Agricultural and Forest Meteorology 260–261 (2018) 216–228

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The carbon balance of a Scots pine forest following severe windthrow: Comparison of reforestation techniques

K. Ziemblińska[a,*], M. Urbaniak[a], L. Merbold[b], T.A. Black[c], A.M. Jagodziński[d,e], M. Herbst[f], Ch. Qiu[g], J. Olejnik[a,h]

[a] Department of Meteorology, Poznań University of Life Sciences, Piątkowska 94, 60-649 Poznań, Poland
[b] Mazingira Centre, International Livestock Research Institute (ILRI), 00100 Nairobi, Kenya
[c] Faculty of Land and Food Systems, University of British Columbia, Vancouver, British Columbia, Canada
[d] Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland
[e] Department of Game Management and Forest Protection, Poznań University of Life Sciences, Wojska Polskiego 71c, 60-625 Poznań, Poland
[f] German Meteorological Service Centre for Agrometeorological Research, Bundesallee 33, 38116 Braunschweig, Germany
[g] Laboratoire des Sciences du Climat et de l'Environnement, UMR8212, CEA-CNRS-UVSQ16F-91191, Gif sur Yvette, France
[h] Department of Matter and Energy Fluxes, Global Change Research Centre, AS CR, v.v.i. Belidla 986/4a, 603 00 Brno, Czech Republic

ARTICLE INFO

Keywords:
Eddy covariance
Net ecosystem exchange
Net ecosystem productivity
Meteorological extremes

ABSTRACT

Even though windthrows are the main disturbance type in European forests, their impact on forest carbon balance is generally understudied. In order to close this knowledge gap, we took advantage of a tornado event, which occurred in July 2012 in Trzebciny Forest District in northwest Poland. The main objective of this study was to determine how two completely different reforestation techniques in windthrow areas impact net ecosystem production (NEP) of this Scots pine forest ecosystem under similar meteorological conditions. The two techniques were: conventional ("Tlen I" site): uprooted stumps pulled out and removed from the site followed by ploughing, and non-conventional ("Tlen II" site): all stumps left on the site to decompose with no ploughing. Therefore, we measured carbon dioxide (CO_2) fluxes using the eddy covariance (EC) technique for four continuous years. Our results indicate that both sites became significant carbon (C) sources after the windthrow (up to 575 ± 56 g C m^{-2} y^{-1} in the first year, Tlen I). However, the Tlen I (conventional technique) lost over 30% less C than Tlen II during the 2015–2016 observation period. In contrast to existing knowledge, ploughing as done at Tlen I, did not substantially increase CO_2 emission, as compared to local soil ripping (non-conventional technique). The decrease in net C emission, estimated on the basis of linear model parameters, was almost five times greater at Tlen I than at Tlen II. We thus hypothesize that the annual NEP at conventionally reforested windthrow site will reach C neutrality (NEP = 0) six years after windthrow at most, while at the non-conventionally managed area it will probably take ca. 18 years. So far then, the currently widely applied conventional reforestation technique in wind-disturbed Polish forest appeared to be more effective in decreasing C losses than a technique that leaves stumps to decompose and avoids ploughing.

1. Introduction

Together with climate, soil and local site conditions, the net carbon (C) balance of a forest ecosystem over a period of one or more years, depends on the occurrence of natural and anthropogenic disturbances (Buchmann and Schulze, 1999). Damages caused by extreme events (fires, insect outbreaks or meteorological extremes) can result in severe changes in a forest's net C balance (e.g. see Frank et al., 2015; Kurtz et al., 2013). A major source of natural forest damages is wind (Panferov et al., 2009). Even though it is hard to draw an unequivocal conclusion about the frequency pattern of the occurrence of hurricanes, cyclones and tornadoes in the last decade globally, there is evidence of an increasing trend in the number of severe storms in north-eastern Europe (Beniston et al., 2007). Moreover, it is expected that this region will experience not only more frequent, but also more intense wind storms in the future (EASAC, 2013; Leckebusch et al., 2006). Understanding the effects of wind damage on forests is very important because they cover almost 1/3 of the world's land area (FAO, 2016). Consequently, wind damage can significantly influence the C balance at regional or even global scale. Forest stands, which were significant C sinks before being damaged by wind, immediately became C sources after the disturbance (Knohl et al., 2002; Lindauer et al., 2014). During

* Corresponding author.
E-mail addresses: klaudiaziemblinska@up.poznan.pl, klaudiaziem@wp.pl (K. Ziemblińska).

https://doi.org/10.1016/j.agrformet.2018.06.012
Received 3 January 2018; Received in revised form 13 June 2018; Accepted 15 June 2018
0168-1923/

the last 60–65 years, there were at least 130 hurricanes recorded in Europe, which resulted in devastation of forests (Don et al., 2012). The most spectacular example of the destructive force of storm was the cyclone *Lothar*, which knocked down millions of trees all over Europe in 1999. As a result, the net biome production of Europe in that year decreased by as much as 30% (i.e. ca. 16 Gt C, Lindroth et al., 2009). Another important change is the appearance of specific types of extreme wind-origin phenomena in places where they have not been encountered before. In Poland, vast areas of forest were devastated by tornadoes in the last 5 years – the first in the center of the country (July 2012, Trzebciny Forest District, 550 ha damaged) and the second time in southern Poland (July 2017, Rudy Raciborskie Forest District, 1500 ha damaged).

The assessments of the impact of windthrows on ecosystem's C balance remain scarce. This is primarily the case due to the technical and logistical difficulties involved in setting up CO_2 flux measurements in areas following windthrow events, resulting in only few existing measuring stations (Knohl et al., 2002; Schulze et al., 1999). Also, the existing observations were made for only short time periods (e.g., three months during summer- Knohl et al., 2002) or were based on a different sampling approach (soil carbon sampling in Tatra National Park (TANAP), Don et al., 2012). So far, available long-term measurements of CO_2 exchange following windthrow have only been conducted in the National Forest of Bavaria (Lindauer et al., 2014). In that study, CO_2 flux measurements were based on the EC technique and covered a period of five years. Similar to all other studies, a wind-disturbed forest in Bavaria was left to naturally regenerate, while in countries such as Poland, Czech Republic and the United Kingdom, amongst others, reforestation plays a major role in forest restoration following windthrow (Zanchi et al., 2007). The procedure of windthrow reforestation is similar across Europe. In brief, fallen trees including trunks and main branches are removed (as in a clearcut) and then tree seedlings are planted after soil preparation. The subsequent short-term effect of clearcutting on soil CO_2 emissions has been well examined in Europe with highly variable results (Don et al., 2012; Spielvogel et al., 2006). Eight out of ten studies showed no significant increase in soil organic carbon (SOC) losses after the disturbance, while the remaining two indicated the opposite. Pumpanen et al. (2004) further examined the effects of different soil preparation treatments on soil CO_2 efflux values at clearcut site in Finland and found that as much as 75% of the total variation in soil CO_2 emissions resulted from the differences in the soil preparation treatments. However, that study only investigated soil respiration, a single component of the forest C balance (Pumpanen et al., 2004). A quantitative description of forest ecosystem transformation from a C sink to a C source as a result of clearcutting (assuming that this is similar to the effect of windthrow and further management) requires a system-scale and possibly long-term observation approach as done by Fluxnet Canada Team (2016). Continuous EC measurements of CO_2 exchange were conducted above a middle-aged Douglas fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) stand for ten years before and three years after clearcutting the stand (Paul-Limoges et al., 2015). The authors found that during the first year after clearcutting the ecosystem emitted approximately 1000 g C m^{-2} more than it absorbed (i.e., annual net ecosystem production, NEP = -1000 g C m^{-2}). This loss was almost twice as much as the annual average C sequestration before the clearcutting (NEP = 560 g C m^{-2}).

Considering the predicted and already noticeable increasing frequency and intensity of severe storms in Eastern and Central Europe in conjunction with the lack of available in-situ CO_2 flux measurement from disturbed and reforested forests, we used the opportunity of windthrow caused by a tornado that occurred in July 2012 in northwest Poland. We used this tornado event to study the impact of two completely different reforestation techniques that can be used at wind-disturbed forests– (I) conventional: uprooted stumps extracted and ploughing applied before replanting, and (II) non-conventional: all stumps left on the site and shallow soil ripping (5–10 cm depth) before replanting – on the NEP of a Scots pine forest ecosystem with similar meteorological and soil conditions. Our specific objectives were:

1 to investigate the C dynamics of a reforested windthrow area over four years following the tornado,
2 to evaluate which of the two reforestation methods - conventional (I) or non-conventional (II) results in the lowest C losses,
3 to determine how many years it takes for the two differently managed windthrow sites to reach C neutrality, i.e., NEP = 0.

We hypothesized that (1) net C losses from the conventionally restored site would exceed those from the non-conventionally reforested area since soil ploughing would lead to a great CO_2 emission and thus (2) the conventionally reforested windthrow site would reach C neutrality ("zero-C point") later than the non-conventionally reforested site.

2. Material and methods

2.1. Site description

The study sites are located in a recently reforested windthrow area in northwest Poland, in the Trzebciny Forest District (Regional Directorate of State Forests in Toruń). The area is under the management of the State Forests National Forest Holding (SF NFH). In July 2012, ca. 550 ha of Scots pine (*Pinus sylvestris* L.) forest were destroyed in a few minutes as a tornado moved over the area from the southwest to the northeast (Fig. 1). Prior to the tornado, the area comprised homogeneous Scots pine stands. Stand age was on average 76–86 years and stand density ranged from 650 to 680 stems ha^{-1}. Average height and the diameter at breast height of the pine trees were 24 m and 27 cm, respectively. Similar to 80% of Polish forests, the area under investigation was a managed forest and therefore was designated to be reforested after severe damage as that resulting from the tornado. The whole process of conventional windthrow reforestation in Poland (similar to reforestation practices in clearcuts) can be divided into four operations:

A harvesting (trunks and branches removal),
B site clearing (extraction of uprooted stumps),
C soil preparation (mainly ploughing furrows),
D tree seedlings planting.

Eight months after the occurrence of the tornado (March 2013), the first EC flux tower was installed in the windthrow area. Due to the proximity of the village called Tleń it was named "Tlen I" (53°38′5.10″N, 18°15′28.85″E, 110 m a.s.l.). The Tlen I study area covers approximately 17 ha. Measurements carried out at Tlen I included all of the four subsequent steps of conventional reforestation. The second site ("Tlen II") was installed two years after windthrow. Tlen II was very similar to Tlen I– location on level terrain, homogeneity of the former pine stand (tree composition, height, age), and no surviving trees within a few hundred meters in all directions from the flux tower. Additionally, the site was chosen to be as similar as possible to Tlen I concerning local habitat conditions (soil type, stand age and structure before tornado, forest floor vegetation) to minimize the risk that observed differences in CO_2 exchange could be due to site effects. Following visual inspection and soil characterization, Tlen II was established in July 2014 at a distance of 2 km north-east of Tlen I (53°38′37.81″N, 18°17′11.36″E, 106 m a.s.l.). The Tlen II area covers about 15 ha.

Since our observational setup aimed at comparing two different reforestation techniques, two of four steps in conventional reforestation were not included in the reforestation of Tlen II. Namely, all stumps were left to decompose at the site (period B), and the soil preparation before final planting was realized by ripping only small parts of the soil