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Long-term monitoring on the dynamics of ecosystem CO_2 balance recovering from a clear-cut harvesting in a cool-temperate forest

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Abstract

Clear-cut harvesting is one of the important types of forest management but is considered to be a large CO_2 source to the atmosphere. Understanding how this form of logging affects a site's CO_2 balance is critical for determining appropriate management scenarios, yet we have little understanding of how wood harvesting affects the ecosystem CO_2 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 CO_2 exchange (NEE) between the ecosystem and the atmosphere until a disturbed ecosystem once more become a net CO_2 sink in the annual budget and recapture all the emitted CO_2 after the harvest. A mixed forest, which had been a weak CO_2 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 CO_2 source just after the harvesting in 2003, and the cumulative net CO_2 emission reached up to 15.4 MgC ha^{-1} at 7 years after the harvesting, then the ecosystem turned to be a CO_2 retrieve mode (CO_2 sink in the annual budget). This ecosystem recaptured all CO_2 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 CO_2 balance.

Key words: carbon balance, clear-cut harvesting, eddy covariance, long-term flux monitoring, net ecosystem exchange of CO_2.

Introduction

Forests are seen as large carbon reservoirs, and precise evaluation of their CO_2 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 CO_2 going into the atmosphere (Houghton 2003). Understanding how this form of logging affects the site's CO_2 balance is critical for determining appropriate management scenarios, yet we have little understanding of how wood harvesting affects the CO_2 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 CO_2 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 CO_2 balance as a function of time since harvest, including the critical compensation point when stands regenerating after a harvest regain their role as a CO_2 sink, must be understood before it is possible to characterize the carbon budget of a managed forest.

The CO_2 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 CO_2 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 CO_2 (NEE) until a disturbed ecosystem once more became a net CO_2 sink on an annual basis and recaptured all the emitted CO_2 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 CO_2 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

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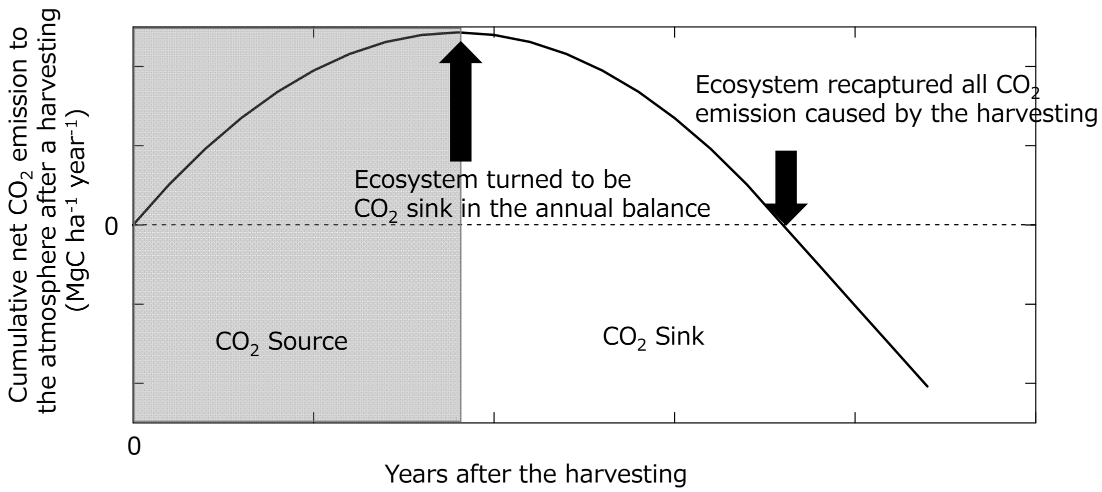

Figure 1. Concept of the forest CO_2 balance after the harvesting

CO_2 emission into the atmosphere during the period when the forest was a net CO_2 source, and the payback period before the forest recaptures as much CO_2 as was emitted during the recovery period.

Dynamics of ecosystem CO_2 balance

A weak CO_2 sink (NEE = –0.44 MgC ha^{-1} 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 CO_2 source just after the harvesting in 2003, and the cumulative net CO_2 emission reached up to 15.4 MgC ha^{-1} seven years after the harvest (Aguilos *et al.* 2014). Then the ecosystem switched to CO_2 retrieve mode (CO_2 sink in the annual budget). Finally, in 2020 this ecosystem recovered all CO_2 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 CO_2 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 CO_2 flux monitoring tower (upper) and sensors (lower)

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