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Author(s)	TAKAGI, Kentaro; AGUILOS, Maricar; LIANG, Naishen et al.
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Long-term monitoring on the dynamics of ecosystem CO₂ balance recovering from a clear-cut harvesting in a cool-temperate forest

TAKAGI Kentaro¹, AGUILOS Maricar², LIANG Naishen³, TAKAHASHI Yoshiyuki³, SAIGUSA Nobuko³, KOIKE Takayoshi⁴ and SASA Kaichiro¹

¹ Field Science Center for Northern Biosphere, Hokkaido University, Sapporo 060-0809, Japan

² Graduate School of Environmental Science, Hokkaido University, Sapporo 060-0809, Japan

³ Earth System Division, National Institute for Environmental Studies, Tsukuba 305-8506, Japan

⁴ Research Faculty of Agriculture, Hokkaido University, Sapporo 060-8589, Japan

Abstract

Clear-cut harvesting is one of the important types of forest management but is considered to be a large CO₂ source to the atmosphere. Understanding how this form of logging affects a site's CO₂ balance is critical for determining appropriate management scenarios, yet we have little understanding of how wood harvesting affects the ecosystem CO₂ balance. An experimental clear-cutting and plantation establishment study has been conducted in a cool-temperate mixed forest in northern Japan to obtain a complete series of pre- and post-harvest data on the net ecosystem CO₂ exchange (NEE) between the ecosystem and the atmosphere until a disturbed ecosystem once more become a net CO₂ sink in the annual budget and recapture all the emitted CO₂ after the harvest. A mixed forest, which had been a weak CO₂ sink, was disturbed by clear-cutting and was replaced with a hybrid larch (*Larix gmelinii* × *L. kaempferi*) plantation. The ecosystem turned to be a large CO₂ source just after the harvesting in 2003, and the cumulative net CO₂ emission reached up to 15.4 MgC ha⁻¹ at 7 years after the harvesting, then the ecosystem turned to be a CO₂ retrieve mode (CO₂ sink in the annual budget). This ecosystem recaptured all CO₂ emission 18 years after the harvesting in 2020, if off-site carbon storage in forest products is not considered. This implies one harvesting operation cause large invisible and long-lasting effect on the forest ecosystem CO₂ balance.

Key words: carbon balance, clear-cut harvesting, eddy covariance, long-term flux monitoring, net ecosystem exchange of CO₂.

Introduction

Forests are seen as large carbon reservoirs, and precise evaluation of their CO₂ sequestration rate is required for their management and adequate forest protection (Millar *et al.* 2007). Clear-cut harvesting is one of the essential types of forest management but is considered to be a significant source of CO₂ going into the atmosphere (Houghton 2003). Understanding how this form of logging affects the site's CO₂ balance is critical for determining appropriate management scenarios, yet we have little understanding of how wood harvesting affects the CO₂ balance (Howard *et al.* 2004; Noormets *et al.* 2012).

Clear-cut harvesting removes the commercial stem wood, leaves residues, decreases canopy photosynthesis, and affects autotrophic and heterotrophic respiration. As a result, the post-harvest stand is expected to be a net source of CO₂ for several years after the operation (Figure 1) (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 duration and magnitude of the carbon loss depend on the balance between photosynthesis and respiration, and both processes are affected by several environmental and biophysical factors. The CO₂ balance as a function of time since harvest, including the critical compensation point when stands regenerating after a harvest regain

their role as a CO₂ sink, must be understood before it is possible to characterize the carbon budget of a managed forest.

The CO₂ exchange rate between the ecosystem and the atmosphere can be measured using a micro-meteorological eddy covariance method (Baldocchi *et al.* 2001). This can characterize the ecosystem response and recovery following the harvest by measuring the CO₂ fluxes for several years prior to the harvest to provide a baseline and monitor the recovery for years after the harvest.

Long-term flux monitoring

To obtain a complete series of pre- and post-harvest data on the net ecosystem exchange of CO₂ (NEE) until a disturbed ecosystem once more became a net CO₂ sink on an annual basis and recaptured all the emitted CO₂ after the harvest, an experimental clear-cutting and plantation establishment study in a cool-temperate mixed forest in northern Japan was conducted. Using the eddy covariance method, NEE measurements started in 2001, 1.5 years before clear-cutting in 2003, and continued for 18 years after harvesting (Figure 2) (Takagi *et al.* 2009; Aguilos *et al.* 2014). The focus of the study was to determine the CO₂ budget during the dramatic shifts that occur during a forest's transition from a sink to a source and back again to a sink, total

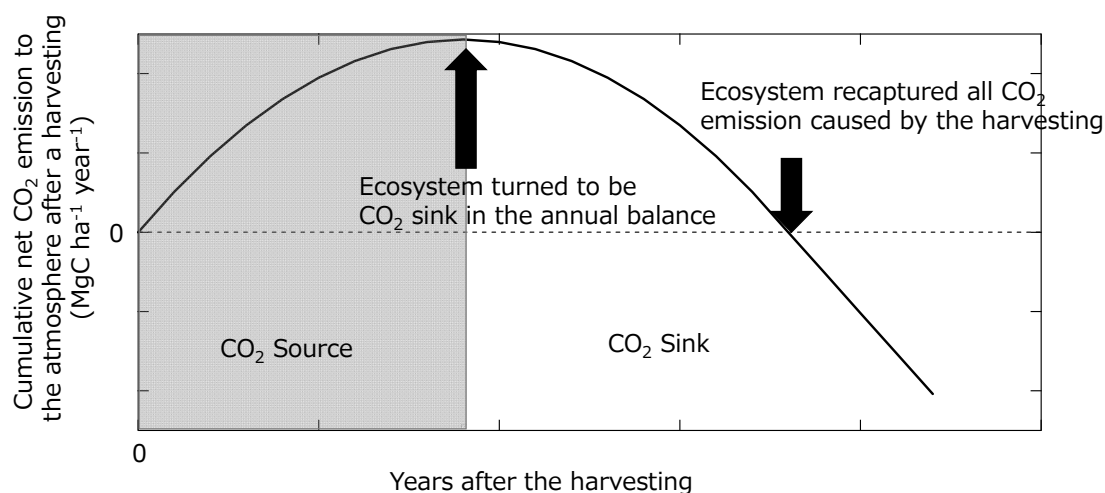


Figure 1. Concept of the forest CO₂ balance after the harvesting

CO₂ emission into the atmosphere during the period when the forest was a net CO₂ source, and the payback period before the forest recaptures as much CO₂ as was emitted during the recovery period.

Dynamics of ecosystem CO₂ balance

A weak CO₂ sink ($NEE = -0.44 \text{ MgC ha}^{-1} \text{ yr}^{-1}$) mixed forest in northern Japan was disturbed by clear-cutting and replaced with a hybrid larch (*Larix gmelinii* × *L. kaempferi*) plantation. The ecosystem turned into a large CO₂ source just after the harvesting in 2003, and the cumulative net CO₂ emission reached up to 15.4 MgC ha⁻¹ seven years after the harvest (Aguilos *et al.* 2014). Then the ecosystem switched to CO₂ retrieve mode (CO₂ sink in the annual budget). Finally, in 2020 this ecosystem recovered all CO₂ emissions 18 years after the harvesting, if off-site carbon storage in forest products is not considered. This implies that one harvesting operation can cause a largely invisible and long-lasting effect on the forest ecosystem's CO₂ balance.

Ecosystem water and light use efficiencies (WUE and LUE, which are determined as ecosystem photosynthesis divided by evapotranspiration and photosynthetically active radiation, respectively) markedly decreased after the harvesting (Okada *et al.* 2019). Then LUE increased with the increase in the leaf area index (LAI) coincident with the vegetation recovery, however the change in LAI had little effect on WUE, because WUE is more sensitive to the atmospheric water deficit than it is to vegetation structure.

Vegetation recovery had significant effect on the temporal variation in soil respiration. Increase of LAI of undergrowth *Sasa* sp. recovering after the harvesting increased the soil respiration (Sun *et al.* 2020). In spite of the strong exponential relationship of soil respiration with soil temperature in their seasonal variation, soil

water and vegetation had strong effect on the inter-annual variation of soil respiration in the recovering young plantation.

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Figure 2. 30-m high CO₂ flux monitoring tower (upper) and sensors (lower)

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