uptake increased continuously up to age 74-years in a Douglas-fir stand with -560 gC m^{-2} y^{-1}. Also, different middle aged stands showed high C-uptake from the atmosphere (Table 2).

Table 2. NEE values of studied stands after clear-cutting (**I**).

Location	Dominant tree species	Time since disturbance	NEE (gC m^{-2} y^{-1})	Source
Canada	Jack pine	29	-66	Grant *et al.* (2010)
Canada	Jack pine	29	-80	Mkhabela *et al.* (2009)
Canada	Jack pine	30	-79	Grant *et al.* (2010)
Canada	Jack pine	30	-79	Mkhabela *et al.* (2009)
Canada	Jack pine	31	-93	Grant *et al.* (2010)
Canada	Jack pine	32	-107	Grant *et al.* (2010)
France	Maritime pine	32	-222	Kowalski *et al.* (2004)
Finland	Scots pine	38	-138	Kowalski *et al.* (2004)
Finland	Scots pine	40	-192	Kolari *et al.* (2004)
Britain	Sitka spruce	41	-496	Kowalski *et al.* (2004)

Measured sites in Estonia also showed varying C-dynamics in forest ecosystems after clear-cutting (Figure 2). Results were from measurement periods between June to September (**II**) and between May to August (**III**). It is clear that an 8-year-old young spruce stand is able to absorb

more C from the atmosphere than other studied 6- and 5-years-old young stands. Five years after disturbance forest ecosystem C-levels vary around zero, being a C-neutral ecosystem during the measurement period.
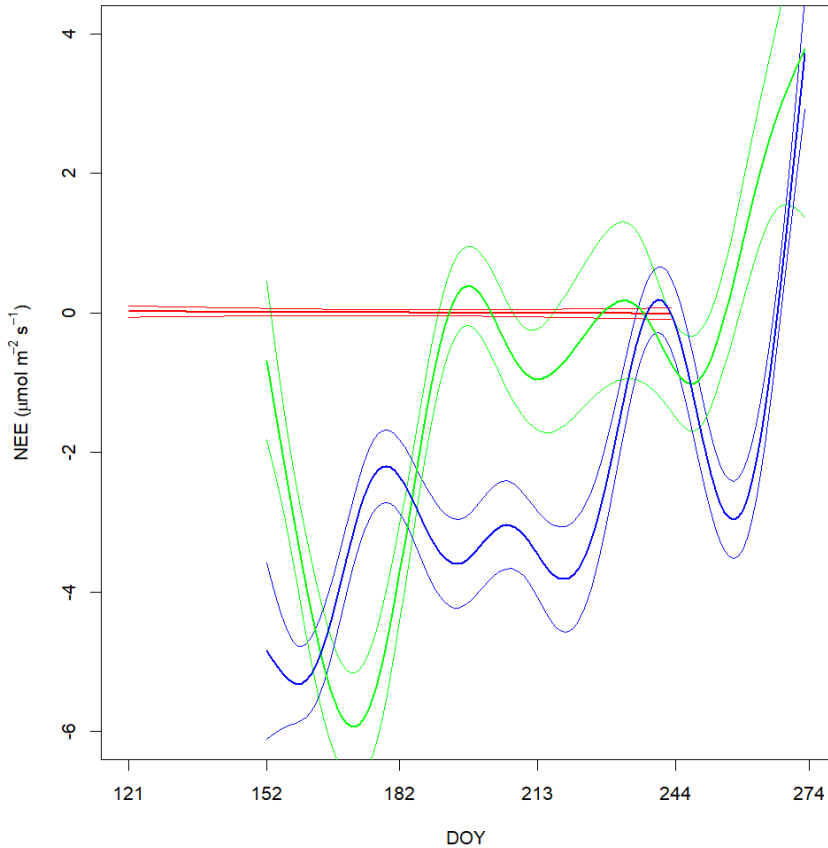
Figure 2. NEE levels over the study period. Red line describes 5-year-old, green line 6-year-old and blue line 8-year-old studied stand. Lines represent GAM model predictions with 95% confidence limits.

The measurement period for NEE varied between -0.0084 (**III**) and -2.22 μmol m^{-2} s^{-1} (**II**). The lowest average C-exchange result was recorded in 5-year-old mixed stand and highest in 8-year-old Norway spruce stand. Recorded average NEE range also included a 6-year-old Silver birch stand with NEE -0.85 μmol m^{-2} s^{-1} (**II**). The study sites (**II−III**) were a C-sink during the measurement periods (Table 3).

Table 3. NEE values of studied stands at the Järvselja Training and Experimental Forest Centre, Estonia.

Study	Dominant tree species	Time since disturbance	NEE (gC m^{-2})	Measurement period
III	Norway spruce	5	−0.0084	May to August
II	Silver birch	6	−0.85	June to September
II	Norway spruce	8	−2.22	June to September

Table 4. Footprint areas distances (m) of the study sites at the Järvselja Training and Experimental Forest Centre, Estonia.

Study	Dominant tree species	Time since disturbance	Cumulative footprint				
			90%	70%	50%	30%	10%
III	Norway spruce; birch; Scots pine	5	98	65.4	46.4	30.6	12.3
II	Silver birch; Norway spruce	6; 8	84.9	31.3	18.7	11.7	5.3

The footprint analysis shows footprint distances from the tower (Table 4). Most of the cumulative footprint (90%) was located at 84.9 (**II**) and 98 m (**III**) distance from the tower; as well, it shows the limits of the maximum extension of the clearcut area. Therefore, cumulative footprints of 70%, 50%, 30% and 10%, which are shown in Table 4, show how much C is absorbed according to distances (**II−III**). South wind prevailed during the measurement periods (**II−III**).

5.2. Driving factors of CO_2 fluxes

A review paper described relationships between different disturbances and considered the effects of the main factors (damage severity, intensity, variability) affecting ecosystem recovery that are directly caused by climate change (**I**).

The environmental factors at study sites (**II−III**) showed variations and interaction between different weather components. The NEE of 6- and 8-year-old stands was affected by time period, temperature, water vapor and day of year (DOY) (**II**) (Figure 3). During the 24-hour time period of measurement, daytime showed higher C-uptake. Temperature describes C-uptake until the temperature rises above 15 °C. Water vapour demonstrates neutral behavior during the daytime, except mornings

and nighttime. DOY expresses natural processes, where every next day during the measurement period helps to promote C-exchange.
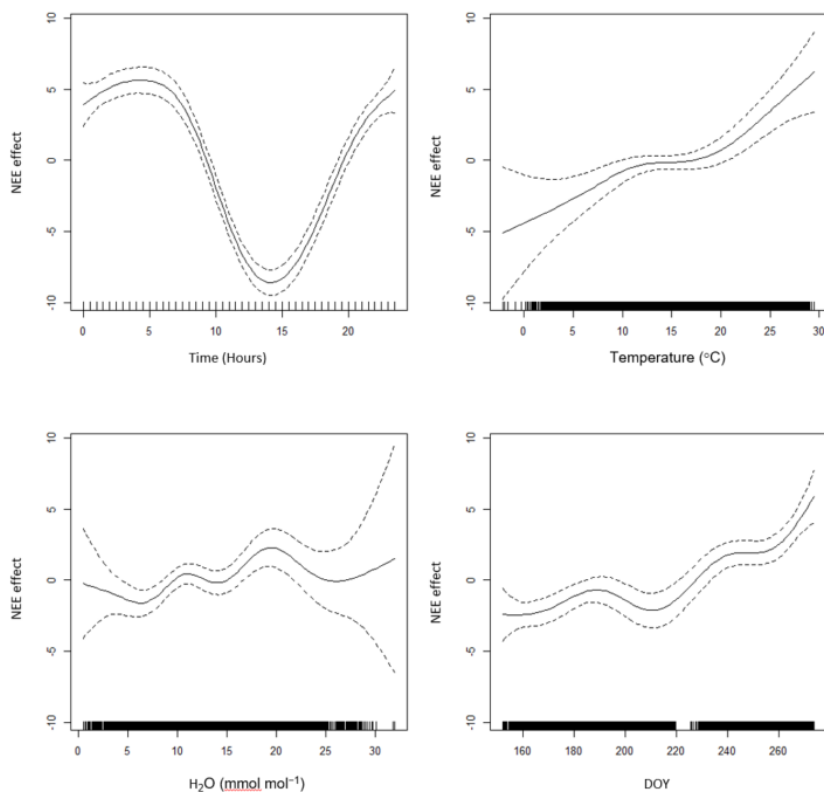
Figure 3. Components of GAM model fits to the NEE during the stand JS223 measurement period (**II**). Lines represent GAM model predictions with 95% confidence limits. Black stripes (rug plots) on x-axes describe univariate distributions of the independent variables (time, temperature, H_2O, DOY).

A similar effect of NEE was observed in the 5-year-old stand (**III**) (Figure 4). Time period affected NEE; clear mornings affected ecosystem C-exchange by raising C-uptake when temperature rose above 15 °C. Water vapour shows typical behavior; during the midday it is limited and it is more available in the morning and during nighttime. DOY describes NEE exchange during the measurement period, and it has no significant effect on NEE.
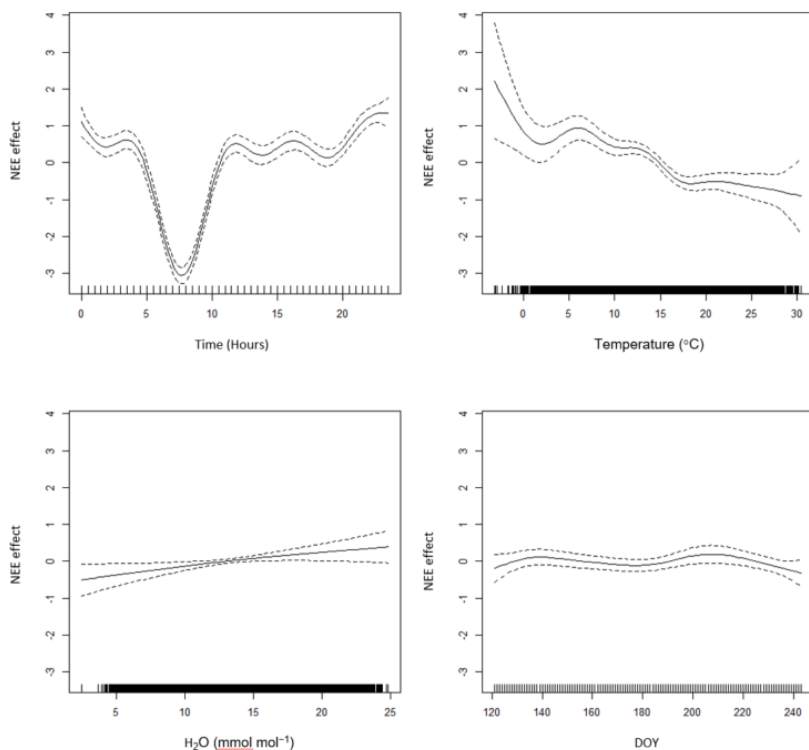
Figure 4. Components of GAM model fits to the NEE during the stand JS338 measurement period (**III**). Lines represent GAM model predictions with 95% confidence limits. Black stripes (rug plots) on x-axes describe univariate distributions of the independent variables (time, temperature, H_2O, DOY).

NEE is directly influenced by photosynthesis and respiration; these processes depend on diurnal time period (e.g., daytime and nighttime). Active photosynthesis was turned on in daytime, confirmed with C-uptake, while at night respiration increased and C-balance was positive (Figure 3). C-uptake is described during the daytime and nighttime over the study sites in Table 5.

Table 5. Daytime and nighttime NEE values of studied stands during the measurement period (II−III).

| Time since clear-cutting (yrs) | Time | Month | | | | | Mean |
		May	June	July	August	September	
5	Day	−0.40	−0.45	−0.47	−0.73		−0.51
	Night	0.85	1.29	1.25	1.27		1.16
6	Day		−6.82	−0.64	−1.26	0.26	−2.11
	Night		2.24	5.37	0.30	0.18	2.02
8	Day		−6.55	−4.98	−3.29	−3.15	−4.49
	Night		2.26	2.19	3.54	3.23	2.80

Interactions between NEE and temperature were obvious and C-exchange in ecosystem was sensitive to temperature during the measurement period (Figure 4). Highest C-uptake occurred between 15 and 25 °C. Extreme temperature causes limitations on C-uptake: too low or high temperatures have negative effects on NEE (the C-uptake decreases). Highest average temperature of the measurement period and over the stands was 18.5 °C in July (Table 6).

Table 6. Average temperature and sum of the precipitation values of studied stands during the measurement period per month (**II−III**).

| Time since clear-cutting | | Month | | | | |
		May	June	July	August	September
5	Temperature (°C)	12.7	23.4	18.2	15.7	
	Precipitation (mm)	8.0	81.0	21.0	87.0	
6	Temperature (°C)		13.1	18.5	16.8	11.4
	Precipitation (mm)		95.0	42.0	87.0	14.0
8	Temperature (°C)		13.1	18.5	16.8	11.4
	Precipitation (mm)		95.0	42.0	87.0	14.0

Water vapour related processes were very important for NEE (Figures 3, 4). Water vapour and precipitation greatly affect the C-cycle. Effective ecosystem functioning is decreased during extreme events, such as drought or high rainfall. Also, if the water component stays at an average level, then C-uptake will not increase. The optimal humidity values (12−20 mmol mol^{-1}) were registered between extremes (which were represented by droughts and excessive rainfalls and torrents). Highest C-uptake occurred in 6- and 8-year-old stands in June with precipitation level of 95 mm (Table 6). In a 5-year-old stand the highest C-uptake was in May with dry weather conditions; however, in June the C-uptake value was similar with precipitation levels ten times higher.

6. DISCUSSION

Stand-replacing disturbances greatly impact the C-cycle of forest ecosystems and cause C emissions to the atmosphere (Baldocchi *et al.*, 2018). Immediately following stand-replacing disturbance, a forest becomes a C-source. Over time, a forest can recover and achieve C-sink status. Recovery means that vegetation growth compensates (by uptake) for C emissions (by decomposition and respiration). With equal uptake and respiration the ecosystem can reach C-balance (Vesala *et al.*, 2005; Ney *et al.*, 2019). The time it takes for a forest to recover productivity with high C-uptake is variable and poorly documented (Chen *et al.*, 2013) and different processes influence C-uptake in forest ecosystems (**I−III**). The C-dynamics of different disturbances are described in the literature review (**I**), where disturbance effects of wildfire, wind, insect attack and clear-cutting on forest ecosystems were examined. The review of literature was comprised of a considerable number of long-term studies, suitable for comparisons, focusing on C-balance after disturbances and the length of the recovery period.

Available information of disturbance effects on forest ecosystems and interaction between them is sometimes different and in some cases similar (Thom & Seidl, 2016). The impact of fire on forest ecosystem was the most studied disturbance type (Littell *et al.*, 2009; Newton *et al.*, 2011). A few disturbance studies were carried out after windstorms and insect attack and many studies were made in clearcut areas.

Studies that have measured NEE in young clearcut areas have found that an ecosystem will show C-source status and respiration processes exceeded photosynthesis (Schulze *et al.*, 1999; Urbanski *et al.*, 2007; Jensen *et al.*, 2017). Many studies after clear-cutting show results where the ecosystem is a C-sink during the daytime and C-source in the nighttime. However it is important to find a balance, where nighttime C-fluxes will not exceed daytime C-uptake. Different studies showed that recovery of forest ecosystems after clearcut may take up to 10 years (Kolari *et al.*, 2004; Mkhabela *et al.*, 2009) and in some cases up to 20 years (Grant *et al.*, 2010).

Studies in a mixed boreal forest stand showed similar patterns of C-dynamics. In a 5-year-old stand during the measurement period, the

ecosystem behaved as a weak C-sink (**III**). Rannik *et al.* (2002) found that a Scots pine stand was a considerable C-source 5 years after clear-cutting. Similar results were found by the several authors, describing conditions where 5-year-old clearcut area is not able to absorb more C from the atmosphere than respiration will release (observations on annual basis) (Rannik *et al.*, 2002; Bergeron *et al.*, 2008; Grant *et al.*, 2010; Coursolle *et al.*, 2012). The C-sink and C-source statuses may change quite quickly with ageing (Kolari *et al.*, 2004).

The effects of clearcut disturbance on C-fluxes were observed in the measured forest stands (**II−III**). Measurements were conducted on two sites of the same forest site type, with similar growing conditions and climate. Results are in general agreement with literature values, with the exception that C-sink status was achieved in younger stands. In 6- and 8-year-old stands C-uptake increased (**II**). Similarly, another study in Estonia by Uri *et al.* (2019) in a 6-year-old Scots pine stand found that C-sink status probably will be achieved within another year.

These results confirm well-known facts: daytime NEE values showed high C-uptake and nighttime respiration was active, but did not exceed daytime NEE. Thus, forest ecosystem C-status is negative and C-uptake is greater than C-emissions (Ney *et al.*, 2019). However, if the respiration exceeds C-uptake then the ecosystem is instantly a C-source. Similar results were found by Kolari *et al.* (2004) as well as Grant *et al.* (2010), where the ecosystem was a C-source during the measurement period and daytime C-sink was not high enough to compensate for respiration. Although functioning of the studied stands was similar, there were yearly differences in how factors affected NEE (**II−III**). For example, the 5-year-old stand showed greater C-uptake in the morning, where other studied stands seemed to have better C-uptake at midday. Also, the C-behavior of the youngest stand during high temperature periods demonstrated increased C-uptake, but other stands acted in the opposite fashion (Figures 2, 3). These differences were not due to age, however; different weather conditions were the cause.

Ecosystem processes and functioning with a high C-uptake depends on different weather components (Niu *et al.*, 2017; Ney *et al.*, 2019). Growing season length and climate change affect the ecosystem C-cycle (Amiro *et al.*, 2010). Growing season length defines a range of active growth by plants as well as the seasonal start and end points (Kolari *et al.*, 2009).

Longer growing season usually means higher productivity and increasing effect on C-uptake (Urbanski *et al.*, 2007). Productivity is also driven by the rise of atmospheric CO_2 concentration (Liu *et al.*, 2006; Jiang *et al.,* 2020). Climate change brings along changes mostly in temperature and precipitation (Tullus *et al.*, 2012). In Estonia, growing season usually starts in May and ends in September. Correlation between NEE and growing season length is high, however, it should take into account other weather factors and recognize it as combination of different components and their interactions. In addition, weather conditions depend on ozone and clouds (Vesala *et al.*, 2005; Jurán *et al.*, 2018, 2019).

Generally, the interaction between temperature and precipitation and its effect on C-uptake is best expressed under extreme conditions (Keenan *et al.*, 2013). Both temperature and precipitation can be extreme weather events, such as drought or excessive rainfall. Under a drought, forest ecosystem C-uptake may decline; heavy rain conditions also may cause decline, especially rain over a long time (Lõhmus *et al.*, 2019). Drought events sometimes increases C-uptake by depressing soil respiration; however this study demonstrated more limited C-uptake under very high temperatures and C-uptake was enhanced by humid conditions (**II**). In some cases, drier ecosystems seem to require wet conditions for higher uptake (**III**) (Novick *et al.*, 2004; Oishi *et al.*, 2018). For example, C-uptake and sequestration often occurred after heavy rainfall (Niu *et al.*, 2017). Kolari *et al.* (2009) found that greatest C-sequestration occurred during the rainy and cool summers, however significant C-sequestration was also a result of a warm and sunny summer (**III**).

Estonian climate may shift to drier conditions under change, where warmer summers and more frequent droughts become a regular pattern (Jaagus & Mändla, 2014). In addition, it has been predicted that precipitation levels would increase during the cold season in the future (Jaagus & Mändla, 2014) with warmer conditions lead to wetter weather in winter (Jaagus & Mändla, 2014), which affects microbial activity in soils (Novick *et al.*, 2004; Frank *et al.*, 2015). The present study offers some preliminary ideas as to C-exchange under drought conditions after clear-cutting (**III**). Longer growing season and drought conditions together may suppress C-uptake. Jaagus & Mändla (2014) found that some models show precipitation decreases in July, August and September, which is comparable with 6- and 8-year-old stands, where June precipitation level and C-uptake were higher than during the rest of the measurement period (**II**).

7. CONCLUSIONS

Natural disturbances and forest management decisions such as regeneration by clear-cutting affect forest ecosystem productivity and C-dynamics in boreal/hemiboreal forests. The boreal forest is important because of the large land it covers, which leads to a significant role of the boreal zone in the global C-cycle. C-balance of forest stand depends on different components: production (uptake and carbon sequestration), respiration, and decomposition. These components interact in forest ecosystems and cumulatively determine the C-sink or C-source status, particularly during and after disturbance. For example, young forests start active C-uptake due to increasing growth and biomass accumulation. Alternatively, several kinds of disturbances result in decaying wood and C-emissions may be greater than the C that trees can absorb.

To fully understand the C-dynamics of young forest ecosystems after different disturbances, especially after clear-cutting, it is useful to monitor stand C-exchange by the eddy covariance (EC) method. Both long-term studies and measurements in young stands are important to understand the effects of disturbances on C-dynamics in forest ecosystems. The critical question is how much time is needed for a forest ecosystem to recover. Many long-term studies using the EC method were reviewed (**I**) to determine the recovery period – the point where C-source status changes to C-sink status. The time to achieve C-sink status can differ according to different kinds of disturbances.

The review showed that recovery after wildfire may take up to 50 years and most likely even longer. Insect outbreaks and windstorm disturbance measurements described recovery from 3 to 6 years; however there was lack of data and more research is needed for further comparisons. Recovery after clear-cutting disturbance could affect a forest for 10 years and in some cases even for 20 years after disturbance (**I**). Monitoring of young forest stands provides critical information about C-dynamics during the early stages of forest regeneration. Successful regeneration helps to activate forest ecosystem C-uptake. After clear-cutting, the 5-year-old mixed stand was C-neutral during the measurement period (May to August) (**III**). In the 6- and 8-year-old stands, the ecosystem already turned into a C-sink during the measurement period (June to September) (**II**).

Recovery depends on environmental factors, mainly on weather and climate. Measurement period length, precipitation and temperature play important roles in the C-cycle. Precipitation and temperature and their interactions have considerable effect on C-uptake; extremes of precipitation and temperature seem to decrease photosynthesis. Articles **II** and **III** were focused on the short-term measurement period following stand replacing disturbance. These measurements helped to determine C-exchange trends under different weather conditions, such as drought, and gave some preliminary indications of how stands may respond to future climates.

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SUMMARY IN ESTONIAN

METSADE MAJANDAMISE MÕJU HINDAMINE SÜSINIKU KONTEKSTIS: TURBULENTSE KOVARIATSIOONI MEETOD

Sissejuhatus

Boreaalsed metsad katavad maakeral kõige suurema maa-ala, olles seega ka suur osa globaalsest süsinikuringest. Sellele tuginedes kannavad boreaalsed metsad ka suuremat rolli kliimamuutustes. Metsade ökosüsteemid on osa biosfäärist ja globaalses mõttes olulised, säilitades märkimisväärset osa elusloodusest. Samuti on metsadel täita tähtis roll: võime reguleerida maakera kliimat ja energiavooge. Nii boreaalsed kui ka hemiboreaalsed metsad on võimelised atmosfäärist süsinikku siduma ja säilitama seda biomassis. Süsinik aga eraldub ökosüsteemist atmosfääri hingamise ja laguprotsesside käigus. Ökosüsteemi süsiniku bilansi mõistmiseks on vaja aru saada peamisest energiavoo liikumisest. Kui hingamine ületab fotosünteesimise, siis käitub ökosüsteem süsinikueraldajana, kui aga fotosünteesimise käigus eraldub hapnik ja süsinikku seotakse rohkem, kui hingamise käigus eraldati süsihappegaasi, siis on ökosüsteem süsinikusiduja rollis. Sellist laadi metsaökosüsteemi uurimiseks on võimalik kasutada täpset ja usaldusväärset meetodit – turbulentset kovariatsiooni. Selle meetodi abil saab mõõta ökosüsteemi neto süsinikuvahetust (*Net Ecosystem Exchange*, NEE) maapinna ja atmosfääri vahel. See on otsene meetod ökosüsteemi energiavoogude tuvastamiseks.

Küsimus seisneb selles, kuidas erinevad häiringud (metsapõlengud, putukad, torm, tuul ja lageraied) mõjutavad metsaökosüsteemi tõusvate temperatuuride tingimustes. Häiringutel on märkimisväärne mõju metsade kasvule ja produktsioonile, elujõulisusele ning loomulikult ka süsinikuringele. Mõned häiringud on metsaökosüsteemi toimimisele tugevama mõjuga kui teised.

Lageraie on tavaline metsauuendamise võte Eestis. On eeldatud, et kohe pärast lageraiet paisatakse suur kogus süsinikku õhku ja ökosüsteem muutub süsinikku eralduvaks. Pärast lageraiest tulenevat metsaökosüsteemi häiringut muutub süsinikubilanss täielikult. Ökosüsteem on siiski võimeline mõni aasta pärast sellist häiringut võrdeliselt puude kasvamise ja vananemisega taas süsinikku siduma.

Selline taastumine tähendab ökosüsteemile muutumist süsinikusidujaks. Kui kiiresti ja kui palju suudab metsaökosüsteem süsinikku siduda ning saavutada kompensatsioonipunkti, oleneb erinevatest asjaoludest.

Käesolev väitekiri on kolme artikli süntees, kus **I** artikkel keskendub erinevatele häiringutele (metsapõlengud, tormid, putukarüüsted ja lageraied) ning annab ülevaate võimalikest mõjutajatest süsiniku sidumisel tuginedes kirjandusele, **II** ja **III** artikkel käsitlevad süsinikuvooge noortes puistutes. Kõikides artiklites vaadeldakse (**I−III**), kuidas metsa majandamine (lageraie) mõjutab süsinikuringet, ja püütakse selgitada, kui kaua võib sellest taastumiseks aega kuluda.

Eesmärgid

1. Saada ülevaade kirjandusest ja erinevate metsas toimuvate protsesside vahelistest seostest, mis mõjutavad süsiniku neeldumist metsaökosüsteemis (**I−III**);

2. Uurida, kui kaua kulub metsaökosüsteemil aega metsahäiringutest taastumiseks, ning saavutada süsinikuneutraalsus või ka süsinikusiduja staatus pikaajaliste uurimuste põhjal (**I**);

3. Uurida ja selgitada süsiniku sidumise dünaamikat pärast häiringut (lageraiet) noortes puistutes (**II−III**);

4. Hinnata ökosüsteemi süsinikuvahetust põua tingimustes ja noore puistu arengut lageraiejärgsel alal kogu mõõteperioodi vältel (**III**);

5. Uurida, kui kaua kulub noorel metsaökosüsteemil aega süsiniku sidujaks muutumiseks pärast edukat metsa uuendamist (**II−III**).

Materjal ja metoodika

Katsealad

Katsealad asuvad Järvselja katse- ja õppemetskonnas, esindades tüüpilisi hemiboreaalseid metsi (**II−III**). Kliima on meil esindatud soojade suvede ja külmade talvedega, kus keskmine temperatuur on +5 °C. Eesti keskmine sademete hulk on 550−800 mm.

Mõõdetud on kahes erinevas asukohas. Esimene neist asub kvartali JS223 eraldistel 2 ja 6 (**II**). Eraldisel 2 teostati lageraie 2008. aastal ja eraldisel 6 aastal 2006. Enne lageraiet olid kasvutingimused üsna sarnased, puistute puhul oli tegemist jänesekapsa-mustika kasvukohatüübiga. Eraldise 2 pindala oli 1,9 ha, peamised puuliigid sellel olid harilik mänd, arukask ja harilik kuusk tagavaraga 352 m^3 ha^{-1}. Ka eraldise 6 peapuuliik oli harilik mänd, kuid esines ka harilikku kuuske ja arukaske ning puistu tagavara oli 333 m^3 ha^{-1} pindalaga 1,6 ha. Alustaimestikus olid esindatud metskastik, tarnad ja mustikas.

Kuus aastat pärast lageraiet oli eraldise 2 peapuuliik harilik kuusk ja esinesid mõned üksikud harilikud männid. Kaheksa aastat pärast lageraiet oli eraldise 6 peapuuliik samuti harilik kuusk ning esines ka arukaske, harilikku haaba ja harilikku mändi. Kuus aastat pärast lageraiet oli puude keskmine kõrgus 1,3 m ja kaheksa aastat pärast lageraiet 2,1 m.

Teine katseala asub kvartali JS338 eraldisel 8, kus lageraie toimus 2,2 ha suurusel alal 2013. aastal (**III**). Tegemist on samuti jänesekapsa-mustika kasvukohatüübiga. Enne lageraiet domineerisid alal kase liigid, kuid leidus ka harilikku mändi ja harilikku haaba tagavaraga 322 m^3 ha^{-1}. Alustaimestikus võis leida mustikat, pohla ja erinevaid samblikke.

Viis aastat pärast lageraiet oli eraldisel 8 peapuuliik harilik kuusk ja esines ka arukaske. Alustaimestikus olid samad liigid mis enne lageraiet. Puude keskmine kõrgus oli 1,43 m.

Turbulentse kovariatsiooni mõõtmised

Mõõtmistega alustati 2014. aastal ja need kestavad endiselt. Mõõtmisseadmete jaoks paigaldati kahele kvartalile kaks torni. Kvartalil JS223 asusid seadmed 6 m kõrgusel. Torn paigaldati stabiilsena kahe lageraieala piirile, et saaks mõõta mõlemat ala. Tuvastamaks, millised vooandmed kuuluvad ühele või teisele alale, kasutatakse turbulentse kovariatsiooni meetodil mõõtmiste puhul tuule suunda, ilmakaari ja kaarti. Samuti pandi paika põhjasuund (nullpunkti) ning määrati vahemikud, kus paiknevad lageraiealad ja külgnevad metsaalad. Kvartalil JS338 mõõdeti 3,8 m kõrgusel ümbritsevat ala kõikides suundades. Ka sellel alal pandi paika nullpunkt, mille järgi sai tuvastada tuule suunda.

Turbulentse kovariatsiooni süsteemi kuulusid anemomeeter (C-SAT 3, Cambpell Scientific, USA) ja gaasianalüsaator (LI-COR Biosciences, Lincoln, NE, USA). Anemomeetri abil saab mõõta tuule komponente ja temperatuuri ning gaasianalüsaatori abil CO_2 ja H_2O kontsentratsiooni.

Mõõtmisperioodi pikkus 2014. aastal oli juunist septembrini (**II**) ja 2018. aastal maist augustini (**III**). Mõõtmistulemused salvestusid seadmes automaatselt 10 Hz sagedusega. Kasutades EddyPro vabavara (LI-COR Biosciences, Lincoln, NE, USA), konverteeriti andmed Exceli formaati 30-minutilisteks andmeridadeks. EddyPro vabavara programmi abil on võimalik teha andmete esmast läbivaatust ja töötlust, selleks seadistatakse programm vajaduse järgi ning läbitakse statistilised testid, mis tagavad andmete hea kvaliteedi. Edasine andmetöötlus toimus R-vabavaras, milles tehti ka joonised.

Alade NEE arvutamisel on kasutatud ainult lageraiealadelt pärinevaid näite. Külgnevate metsaalade näidud on kvartalis JS223 andmepäringu ja -filtritega välja jäetud. Samamoodi on kvartalis JS338 pööratud andmete läbivaatusel tähelepanu kvaliteedile ning tarbetu eemaldamisele. Süsinikubilansi arvutamisel kasutati andmeaukude täitmisel vastavat meetodit (ingl *gap-filling method*).

Tulemused

Erinevate häiringute mõju metsaökosüsteemile on tugev ja kulub aastaid, enne kui ökosüsteem on võimeline jälle süsinikku siduma (**I−III**).

Lageraiejärgsed puistud olid suutelised taastuma kümne aasta jooksul pärast häiringut, mõnel juhul võis selleks kuluda isegi 20 aastat (**I**).

Pärast põlengut taastusid metsaalad märksa kauem, umbes 50 aastat (**I**).

Putukarüüstete ja tormide korral näitasid mõõtmistulemused kolme kuni kuue aasta pikkust taastumisaega, kuid andmete vähesuse tõttu ei ole võimalik põhjalikumaid järeldusi teha (**I**).

Viis aastat pärast lageraiet oli metsaökosüsteem mõõtmisperioodi (mai-august) vältel süsinikuneutraalne (**III**).

Uuritud kuue ja kaheksa aasta vanustes puistutes oli metsaökosüsteem saavutanud mõõteperioodil (juuni-september) süsinikusiduja rolli (**II**).

Peamiseks metsaökosüsteemi süsinikuvoogude mõjutajaks võib pidada ilmastikku ja kliimat ning nendest tulenevate näitajate mõju (**I−III**).

Arutelu

Häiringutel on tugev mõju metsade ökosüsteemidele ja nende süsinikuringele. Selleks, et fotosünteesimise võimekus oleks suur, on eraldunud süsinikukadude kompenseerimiseks vaja taimestiku kiiret taastumist. Süsinikuneutraalsuse ja -sidumise saavutamiseks võib aga kuluda mitu aastat ning see sõltub suuresti ilmastikust. Süsinikuringet ja metsade dünaamikat pärast häiringuid on kirjeldatud ülevaateartiklis (**I**), milles on analüüsitud metsapõlenguid, tuule ja tormi mõju, putukarüüstet ning lageraie mõju ökosüsteemile. Ülevaateartiklis on käsitletud palju erinevaid kirjandusallikaid. Fookus on suunatud metsaökosüsteemi süsinikubilansi taastumisele ja selleks kuluvale ajale.

Lageraiest tulenevat häiringut uuriti ja mõõdeti katsealadel (**II−III**). Katsealadel olid sarnased kasvutingimused ja kasvukohatüüp. Meie mõõtmistulemused ühtisid ülevaateartiklis saadud tulemustega. Uuritud viieaastane puistu oli mõõtmisperioodi vältel nõrk süsinikusiduja (**III**). Soomes tehtud uuringu tulemusena käitus ala viis aastat pärast lageraiet süsinikueraldajana, mis näitab seda, et noor mets ei suutnud siduda rohkem, kui hingamise tulemusena süsinikku eraldus. Vanuse kasvades toimuvad metsaökosüsteemis muutused ja varem või hiljem muutub puistu süsinikusidujaks.

Uuritud kuue- ja kaheksa-aastaste katsealade tulemused näitasid süsinikusiduja rolli (**II**). Eestis korraldati teise uurimisrühma eestvedamisel samuti süsinikubilansi uuringuid, mille tulemusena kuueaastane hariliku männi enamusega puistu oli süsinikuemiteerija, kuid jõuti järeldusele, et järgneva aasta jooksul võib puistu muutuda süsinikusidujaks. Paljud uuringud viitavad noortes metsaökosüsteemides süsinikueraldaja rollile, kuid on vaid aja küsimus, millal need muutuvad süsinikusidujaks. Paljude uuringute tulemused on toonud välja asjaolu, et päeval toimub tõhus sidumine, kuid öise hingamise käigus tekkinud emissiooni ei suudeta veel ületada. Kokkuvõttes võib selleks aega kuluda kuni kümme aastat pärast lageraiet, mõnel juhul aga kuni 20 aastat (**I**).

Üldiselt on metsaökosüsteemi protsessid samaväärsetes oludes sarnased (**II−III**). Erinevused võivad ilmneda siis, kui tegurite mõjud avalduvad sõltuvalt hetkeolukorrast pisut teisiti, mis muudab üldpildis pika aja jooksul lõpptulemust. Näiteks viis aastat pärast lageraiet on selgelt näha kellaaja (hommikutundide) efekti süsinikusidumise aktiviseerumisel. Samas teised uuritud kuue- ja kaheksa-aastased puistud ei näita samasugust trendi. Pigem sõltub seal sidumine kogu päevast. Süsinikusidumise tõhususele aitas kaasa ka temperatuuri tõus, aga seda ainult viieaastases puistus. Metsapõlengute puhul on tegemist ühe enim uuritud valdkonnaga, mida kinnitavad paljud uurimused. Uurimuste arvukus on märgatav ka lageraiete puhul, kuid märksa vähem võib leida teadustöid tormi ja putukarüüstete kohta. Seega on ka keeruline teha põhjapanevaid järeldusi.

Kliimamuutused mõjutavad metsaökosüsteemi süsinikuringet tuues endaga kaasa ka temperatuuri ja sademete muutusi. Mainimata ei saa jätta ka osooni ja pilvede mõju ökosüsteemide funktsioneerimisele. Üldiselt on seos temperatuuri ja sademete vahel tugev ning looduses esineb üha enam ekstreemseid olukordi, nagu põud ja tulekahjud. Põuatingimused vahel isegi soosivad süsinikusidumist õhust. Äärmuslike niiskustingimuste korral (laiemalt võttes ka teiste keskkonnategurite äärmuste korral) võib leida kirjandusallikaid, kus on viidatud pigem nende süsinikusidumise pärssivale mõjule. Käesoleva töö tulemused näitavad, et keskmisest kõrgemad (ilmastikuandmete keskmisest erinev) temperatuurid soosivad süsinikusidumist (**II**), aga samas võivad ka niiskemad olud süsinikusidumisele kaasa aidata (**III**). Mõned uuringud on näidanud, et suur süsinikusidumine toimub just suure vihmasaju järel ning seda isegi jahedatel suvedel. Meie tulemused viitavad pigem, et süsiniku sidumisele on oluline õhutemperatuur ja päikesekiirgus (soojad ja päikesepaistelised suved suurendavad fotosünteesi efektiivsust) (**III**).

Sellest hoolimata on Eesti ilmastik muutumas ja liikumas pigem kuivema perioodi suunas, kus põud võib muutuda tavaliseks. Sellest tulenevalt võib ka vegetatsiooniperiood lüheneda. Talved võivad muutuda vihmasemaks, mille tulemusena aktiveerub mullaelustik. Samas on täheldatud, et sademete hulk kasvab, mis omakorda mõjutab süsinikuringet. Mõned uuringud väidavad, et osad suvekuud võivad veelgi kuivemaks muutuda. Käesoleva töö puhul on mõõtmised teostatud keskmisest madalama sademetemäära tingimustes, kus on vaadeldud kuue ja kaheksa aasta vanuste puistute reaktsiooni antud tingimustele.

Kokkuvõte

Nii looduslikud häiringud kui ka metsamajandamise otsused mõjutavad boreaalsetes metsades metsaökosüsteemi produktiivsust ja dünaamikat. Boreaalsed metsad on tähtsad, kattes suurt osa maakera pindalast, mis viitab nende metsade kaalukale osale süsinikuringes. Metsade süsinikubilanss sõltub erinevatest tingimustest: produktsioonist (süsiniku neelamisest) ja puidu lagunemisest. Need komponendid sõltuvad ja mõjutavad üksteist, mis omakorda mõjutab metsaökosüsteemi staatust süsinikuneelaja või -eraldajana. Vanemad metsad võivad olla nii süsinikuneutraalsed kui ka muutuda süsinikueraldajateks, nooremad aga suudavad atmosfäärist aktiivselt süsinikku siduda. Üldjoontes suureneb süsiniku sidumisvõime noortes puistutes võrdeliselt kasvuga, kuid kindlasti võib olla erandeid.

Ülevaateartikli tulemusena selgus, et metsapõlengutest taastumiseks võib kuluda aega kuni 50 aastat ja mõnedel juhtudel isegi kauem. Putukarüüste ja tormi korral võib taastumiseks kuluda kolm kuni kuus aastat, kuid väheste andmete tõttu oleks vaja rohkem selle teemalisi teadusuuringuid. Metsaökosüsteemi süsiniku sidumise täielik taastumine pärast lageraiet võib mõjutada puistut kuni kümme aastat ning mõnedel juhtudel võib häiringust taastumiseks kuluda kuni 20 aastat. Noorte metsaökosüsteemide uurimine annab olulist teavet süsiniku dünaamikast puistu varajases arenguetapis. Metsa edukas uuendamine aitab kaasa kiiremale süsiniku sidumise taastumisele. Pärast lageraiet oli viieaastane puistu süsinikuneutraalne kogu mõõteperioodi vältel. Uuritud kuue- ja kaheksa-aastased puistud olid mõõteperioodi jooksul juba muutunud süsinikku siduvateks ökosüsteemideks.

Süsinikuneutraalsuse saavutamiseks ja metsaökosüsteemi taastumiseks võib kuluda mitu aastat ja seda protsessi võivad mõjutada erinevad keskkonnategurid. Peamised põhjused on ilm ja kliima, sealhulgas mängivad tähtsat osa kasvuperioodi kestus, sademed ning temperatuur. Kasvuperioodi pikkus määrab aktiivse süsinikuneelamise vahemiku ja viitab pikemale fotosünteesimise perioodile. Samuti on sademetel ja temperatuuril tugev toime süsinikuringele, kuivõrd nad mõjutavad üksteist. Suurema sademehulga ja kõrgema temperatuuri korral näib fotosüntees aeglustuvat, samamoodi põua korral. Ekstreemsed ilmastikuolud pigem pärsivad süsinikusidumist, järelikult on vajalik leida süsinikusidumiseks sobiv niiskuse ja temperatuuri vahekord.

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I

ORIGINAL PUBLICATIONS

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Direct measurements of carbon exchange at forest disturbance sites: a review of results with the eddy covariance method

Sille Rebane, Kalev Jõgiste, Eneli Põldveer, John A. Stanturf & Marek Metslaid

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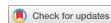
Direct measurements of carbon exchange at forest disturbance sites: a review of results with the eddy covariance method

Sille Rebane [a], Kalev Jõgiste[a], Eneli Põldveer[b], John A. Stanturf[b,c] and Marek Metslaid[a,d]

[a]Chair of Silviculture and Forest Ecology, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Tartu, Estonia; [b]Chair of Forest Management Planning and Wood Processing Technologies, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Tartu, Estonia; [c]Center for Forest Disturbance Science, US Forest Service, Athens, USA; [d]Norwegian Institute of Bioeconomy Research, Ås, Norway

ABSTRACT
Boreal and temperate forests cover a large part of the Earth. Forest ecosystems are a key focus for research because of their role in the carbon (C) balance and cycle. Increasing atmospheric temperatures, different disturbances (fire, storm and insects) and forest management (clear-cutting) will change considerably the C status of forest ecosystems. Using the eddy covariance (EC) method, we can define interactions among environmental factors that influence the C-balance and whether a forest ecosystem is functioning as a C-sink or C-source or possibly is C-neutral. In our review of published studies of different disturbances, we found that most of the post-disturbance studies based on EC method focused on the effects of forest fire and clear-cutting, only a few studies studies focused on the effects of storms and insects. Generally a forest is a C-source until several years after disturbance and then a forest is able to absorb C and become a C-sink. Recovery to C-sink status required up to 20 years in clear-cut areas. Recovery following wildfire disturbance was much longer, possibly more than 50 years. Recovery to C-sink status required approximately 5 years after storm and insect outbreak, however we can not predict overall recovery period because of the missing data.

Introduction

There is high interest in forests as carbon sinks to mitigate climate change; international efforts such as REDD+ and other efforts seek to sequester carbon in terrestrial biomass and soil to offset or avoid carbon released from fossil fuels and land use change (Houghton et al. 2012; Mahmood et al. 2014; Stanturf et al. 2015). The reality, however, is that carbon in forests is not sequestered indefinitely and is subject to disturbances. Rising carbon emissions influence global climate through the greenhouse effect that in turn, affects forest ecosystems through multiple interactions including drought and fire (Janssens et al. 2001; Noe et al. 2011; Goetz et al. 2012). Forests can be either a sink or a source of terrestrial carbon and generally, mature forests are carbon sinks or carbon neutral (Anthoni et al. 2004; Hyvönen et al. 2007; Bellassen et al. 2011; Pan et al. 2011). Carbon pools in forests depend on plant photosynthesis and this fixation can exceed carbon release to the atmosphere (Hyvönen et al. 2007; Baldocchi 2008). Productivity, and therefore the strength of carbon sinks in plants, depends on growing-season length, temperature, humidity and other adaptivetraits as well as age (Wang et al. 2004; Schaphoff et al. 2016; Curtis and Gough 2018).

Boreal and temperate forests play a key role in the global carbon cycle that affects Earth's climate (Dixon et al. 1994; Randerson et al. 2006; Bonan 2008; Balshi et al. 2009; Pan et al. 2011; Mahmood et al. 2014; Harris et al. 2016). Forests in temperate biomes are generally more efficient carbon sinks than boreal forests (Pan et al. 2011). Differences in productivity between boreal and temperate forest ecosystems are largely due to climate (Dixon et al. 1994; Janssens et al. 2001) with temperature as the main regulating factor on plant productivity and soil processes. Soils are the main carbon sink, as much as three times greater than aboveground biomass (Post et al. 1990; Prentice et al. 2001); warming increases soil respiration and may affect ecosystem C source/sink relationships (Janssens et al. 2001; Köster et al. 2016; Schaphoff et al. 2016). Carbon storage in soils may be similar in different locations even if forest productivity varies significantly (Dixon et al. 1994; Janssens et al. 2001).

Disturbances influence forest growth dynamics, mortality, and decomposition processes (Kurz and Apps 1999; Köster et al. 2009; Laarmann et al. 2009; Hicke et al. 2012; Seidl et al. 2014; Köster et al. 2015) and therefore carbon cycling (Chen et al. 2003; Goulden et al. 2011; Schaphoff et al. 2016). Effects on the carbon cycle include emissions to the atmosphere and fixing C level in biomass after post-disturbance (Niu et al. 2017; Baldocchi et al. 2018). Different types, frequencies, and intensities of disturbance alter environmental conditions in diverse ways and play a major role in carbon cycling and balance (Dale et al. 2001; Campbell et al. 2004). For example, hurricane categories are differentiated

CONTACT Sille Rebane ✉ sille.rebane@emu.ee 🏛 Chair of Silviculture and Forest Ecology, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, Tartu 51014, Estonia; Marek Metslaid ✉ marek.metslaid@emu.ee 🏛 Chair of Silviculture and Forest Ecology, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, Tartu 51014, Estonia; Norwegian Institute of Bioeconomy Research, PO Box 115, Ås 1431, Norway

by sustained wind speeds and depending upon characteristics of the affected ecosystem, the severity of effects varies (White and Jentsch 2001; Stanturf et al. 2007).

Direct and indirect effects of disturbances such as windstorms, wildfires, and insects outbreaks are expected to increase in the future (Jentsch and Beierkuhnlein 2008; Reichstein et al. 2013; Seidl et al. 2014; Teskey et al. 2015; Schaphoff et al. 2016). Active forest management, which includes clearcut harvesting, also affects carbon cycling and along with fires, affects source and sink values differently as stands develop. In comparison, windstorms and insects do not demonstrate clear trends (Seidl et al. 2014). Understanding how current disturbance regimes affect carbon source-sink relationships could improve the ability to predict how climate change affects disturbance and carbon cycling (Dixon et al. 1994; Lindroth et al. 1998; Thom and Seidl 2016).

Due to the large area of boreal forests, especially the large carbon sink in boreal soils, the condition of this vegetation plays an important role in regulating the energy balance at the Earth's surface (Goulden et al. 2011; Noe et al. 2011). To fully understand the relationships between net ecosystem exchange (NEE) and the global carbon cycle (Yi et al. 2010), source and sink relationships must be quantified at the landscape level (Houghton 2003). The basic model for NEE is GPP = NEE + RE where RE (ecosystem respiration) and GPP (gross primary production – total rate of ecosystem carbon fixation in biomass) (Sano et al. 2010). If RE is greater than GPP then NEE is positive and the ecosystem is a carbon source to the atmosphere. If RE is less than GPP, then NEE is negative and the ecosystem is a carbon sink. The direct measurement of NEE is straightforward and carried out by eddy covariance systems (Schulze et al. 1999).

The eddy covariance technique has been used to gain a better understanding of the carbon cycle and sink-source relations (Chen et al. 2003; Hirata et al. 2007; Gielen et al. 2013). The eddy covariance technique, with instrumented towers to measure fluxes (carbon dioxide, water vapor, and energy) between the atmosphere and land surface (Baldocchi 2003; Baldocchi 2008; Noe et al. 2011), has been used for long-term studies although less commonly than classical inventory approaches (e.g. Pan et al. 2011). Temperature, wind direction and velocity are measured to calculate fluxes (Baldocchi 2008). Nevertheless, this technique provides reasonably accurate estimates of carbon NEE (Baldocchi 2003; Peichl et al. 2010). Studies using eddy covariance techniques show that middle-aged stands are stronger carbon sinks than very old stands (Hyvönen et al. 2007; Luyssaert et al. 2008).

In this review, we examine how long forest ecosystems recover and become carbon sinks after stand-replacing disturbances. The main question is how long it takes after disturbance before forest ecosystems recover and become carbon neutral and begin to be sinks. We provide an overview of eddy covariance studies focused on disturbance effects, emphasizing different factors including disturbance type (wildfire, storms, and insects) and management actions (clear-cutting). We focus our review on published long-term studies (at least 1 full year of eddy covariance measurements) of stand-replacing disturbances, mostly in boreal forests where interannual variability of carbon exchange is relatively low (Baldocchi et al. 2018), including important references from temperate forests. Because so little data are available for windstorm and insect disturbances, we included some short-term studies. The studies included in our review were grouped according to disturbance type, tree species, and time since disturbance. Where available, LAI and growing season length were noted but generally, tree species are a good indicator of productivity and C-source/sink potential.

Fire disturbance

Studies to determine how long it takes for boreal and temperate forest ecosystems to recover from stand-replacing wildfire and become carbon neutral utilize chronosequences (Table 1). Most of the CO_2 flux measurements were carried out in boreal forests in North America (Amiro et al. 2006; Dunn et al. 2007; Welp et al. 2007; Mkhabela et al. 2009), and in a temperate forest in Arizona (Dore et al. 2008, 2010, 2012).

Fire-killed trees typically do not all fall over immediately; many dead trees may still be standing or leaning for some years. Until boles contact the ground, decomposition is delayed (Amiro 2001; Amiro et al. 2003). Decomposition will increase on the ground as dead trees moisten and become accessible to soil microbes (Harmon et al. 1986) and their activity (fast, slow, passive) depends on temperature and water limitations (Davidson and Janssens 2006). At the same time, it is quite a slow process and the increased decomposition of dead trees may not be enough to balance the increased sink strength of growing vegetation (Amiro 2001).

Immediately after fire, forests became carbon sources and gradually shifted from carbon source to being a carbon sink due to slow post-fire recovery of vegetation (Dore et al. 2008). Most sites were a C-source up to 10 years post-fire (Amiro et al. 2006; Welp et al. 2006; Mkhabela et al. 2009). An exception was a boreal mixed stand of jack pine (*Pinus banksiana* Lamb), black spruce (*Picea mariana* (Mill.) BSP) and trembling aspen (*Populus tremuloides* Michx.) in Saskatchewan that at age 6 was a C-sink (-3 gC m^{-2}y^{-1}), however, the following year, this site was a C-source (43 gC m^{-2}y^{-1}), returning to C-sink by age 15 years (Mkhabela et al. 2009). Another boreal black spruce stand in Quebec was a C sink by age 10 years (-9 gC m^{-2}y^{-1}) (Coursolle et al. 2012). Sites in Manitoba and Saskatchewan were C-sinks at age 11 (-0.2 gC m^{-2}y^{-1}) and age 13 (-68 ± 44 gC m^{-2}y^{-1}), respectively (Litvak et al. 2003; Amiro et al. 2006). In contrast, a 10-year-old Arizona stand was a C-source (109 ± 6 gC m^{-2} year^{-1}) (Dore et al. 2008, 2010, 2012) as was the same burned site in a semi-arid forest in Arizona at age 11 (45 ± 19 gC m^{-2} y^{-1}), age 12 (63 ± 13 gC m^{-2}y^{-1}), age 13 (27 ± 10 gC m^{-2}y^{-1}) and age 14 (49 ± 12 gC m^{-2}y^{-1}) (Dore et al. 2010, 2012).

After almost 30 years post-fire, a Saskatchewan site showed two years with consecutive positive NEE, at age 27 and 28 releasing 39 gC m^{-2}y^{-1} and, 78 gC m^{-2}y^{-1}, respectively (Mkhabela et al. 2009). The site in Saskatchewan was a slight C-sink at age 75 (-4 gC m^{-2}y^{-1}) (Mkhabela et al. 2009), becoming a stronger C-sink the following year (age 76, -36 gC m^{-2}y^{-1}) (Mkhabela et al. 2009). The site in Alaska was also a C-sink at age 80 (-69.6 gC m^{-2}y^{-1}) (Welp et al. 2006).

Table 1. Net ecosystem exchange (NEE) values in forest stands in years after wildfire.

Location	Latitude	Longitude	Dominant tree species	Regeneration method	Time since disturbance (yrs)	LAI (m² m⁻²)	Growing season length (days)	NEE (gC m⁻² y⁻¹)	C-status	Source
Canada	53.917° N	106.078° W	Jack pine	Natural	6	1.3	153 (May–September)	−3	sink	Mkhabela et al. (2009)
Canada	53.917° N	106.078° W	Jack pine	Natural	7	1.3	153 (May–September)	43	source	Mkhabela et al. (2009)
Canada	54.254° N	105.877° W	Jack pine	Natural	15	3	153 (May–September)	−115	sink	Mkhabela et al. (2009)
Canada	54.254° N	105.877° W	Jack pine	Natural	16	3	153 (May–September)	−53	sink	Mkhabela et al. (2009)
Canada	54.485° N	105.818° W	Jack pine	Natural	27	2.8	153 (May–September)	39	source	Mkhabela et al. (2009)
Canada	54.485° N	105.818° W	Jack pine	Natural	28	2.8	153 (May–September)	78	source	Mkhabela et al. (2009)
Canada	53.916° N	104.690° W	Jack pine	Natural	75	2	153 (May–September)	−4	sink	Mkhabela et al. (2009)
Canada	53.916° N	104.690° W	Jack pine	Natural	76	2	153 (May–September)	−36	sink	Mkhabela et al. (2009)
USA	63° 54' N	145° 44' W	Deciduous shrubs <1 m tall	Natural	3		150 (May–September)	40.8	source	Welp et al. (2006)
USA	35°26' 43.43'' N	111° 46' 18.64'' W	Grasses, forbs, and a few shrubs	Natural	10	0.63 ± 0.15 (trees and understory)	219 (April–October)	109 ± 6	source	Dore et al. (2008, 2010, 2012)
USA	35°26' 43.43'' N	111° 46' 18.64'' W	Grasses, forbs, and a few shrubs	Natural	11	0.55 ± 0.13 (understory)	219 (April–October)	45 ± 19	source	Dore et al. (2010, 2012)
Canada	53.917° N	106.078° W	Mixed: Aspen, Jack pine, Black spruce	Natural	3	1	150 (May–September)	132 ± 22	source	Amiro et al. (2006)
Canada	53.917° N	106.078° W	Mixed: Aspen, Jack pine, Black spruce	Natural	4	1	150 (May–September)	87 ± 41	source	Amiro et al. (2006)
Canada	54.25°4 N	105.877° W	Mixed Aspen/poplar, jack pine, black spruce	Natural/Artificial (partly seeded aerially with Jack pine seeds)	13	3	150 (May–September)	−68 ± 44	sink	Amiro et al. (2006)
USA	63° 55' N	145° 23' W	Mixed: Aspen, willow shrubs, black spruce regeneration	Natural	15		150	−114	sink	Welp et al. (2006)
USA	35°26' 43.43'' N	111°46' 18.64'' W	Ponderosa pine	Natural	12	0.93 ± 0.27 (understory)	219 (April–October)	63 ± 13	source	Dore et al. (2012)
USA	35°26' 43.43'' N	111°46' 18.64'' W	Ponderosa pine	Natural	13	0.64 ± 0.28 (understory)	219 (April–October)	27 ± 10	source	Dore et al. (2012)
USA	35°26' 43.43'' N	111°46' 18.64'' W	Ponderosa pine	Natural	14	1.08 ± 0.51 (understory)	219 (April–October)	49 ± 12	source	Dore et al. (2012)
USA	63° 53' N	145° 44' W	Black spruce	Natural	80		150 (May–September)	−69.6	sink	Welp et al. (2006)
Canada	55.88° N	98.48° W	Black spruce	Natural	160	4.2	173	41	source	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	161		159	84	source	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	162		146	39	source	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	163		194	−7	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	164		183	−7	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	165		186	−3	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	166		184	−23	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	167		153	−27	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	168		191	−58	sink	Dunn et al. (2007)
Canada	55.88° N	98.48° W	Black spruce	Natural	169		151	−21	sink	Dunn et al. (2007)

After 150 years, a site in Manitoba was a C-source for 3 consecutive years, 41 gC m^{-2}y^{-1}, 84 gC m^{-2}y^{-1} and 39 gC m^{-2}y^{-1}, at ages 151, 152 and 153, respectively (Dunn et al. 2007). Thereafter, this site was a slight C sink (at ages 154–155, −7 gC m^{-2}y^{-1} and −3 gC m^{-2}y^{-1} at age 156, Dunn et al. 2007). The Manitoba site continued to show negative NEE at ages 157, 158, 159 and 160, respectively −23 gC m^{-2}y^{-1}, −27 gC m^{-2}y^{-1}, −58 gC m^{-2}y^{-1} and −21 gC m^{-2}y^{-1} (Dunn et al. 2007).

Storm and insect disturbance

We considered biotic (insects) and abiotic (windstorm) disturbances together because often they are partial rather than stand-replacing disturbances. Even though the overstory may be severely damaged, typically much of the mid-story and understory are little impacted. Of course, this is not true of all insect outbreaks and windstorms but does apply to the studies in our sample. The resulting patterns of storm and insect disturbance have higher variation and lower mean values than is typical of wildfire disturbance (Table 2). Depending on the damage severity and rapidity of vegetation recovery, the impacted stand can quickly turn from a C-source into a C-sink (Lindroth et al. 1998, 2009; Dale et al. 2001).

Wind disturbance

Drastic changes in forest conditions occur during and after a windstorm (Dale et al. 2001; Schaphoff et al. 2016). The most immediate effect is the surge of dead biomass that evokes rapid respiratory activity of heterotrophic organisms. The subsequent CO$_2$ emission creates a substantial C-source for the whole ecosystem (Sano et al. 2010; Pan et al. 2011). The value of the C-sink appears at later stages of stand development (not immediately after windthrow) and depends upon the balance between the source effects of the load of decomposing wood (Lindroth et al. 1998; Knohl et al. 2002) and the sink effects of the recovering vegetation that may include a profusion of ground vegetation (Hari et al. 2017). Most of the studies provide results after 1 or 2 years and indicate the wind damaged stands are a C-source (Table 2).

Currently annual measurements of NEE following storm disturbance are lacking. As soon as annual measurements become available it should be possible to improve carbon balance models and include the effect of wind disturbance in the boreal forest (Amiro et al. 2003).

Insect disturbance

Insect outbreaks can significantly impact forest ecosystems over large forest areas (Kurz and Apps 1999; Dale et al. 2001; Edburg et al. 2012; Seidl et al. 2014). Insects, particularly bark beetles, can affect forest net ecosystem productivity (NEP) and turn the affected stand into a C-source (Table 2). Modeled impacts of biotic disturbances in US forests singled out bark beetles as having the greatest impact on forest C-cycling (61% of total flux) and tree mortality as 20 times higher compared to defoliation (Kautz, Anthoni et al. 2017).

Table 2. Net ecosystem exchange (NEE) values in forest stands in years after windstorm and insect disturbance.

Location	Latitude	Longitude	Dominant tree species	Time since disturbance (yrs)	LAI (m^2 m^{-2})	Growing season length (days)	NEE (gC m^{-2} y^{-1})	C – status	Source
				STORM					
Poland	53°38′ N	18°15′ E	Spruce forest	1		214 (March–September)	575	source	Ziemblińska et al. (2018)
Poland	53°38′ N	18°15′ E	Spruce forest	2		214 (March–September)	504	source	Ziemblińska et al. (2018)
Poland	53°38′ N	18°17′ E	Spruce forest	3		214 (March–September)	525	source	Ziemblińska et al. (2018)
Poland	53°38′ N	18°15′ E	Spruce forest	3		214 (March–September)	439	source	Ziemblińska et al. (2018)
Poland	53°38′ N	18°17′ E	Spruce forest	4		214 (March–September)	482	Source	Ziemblińska et al. (2018)
Poland	53°38′ N	18°15′ E	Spruce forest	4		214 (March–September)	250	source	Ziemblińska et al. (2018)
				INSECTS					
British Columbia (Kennedy Siding)	55°06′ N	122°50′ E	Lodgepole pine	1	1.4	153 (May–September)	82	source	Brown et al. (2010)
British Columbia (Crooked River)	54°28′ N	122°42′ E	Lodgepole pine	1	0.9	153 (May–September)	56	source	Brown et al. (2010)
British Columbia (Kennedy Siding)	55°06′ N	122°50′ E	Lodgepole pine	2	0.31	153 (May–September)	58	source	Brown et al. (2012)
British Columbia (Kennedy Siding)	55°06′ N	122°50′ E	Lodgepole pine	2	1.3	153 (May–September)	33	source	Brown et al. (2010)
British Columbia (Crooked River)	54°28′ N	122°42′ E	Lodgepole pine	2	0.8	153 (May–September)	−4	sink	Brown et al. (2010)
British Columbia (Kennedy Siding)	55°06′ N	122°50′ E	Lodgepole pine	3	0.3	153 (May–September)	−10	sink	Brown et al. (2012)
British Columbia (Crooked River)	55°06′ N	122°50′ E	Lodgepole pine	4	0.22	153 (May–September)	−63	sink	Brown et al. (2012)
British Columbia (Crooked River)	54°28′ N	122°42′ E	Lodgepole pine	4	0.9	153 (May–September)	57	source	Brown et al. (2012)
British Columbia (Crooked River) (From second attack 1)	54°28′ N	122°42′ E	Lodgepole pine	5		153 (May–September)	−3	sink	Brown et al. (2012)
British Columbia (Crooked River) (From second attack 2)	54°28′ N	122°42′ E	Lodgepole pine	6		153 (May–September)	−6	sink	Brown et al. (2012)
British Columbia (Crooked river) (From second attack 3)	54°28′ N	122°42′ E	Lodgepole pine	7	0.55	153 (May–September)	30	source	Brown et al. (2012)

Figure 1. NEE values up to 160 years after fire. Positive NEE value shows that the ecosystem is a CO_2 source and negative that the ecosystem is a CO_2 sink relative to the atmosphere. The turnover boundary from C source to sink is marked as grey dots (y-axis 0 value). The figure was created in R environment using the xyplot function and smooth trendline from the lattice package. The fitted line suggests a possible recovery trajectory and does not assert a pattern.

In the examined stands, two areas of lodgepole pine (*Pinus contorta* var. *latifolia*) forests in British Columbia, Canada show the effects of mountain pine beetle (*Dendroctonus ponderosae*) attacks over multiple years. Immediately after the first year of insect attack, the Kennedy Siding site was a C-source (81 gC $m^{-2}y^{-1}$). At the end of the second year, the site remained a C-source (58 gC $m^{-2}y^{-1}$) (Brown et al. 2012). By the third year however, Kennedy Siding was rapidly becoming a C-sink and remained so in the fourth year (−63 gC $m^{-2}y^{-1}$) (Brown et al. 2012). The Crooked River site was subject to two insect infestations and exhibited a different pattern of source-sink relationships. After one year of mountain pine beetle attack, it was a C-source (56 ± 26 gC $m^{-2}y^{-1}$) but was a slight sink after the second year (Brown et al. 2010). After the fourth year of disturbance, the area was C-source (57 gC $m^{-2}y^{-1}$) and subjected to a second bark beetle attack (Brown et al. 2012). At age 5, Crooked River was again a C-sink (−3 gC $m^{-2}y^{-1}$). Two years after the second attack (stand age 6), the site remained a C-sink (−6 gC $m^{-2}y^{-1}$) but by age 7 and two insects outbreaks the site was again a C-source (30 gC $m^{-2}y^{-1}$) (Brown et al. 2010). After insect disturbance both sites were strongly affected and ecosystem carbon exchange was slightly out of balance (Amiro et al. 2010; Brown et al. 2010).

Bark beetle attacks may affect stands viability noticeably for up to five years and are similar to wildfire disturbances (Edburg et al. 2012). Some studies show that insects and fire disturbances significantly impact carbon pools and cause net forest C-losses (Amiro et al. 2010). Changes in NEE over time following wildfire and insect attacks show different patterns (Figures 1 and 2), partly due to the different stand ages of the available studies and therefore the amount of carbon accumulated in the stands. Nevertheless, disturbance causes loss of carbon and stands are C-sources. As vegetation recovers, stands switch into C-sinks; the time to recover to C-neutral status is likely a function of disturbance severity, time, and site productivity.

Clear-cutting

Eddy covariance studies of the effects of clear-cutting in boreal forest mostly were carried out in Canada (Amiro et al. 2006; Bergeron et al. 2008; Mkhabela et al. 2009; Grant et al. 2010; Coursolle et al. 2012), Finland (Kolari et al. 2004; Kowalski et al. 2004), Estonia (Uri et al. 2019) and Britain (Kowalski et al. 2004), with a few in temperate forests in Canada (Humphreys et al. 2005; Humphreys et al. 2006; Paul-Limoges et al. 2015) and France (Kowalski et al. 2004) (Table 3). One advantage of studies of clear-cutting is the possibility of pre-treatment measurements. For example, a 62-year-old mature Canadian Douglas-fir (*Pseudotsuga menziesii*) stand (74 years post-disturbance) was a moderate (−560 gC$m^{-2}y^{-1}$) C-sink before clear-cutting (Paul-Limoges et al. 2015).

Immediately after clear-cutting, a large amount of carbon is released back to the atmosphere as seen from the three 1-year-old Douglas-fir stands in Canada (Humphreys et al. 2005; Grant et al. 2010; Paul-Limoges et al. 2015). Humphreys et al. (2005, 2006) found that coastal Douglas-fir stands are very strong C-sources (520–620 gC $m^{-2}y^{-1}$) immediately and for several years after harvesting. Paul-Limoges et al. (2015) found even higher NEE the first year post-harvest, 1000 gC $m^{-2}y^{-1}$. A 2–3-year-old Canadian jack pine stand was a C-source, losing more than 120 gC$m^{-2}y^{-1}$ (Mkhabela et al. 2009). Another jack pine stand in the same study was close to C-neutral by age 10–11 (−34–7 gC $m^{-2}y^{-1}$). A Douglas-fir stand remained a C-source until age 15 years after disturbance but was a C-sink 46 years later (Humphreys et al. 2005).
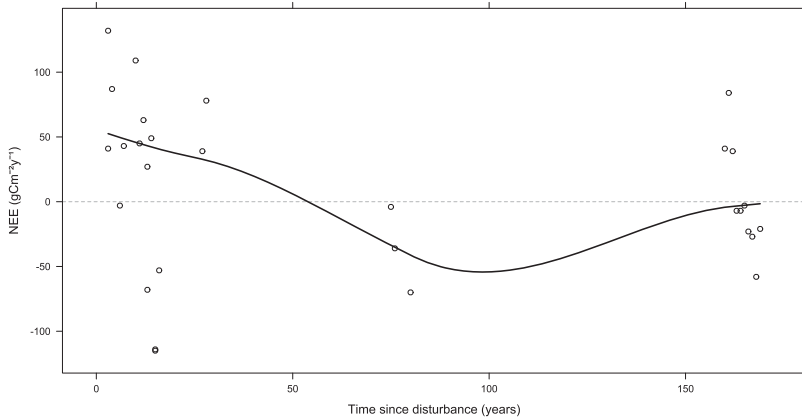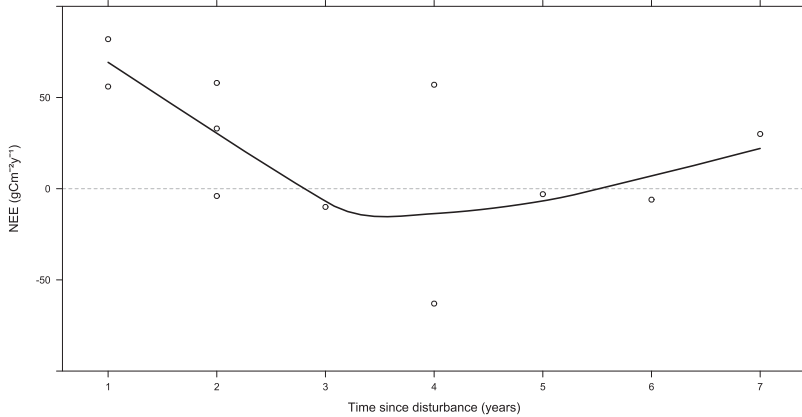
Figure 2. NEE values up to 7 years after insects attack. Positive NEE value shows that the ecosystem is a CO_2 source and negative that the ecosystem is a CO_2 sink relative to the atmosphere. The turnover boundary from C source to sink is marked as grey dots (y-axis 0 value). The figure was created in R environment using the xyplot function and smooth trendline from the lattice package. The fitted line suggests a possible recovery trajectory and does not assert a pattern.

Although a moderate C-source annually (133 gC m^{-2}y^{-1}), this stand was a C-sink during the growing season (Humphreys et al. 2006). Another stand of the same species became a C-sink 17 after disturbance (Grant et al. 2010).

Source-sink relationships may vary over the course of a year. Rannik et al. (2002) found that a 5-year-old Scots pine (*Pinus sylvestris* L.) clear-cut in Finland was close to C-balance during the daytime as the ground vegetation balanced the release of CO_2 from the soil, but during the whole study period from July to September, the stand was a C-source. Kolari et al. (2004) found that C-sink strength during the daytime did not decline with stand development until 75 years; 12, 40 and 75-year-old Scots pine stands were all C-sinks. A 7–8-year-old Canadian jack pine stand was almost C-neutral throughout the year (55–59 gC m^{-2}y^{-1}), but acted like C-source for a longer period than it was a C-sink (Amiro et al. 2006).

Mature forests change from being a C-sink into a C-source after clear-cutting, as shown by the annual source strength of 3-year-old Sitka spruce (*Picea sitchensis* (Bong.)) in Britain, 5-year-old Scots pine in Finland, and 2-year-old maritime pine in France, respectively 112, 239, and 222 gC m^{-2}y^{-1} (Kowalski et al. 2004). Similarly, under Canadian conditions, the annual NEE values after harvesting of 1- to 5-year-old and 8- to 11-year-old jack pine stands and 1- to 4-year-old black spruce stands 2–7 years after disturbance (Grant et al. 2010) were relatively strong C-sources (125–169, 16–73, and 76–168 gC m^{-2}y^{-1}, respectively). Bergeron et al. (2008) found that a 4- and 5-year-old black spruce and jack pine stand was a fairly strong C-source (124–167 gC m^{-2}y^{-1}) during the whole two-year study period. A 4-year-old Finnish Scots pine. clear-cut was a C-source throughout the year (386 gC m^{-2}y^{-1}, Kolari et al. 2004). Uri et al. (2019) found that

an Estonian Scots pine clear-cut was a modest C-source 6 years after harvest 119 gC m^{-2} y^{-1} (1.19 ± 0.36 t C ha^{-1}).

As clear-cut stands develop and NPP approaches and exceeds heterotrophic respiration (RE), forests begin to act as C-sinks (Valentini et al. 2000). Mature Sitka spruce (41-year-old) in Britain, 38-year-old Scots pine in Finland, and 32-year-old maritime pine in France were all C-sinks annually, as the estimated C-strength was respectively 496, 138 and 222 gC m^{-2}y^{-1} (Kowalski et al. 2004). In Canada, Humphreys et al. (2006) showed that over six years (61–66 years after disturbance), a 49- to 54-year-old Douglas-fir stand was an annual C-sink. Similarly, jack pine stands 29- to 32-years-old (Grant et al. 2010) and 29- to 30-years-old (Mkhabela et al. 2009) remained fairly strong annual C-sinks (−66– −107 gC m^{-2}y^{-1} and −79– −80 gC m^{-2}y^{-1}, respectively).

Discussion

Managing forest carbon (Kaipainen et al. 2004; Canadell and Raupach 2008; Keith et al. 2014), or at least accounting for it in national carbon accounting systems (e.g. Kurz and Apps 2006) or compensating forest owners as a payment for an ecosystem service (e.g. Richards and Stokes 2004; Guthrie and Kumareswaran 2009) presents new challenges to forest managers as well as policymakers. Disturbance turns a forest ecosystem into a carbon source, at least temporarily, as biomass subject to decomposition increases and productivity decreases (Kautz, Meddens et al. 2017). Increased disturbances, along with global warming due to climate change may increase forest carbon emissions. Following a stand-replacing disturbance, the time required for a forest to switch from being a C-source to a C-sink depends upon the severity of disturbance, the amount of dead material left

Table 3. Net ecosystem exchange (NEE) values in forest stands in years after clear-cutting.

Location	Latitude	Longitude	Dominant tree species	Regeneration method	Time since disturbance (yrs)	LAI (m² m⁻²)	Temperature (°C)	Growing season length (days)	NEE (gC m⁻² y⁻¹)	C-status	Source
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	1	0.91	1.3	146	139 ± 10	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	2	1.22	0.3	156	222 ± 5	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	3	0.59	0.6	145	173 ± 8	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	4	0.82	1.7	166	133 ± 6	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	5	1.22	1.9	162	113 ± 5	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	6	1.53	1.6	158	73 ± 5	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	7	1.57	0.8	165	83 ± 6	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	8	2.42	0.3	156	23 ± 8	source	Coursolle et al. (2012)
Canada	49°26'08" N	74°03'53' W	Black spruce	Artificial	9	2.49	3.1	183	9 ± 6	source	Coursolle et al. (2012)
Canada	49°3' N	74°0' W	Black spruce	Artificial	2				137	source	Grant et al. (2010)
Canada	49°3' N	74°0' W	Black spruce	Artificial	3				119	source	Grant et al. (2010)
Canada	49°3' N	74°0' W	Black spruce	Artificial	4		0		168	source	Grant et al. (2010)
Canada	49°3' N	74°0' W	Black spruce	Artificial	5				125	source	Grant et al. (2010)
Canada	49°3' N	74°0' W	Black spruce	Artificial	6				109	source	Grant et al. (2010)
Canada	49°3' N	74°0' W	Black spruce	Artificial	7				76	source	Grant et al. (2010)
Canada	49.267° N	74.037° W	Black spruce and jack pine	Artificial	4		0.1	160 (April–July)	167 ± 9	source	Bergeron et al. (2008)
Canada	49°267' N	74°037' W	Black spruce and jack pine	Artificial	5	0.8	1.9	175 (April–July)	124 ± 4	source	Bergeron et al. (2008)
Britain	55°10' N	2°3' W	Sitka spruce	Artificial	3	2.5	7		112	source	Kowalski et al. (2004)
Britain	55°10' N	2°3' W	Sitka spruce	Unknown	41	12	7		−496	sink	Kowalski et al. (2004)
Canada	49°9' N	125°3' W	Sitka spruce	Artificial	1				571	source	Grant et al. (2010)
Canada	49°52,330' N	125°17,537' W	Douglas-fir	Artificial	1	0.13	8.2 (0.3)	154 (March–August)	620	source	Humphreys et al. (2005)
Canada	49°52' N	125°20 W	Douglas-fir	Artificial	1			184 (May–October)	1000	source	Paul-Limoges et al. (2015)
Canada	49°52' N	125°20 W	Douglas-fir	Artificial	2	1.78		184 (May–October)	700	source	Paul-Limoges et al. (2015)
Canada	49°52' N	125°20 W	Douglas-fir	Artificial	3			184 (May–October)	725	source	Paul-Limoges et al. (2015)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	2				606	source	Grant et al. (2010)
Canada	49°52,330' N	125°17,537' W	Douglas-fir	Artificial	3	0.11	8.4 (0.3)	154 (March–August)	520	source	Humphreys et al. (2005)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	3				580	source	Grant et al. (2010)
Canada	49°52,330' N	125°17,537' W	Douglas-fir	Artificial	3	0.13	9.3 (0.3)	154 (March–August)	600	source	Humphreys et al. (2006)
Canada	49°52' N	125°17 W	Douglas-fir	Artificial	3	0.5–2.2	9.4 (4.4)	153 (May–September)	606	source	Humphreys et al. (2006)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	4				592	source	Grant et al. (2010)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	5				450	source	Grant et al. (2010)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	6				418	source	Grant et al. (2010)
Canada	49°9' N	125°3' W	Douglas-fir	Artificial	7				440	source	Grant et al. (2010)
Canada	49°31' N	124°54 W	Douglas-fir	Artificial	15	3.0–6.7	6.2 (3.1)	153 (May–September)	133	source	Humphreys et al. (2006)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	14				121	source	Grant et al. (2010)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	15				124	source	Grant et al. (2010)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	16				132	source	Grant et al. (2010)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	17				−20	sink	Grant et al. (2010)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	18				−15	sink	Grant et al. (2010)
Canada	49°5' N	124°9 W	Douglas-fir	Artificial	19				−109	sink	Grant et al. (2010)
Canada	49°52' N	125°20 W	Douglas-fir	Natural	61			153 (May–September)	−270	sink	Humphreys et al. (2006)
Canada	49°52' N	125°20 W	Douglas-fir	Natural	62			153 (May–September)	−370	sink	Humphreys et al. (2006)
Canada	49°52' N	125°20 W	Douglas-fir	Natural	63			153 (May–September)	−375	sink	Humphreys et al. (2006)
Canada	49°52' N	125°20 W	Douglas-fir	Natural	64	8.4 (15–25%)	5.6 (3.0)	153 (May–September)	−425	sink	Humphreys et al. (2006)
Canada	49°52' N	125°20 W	Douglas-fir	Natural	65			153 (May–September)	−254	sink	Humphreys et al. (2006)

(Continued)

Table 3. Continued.

Location	Latitude	Longitude	Dominant tree species	Regene-ration method	Time since distur-bance (yrs)	LAI (m² m⁻²)	Tempera-ture (°C)	Growing season length (days)	NEE (gC m⁻² y⁻¹)	C-status	Source
Canada	49°52' N	125°20' W	Douglas-fir	Natural	66			153 (May–September)	−330	sink	Humphreys et al. (2006)
Canada	49°52' N	125°20' W	Douglas-fir	Artificial	74	7.3		184 (May–October)	−560	sink	Paul-Limoges et al. (2015)
Canada	53°9' N	104°7' W	Jack pine	Natural	1				169	source	Grant et al. (2010)
Canada	53°9' N	104°7' W	Jack pine	Natural	2				156	source	Grant et al. (2010)
Canada	53.945° N	104.649° W	Jack pine	Natural	2			153 (May–September)	155	source	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	3				125	source	Grant et al. (2010)
Canada	53.945° N	104.649° W	Jack pine	Natural	3			153 (May–September)	123	source	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	4				146	source	Grant et al. (2010)
Canada	53°9' N	104°7' W	Jack pine	Natural	5				126	source	Grant et al. (2010)
Estonia	58°17' N	27°09' E	Scots pine	Artificial	6			May–October	119 (1.19 ± 0.36 t C ha⁻¹)	source	Uri et al. (2019)
Canada	53.908° N	104.656° W	Jack pine	Natural	7	0.6–1.0		122 (June–September)	55	source	Amiro et al. (2006)
Canada	53.908° N	104.656° W	Jack pine	Natural	8	0.6–1.0		122 (June–September)	59	source	Amiro et al. (2006)
Canada	53°9' N	104°7' W	Jack pine	Natural	8				67	source	Grant et al. (2010)
Canada	53°9' N	104°7' W	Jack pine	Natural	9				16	source	Grant et al. (2010)
Canada	53°9' N	104°7' W	Jack pine	Natural	10				73	source	Grant et al. (2010)
Canada	53.908° N	104.656° W	Jack pine	Natural	10	0.8		153 (May–September)	7	source	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	11				30	source	Grant et al. (2010)
Canada	53.908° N	104.656° W	Jack pine	Natural	11			153 (May–September)	−34 gC	sink	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	29				−66	sink	Grant et al. (2010)
Canada	53.876° N	104.645° W	Jack pine	Natural	29	3.1		153 (May–September)	−80	sink	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	30				−79	sink	Grant et al. (2010)
Canada	53.876° N	104.645° W	Jack pine	Natural	30			153 (May–September)	−79	sink	Mkhabela et al. (2009)
Canada	53°9' N	104°7' W	Jack pine	Natural	31				−93	sink	Grant et al. (2010)
Canada	53°9' N	104°7' W	Jack pine	Natural	32				−107	sink	Grant et al. (2010)
France	44°35' N	0°52' E	Maritime pine	Natural	2	1.9	12.8		222	source	Kowalski et al. (2004)
France	44°35' N	0°52' E	Maritime pine	Artificial	32	3 + 1.5	12.8		−222	sink	Kowalski et al. (2004)
Finland	61°51' N	24°17' E	Scots pine	Natural	4	0	3	110–270	386	source	Kolari et al. (2004)
Finland	61°51' N	24°17' E	Scots pine	Natural (soil scarification after clearcut)	5	7	3	92 (July–September)	239	source	Kowalski et al. (2004), Rannik et al. (2002)
Finland	61°51' N	24°17' E	Scots pine	Artificial	12	0.6	3	110–240	−24	sink	Kolari et al. (2004)
Finland	61°51' N	24°17' E	Scots pine	Unknown	38	3 + 1.2	3		−138	sink	Kowalski et al. (2004)
Finland	61°51' N	24°17' E	Scots pine	Artificial	40	2.9	3	120–270	−179—192	sink	Kolari et al. (2004)
Finland	61°51' N	24°17' E	Scots pine	Natural	75	2.5	3	120–270	−323	sink	Kolari et al. (2004)
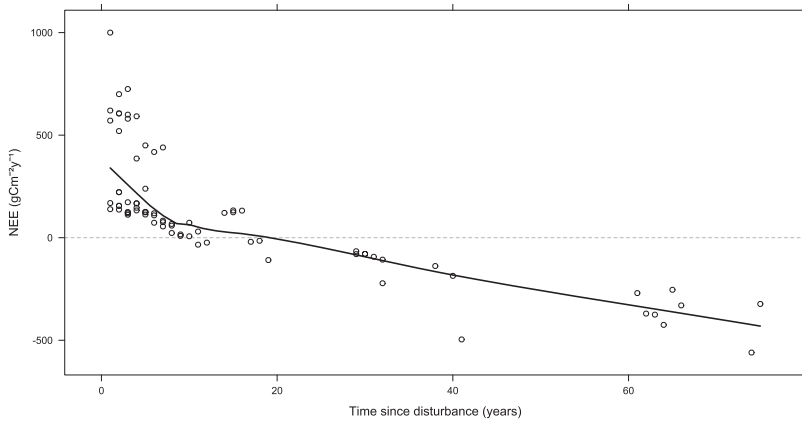
Figure 3. NEE values up to 80 years after clear-cutting. Positive NEE value shows that the ecosystem is a CO_2 source and negative that the ecosystem is a CO_2 sink relative to the atmosphere. The turnover boundary from C source to sink is marked as grey dots (y-axis 0 value). The figure was created in R environment using the xyplot function and smooth trendline from the lattice package. The fitted line suggests a possible recovery trajectory and does not assert a pattern.

on the site to decompose, the productivity and rate of vegetation development, and environmental conditions.

Disturbance intensity is difficult to specify and most studies report severity as indicated by the amount of damage (i.e. biomass killed or removed). Disturbance effects are correlated with productivity, which is a function of species composition and stand structure. Contagious disturbances such as wildfire interact with ecosystem characteristics that affect fire behavior (Peterson 2002; Larson and Churchill 2012). For example, wildfire may modify the soil organic matter and produce more stable forms such as black carbon (González-Pérez et al. 2004) that are resistant to decomposition thereby increasing sink strength. Similarly, site factors that affect decomposition rates are highly variable spatially and temporally. Soil variability is well-known (e.g. Oishi et al. 2013) and interannual variability in weather can affect gross primary productivity and ecosystem respiration with warmer weather changing the balance between source and sink (e.g. Coursolle et al. 2012; Ueyama et al. 2014). Site conditions, particularly soil moisture, affects decomposition rates of woody debris; rates are thought to be more rapid on moderately well-drained soils and slower on very wet or very dry sites (Shorohova and Kapitsa 2014). Nevertheless, differences among species may be more important than specific site conditions (e.g. Köster et al. 2015).

The studies included in our review were grouped according to disturbance type, tree species, and time since disturbance. Tree species are a good indicator of productivity and C-source/sink potential. Jack pine and ponderosa pine are tolerant of drier sites and black spruce of wetter sites, hence the lower productivity values indicated by observed LAI. The maximum reported LAI in the studies included in this review was 3.1 and 4.2, respectively for jack pine and black spruce. Douglas-fir and Sitka spruce are highly productive

with respective LAI values of 12 and 8.4. The NEE values reported in the clear-cutting studies provide a window into source/sink relationships (Table 3). Arraying these species along a putative productivity gradient, source/sink values were 169/–107 gC m^{-2}y^{-1} for jack pine and 168/–58 gC m^{-2}y^{-1} for black spruce. The higher productivity species had reported values of 386/–496 gC m^{-2}y^{-1} for Sitka spruce and 1000/–560 gC m^{-2}y^{-1} for Douglas-fir. Scots pine was intermediate (386/–383 gC m^{-2}y^{-1}).

In the studies we reviewed, stands disturbed by insects (bark beetles) recovered carbon neutrality quickest, followed by clear-cut stands. The time required to reach the turnover from source to sink was longest following wildfire (Figures 1–3). In the boreal vegetation zone, the C-balance turnover will occur about 10–20 years after clear-cutting (Figure 3). The shorter time required for a clear-cut to recover to C-neutrality compared to a burned over area may be related to the removal of much of the carbonaceous materials, i.e. the harvesting of the timber that is not available to decompose. Nevertheless, a young forest regenerating after clear-cutting is a strong C-source (Table 3) as logging residues and soil organic matter emit CO_2 during decomposition and heterotrophic respiration to compensate for the decrease of autotrophic respiration, as well as the time needed to recover leaf area and sequester carbon in live tissue. Recovery to a C-sink after clear-cutting also depends on the regeneration method (natural vs. artificial, conifer vs. broadleaf planting material, fertilization, weed control, etc.) and some site preparation methods such as soil scarification may impact on recovery (e.g. Coursolle et al. 2012). Greater NEE at burned sites compared to harvested sites can be caused by local differences in soil moisture and nutrients, vegetation development, and decomposition of coarse woody debris (Mkhabela et al. 2009).

Several studies have compared wildfire and clear-cutting in similar ecosystems. For example, Dore et al. (2012) reported that intense wildfire resulted in large and persistent effects on carbon and water exchanges, while thinning showed minor and short-lived effects in Arizona ponderosa pine forests. Rapid recovery of carbon sequestration after thinning and slow recovery after severe fire showed clearly the effects of forest management on carbon storage. Net biomass accumulation occurred approximately 20–70 years after a wildfire. Younger stands (<20 years-old) lacked sufficient leaf area for rapid carbon accumulation, while older stands (>70 years-old) seemed to reach carbon balance (Litvak et al. 2003). Recovery may require 20 years after clear-cutting although it can be shorter. For example, carbon balance in daytime fluxes was attained after five years in a Scots pine clear-cut in Finland (Rannik et al. 2002) and annual carbon neutrality was reached after 7–8 years in a jack pine stand in Canada (Amiro et al. 2006), and a Scots pine clear-cut in Estonia is able to turn into C sequestering ecosystem before ten years (Uri et al. 2019). Comparing the jack pine stands disturbed by wildfire and clear-cutting (Tables 1 and 3), source to sink turnover occurred between 6 and 10 years post disturbance. However, some studies in North America show at the age of 30 temperate deciduous forest NEP declines 16% and Canadian forest NEE declined to zero by the age of 100 (Gough et al. 2016).

Windstorms and insects attacks can drastically affect forests by influencing forest productivity and growth during recovery and stand development (Clark et al. 2010). There are few studies using eddy covariance techniques to estimate NEE following storm and insect disturbance (Schulze et al. 1999; Brown et al. 2012). A storm-felled area, however, will recover after several years and become a C-sink (Hicke et al. 2012). Salvage logging that removes large wood and disturbs the site may also affect carbon balance similar to a clear-cut. Recovery after an insect attack depends on forest ecosystem sensitivity and secondary stress factors, which mainly depend on weather conditions. Generally, 5–6 years are needed to recover after insect attacks (Seidl et al. 2014). After a storm, the recovery period is typically 3–5 years for younger stands but older stands need up to 10 years for stable functioning (Knohl et al. 2002; Lindauer et al. 2014).

Conclusions

Natural and anthropogenic disturbances influence forest dynamics, growth, mortality, and decomposition processes in boreal ecosystems and therefore carbon cycling (Dale et al. 2001; Schaphoff et al. 2016). Boreal forests cover large areas and they affect, and are themselves affected by climate (Houghton et al. 2012; Reichstein et al. 2013; Kulmala et al. 2014; Harris et al. 2016). We focused on studies of carbon fluxes using eddy covariance techniques to better understand the effects of wildfire, wind storms, insect outbreaks, and clear-cutting. Generally we found that:

- Insect outbreaks have the least severe effects, mostly in the upper canopy trees. Wildfires and clear-cutting have the greatest effects on both vegetation and soils; windstorms have intermediate effects, somewhat depending on whether salvage logging occurs.
- While all disturbances resulted as a immediate C-sources, the time needed to recover to C-neutrality and for stands to become C-sinks varied among ecosystems depending on several factors, such as tree species, climate conditions, soil water regime etc.
- Immediate effects ranged over 30 times from annual emissions in a lodgepole pine stand following insect attack (Brown et al. 2010) in a Douglas-fir stand after clear-cutting (Paul-Limoges et al. 2015).
- Recovery periods (i.e. time to return to carbon neutral or sink status) were up to 20 years after clear-cutting and likely more than 50 years after wildfire.
- Recovery periods after storm or insect attack ranged from 3 to 6 years; however the data are sparse. Salvage logging that removes large wood and disturbs the site may also affect carbon balance similar to a clear-cut.
- Clear-cutting studies illustrate the effect of productivity on source/sink relationships; source/sink values for the least productive species jack pine and black spruce were respectively 169/–107 gC m^{-2}y^{-1} and 168/–58 gC m^{-2}y^{-1}. The higher productivity species Sitka spruce and Douglas-fir had reported values respectively of 386/–496 gC m^{-2}y^{-1} and 1000/–560 gC m^{-2}y^{-1}.

Future research needs

Most of the post-disturbance studies based on eddy covariance focused on the effects of forest fire and harvesting; only a few flux towers have been established to study the effects of storms and insects. Furthermore, most of the studies are carried out in North America and it is very important to study post-disturbance effects in Europe and Russia in order to gain an understanding of global C-balance and improve our knowledge of forest recovery after disturbances. In particular, forest carbon stocks in boreal Asia (primarily Siberia) have higher carbon stocks than found on other continents (Thurner et al. 2014).

Future carbon losses from boreal forest are expected to increase, mainly because of increased disturbances that offset growth increases in a warming climate (Jentsch and Beierkuhnlein 2008; Frank et al. 2015). Fire (Flannigan et al. 2005; Balshi et al. 2009; Flannigan et al. 2009; Liu et al. 2010) and insect effects (Logan et al. 2003; Clark et al. 2010) are likely to increase, even if harvesting is reduced. As managers contend with increases in wildfire by use of prescribed burning (Wiedinmyer and Hurteau 2010), studies are needed in the boreal forest to compare the effects of controlled fire (e.g. Starr et al. 2015) as compared to wildfire. Because of fire intensity it is emitting more carbon to atmosphere. Estimates of disturbance effects on carbon balance in boreal forests are needed for improved predictions of climate change effects on forest ecosystems (Harden et al. 2000; Randerson et al. 2006; Balshi et al. 2009) and the utility of mitigation programs based on forests as carbon sinks (Canadell and Raupach 2008; Canadell and Schulze 2014; Smyth et al. 2014). The eddy covariance technique

provides reliable estimates of NEE and can be integrated with inventory-based methods, particularly in boreal forests with relatively small C-fluxes (Campioli et al. 2016).

Natural disturbances are episodic and pre-disturbance measurements are seldom available, hence most studies rely on comparisons to undisturbed stands for controls and chronosequences to assess post-disturbance recovery. In contrast, clear-cutting, prescribed fire and other management interventions provide opportunities to assess immediate and long-term effects of disturbance by repeated measurements. They also offer at least a limited ability to control or measure spatial and temporal variability in disturbance intensity. Eddy covariance measurements combined with models of management effects on vegetation and soil could improve our understanding of the ways that disturbance regimes affect carbon source-sink relationships, resulting in improved ability to predict how climate change affects disturbance and carbon cycling (Dixon et al. 1994; Lindroth et al. 1998; Thom and Seidl 2016).

Disclosure statement

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ORCID

Sille Rebane http://orcid.org/0000-0002-2058-829X

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Article

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

Sille Rebane [1],*, Kalev Jõgiste [1], Andres Kiviste [2], John A. Stanturf [2] and Marek Metslaid [1,3]

[1] Silviculture and Forest Ecology, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia; kalev.jogiste@emu.ee (K.J.); marek.metslaid@emu.ee (M.M.)

[2] Forest Management Planning and Wood Processing Technologies, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia; andres.kiviste@emu.ee (A.K.); johnalvin.stanturf@emu.ee (J.A.S.)

[3] Norwegian Institute of Bioeconomy Research, P.O. Box 115, 1431 Ås, Norway; marek.metslaid@emu.ee

* Correspondence: sille.rebane@emu.ee

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 $\mu mol\ m^{-2}\ s^{-1}$. June NEE was -4.60 $\mu mol\ m^{-2}\ s^{-1}$; July, August, and September NEE was -1.17, -0.77, and -0.25 $\mu mol\ m^{-2}\ s^{-1}$, 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.

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
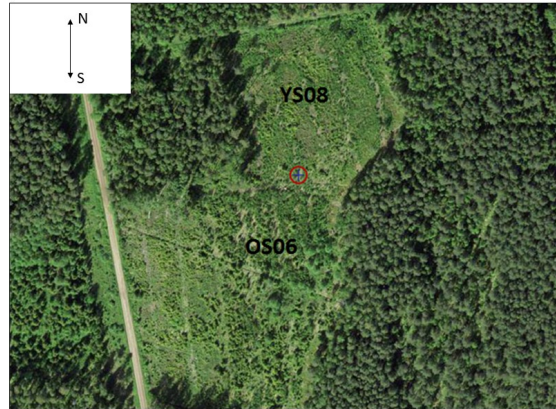
Figure 1. Location of the eddy flux tower (**red circle**) and the study stands (YS08, OS06).

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}).
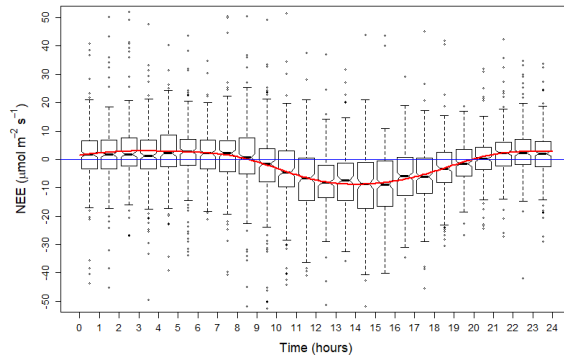
Figure 2. Values of net ecosystem exchange (NEE, μmol m^{-2} s^{-1}) over the study period (June to September, 2014) on a 24-h timescale. Red line describes smooth mean of the NEE.

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.

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.
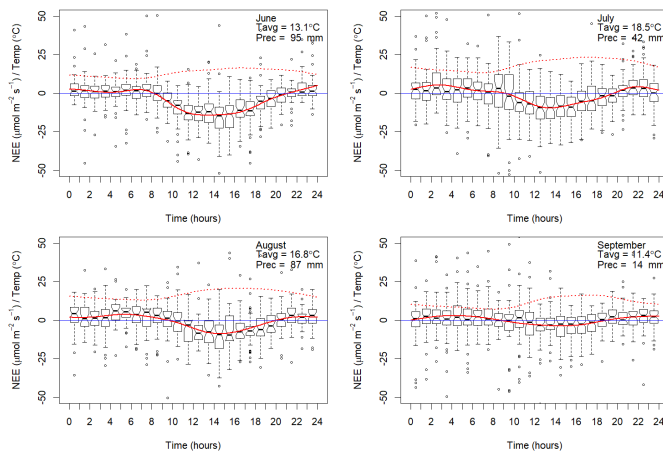
Figure 3. NEE (μmol m^{-2} s^{-1}) values per 24-h timescale and precipitation (mm) levels over the study period (June to September 2014). Dark red line describes smooth mean of the NEE, dotted red line illustrates average temperature.

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.
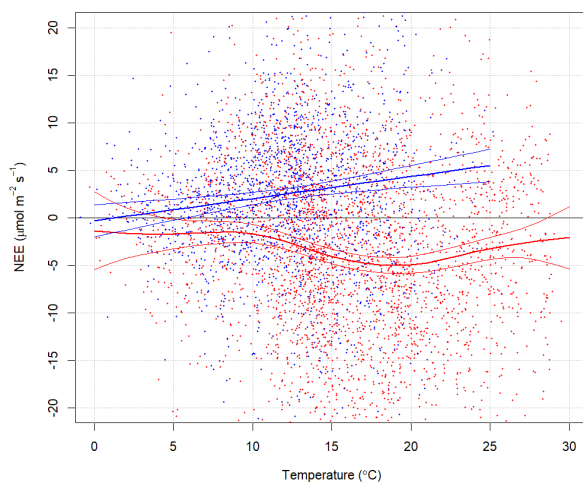
Figure 4. NEE (μmol m^{-2} s^{-1}) and temperature (°C) over the study period (2014). Blue dots represent nighttime and red dots daytime eddy flux measurements. Lines represent GAM model predictions with confidence intervals.

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}.

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.
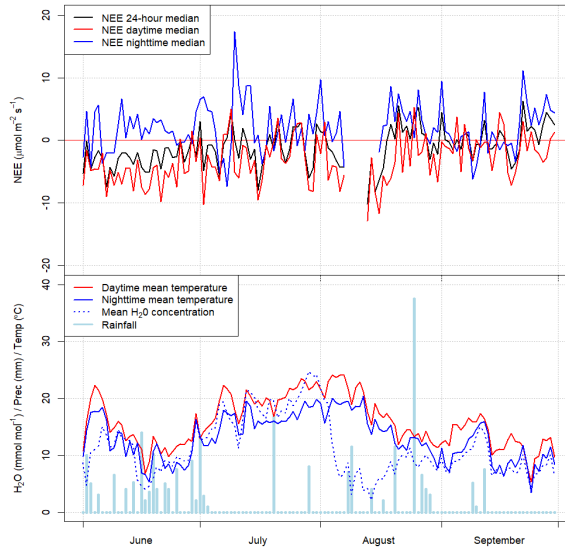
Figure 5. Daily NEE (µmol m^{-2} s^{-1}) values; nighttime flux (µmol m^{-2} s^{-1}), daytime flux (µmol m^{-2} s^{-1}), NEE average (µmol m^{-2} s^{-1}), temperature (C°), H$_2$O concentration (mmol mol^{-1}), and rainfall (mm) levels over the study period (2014).

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).

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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C-exchange and balance following clear-cutting in hemiboreal forest ecosystem under summer drought

Sille Rebane[a,*], Kalev Jõgiste[a], Andres Kiviste[b], John A Stanturf[b,c], Ahto Kangur[b], Marek Metslaid[a,d]

[a] Chair of Silviculture and Forest Ecology, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia
[b] Chair of Forest Management Planning and Wood Processing Technologies, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia
[c] InNovaSilva TpS, Højen Tang 80, 7100 Vejle, Denmark
[d] Norwegian Institute of Bioeconomy Research, PO Box 115, 1431 Ås, Norway

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ABSTRACT

Growth of CO_2 concentration level has strong interactions with forests. Forests are able to sequester carbon (C) through photosynthesis and can help to mitigate the effects of climate warming, as well as to reduce the CO_2 concentration in the atmosphere. Drought and other extreme weather conditions play a key role in ecosystem functioning and the C-cycle. The eddy covariance (EC) method can be used to better understand forest eco-systems CO_2 exchange by directly measuring net carbon and water fluxes. In our study, EC results for measurement of fluxes between the atmosphere and forest canopy are reported for the study period from May to August 2018 in Järvselja, Estonia. Stand-replacing disturbance (clear-cutting) took place in April 2013. The young forest stand is dominated by Norway spruce (*Picea abies*) and birch (*Betula* spp.). Findings so far include (1) a C-budget for the study period that showed a slight C-sink status; (2) net ecosystem exchange (NEE) was -0.0084 µmol m^{-2} s^{-1} indicating C-uptake during the measurement period; (3) in May, June, July and August, NEE was -0.027, -0.015, 0.001 and 0.006 µmol m^{-2} s^{-1}, respectively; (4) NEE fluxes are lower in drought conditions and are affected by temperature that averaged 15 °C.

1. Introduction

Forest ecosystems store significant amounts of carbon (C) and play an important role in the global C-cycle (Saunders et al., 2012; Wilkinson et al., 2012; Lindroth et al., 2018). All forests, tropical, temperate and boreal, are predominantly C-sinks (Pan et al., 2011; Lindroth et al., 2018). Through their C-sink role, forests help to regulate the atmospheric CO_2 concentration level (Tang et al., 2017) and by storing C, forests can contribute to mitigating global warming (Wilkinson et al., 2012; Lindroth et al., 2018). Boreal forests can quickly sequester C and they are one of the main global C storages (Pan et al., 2011). Also due to climate warming, forests apparently are se-questering increased amounts of C (Tang et al., 2017; Ney et al., 2019). In forests, disturbances affect the net ecosystem exchange (NEE) of C and interaction effects of climate warming.

Stand-replacing disturbances, such as fires, insect outbreaks and clear-cutting greatly impact the ecosystem C-exchange (Humphreys et al., 2005; Bergeron et al., 2008; Williams et al., 2014; Ney et al., 2019; Rebane et al., 2019). Ecosystem processes drive NEE between the forest canopy and atmosphere (Bergeron et al., 2008), including pho-tosynthesis, heterotrophic and autotrophic respiration (Baldocchi et al., 2018; Rebane et al., 2019). NEE describes ecosystem status as a C-sink or C-source, as well expressing the recovery of a forest stand following disturbance (Kolari et al., 2004; Krasnova et al., 2019). In addition, weather components such as precipitation and temperature affect NEE (Williams et al., 2016; Geddes et al., 2014).

In Estonian forest ecosystems, stand-replacing clear-cutting is the anthropogenic disturbance with the strongest effect on carbon fluxes and storage (Estonian Environment Agency, 2018). Even-aged man-agement using clear-cutting is the main forest regeneration method, causing changes in forest structure and functioning (Geddes, et al., 2014; Lindroth et al., 2018; Jõgiste et al., 2018; Uri et al., 2019). After clear-cut harvesting, it is assumed that a large amount of CO_2 is re-leased (emitted) to the atmosphere (Ney et al., 2019). However, forest ecosystem C-status can change quickly with almost immediate vegeta-tion recovery (Amiro et al., 2010; Ney et al., 2019). Vegetation devel-opment depends on forest site type and disturbance intensity (Amiro et al., 2010; Tang et al., 2017). Forest ecosystems are able to recover

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from clear-cutting and return to C-sink status (Freeden et al., 2007; Lindroth et al., 2018; Uri et al., 2019). Recovery after stand-replacing disturbance can take several years, depending on tree growth; for example, recovery to C-sink status 7-years after clear-cutting (Ney et al., 2019; Uri et al., 2019), or up to 10 years (Amiro et al., 2006, 2010, Lindroth 2009; Coursolle et al., 2012; Aguilos et al., 2014).

While it is well known that clear-cutting greatly influences the C-cycle and affect C-dynamics at the ecosystem level, a better understanding is needed of C fluxes and budget after clear-cutting. In this study the eddy-covariance (EC) method was used to measure forest ecosystem NEE (Baldocchi et al., 2001; Aguilos et al., 2014). It is a widely used method for carbon balance estimations, through direct atmosphere and stand-level C-exchange. We hypothesized that (1) a 5-year-old forest stand is C-neutral during a measurement period; (2) daytime NEE exceeds nighttime respiration; and (3) C-uptake is decreased under short-term drought conditions.

2. Material and methods

2.1. Site description

The eddy flux tower was located in a mixed hemiboreal forest at Järvselja Training and Experimental Forest Centre, Estonia (58°17′09.5″N 27°17′56.6″E). Forest site type is *Oxalis-Vaccinium myrtillus* (Lõhmus 1984). The climate in Estonia is temperate and mild with warm summers, with mean annual temperature + 5 °C, annual mean precipitation is 550–800 mm, and the active vegetation period usually starts in May and ends in September. The dominating wind directions within the study period are mostly from the south (S) or south-west (SW). The study site was clear-cut in April 2013; the total area of the clear-cut was 0.71 ha. Soil scarification and planting with Norway spruce was carried out in 2013 and 2014, respectively.

The tree layer on the study site before clear-cutting was dominated by birch (*Betula* spp.), Norway spruce (*Picea abies* (L.) Karst) and European aspen (*Populus tremula* L.) with growing stock 322 m³ ha⁻¹. Main species in the ground layer vegetation were European blueberry (*Vaccinium myrtillus* L.), lingonberry (*Vaccinium vitis-idaea* L.) and bryophytes including red-stemmed feathermoss (*Pleurozium schreberi* (Brid.) Mitt.), glittering woodmoss (*Hylocomium splendens* (Hedw.) Schimp.), broom forkmoss (*Dicranum scoparium* Hedw.) and common haircap (*Polytrichum commune* Hedw.). Vegetation 5 years after clear-cutting was Norway spruce (2100 trees per hectare), birch (2100 trees per hectare) and Scots pine (*Pinus sylvestris* L.) (300 trees per hectare); ground layer vegetation was dominated by rough small reed (*Calamagrostis arundinacea* (L.) Roth), sedges (*Carex* spp. L.), also May lily (*Maianthemum bifolium* (L.) F.W.Schmidt), arctic starflower (*Trientalis europaea* L.) and wood sorrel (*Oxalis acetosella* L.). Bryophytes present after harvest remained the same as before disturbance.

2.2. Eddy covariance measurements and data processing

Eddy covariance measurements were started in 2014. The present study focuses on the summer period, from May to August 2018. The tower was located at the center of the clear-cut area; equipment was mounted 3.79 m above the developing canopy, which averaged 1.43 m (tallest stem was 2 m). The air-sampling tube was 1 m long, with a diameter of 6 mm. Eddy covariance instrumentation included a 3D sonic anemometer (C-SAT 3, Campbell Scientific, USA) measuring wind velocity (m⁻² s⁻¹), sonic air temperature (°F) and a closed-path infrared gas analyzer LI-7200 (LI-COR Biosciences, Lincoln, NE, USA) measuring concentrations of CO_2 (ppm) and H_2O (mmol m⁻² s⁻¹), fluxes of C (µmol m⁻² s⁻¹) and H_2O (mmol m⁻² s⁻¹). Meteorological variables including temperature, wind speed and direction were measured by anemometer (C-SAT 3, Campbell Scientific, USA).

Measurements were saved automatically by a data logger with a high sampling frequency (10 Hz). All raw data were converted into an Excel format using EddyPro software (LI-COR Biosciences, Lincoln, NE, USA) to obtain the 30-minute average turbulent fluxes of CO_2 daily. Data processing included statistical screening and spike removals (Vickers and Mahrt, 1997), double rotation, block averaging, time lag compensation and spectral correction of low and high-frequency (Vickers and Mahrt, 1997, Foken et al., 2004). A quality check flagging policy was selected for results of the steady-state and developed tests (quality classes 1–9) according to Foken et al. (2004).

Further data processing, analysis, final calculations and figures were made using R-Statistics software. In this study the method of Iglewicz and Hoaglin (1993) was followed with threshold value of 3.5 (abs(x − me(x))/mad(x) > 3.5) to detect bad values, where me(x) was the median and mad(x) the median absolute deviation. To avoid excluding true measurements and eliminate physically impossible values, we rounded up the allowable data region ± 30 µmol m⁻² s⁻¹ for CO_2 flux. For defining daytime and nighttime, data were separated as sunset and sunrise. Positive NEE values represent a release of CO_2 from ecosystem to the atmosphere and negative NEE values represent an uptake of CO_2 by the ecosystem from the atmosphere.

2.3. Gap-filling

For NEE budget estimation we used gap-filling as a standard procedure (Reichstein et al., 2005). Gap-filling requires data on radiation, vapor pressure deficit, and temperature, which are the meteorological variables that NEE depends upon (Graf, 2017). Data gaps in variables such as air temperature, radiation or C-fluxes were filled using the Reddy ProcWeb online tool (http://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWeb), which was applied with lookup tables to fill NEE gaps by taking into account the original NEE values from similar conditions (Falge et al., 2001; Chi et al., 2019). The estimation of flux random uncertainty due to sampling errors was computed according to Finkelstein and Sims (2001). The gap-filled NEE data were used only for NEE budget estimations, not for the other analyses. Meteorological data that were not available because of the gaps, but still needed for gap-filling, were obtained from the automated local weather station of the Järvselja Training and Experimental Forest Centre, located about 2 km south from the study site in an open area next to the Järvselja Hunting Lodge.

2.4. Footprint of the EC tower

We evaluated the cumulative footprint of the tower every 30 min at the clear-cut area using the Kljun et al. (2004) method for footprint analyses. Therefore, fluxes are measured and taken into account from 0° to 360°. The footprint analysis showed that 90% of the cumulative footprint was located at 98 m distance from the tower. Also, 90% of the footprint showed the maximum extension of the clear-cut area. Fluxes 70%, 50%, 30% and 10%, of cumulative footprint originated at 65.4, 46.6, 30.6 and 12.3 m from the EC tower, respectively. The fluxes that were less than 1% (2.7 m) from the tower showed at the same time the offset of this tower. During the measurement period the prevailing wind was from the south.

3. Results

The growth period in 2018 from May to August, day of year (DOY) 121–243, was very warm with some droughty periods (an extended period of below-average precipitation and above-average temperature, likely leading to a shortage of water that was not measured). Precipitation levels in May and July were very low and temperatures stayed above 0 °C, peaking up to 30 °C (Fig. 1). Average temperatures stayed around 15 °C and precipitation levels varied during the study period (Fig. 1, Fig. 2); May was the driest month compared to usual Estonian conditions and July was also very dry. However, during the summer period precipitation levels were highest in June and August.
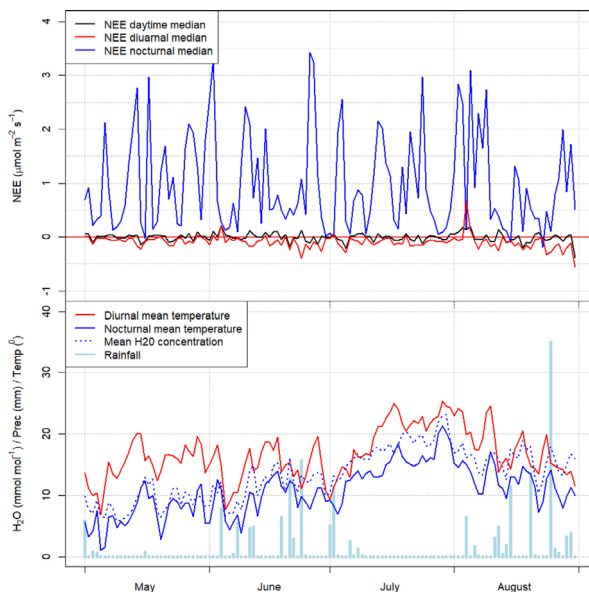
Fig. 1. Different variables of study period: NEE (daytime, diurnal, nocturnal), mean values of H_2O concentration, temperature and sum of precipitation from May to August (2018).

May was the warmest summer month, but June was cooler. In July the temperature increased and precipitation decreased, similar to the drought condition in May. August was a rainy month again and presented a lower average temperature than the previous month.

The mixed forest stand in this study acted as a weak C-sink or was C-neutral over the study period (Table 1). On the one hand, at the beginning of the summer NEE values indicated that the young forest ecosystem acted as a weak C-sink but in July and August, it became C-neutral. Nevertheless, the highest C-uptake (-0.027 μmol m^{-2} s^{-1}) was measured in May. Daily NEE values were negative, varying between -0.397 and -0.730 μmol m^{-2} s^{-1}; average daytime NEE was -0.510 μmol m^{-2} s^{-1} (Table 2). On the other hand, during the nighttime the forest was a C-source, emitting carbon to the atmosphere on average 1.163 μmol m^{-2} s^{-1} over the study period.

During the study period, net ecosystem exchange represented a similar diurnal pattern in C-fluxes (Fig. 2). Generally, fluxes acted as a C-sink during the morning (between 05.00 and 12.00). NEE showed a higher uptake from atmosphere in May, a weak C–sink in the mornings after being a nighttime C-source. C-uptake increased with higher precipitation values; C-uptake was diminished under very dry and too wet conditions, as compared to long-term averages. The temperature in May was optimal for Estonian conditions, which had a positive effect for C-absorption from the atmosphere.

During the entire study period (May – August) the 5-year-old mixed stand was a C-sink with average NEE -0.0084 μmol m^{-2} s^{-1} (Fig. 3). The C-budget was -0.011 t C ha^{-1}, which confirms the C-sink or C-neutrality status.

NEE may be affected by different factors, but temperature is one of the most important (Fig. 4). With rising temperature, C-uptake will rise continuously or maintain same level, and decrease with decreasing temperature. However, during a hot daytime or a drought, plants increase C absorption to an optimum and will decrease after exceeding this point. During the drought conditions in May and June, plants were not able to absorb C.

4. Discussion

In Estonia logging residues and deadwood are left on site if clear-cutting is located on fragile, wet and seasonally wet soils (Kurvits et al., 2020). Decomposing residues on these sites will continue to emit C to the atmosphere and NEE will be positive until vegetation recovery (Grant et al., 2010). The time necessary for forest ecosystem recovery after clear-cutting depends on the choice of regeneration method. Natural regeneration usually takes more time than artificial regeneration by planting or sowing and the proper regeneration method may shorten the recovery period (Tang et al., 2017). Clear-cutting is the common forest management system in Estonia, followed by planting to establish the new forest generation (Uri et al., 2019). Planting may speed up revegetation (Ciais et al., 2005) that increases C sequestration (Tang et al., 2017). Thus, proper forest management practices provide important strategies to mitigate global climate change and temperature increase (Tang et al., 2017).

Several studies (Kolari et al., 2004; Aguilos et al., 2014; Uri et al., 2019) have found that young forest stands reach a C-balance shortly after the disturbance. For example, a 6-year-old Scots pine (*Pinus sylvestris*) stand in Estonia was a C-source (119 g C m^{-2} year^{-1}) and at the age 7, this stand probably will turn into a weak C-sink or C-neutral (Uri et al., 2019). Another short-term study in Estonia showed 6- and 8-year-

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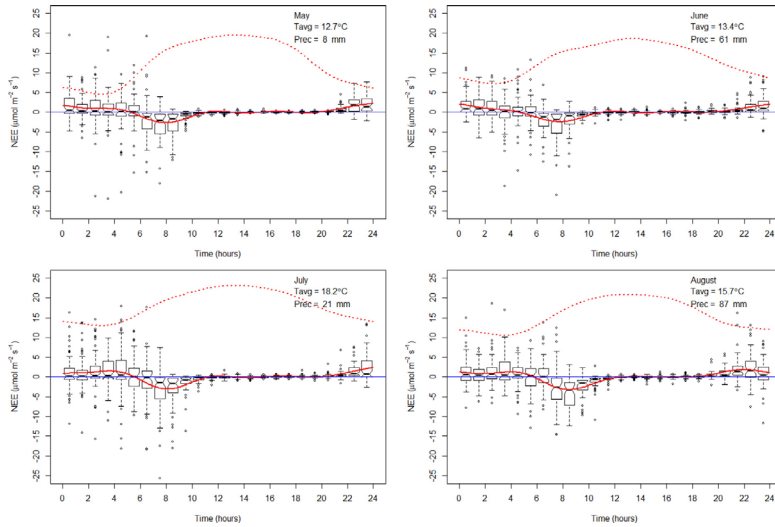
Fig. 2. NEE (µmol m^{-2} s^{-1}) values per 24-h timescale, temperature and precipitation levels over study period (2018). Solid red line describes the smoothed mean of the NEE; dotted red line illustrates average temperature. Highest day- and nighttime temperatures were in July and August; precipitation was highest in August. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
NEE (µmol m^{-2} s^{-1}) and CO_2 concentration values per month.

	NEE (µmol m^{-2} s^{-1})	Standard deviation	CO_2 (ppm)	Standard deviation
May	−0.027	3.115	414.651	44.578
June	−0.015	2.542	402.929	47.934
July	0.001	3.457	397.883	53.412
August	0.006	3.258	417.88	60.299

Table 2
NEE values of daytime* and nighttime** per month.

Month	NEE* (µmol m^{-2} s^{-1})	NEE** (µmol m^{-2} s^{-1})
May	−0.397	0.847
June	−0.450	1.285
July	−0.465	1.254
August	−0.730	1.266

Fig. 3. NEE (µmol m^{-2} s^{-1}) values per 24-hour timescale over study period (2018). Solid red line describes smoothed mean of the NEE, dotted red line illustrates average temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

old stands reaching weak C-sink status (Rebane et al., 2020). The 5-year-old clear-cut stand in our study was a weak C–sink and showed similar trends with other studies, for example a 7- to 8-year-old Canadian jack pine (*P. banksiana*) stand was C-neutral during the 1-year-long study period (Amiro et al., 2006). Another 10- to 11-year-old jack pine stand was close to C-neutral, where NEE changed from − 34 to 7 g C m^{-2} yr^{-1} (Mkhabela et al., 2009).

On a daily basis, forest ecosystems may achieve C-neutral or C-sink status quite quickly, but annually behave as a C-source (Mamkin et al., 2019). During the vegetative growth period, daytime NEE can be negative, showing C-uptake from the atmosphere as the active growth begins (Kolari et al., 2004; Grant et al., 2010; Mamkin et al., 2019). In our study, during the summer period the C budget was − 0.011 t C

ha^{-1}, indicating a weak C-sink or possibly a C-neutral ecosystem. Within 10 years after a stand-replacing disturbance, a forest ecosystem may be able to and reach the compensation point and become C-neutral or a C-sink (Aguilos et al., 2014; Tang et al., 2017 Uri et al., 2019; Rebane et al., 2020). Aguilos et al. (2014) estimated that it took 7 years in a hybrid larch stand to reach to a compensation point. Nevertheless, some studies show that a longer recovery period is needed to balance C-losses in a forest stand (Schulze et al., 1999; Rannik et al., 2002). For example, in Finland a 12-year-old Scots pine stand reached C-balance, where ground vegetation had an important role in photosynthesis and C-uptake (Kolari et al., 2004).

Temperature plays a key role in ecosystem functioning (Barr et al.,

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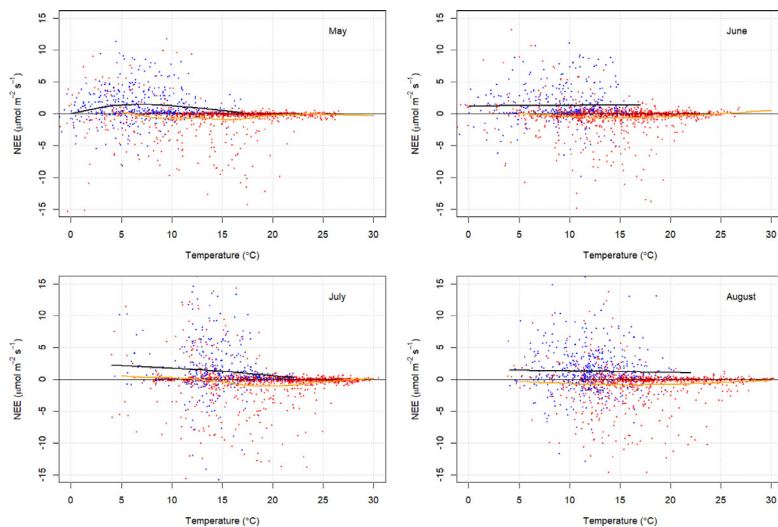
Fig. 4. NEE (μmol m^{-2} s^{-1}) and temperature (°C) over study period (2018). Blue dots represent nighttime and red dots daytime eddy flux measurements. Lines represent relationship between NEE and temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2007) including C-uptake (Hadden and Grelle, 2016; Mamkin et al., 2019). Air temperature determines the start of the growing season in northern Europe (Kolari et al., 2004; Welp et al., 2007). With rising temperatures, increases in C-uptake are also noticed (Barr et al., 2007; Hadden and Grelle, 2016; Mamkin et al., 2019). Under very cold conditions, C-uptake will cease (Kolari et al., 2004; Welp et al., 2007). Temperature also affects soil microbial processes and soil moisture; temperature has an effect on respiration and is related to soil effluxes (Barr et al., 2007; Kulmala et al., 2014). Welp et al. (2007) noticed that with a continuous increase in air temperature there was a decrease in soil moisture. However, other studies have found that temperature did not affect C-balance (Barr et al., 2007). In our study, air temperatures in May were optimal for growth and daytime C-uptake was positive (negative NEE) despite low precipitation, which likely was offset by stored soil moisture. Over the entire May to August study period, our 5-year-old stand was a C-sink with average NEE -0.0084 μmol m^{-2} s^{-1}.

The last decade has been drier and slightly warmer than the past couple of decades in Estonia (Jaagus et al., 2017; Jaagus and Mändla, 2014). The changing climate may increase disturbance frequency and extreme weather events in the future, such as extreme heatwaves and drought periods (Ciais et al., 2005; Williams et al., 2016; Tang et al., 2017). For example, the severe drought and extremely high temperatures experienced in Europe over the summer of 2003 led to an estimated net release of C from the continent's forests of 0.5 Pg C yr^{-1} (Ciais et al., 2005). On the contrary, drought in boreal forests in 2003 showed slightly higher sequestration compared to the previous year; NEE in 2003 was -0.32 g C m^{-2} d^{-1} and 2002 it was -0.23 g C m^{-2} d^{-1}. The variation may have been caused by differences in water deficit and moisture stress (Williams et al., 2016, Geddes et al., 2014, Tang et al., 2017). However, greater C-uptake cannot be achieved without sufficient availability of water (Baldocchi et al., 2001) and extreme droughts in 2006 and 2010 confirmed the heatwave effect by reducing

C-uptake and causing a decline in forest production (Williams et al., 2016, Ciais et al., 2005). Our short-term study illustrates the interacting effects of temperature and precipitation and effects of short-term drought conditions on C-fluxes and points to the importance of the stored soil moisture, a short-coming of our study but necessary to fully understand the effects of temperature in C-fluxes.

5. Conclusions

Our study focused on C-fluxes and C-exchange after clear-cutting over a four-month-long study period in the summer of 2018, 5 years after forest disturbance. After clear-cutting, the artificially regenerated study site was dominated by Norway spruce and silver birch. Generally mixed stands such as this vary in terms of NEE but this site acted as a C-sink. These results showed that climate conditions greatly affected C-exchange. Temperature impacted C-uptake and may influence ecosystem C-balance negatively by shutting down photosynthesis. Extreme weather events, such as droughts, limit C-cycle and effectiveness of C-uptake. This kind of feedback is important on a global scale and gives opportunities to predict changes in C-uptake during global warming.

Long-term measurements are needed to better understand forest ecosystem functioning and C-cycle. It is important to continue with such studies as ours, for a longer time period, to better understand the C-cycle over stand development. It would be interesting to investigate if an increase in stand-replacing disturbance (clear-cutting) as a main management strategy is in good accordance with climate change mitigation and adaptation strategies.

Declaration of Competing Interest

None.

Acknowledgments

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118249.

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CURRICULUM VITAE

First name: Sille
Surname: Rebane
Citizenship: Estonian
Date of birth: 25.03.1992
Address: Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, 51006 Tartu, Estonia
Telephone: +372 5611 1702
E-mail: sille.rebane@emu.ee

Education:
2016−2020   PhD studies in forestry, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences
2018−2020   Activity instructor, Department of tourism, Tartu Vocational Education Centre
2014−2016   Master studies in natural resources management, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences
2011−2014   Bachelor studies in natural resources management, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences
1999−2011   Vastseliina High School

Professional employment:
2017−…   Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Chair of Silviculture and Forest Ecology, junior scientist (0.4)

Research interests:
             forest sciences, silviculture, forest ecology, carbon balance, disturbance regime

Foreign languages: English, Russian

Training and special courses:

2019	"New solutions for forest regeneration". Workshop organized by Estonian University of Life Sciences
2018	Summer school of land use history. Course organized by Estonian University of Life Sciences
2018	"Disturbance legacy and forest soil carbon". Workshop organized by Estonian University of Life Sciences and University of Helsinki
2017	"IFGI Summer School – International Forestry and Global Issues". Course organized by Inra Research Center Nancy-Lorraine
2017	"Flux measurements experiment – Summer School". Course organized by Estonian University of Life Sciences and University of Tartu
2016	"The challenge of global change: disturbance and risk in forest ecosystem management". Workshop organized by Estonian University of Life Sciences

Awards:

2019	Scholarship of Olevi Kulli (University of Tartu)
2018	Scholarship of EMÜ Raefond (Tartu City Government and Estonian University of Life Sciences)

Projects:

2020−2021	P200029MIME "Effects of forest fires on dynamics of vegetation, soil fungal community and physical-chemical properties in hemiboreal forests", Estonian University of Life Sciences, investigator
2019−2021	T190074MIME "Post-storm bark beetle damages and forest protection measures to prevent spread", Environmental Investment Centre, investigator
2018−2019	P180024MIME "Effects of forest fires on soil fungal community and carbon and nitrogen

	dynamics in hemiboreal forests", Estonian University of Life Sciences, investigator
2015—2016	PUT715 "How much will the increasing fire frequency change the carbon stocks in forests?", Estonian Research Council, investigator

ELULOOKIRJELDUS

Eesnimi:	Sille
Perekonnanimi:	Rebane
Kodakondsus:	Eesti
Sünniaeg:	25.03.1992
Aadress:	Metsandus- ja maaehitusinstituut, Eesti Maaülikool, Kreutzwaldi 5, 51006 Tartu, Eesti
Telefon:	+372 5611 1702
E-mail:	sille.rebane@emu.ee

Hariduskäik:

2016−2020	Eesti Maaülikool, metsandus- ja maaehitus-instituut, metsanduse doktoriõpe
2018−2020	Aktiivtegevuste instruktor, toitlustuse ja turismi osakond, Tartu Kutsehariduskeskus
2014−2016	Eesti Maaülikool, metsandus- ja maaehitus-instituut, loodusvarade kasutamine ja kaitse, magistriõpe
2011−2014	Eesti Maaülikool, metsandus- ja maaehitus-instituut, loodusvarade kasutamine ja kaitse, bakalaureuseõpe
1999−2011	Vastseliina Gümnaasium

Teenistuskäik:

2017−…	Eesti Maaülikool, metsandus- ja maaehitus-instituut, metsakasvatuse ja metsaökoloogia õppetool, nooremteadur (0.4)

Teadustöö põhisuunad:

metsateadus, metsakasvatus, metsaökoloogia, süsinikubilanss, häiringute režiim

Võõrkeelte oskus: inglise, vene

Täiendkoolitused:

2019	"New solutions for forest regeneration". Seminar korraldatud Eesti Maaülikooli poolt
2018	Summer school of land use history. Kursus korraldatud Eesti Maaülikooli poolt
2018	"Disturbance legacy and forest soil carbon". Seminar korraldatud Eesti Maaülikooli ja Helsingi Ülikooli poolt
2017	"IFGI Summer School – International forestry and global issues". Kursus korraldatud Inra Research Center Nancy-Lorraine poolt
2017	"Flux measurements experiment – Summer School". Kursus korraldatud Eesti Maaülikooli ja Tartu Ülikooli poolt
2016	"The challenge of global change: disturbance and risk in forest ecosystem management". Seminar korraldatud Eesti Maaülikooli poolt

Tunnustused:

2019	Olevi Kulli Mälestusstipendium (Tartu Ülikool)
2018	EMÜ Raefondi stipendium (Tartu Linnavalitsus ja Eesti Maaülikool)

Projektid:

2020−2021	P200029MIME "Metsapõlengute mõju taimestiku, mullaseenestiku ning mulla füüsikalis-keemiliste omaduste dünaamikale hemiboreaalsetes metsades", Eesti Maaülikool, täitja
2019−2021	T190074MIME "Tormijärgne üraskikahjustuste levik ja metsakaitseabinõud leviku tõkestamiseks", SA Keskonnainvesteeringute Keskus, täitja
2018−2019	P180024MIME "Metsapõlengute mõju mullaseenestikule ning mulla süsiniku ja lämmastiku dünaamikale hemiboreaalsetes metsades", Eesti Maaülikool, täitja
2015−2016	PUT715 "Kui suurel määral kasvav põlengute sagedus muudab metsade süsinikuvaru?", SA Eesti Teadusagentuur, täitja

LIST OF PUBLICATIONS

Publications indexed in the ISI Web of Science database

Jõgiste, K., Frelich, L.E., Laarmann, D., Vodde, F., Baders, E., Donis, J., Jansons, A., Kangur, A., Korjus, H., Köster, K., Kusmin, J., Kuuluvainen, T., Marozas, V., Metslaid, M., Metslaid, S., Polyachenko, O., Poska, A., **Rebane, S.,** Stanturf, J.A. 2018. Imprints of management history on hemiboreal forest ecosystems in the Baltic States. Ecosphere, 9(11), Article e02503.

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J.A., Metslaid, M. 2020. Patterns of carbon sequestration in a young forest ecosystem after clear-cutting. Forests, 11(2), 216.

Rebane, S., Jõgiste, K., Põldveer, E., Stanturf, J.A., Metslaid, M. 2019. Direct measurements of carbon exchange at forest disturbance sites: A review of results with the eddy covariance method. Scandinavian Journal of Forest Research, 34(7), 585−597.

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J.A., Kangur, A., Metslaid, M. 2020. Forest ecosystem C exchange and balance under drought in mixed hemiboreal forest zone. Forest Ecology and Management, 472, 118249.

Abstracts

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J., Metslaid, M. 2019. Forest ecosystem carbon fluxes after stand-replacing disturbance. Book of Abstracts: Brazilian Journal of Forestry Research, 39: "XXV IUFRO World Congress" Curitiba, Brazil, 29. September - 5. October, 2019. Ed. Patrícia Póvoa de Mattos. Brazil, Curitiba: Embrapa Floresta, Colombo, Brazil, 227−227. (e201902043).

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J.A., Metslaid, M. 2019. Dynamics of CO_2 fluxes in hemiboreal forest ecosystems. Book of Abstracts: 2. International Conference on "Agriculture, Forestry & Life Sciences" April 18−20, 2019. Prague, Czech Republic. Prague, Czech Republic: ICAFLS, 44−44.

Rebane, S., Jõgiste, K., Allikmäe, E., Stanturf, J.A., Metslaid, M. 2018. Eddy covariance measurements: Carbon exchange of forest ecosystems after different disturbances (A review). Geophysical Research Abstracts, 20: EGU General Assembly 2018. Vienna: European Geosciences Union, EGU2018-162.

Rebane, S. 2017. Interactions of global forest resources and climate. Book of Abstracts: IUFRO 125th Anniversary Congress. Freiburg, Germany, 18−22 September 2017. Freiburg: University of Freiburg, 496−496.

Rebane, S. 2017. Predicting climate change by analysing greenhouse gases of forest atmosphere. Book of Abstracts: International Scientific Conference: Problems of landscape protection and management in XXI century. Warsaw, Poland, April 20−22, 2017. Warsaw, Poland: Warsaw University of Life Sciences, 38−38.

APPROBATION

International conferences and meetings

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J.A., Metslaid, M. 2019. Forest ecosystem carbon fluxes after stand-replacing disturbance. Posterettekanne rahvusvahelisel konverentsil "XXV IUFRO World Congress" Brazil, 29. September – 05. October 2019.

Rebane, S., Jõgiste, K., Kiviste, A., Stanturf, J.A., Metslaid, M. 2019. Dynamics of CO_2 fluxes in hemiboreal forest ecosystems. Suuline ettekanne rahvusvahelisel konverentsil "Agriculture, Forestry & Life Sciences" Chezh Republic, 18−20. April 2019.

Rebane, S., Jõgiste, K., Allikmäe, E., Stanturf, J.A., Metslaid, M. 2018. Carbon dynamics of boreal forest after stand-replacing disturbances. Posterettekanne rahvusvahelisel seminaril "Disturbance legacy and forest soil carbon" Finland, 07−09. October, 2018.

Rebane, S., Jõgiste, K., Allikmäe, E., Stanturf, J.A., Metslaid, M. 2018. Eddy covariance measurements: Carbon exchange of forest ecosystems after different disturbances (A review). Posterettekanne rahvusvahelisel konverentsil "European Geosciences Union General Assembly 2018" Austria, 8−13. Aprill 2018.

Rebane, S. 2017. Interactions of global forest resources and climate (Young spruce stand carbon sequestration in Estonia: EC measurements). Posterettekanne rahvusvahelisel konverentsil "125 years of IUFRO" Germany, 19−22. September 2017.

Krasnova, A., Repp, K., **Rebane, S.** 2017. Eddy covariance method: CO_2, N_2O and CH_4 measurements VOC – volatile organic compounds. Suuline ettekanne rahvusvahelisel seminaril "Flux measurements experiment – Summer School" Estonia, 15. August 2017.

Rebane, S. 2017. Predicting climate change by analysing greenhouse gas fluxes of forest. Posterettekanne rahvusvahelisel konverentsil "Problems of landscape protection and management in XXI century" Poland, 20−22. April 2017.

Local conferences and meetings

Rebane, S., Jõgiste, K., Põldveer, E., Stanturf, J.A., Metslaid, M. 2018. Effects of disturbances on carbon balance in a boreal forest ecosystems. Posterettekanne konverentsil "Metsateaduselt praktikale" Tartu, 07. november 2018.

Rebane, S., Jõgiste, K., Allikmäe, E., Stanturf, J.A., Metslaid, M. 2018. Carbon dynamics of boreal forest after stand-replacing disturbances. Posterettekanne konverentsil "Forestry conference for Baltic PhD students" Valgamaa, 26−27. aprill 2018.

Rebane, S., Jõgiste, K. 2017. Metsaökosüsteemi süsiniku dünaamika noores raiejärgses segapuistus Järvseljal. Posterettekanne konverentsil "Eesti metsade süsiniku dünaamika ja jätkusuutlik majandamine" Tartu, 06. september 2017.

Rebane, S. 2017. Metsaökosüsteemi süsiniku dünaamika Järvselja katseala näitel. Suuline ettekanne metsabioloogia osakonna seminaril Tartu, 30. juuni 2017.

VIIS VIIMAST KAITSMIST

LISANDRA MARINA DA ROCHA MENESES
SECOND-GENERATION BIOETHANOL PRODUCTION: STRATEGIES FOR
SIDESTREAMS VALORISATION IN A SUSTAINABLE CIRCULAR ECONOMY
TEISE PÕLVKONNA BIOETANOOLI TOOTMINE: KÕRVALVOOGUDE
VALORISEERIMINE JÄTKUSUUTLIKU RINGMAJANDUSE KONTSEPTSIOONIS
Professor **Timo Kikas**, dotsent **Kaja Orupõld**
24. august 2020

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FORMATION
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TEGURID
Dotsent **Ulvi Moor**, professor **Eivind Vangdal**
31. august 2020

OLEKSANDR KARASOV
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Professor **Mart Külvik**, professor **Ihor Chervanyov**
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RIINU KIIKER
DIVERSITY IN BALTIC POPULATIONS OF POTATO LATE BLIGHT PATHOGEN
PHYTOPHTHORA INFESTANS
KARTULI-LEHEMÄDANIKU TEKITAJA PHYTOPHTHORA INFESTANS
BALTIMAADE POPULATSIOONIDE MITMEKESISUS
Professor **Marika Mänd**, dotsent **Eve Runno-Paurson**
10. september 2020

KAARI REIMUS
ON-FARM MORTALITY AND RELATED RISK FACTORS IN ESTONIAN DAIRY
AND BEEF HERDS
SUREMUS FARMIS JA SELLEGA SEOTUD RISKITEGURID EESTI PIIMA- JA
LIHAVEISEKARJADES
Dotsent **Kerli Mõtus**, professor **Arvo Viltrop**
16. september 2020