



Effect of clearcut harvesting on the carbon balance of a Douglas-fir forest



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ABSTRACT

Stand-replacing disturbances, such as harvesting, change former forest net CO₂ sinks into net sources due to significantly reduced photosynthetic uptake and continued respiratory losses. To quantify these effects, this study used data from a Fluxnet-Canada Douglas-fir chronosequence on Vancouver Island, where the most mature site (62-year-old; DF49) was commercially harvested in 2011 creating a 77-ha clearcut (HDF11). Carbon (C) exchange was measured continuously using the eddy-covariance technique for more than a decade pre-harvest and for three years after harvesting. Automated non-steady-state chambers were used to measure soil respiration (R_s) before and after harvesting. The mature stand transitioned from a moderate C sink (net ecosystem productivity (NEP) = 560 g C m⁻² yr⁻¹) before harvesting to a strong C source (NEP = -1000 g C m⁻² yr⁻¹) in the first year after harvesting. Gross ecosystem photosynthesis (GEP) decreased from 1890 g C m⁻² yr⁻¹ before harvesting to 130 g C m⁻² yr⁻¹ in the first year after harvesting, while ecosystem respiration (R_e) decreased by just 15% from 1325 to 1130 g C m⁻² yr⁻¹. This small decrease in R_e suggests that heterotrophic respiration (R_h) increased to partially compensate for a significant reduction in autotrophic respiration (R_a) due to the loss of respiring roots, boles, branches and foliage. The post-harvest C balance results from HDF11 were also compared with those for a previously harvested stand (HDF00) in the same chronosequence. It was harvested in 2000 and was located 3 km away from HDF11. Considerable differences in NEP, GEP and R_e were observed in the two clearcuts for the first two comparison years following harvesting, with HDF11 being a stronger source of C (NEP = -780 and -697 g C m⁻² yr⁻¹) than HDF00 (NEP = -620 and -520 g C m⁻² yr⁻¹). This was mostly due to greater R_e at HDF11 likely due to a greater amount of decomposing organic matter and logging residue. These results show that caution is necessary when drawing conclusions about C fluxes from a single site in an ecozone.

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1. Introduction

Disturbance and succession in terrestrial ecosystems have been of interest to ecologists for more than a century (Clements, 1916). After a disturbance, the functional characteristics of ecosystems including carbon (C) exchange vary with the structural characteristics (Odum, 1969; Sprugel, 1985). The net ecosystem productivity (NEP) of an ecosystem depends on the balance between the amount fixed by photosynthesis or gross ecosystem productivity (GEP)

and the amount released through ecosystem respiration (R_e) (i.e., NEP = GEP - R_e). Stand-replacing disturbances, such as harvesting, have a major impact on the CO₂ exchange between forested land and the atmosphere. After harvesting, former forest net CO₂ sinks become net CO₂ sources due to continued respiratory losses and to significantly reduced photosynthetic uptake. On a global scale, deforestation is responsible for approximately 20% of the rise in atmospheric CO₂ (Denman et al., 2007; Schimel et al., 2001). An accurate quantification of C fluxes following disturbance is therefore important in order to model regional C budgets and improve management strategies to achieve greater C sequestration.

Through the Fluxnet network (Baldocchi et al., 2001), efforts have been made to quantify C dynamics at different stages of succession using chronosequence studies, where current different-aged stands are used to reconstruct the development of

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an older stand, thereby contributing considerable information on the trajectories of NEP following disturbances (often referred to as trading space for time). To date, all studies investigating the influence of a stand-replacing disturbance on the C exchange of a stand have used chronosequences (Amiro, 2001; Anthoni et al., 2002; Chen et al., 2002; Clark et al., 2004; Goulden et al., 2011, 2006; Humphreys et al., 2006; Kolari et al., 2004; Kowalski et al., 2003; Law et al., 2001; Litvak et al., 2003; Mkhabela et al., 2009; Rannik et al., 2002; Schulze et al., 1999; Zha et al., 2009). Chronosequence studies are a useful tool to obtain long-term age-related data in a short period of time. The option of quantifying the effect of a stand-replacing disturbance for a specific stand is often unavailable and would require a much longer period to study ecosystem development, which is often not available with eddy-covariance (EC) measurements (Amiro, 2001). However, at some locations, EC measurements have now been made in different forest stands for more than a decade (Barr et al., 2007; Dunn et al., 2007; Krishnan et al., 2009; Urbanski et al., 2007), providing possible opportunities to study the impact of disturbances at specific sites.

The issue with chronosequence studies is that they rely on the assumption that differences in C fluxes measured at sites with similar characteristics can be linked to age or disturbances, despite other differences including site location, soil texture, soil moisture dynamics and management history. It assumes that all sites differ only in stand age, and have had the same history in their abiotic and biotic components; this main assumption has been shown to be invalid for many chronosequence studies (Howard et al., 2004; Johnson and Miyanishi, 2008; Yanai et al., 2003). A study by Goulden et al. (2011) underlined the large source of uncertainty in chronosequence studies due to landscape heterogeneity. The study was based on a fire chronosequence, and one of the stands showed anomalously low productivity. Later remote sensing analyses showed lower enhanced vegetation indices for this stand when compared to other similarly aged stands (Goulden et al., 2006). Although in this case it was apparent that one of the sites in the sequence was different in more than just age, this type of uncertainty is present in most chronosequence studies.

However, disregarding the findings from chronosequence studies would impede the improvement in our understanding of ecological processes occurring over the long term (Walker et al., 2010). Inferences from chronosequence studies must therefore be validated using a different method of study; unfortunately, this is rarely done and results from chronosequence studies are assumed to hold true without any validation (Johnson and Miyanishi, 2008). Many studies simply justify the use of a chronosequence based on the justification of a similar soil, topography or climate (e.g., Humphreys et al., 2006; Zha et al., 2009) and, although these conditions are necessary, they may not be sufficient.

In addition, due to financial and technical limitations, current Fluxnet studies have usually used only one site to characterize a species-specific stand age after a certain disturbance, without any replication (Amiro, 2001; Anthoni et al., 2002; Chen et al., 2002; Clark et al., 2004; Goulden et al., 2011, 2006; Humphreys et al., 2006; Kolari et al., 2004; Law et al., 2001; Litvak et al., 2003; Mkhabela et al., 2009; Rannik et al., 2002; Schulze et al., 1999; Zha et al., 2009). A particular site might differ from other same-age stands within a certain forest type and replications are needed to account for that. Site-to-site variations can be expected due to the influence and interaction of many factors including climate and site microclimate; soil carbon, nutrients and water dynamics; historical and current management practices; below-ground and above-ground respiration processes; and type and rate of the re-colonizing vegetation (Amiro et al., 2006; Humphreys et al., 2005). Multiple trajectories are therefore possible following stand-replacing disturbances, and the addition of same-age sites

within a certain forest type would help account for the possible spatial and temporal variations (Amiro et al., 2010).

One of these Fluxnet chronosequence studies is located on Vancouver Island, BC, Canada. This chronosequence comprises three Douglas-fir stands. The oldest stand (DF49), which was established in 1949 and nitrogen-fertilized in 1994 and 2007, recently reached harvesting age and was clearcut harvested in January–March 2011, thereby providing a unique and unprecedented opportunity to study the influence of a disturbance at a specific site that has pre-disturbance flux and climate data. The main objectives of this study were (1) to determine NEP, GEP and R_e at the recently harvested site for three years after harvesting, (2) to compare pre- and post-harvest C fluxes at the same site and assess how the ratio of soil to ecosystem respiration changed, and (3) to assess the rate of recovery of the C balance in comparison to a clearcut resulting from harvesting a nearby stand about 10 years earlier.

2. Methods

2.1. Site descriptions

The Douglas-fir harvest chronosequence is located near Campbell River on the east coast of Vancouver Island, BC, Canada. This chronosequence is located in the dry maritime Coastal Western Hemlock biogeoclimatic subzone, with an average annual precipitation of 1500 mm and mean annual temperature of 9.1 °C (Pojar et al., 1991). This subzone experiences a maritime climate with generally cool summers and warm winters (Pojar et al., 1991).

Prior to harvesting in 2011, DF49 (49°52' N, 125°20' W, 300 m.a.s.l.; Table 1) was a dense (1100 stems ha⁻¹) coniferous stand of 62 years-of-age with tree heights varying between 30 and 35 m (Hilker et al., 2010). The leaf area index was 7.3 m² m⁻² (Chen et al., 2006), and the mean tree diameter at breast height was 29 cm (Morgenstern et al., 2004). This 130-ha area was planted in 1949 after the eastern half of the original old-growth stand was logged and slashed-burned in 1937, and the remainder logged and slashed-burned in 1943 (Ferster et al., 2011; Humphreys et al., 2006). DF49 comprised 80% Douglas-fir, 17% western red cedar (*Thuja plicata* Donn), and 3% western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) with only a sparse understory (Humphreys et al., 2006; Morgenstern et al., 2004). Continuous measurements of CO₂, water vapour and energy exchanges at this site started in 1998. Detailed descriptions of EC and climate measurements at DF49 can be found in Humphreys et al. (2003) and Morgenstern et al. (2004). DF49 was fertilized with 200 kg urea-N ha⁻¹ in January 2007. A large section (77 ha) of DF49 was harvested from January to March 2011, and replanted with 1-year-old plug-grown seedlings in April 2011 with 97% Douglas-fir and 3% Sitka spruce (*Picea sitchensis*) at 870 seedlings ha⁻¹. This section of DF49 was subsequently named HDF11. Continuous EC and climate measurements at HDF11 started in April 2011 as part of this study.

This study also makes use of previously published measurements made at a different clearcut harvested site, HDF00 (49°52' N, 125°17' W, 175 m.a.s.l.; Table 1), located 3 km ESE of DF49. HDF00 was clearcut harvested in the winter of 1999/2000 with roadside debris piles burnt, and replanted in March 2000 at a density of 1600 stems ha⁻¹ with 93% Douglas-fir and 7% western red cedar (Humphreys et al., 2006). Prior to harvesting, this 32-ha area was a second growth Douglas-fir stand established in 1940 (Humphreys et al., 2006). Continuous measurements at HDF00 began in September 2000. Detailed descriptions of EC and climate measurements can be found in Humphreys et al. (2005) and Humphreys et al. (2006).

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