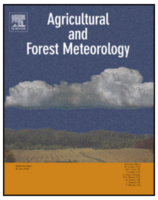
Agricultural and Forest Meteorology 197 (2014) 26–39

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Dynamics of ecosystem carbon balance recovering from a clear-cutting in a cool-temperate forest

Maricar Aguilos[a], Kentaro Takagi[b,*], Naishen Liang[c], Masahito Ueyama[d], Karibu Fukuzawa[b], Mutsumi Nomura[b], Osamu Kishida[b], Tatsuya Fukazawa[e], Hiroyuki Takahashi[b], Chikara Kotsuka[b], Rei Sakai[b], Kinya Ito[b], Yoko Watanabe[b], Yasumi Fujinuma[f], Yoshiyuki Takahashi[c], Takeshi Murayama[g], Nobuko Saigusa[c], Kaichiro Sasa[b]

[a] *Graduate School of Environmental Science, Hokkaido University, Sapporo 060-0809, Japan*
[b] *Field Science Center for Northern Biosphere, Hokkaido University, Sapporo 060-0809, Japan*
[c] *Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba 305-0056, Japan*
[d] *School of Life and Environmental Science, Osaka Prefecture University, Sakai 599-8531, Japan*
[e] *Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan*
[f] *Department of Environmental Management, Tottori University of Environmental Studies, Tottori 689-1111, Japan*
[g] *Research and Development Department, Hokkaido Electric Power Co., Inc., Ebetsu 067-0033, Japan*

ARTICLE INFO

Article history:
Received 30 October 2013
Received in revised form 31 May 2014
Accepted 4 June 2014
Available online 2 July 2014

Keywords:
BIOME-BGC
Carbon budget
Carbon compensation point
Clear-cutting
Forest disturbance
Sasa

ABSTRACT

A mixed forest in northern Japan, which had been a weak carbon sink (net ecosystem CO_2 exchange [NEE] = −0.44 ± 0.5 Mg C ha^{-1} yr^{-1}), was disturbed by clear-cutting in 2003 and was replaced with a hybrid larch (*Larix gmelinii* × *L. kaempferi*) plantation in the same year. To evaluate the impact of the clear-cutting on the ecosystem's carbon budget, we used 10.5 years (2001–2011) of eddy covariance measurements of CO_2 fluxes and the biomass observation for each ecosystem component. BIOME-BGC model was applied to simulate the changes in the carbon fluxes and stocks caused by the clear-cutting. After clear-cutting in 2003, the ecosystem abruptly became a large carbon source. The total CO_2 emission during the first 3 years after the disturbance (2003–2005) was 12.2 ± (0.9–1.5; possible min–max range of the error) Mg C ha^{-1}, yet gradually decreased to 2.5 ± (1–2) Mg C ha^{-1} during the next 4 years. By 2010, the ecosystem had regained its status as a carbon sink (NEE = −0.49 ± 0.5 Mg C ha^{-1} yr^{-1}). Total gross primary production, ecosystem respiration, and NEE during the 7 years after the clear-cutting (2003–2009) were 64.5 ± (2.6–7), 79.2 ± (2.6–7), and 14.7 ± (1.3–3.5) Mg C ha^{-1}, respectively. From 2003 to 2009, the understory *Sasa* biomass increased by 16.3 ± 4.8 Mg C ha^{-1}, whereas the newly planted larch only gained 1.00 ± 0.02 Mg C ha^{-1}. The BIOME-BGC simulated observed carbon fluxes and stocks, although further modification on the parameter set may be needed according with the tree growth and corresponding suppression of *Sasa* growth. Ecosystem carbon budget evaluation and the model simulation suggested that the litter including harvest residues became a large carbon emitter (∼31.9 Mg C ha^{-1}) during the same period. Based on the cumulative NEE during the period when the forest was a net carbon source, we estimate that the ecosystem will require another 8–34 years to fully recover all of the CO_2 that was emitted after the clear-cutting, if off-site carbon storage in forest products is not considered.

---

* Corresponding author at: Teshio Experimental Forest, Field Science Center for Northern Biosphere, Hokkaido University, Toikanbetsu, Horonobe 098-2943, Japan. Tel.: +81 1632 6 5211; fax: +81 1632 6 5003.

E-mail addresses: mmaguilos@yahoo.com (M. Aguilos), kentt@fsc.hokudai.ac.jp (K. Takagi), liang@nies.go.jp (N. Liang), miyabi-flux@muh.biglobe.ne.jp (M. Ueyama), caribu@fsc.hokudai.ac.jp (K. Fukuzawa), nomu@fsc.hokudai.ac.jp (M. Nomura), kishida@fsc.hokudai.ac.jp (O. Kishida), tatsuya@eng.hokudai.ac.jp (T. Fukazawa), frsthiro@fsc.hokudai.ac.jp (H. Takahashi), ckozuka@fsc.hokudai.ac.jp (C. Kotsuka), reisakai@fsc.hokudai.ac.jp (R. Sakai), kinya-i@fsc.hokudai.ac.jp (K. Ito), youko@for.agr.hokudai.ac.jp (Y. Watanabe), fujinuma@kankyo-u.ac.jp (Y. Fujinuma), yoshiyu@nies.go.jp (Y. Takahashi), murayama@epmail.hepco.co.jp (T. Murayama), n.saigusa@nies.go.jp (N. Saigusa), sasa@fsc.hokudai.ac.jp (K. Sasa).

http://dx.doi.org/10.1016/j.agrformet.2014.06.002
0168-1923/

1. Introduction

The anthropogenic land cover change constitutes a source of emissions mainly from the loss of terrestrial biomass, and Houghton (2003) estimated that ca. one-third of the anthropogenic CO_2 emissions over the last 150 years is considered to be the direct consequence of land use changes. Clear-cut harvesting is one of the important type of forest management, and understanding how this form of logging affects a site's carbon balance is critical not only for determining appropriate carbon management scenarios of forests, but also for including such effect into global carbon cycling models to obtain better prediction (Pongratz et al., 2009). However, accurate quantification of wood harvesting effects on the carbon dynamics including harvest residues and belowground carbon dynamics is still lacking (Howard et al., 2004; Noormets et al., 2012).

Clear-cutting removes the commercial stem wood and leaves residues (foliage, twigs, branches, stumps, and roots) on the site. It eliminates canopy photosynthesis and affects autotrophic and heterotrophic respiration both directly and indirectly. As a result, the post-harvest stand is expected to be a net source of carbon for several years after disturbance (Kolari et al., 2004; Amiro et al., 2006; Humphreys et al., 2006; Zha et al., 2009; Grant et al., 2010; Goulden et al., 2011; Noormets et al., 2012). The ecosystem carbon compensation point is the time when stands regain their role as a carbon sink by regenerating after a harvest or a similarly severe disturbance. It is a critical index to characterize the carbon budget of a managed forest (Kowalski et al., 2004). For example, it takes a warm template plantation 3 years (Clark et al., 2004) or boreal forests 7–20 years (Bond-Lamberty et al., 2004; Howard et al., 2004; Kolari et al., 2004; Freeden et al., 2007; Amiro et al., 2010) to recover from carbon source to sink. Another critical index is the payback period before the forest recaptures as much CO_2 as was emitted during the recovery period, however, quantitative evaluation of these indexes based on the long-term observation is still a challenge.

Carbon dynamics of forest ecosystems can be investigated by using the eddy covariance method (Mission et al., 2005; Giasson et al., 2006; Amiro et al., 2010). Previous studies often use sites of different ages in parallel to infer the status of an ecosystem as a function of the time since disturbance (Amiro et al., 2010; Goulden et al., 2011). However, it is difficult to judge whether the sites of different ages are following the same trajectory (Walker et al., 2010). In addition, estimating the total carbon emission during the period when the forest was a net carbon source, which is an important factor that determines the magnitude of a disturbance and the payback period, is difficult when dealing with such chronosequence studies because of the gaps in the CO_2 flux data among the measurements at different stands for several years within the chronosequence.

To obtain a complete series of pre- and post-harvest NEE data until a disturbed ecosystem reached its carbon compensation point (i.e., until it once more became a net carbon sink), we conducted an experimental clear-cutting and plantation establishment study in a cool-temperate mixed forest in northern Japan. Using the eddy covariance method, we started our measurements 1.5 years prior to clear-cutting and continued for 9 years after harvesting to shed light on several doubts that are raised by chronosequence studies. In addition, the BIOME-BGC model (Kimball et al., 1997a,b) was applied to simulate these characteristics and to complement the change in the carbon stocks in the soil and litter compartments. This model is widely applied to many types of terrestrial ecosystems and succeeds in simulating the carbon cycles with substantial information on each parameter values (White et al., 2000; Pietsch et al., 2005). The model has been successfully applied in simulating the disturbance effects on the cycles (Thornton et al., 2002).

Our focus was to determine the carbon budget during the dramatic shifts that occur during the forest transitions from a sink to a source and back again to a sink, total CO_2 emission into the atmosphere during the period when the forest was a net carbon source, and the estimated payback period before the forest recaptures as much CO_2 as was emitted during the recovery period. The results from the first 5 years (2001–2005) of the assessment were reported by Takagi et al. (2009) and revealed the shift of the ecosystem from a carbon sink to a carbon source. In the present paper, we added the subsequent 6 years (2006–2011) data to document the transition from a carbon source to a carbon sink and to discuss the ecosystem carbon compensation caused by clear-cutting.

2. Methods

2.1. Site description and management

The study site lies on a flat terrace inside the Teshio Experimental Forest of Hokkaido University (45°03′ N, 142°06′ E, 66 m a.s.l.). Its soil, mainly a Gleyic Cambisol, has a surface organic horizon that is about 10 cm thick. Prior to clear-cutting, the forest was a naturally regenerated mature forest in the late successional stage and large trees were more than 200 years old (Tsuji et al., 2006), although a blizzard caused a severe tree-fall damage in December 1972. The dominant tree species were *Quercus crispula* Blume, *Betula ermanii* Cham., *Abies sachalinensis* (F. Schmidt) Mast., and *Betula platyphylla* var. *japonica* (Miq.) Hara. Maximum and mean tree heights were 24 and 20 m, respectively. The forest floor was covered with dense evergreen dwarf bamboos (*Sasa senanensis* Rehd. and *Sasa kurilensis* (Rupr.) Makino *et* Shibata). The plant area index (PAI) values for the canopy trees and the *Sasa* bamboos, measured using a LAI-2000 leaf-area meter (Li-Cor, Lincoln, NE, USA), were 3.2 and 4.1 $m^2\,m^{-2}$, respectively, at this parameter's seasonal maximum in 2002 (Fig. 1). From January to March 2003, trees covering an area of 13.7 ha were clear-cut. The total biomass volume of trees at the site was 2193 m^3 (Koike et al., 2001), of which 1203 m^3 (ca. 25 Mg C ha^{-1}) were removed as logs.

Sasa was left intact under the snowpack, but 7 months later, just before the planting of hybrid larch seedlings (in late October 2003), they were strip-cut into alternating 4-m-wide cut and uncut rows in the clear-cut area to give space for the planting of ca 30,000 2-year-old hybrid larch (*Larix gmelinii* (Rupr.) Kuzen. ver *japonica* (Maxim. Ex Regel) Pilg. × *L. kaempferi* (Lamb.) Carrière) at a density of 2500 ha^{-1} (0.04 Mg C ha^{-1}). In the rows where *Sasa* remained, *Sasa* PAI increased steeply from 1 year after clear-cutting until 2007, reaching a peak at 8.0 $m^2\,m^{-2}$ in 2010, which is about double the value in 2002 before clear-cutting. In the rows where *Sasa* was strip-cut, *Sasa* weeding was conducted from once (2005 and 2006) to three times (2004) per year between late May and late July to eliminate all *Sasa* growing between the larch trees. The *Sasa* was no longer weeded starting in 2007 because the larch was higher than the surrounding *Sasa*, and was able to receive enough solar radiation to grow without interference. *Sasa* soon recovered in the strip-cut rows, and in 2008, 2 years after the last weeding, the PAI was almost the same as that in the surrounding uncut rows, blanketing all gaps between the trees. On the other hand, the PAI of the larch remained low (1.7 $m^2\,m^{-2}$ in 2010) at its seasonal maximum, lower than that of *Sasa*.

2.2. The eddy covariance system

A closed-path eddy covariance system was established in August 2001 on a 32-m-tall tower in the mixed forest to evaluate the CO_2 fluxes. A sonic anemometer (DA600-3TV, Kaijo, Tokyo, Japan) and an infrared gas analyzer (IRGA; LI-7000, Li-Cor, Lincoln, NE, USA) were used to evaluate the fluxes. In addition, another closed-path system comprising the same instruments was installed at a height