Quick Recovery of Carbon Dioxide Exchanges in a Burned Black Spruce Forest in Interior Alaska

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Abstract

Observations of carbon dioxide (CO2) flux with the eddy covariance technique were conducted at a burned boreal forest site five years after a wildfire and at a mature forest site in Interior Alaska to investigate the effects of wildfire on CO2 exchange in a boreal forest. Both gross primary productivity and ecosystem respiration were lower at the burned site. The lower amount of vegetation explains the lower gross primary productivity and ecosystem respiration at the burned site. The reduced soil organic layer at the burned site further explains the lower respiration. On an annual basis, the five-year-old burned site was a CO2 sink, which indicated earlier recovery of CO2 exchange compared to other burned boreal forests in North America reported in the literature. The quick recovery of net CO2 exchange is associated with constrained heterotrophic respiration, rather than recovery of vegetation. Burn severity can be a key variable in determining CO2 exchange during the early stage of succession after wildfire.

1. Introduction

Wildfire is a major disturbance in boreal forests. It significantly alters carbon exchange and hydrology at the land surface over a decadal timescale during vegetation succession after wildfire. The change of energy fluxes directly affects the local climate and, together with the carbon release, may influence the larger-scale climate. To clarify the variation of energy and carbon exchanges over vegetation succession after wildfire, a considerable amount of research has been conducted in boreal forest chronosequence (e.g., Chambers and Chapin III 2002; Litvak et al. 2003; Welp et al. 2006; Liu and Randerson 2008; Amiro et al. 2010; Goulden et al. 2011). These studies have revealed that carbon dynamics change significantly in the first 20 years after wildfire, and the ecosystem switches from a carbon dioxide (CO2) source to a sink at 10 years on average. However, relatively little is known about how vegetation recovery and related variations of energy, water, and carbon fluxes differ at the early stage of succession, depending on burn severity (Goulden et al. 2011).

To answer these questions, more data should be obtained and compiled for burned areas with different burn severity. We started a flux observation in a severely burned black spruce forest in Interior Alaska in summer 2008. In this article, CO2 flux observed at the burned black spruce forest was compared with that observed at a mature black spruce forest nearby for year 2009 to investigate the effects of wildfire on CO2 exchange in a boreal forest. CO2 exchange at the burned forest was also compared with that at other burned forests in North America to examine what variables determine the difference in CO2 exchange at the early stage of succession.

2. Observation

2.1 Burned forest site

The burned black spruce forest is located in Poker Flat Research Range of the University of Alaska Fairbanks, Interior Alaska. A wildfire started in the middle of June 2004 and continued until early August 2004. We started the flux observation using the eddy covariance technique, with relevant micrometeorological observations, in August 2008 at a severely burned site (65°08’N, 147°26’W, 491 m a.s.l., cited hereafter as the burned site). The remaining soil organic layer was 2 cm deep (Table 1), underlain by sandy silt with gravels. Around the observation mast, almost none of the black spruce survived after the fire, but most of the dead trees remained standing. The fractional area covered with vegetation (Tsuyuzaki et al. 2009) was 26% in August 2005 at a nearby area with similar burn conditions; this increased to 85% in August 2008, four years after the fire. The major vegetation consisted of white birch, trembling aspen, Labrador tea, bog blueberry, sedge, fireweed, and mosses.

2.2 Mature forest site

The mature black spruce forest is located in Fairbanks (64°52’N, 147°51’W, 155 m a.s.l., 35 km from the burned site, cited hereafter as the mature site). The forest is approximately 120 years old (Vogel et al. 2005) with an approximate mean canopy height of 3 m. The canopy is open, and the understory is dominated by Labrador tea, bog cranberry, bog blueberry, tealeaf willow, dwarf birch, and sedges. The ground is almost completely covered with mosses. Leaf area index (LAI) measured with a plant canopy analyzer (LAI-2000, Li-Cor, USA) above the moss surface was typically 2.0 during summer. The soil is silt-loam overlain by an organic layer of 25–45 cm (Heijmans et al. 2004), and it is poorly drained due to the presence of permafrost. The depth of the active layer is 40–50 cm.

2.3 Flux measurement

Fluxes of momentum, sensible heat, water vapor, and CO2 were observed at both sites using a three-dimensional ultrasonic anemometer, a Windmaster (Gill, UK) at the burned site and a CSAT3 (Campbell Scientific, USA) at the mature site, and an open-path infrared gas analyzer, LI-7500 (Li-Cor, USA) at both sites. The observation height was 2.6 m at the burned site and

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Burned</th>
<th>Mature*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth (cm)</td>
<td>Stored carbon (g C m⁻²)</td>
</tr>
<tr>
<td>Oi</td>
<td>0−2</td>
<td>1250</td>
</tr>
<tr>
<td>Oe+Oa</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* A soil core was sampled at a relatively dry point at the mature site.

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6.0 m at the mature site. Micrometeorological variables such as air temperature, photosynthetic photon flux density (PPFD), soil temperature, and soil water content were also observed at both sites. More details are provided in Iwata et al. (2010, 2011) and Ueyama et al. (2006, 2009).

3. Data analysis

3.1 Flux calculation

Fluxes were calculated with the eddy covariance method for each half-hour period. Before the calculation, data spikes were removed (Vickers and Mahrt 1997) and an appropriate coordinate rotation of wind vectors was performed. The calculated fluxes were corrected for high-frequency attenuation due to sensor separation and line averaging (Massman 2000). For water vapor and CO₂ fluxes, a correction proposed by Webb et al. (1980) was applied. The data containing measurement errors related to rain events, those with insufficient turbulence conditions, and those exhibiting non-stationarity were discarded before the analysis.

3.2 Ecosystem parameters and flux partitioning

Ecosystem parameters related to gross primary productivity (GPP) and ecosystem respiration (RE) were obtained for several periods within one year as follows. During nighttime, CO₂ flux is equal to RE, since photosynthesis does not occur. A temperature-dependent respiration equation was fitted to nighttime CO₂ flux to obtain a respiration rate at 0°C ($R_0$). The respiration equation was expressed as,

$$RE = R_0 \exp[\ln(Q_{10})T_a/10],$$

(1)

where $Q_{10}$ is a coefficient for temperature sensitivity of RE and $T_a$ is air temperature. The value of $Q_{10}$ was assumed to be 2 in this study.

To obtain parameters related to GPP, a light-response curve was fitted to GPP,

$$GPP = \frac{\alpha P_{\text{max}} \text{APPFD}}{P_{\text{max}} + \alpha \text{APPFD}},$$

(2)

where $\alpha$ is the ecosystem quantum yield, $P_{\text{max}}$ is the maximum GPP, and APPFD is absorbed PPFD calculated as incident PPFD minus reflected PPFD. $P_{\text{max}}$ is defined as GPP when APPFD → $\infty$, which is not useful to examine for the real ecosystem condition, since $P_{\text{max}}$ can become unreasonably large when APPFD → $\infty$. Instead, we used GPP at APPFD = 1500 µmol m⁻² s⁻¹ ($P_{\text{APPFD = 1500}}$) to describe the ecosystem condition. The equations (1) and (2) were also used to fill gaps of CO₂ flux (Falge et al. 2001).

GPP was calculated as daytime RE minus observed CO₂ flux, where negative CO₂ flux indicates downward transfer. The daytime RE was estimated from the relationship between RE and $T_a$ for nighttime, assuming that the relationship applies for daytime.

4. Results and discussion

4.1 Carbon dioxide flux

GPP and RE showed similar seasonal patterns at the burned site and the mature site (Fig. 1), even though the vegetation structure was different. At the mature site, the understory vegetation largely contributed to ecosystem CO₂ exchange, which resulted in the similar seasonal patterns affected by the snow cover. The seasonal peaks of GPP and RE occurred in July in response to high radiation and high temperature. However, the amplitudes of GPP and RE were different at the two sites; both GPP and RE were smaller at the burned site than those at the mature site. The maximum GPP in mid-summer was 12.8 and 24.5 g CO₂ m⁻² day⁻¹ at the burned site and the mature site, respectively. The maximum RE was 9.2 and 20.0 g CO₂ m⁻² day⁻¹ at the burned site and the mature site, respectively.

Cumulative GPP, RE, and NEE from May through September were, respectively, 1043, 667, and −376 g CO₂ m⁻² for the burned site and 1824, 1346, and −477 g CO₂ m⁻² for the mature site. At the burned site, GPP was smaller than the mature site, but RE was also smaller, which led to a similar cumulative value of NEE at the burned site.

Wildfire significantly affected the CO₂ exchange by altering the amount of vegetation, soil environments, and stored soil carbon. The lower GPP at the burned site is mostly attributable to the lower amount of vegetation after the wildfire. In contrast to GPP, the influence of wildfire on RE may be more complicated. In general, wildfire reduces the amount of vegetation including mosses and the depth of the organic soil layer, leading to lower potential of autotrophic and heterotrophic respiration, respectively. However, the reduced moss layer results in a loss of effective thermal insulation. The soil then becomes warm, which enhances...
was lower for the burned site (Fig. 3b). However, per unit leaf area was actually higher at the burned site. Some fraction of incident PPFD to lower LAI at the burned site. This fraction is probably small for the open mature sites, respectively. LAI for the burned site was assumed to be equal to the fractional vegetation cover (0.85). In the burned site, most of the soil organic layer (Table 1). Although the soil was warmer at the burned site than at the mature site (Fig. 2b), the lower stored carbon in the soil organic layer constrained RE at the burned site.

4.2 Ecosystem parameters

An ecosystem parameter \( R_0 \) is useful to compare RE from different sites, accounting for the difference in thermal environment. The maximum \( R_0 \) was 0.08 and 0.14 g CO\(_2\) m\(^{-2}\) h\(^{-1}\) at the burned and mature sites, respectively (Fig. 3a). This difference may not be as large as expected from the difference in stored carbon in the soil organic layer (Table 1). This may imply that the contribution from autotrophic respiration to ER is also important to explain the difference in \( R_0 \). Thus the lower amounts of both vegetation and soil carbon explain the lower \( R_0 \) at the burned site.

\( P_{APPFD = 1500} \) was lower for the burned site (Fig. 3b). However, \( P_{APPFD = 1500} \) per unit leaf area was actually higher at the burned site: 1.14 g CO\(_2\) m\(^{-2}\) h\(^{-1}\) and 0.78 g CO\(_2\) m\(^{-2}\) h\(^{-1}\) for the burned and mature sites, respectively. LAI for the burned site was assumed to be equal to the fractional vegetation cover (0.85). In the burned site, young deciduous broadleaf trees were dominant, which probably explains the higher \( P_{APPFD = 1500} \) per unit leaf area (Reich et al. 1997). In case of a closed forest canopy, shading of understory leaves by overstory leaves apparently decreases \( P_{APPFD = 1500} \) per unit leaf area. However, this effect is probably small for the open forest canopy of the mature site.

\( \alpha \) was also lower for the burned site (Fig. 3c). This is related to lower LAI at the burned site. Some fraction of incident PPFD was absorbed into the bare ground at the burned site, which also lowered \( \alpha \).

4.3 Comparison with other burned boreal forests

The annual total GPP, RE, and NEE including winter season at the burned site were 1096, 840, and −256 g CO\(_2\) m\(^{-2}\), respectively. Thus the five-year-old burned site was a CO\(_2\) sink. The switch from a CO\(_2\) source to a sink after wildfire seems to have occurred earlier than in most other burned boreal forests reported in chronosequence studies in North America (Table 2). Quick recovery of CO\(_2\) exchange can be associated with quick recovery of vegetation, but the total GPP of our burned site was lower than that for Canadian burned sites of similar age. Total RE was far lower at our burned site than at the Canadian sites. Thus the significantly lower RE is attributable to the earlier switch to a CO\(_2\) sink at our burned site. A site in Delta Junction, Alaska, showed a similar value of RE, but GPP was lower than our burned site due to the younger age of the site. Hence the Delta Junction site was still a CO\(_2\) sink three years after wildfire.

One reason for the lower RE at our burned site is probably the lower stored carbon in the remaining soil organic layer after the wildfire, which results in low heterotrophic respiration. In contrast, at a site in Saskatchewan, stored soil carbon was quite high, which explains the higher RE. A severe wildfire consumes most of the moss and accumulated soil organic layer as well as overstory vegetation, resulting in a thin remaining soil organic layer. Heterotrophic respiration is constrained in the thin organic layer. Thus burn severity can be an important variable in determining whether the burned area at the early stage of succession is a CO\(_2\) source or a sink. The Manitoba site was an exception, which had higher RE regardless of low stored soil carbon. Other factors that enhance heterotrophic respiration, such as soil moisture, might influence CO\(_2\) exchange at the Manitoba site.

The observations in this study were confined to one year; hence the effects of the interannual variability of weather conditions on CO\(_2\) exchange should be considered in the interpretation of observed data. The fire chronosequence data obtained by Amiro et al. (2010) indicate that NEE can vary by about 350 g CO\(_2\) m\(^{-2}\) depending on weather conditions, but no site was an obvious CO\(_2\) sink before 10 years. In addition, drought conditions occurred in 2009 in Interior Alaska, implying that the ecosystem at the burned site could uptake more CO\(_2\) if the weather was favorable for vegetation productivity. Hence it can be concluded that, in terms of CO\(_2\) exchange, our burned site is recovering more quickly than other boreal forests in North America.

5. Concluding remarks

Our observations revealed that the five-year-old burned site was a CO\(_2\) sink. This recovery in terms of net CO\(_2\) exchange seems to be quicker than in burned boreal forests in Canada. At our burned site, the severe fire consumed most of the soil organic layer, and it is probable that heterotrophic respiration was greatly reduced. As a result, the annual ecosystem respiration at our burned site was lower than reported values for other burned boreal forests of similar age in North America. In contrast, gross photosynthesis was relatively similar to other burned forests of similar age. Thus fire severity can be a key variable that influences net ecosystem CO\(_2\) exchange after wildfire. This study suggests that it is important to take burn severity, in addition to vegetation recovery, into account in modeling CO\(_2\) exchange in the burned area at the early stage of succession. Further research should be conducted to clarify the influence of fire severity on CO\(_2\) exchange in burned forests.

Acknowledgments

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Table 2. A comparison with other burned boreal forests in North America reported in the literature.

<table>
<thead>
<tr>
<th>Site</th>
<th>Years after fire</th>
<th>GPP*</th>
<th>RE*</th>
<th>NEE*</th>
<th>LAI</th>
<th>Soil carbon content</th>
<th>Typical summertime SWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pokur Flat, Alaska (this study)</td>
<td>5</td>
<td>1096</td>
<td>840</td>
<td>−256</td>
<td>0.85 (fractional cover)</td>
<td>1250^1</td>
<td>0.2 (0–30 cm)</td>
</tr>
<tr>
<td>Delta Junction, Alaska</td>
<td>1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>1831^1</td>
</tr>
<tr>
<td>(Welp et al. 2006; Neff et al. 2005; Liu et al. 2005)</td>
<td>3</td>
<td>708</td>
<td>858</td>
<td>150</td>
<td>1.1 (MODIS)</td>
<td>−</td>
<td>0.2 (0–4 cm)</td>
</tr>
<tr>
<td>Manitoba, Canada (Goulden et al. 2011)</td>
<td>1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>0.3 (harvest and allometry)</td>
<td>2985^1</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1404</td>
<td>1632</td>
<td>228</td>
<td>2.1 (harvest and allometry)</td>
<td>1006^1</td>
<td>−</td>
</tr>
<tr>
<td>Saskatchewan, Canada</td>
<td>(Amiro et al. 2006; Mkhabela et al. 2009)</td>
<td>3</td>
<td>−</td>
<td>484</td>
<td>1.0 (unspecified)</td>
<td>−</td>
<td>0.2 (0–30 cm)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>−</td>
<td>−</td>
<td>319</td>
<td>−</td>
<td>−</td>
<td>0.2 (0–30 cm)</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1423</td>
<td>1412</td>
<td>−11</td>
<td>1.3 (unspecified)</td>
<td>2740^1</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1672</td>
<td>1830</td>
<td>158</td>
<td>−</td>
<td>−</td>
<td>0.2 (0–30 cm)</td>
</tr>
</tbody>
</table>

* Unit: g CO2 m2 y−1.
1 Unit: g C m−2.
2 Moderately and highly decomposed layers.
3 Slightly and moderately decomposed organic layer, and interface of the humic horizon and the A horizon.
4 Dead moss, leaf litter, fine debris, and partially decomposed organic material above the mineral soil.
5 Litter, fermentation, and humus layer (top forest floor organic layer).

References


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SOLA: http://www.jstage.jst.go.jp/browse/sola