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Forest Ecology and Management 498 (2021) 119520

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Effects of clearcutting and girdling on soil respiration and fluxes of dissolved organic carbon and nitrogen in a Japanese cedar plantation

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ARTICLE INFO

Keywords:
Dissolved organic matter
Mineralization
Nitrification
Soil organic matter
Soil respiration, *Cryptomeria japonica*

ABSTRACT

Impacts of forest management practices on soil carbon (C) and nitrogen (N) dynamics remain under debate due to complex interactions between belowground biogeochemical processes. To optimize practices that minimize soil C and N losses, we investigated the effects of management practices on soil C and N fluxes, including the leaching of dissolved organic C (DOC) and N, by comparing clearcutting, stem girdling (removal of the bark and phloem tissue), and control treatments in a Japanese cedar plantation. Canopy opening by clearcutting is hypothesized to have a greater effect on soil C loss and the leaching of nitrate-N relative to girdling. Results showed that clearcutting increased soil heterotrophic respiration (organic matter decomposition) and lead to a loss of soil organic C (2.9–3.7 Mg C ha^{-1} yr^{-1}). Higher litter inputs from girdled tree dieback caused an increase in DOC fluxes from the organic horizon, whereas the loss of fresh litter inputs decreased DOC fluxes from the organic horizon following clearcutting. Clearcutting increased nitrate-N leaching by 3.3–4.8 kg N ha^{-1} yr^{-1} due to the loss of plant N uptake and the increased mineralization of soil organic matter, but high C/N ratios in dissolved organic matter limited nitrate leaching in the girdled treatment. Effects of forest management practices on soil C loss and nitrate leaching loss could be variable, but the slash application in clearcutting and the slow dieback in stem girdling could mitigate soil C loss and nitrate leaching loss.

1. Introduction

Forest soils plays roles in carbon (C) sequestration and nitrogen (N) cycling (Berthrong et al., 2009; Bowd et al., 2019), but forest management practices hugely impact soil C and N dynamics (Johnson, 1992; Johnson and Curtis, 2001; Bowd et al., 2019). Forest disturbance resulting from clearcutting and timber harvesting is widely known to accelerate the loss of soil organic matter (SOM) and nutrients (Berthrong et al., 2009; Bowd et al., 2019). However, the magnitude of these processes may vary among sites, and the impacts of management practices on soil C and N dynamics are inconsistent in the literature (Chantigny, 2003; Jandl et al., 2007; Jerabkova et al., 2011; James et al., 2021). Key processes and factors regulating soil C and N fluxes under different forest management practices need to be assessed to minimize C and nutrient losses by disturbances.

Clearcutting typically increases the net mineralization of SOM and leaching of N due to increased soil microbial activity (Burns and Murdoch, 2005; Bowd et al., 2019). The considerable amounts of soil C loss and N leaching have been reported for the clearcut beech forests, where a combination of clearcutting and herbicide application increased the net mineralization of SOM and nitrification in the absence of N uptake by plants (Likens et al., 1970; Dahlgren and Driscoll, 1994). However, the effects of forest management practices on soil C and N dynamics vary depending on climate, vegetation, disturbance intensity, and soil type (Johnson et al., 1991; Knight et al., 1991; Tutua et al., 2019; James et al., 2021). In the Kii Peninsula, Japan, plantations of Japanese cedar (*Cryptomeria japonica*) are subject to heavy rainfall (2000–4000 mm yr^{-1}) and a warm temperate climate, which may increase the risk for soil C loss and N leaching when forests are disturbed by harvesting.

In Japan, stem girdling as well as common clearcutting practice has been introduced for labor-saving thinning or low-impact conversion of the unmanaged cedar plantations to broadleaved forests. However, the impacts of two management practices have rarely been quantified.

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https://doi.org/10.1016/j.foreco.2021.119520
Received 10 May 2021; Received in revised form 4 July 2021; Accepted 7 July 2021
Available online 24 July 2021

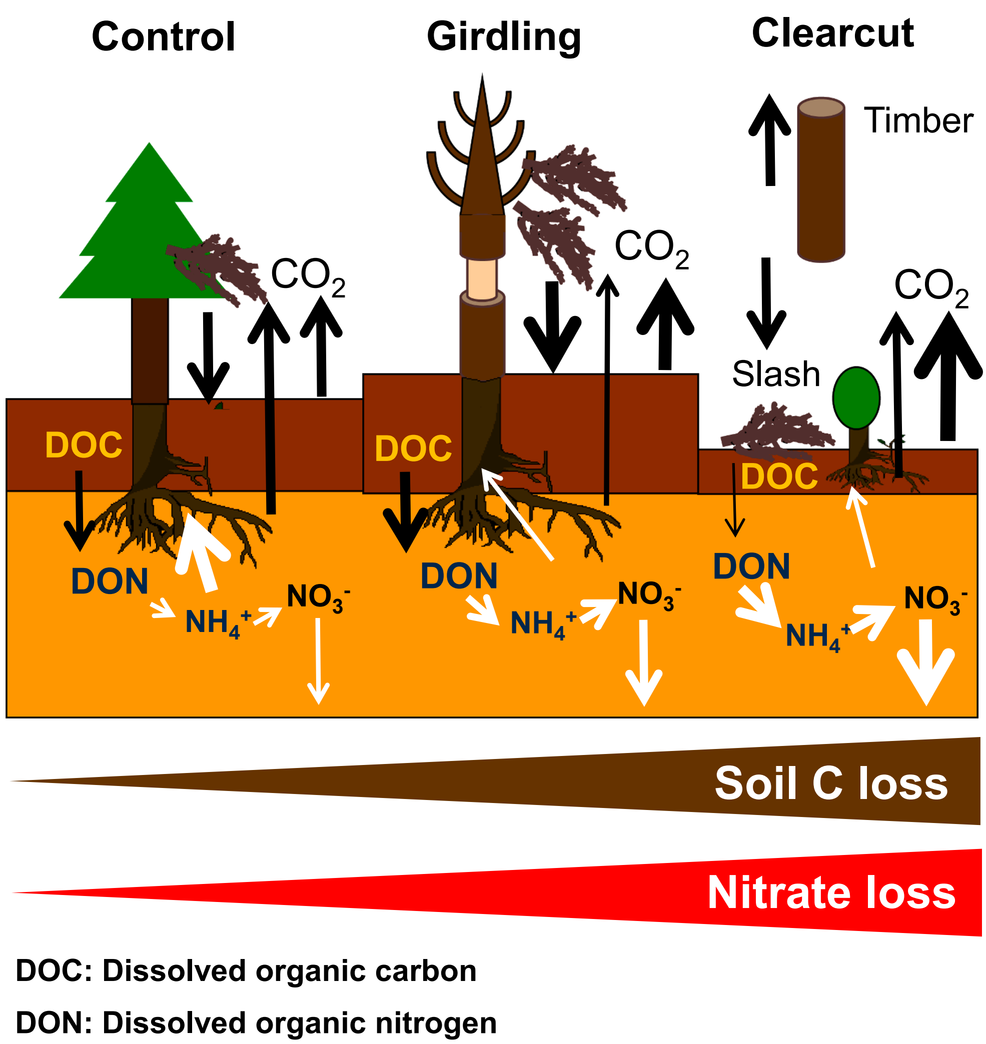

Fig. 1. Hypothetical diagram of soil carbon and nitrogen dynamics under different forest management practices. DON represents dissolved organic nitrogen. In the control plot, C input via litterfall is balanced with soil heterotrophic respiration. Mineralized N is taken up by plants. In the girdling plot, dead organic matter is supplied. Root respiration and N uptake is limited by removal of phloem tissue. In the clearcut plot, soil heterotrophic respiration increases net mineralization of organic N and nitrification.

Harvesting practices, including thinning and clearcutting, affect soil C and N dynamics directly and indirectly (Vitousek and Melillo, 1979; Nieminen et al., 2017). Clearcutting removes tree biomass and litter input from the ecosystem, whereas girdling, which kills trees by removing bark and phloem tissue, reduces the transfer of photosynthetic C to the belowground environment (Fig. 1; Högberg and Högberg, 2002). These direct changes in C and N inputs, as well as indirect changes associated with soil warming, can stimulate microbial activity and thus affect SOM mineralization and nitrification (Johnson et al., 1995; Piirainen et al., 2002; Fukushima et al., 2011).

Changes in soil C fluxes occur as leaching of dissolved organic matter (DOM) as well as CO_2 flux related to soil heterotrophic respiration (Qualls et al., 2000). The downward flux of dissolved organic C (DOC) is generally small relative to the CO_2-C flux associated with heterotrophic soil respiration (Michalzik et al., 2001), but DOC flux account for a major significant proportion of soil C balance (Nakhavali et al. 2020). Clearcutting may increase DOC fluxes due to the increased organic matter decomposition (Qualls et al., 2000; Piirainen et al., 2002; Nieminen et al., 2017), while stem girdling decreases DOC fluxes due to the loss of root exudates (Högberg and Högberg, 2002; Giesler et al., 2007).

Table 1
Mean physicochemical properties of the cedar plantation soil studied.

Horizon	Depth	pH[a]		Total C[b]	Total N[b]	C/N	Particle size distribution[c]			Soil hydrological parameter[d]			
							Clay	Silt	Sand	K_s	θ_s	θ_r	n
	(cm)	H_2O	KCl	(g kg^{-1})				(%)		(cm day^{-1})	(L L^{-1})		
O	+4–0	4.7	3.6	462.0	10.0	46.4							
A	0–5	4.4	3.8	89.2	4.1	21.9	19	16	64	–	0.54	0.19	1.27
Bw	5–30	4.4	3.9	24.1	1.5	16.3	28	19	54	259	0.58	0.26	1.19
BC	30–45	4.5	3.6	5.5	0.8	7.3	33	21	46	–	–	–	–
C	45–60+	4.6	3.6	4.2	0.6	6.5	26	19	54	–	–	–	–

[a] Soil pH was measured using a soil to solution (H_2O or 1 M KCl) ratio of 1:5 after shaking for 1 h.
[b] Oven dry basis. Soil C and N concentrations were determined using a CN analyzer (Vario Max CN, Elementar Analysensystem GmbH).
[c] Clay (<0.002 mm); Silt (0.002–0.05 mm); Sand (0.05–2 mm).
[d] K_s represents saturated hydraulic conductivity. θ_s and θ_r represent saturated and residual water contents in soil, respectively. n represents fitting parameter of water retention curves.

The DOM pool, which includes DOC and dissolved organic N (DON), affects N leaching as well as CO_2 production (Fujii et al., 2010). Forest management practices could change substrate C and N ratios (DOC/DON) (Yang et al., 2021) and affect microbial N immobilization and mineralization and thus soil C and N fluxes (Schimel and Weintraub, 2003; Fukushima et al., 2011).

The canopy opening by clearcutting is hypothesized to have a greater effect on the rate of net mineralization of SOM and the downward flux of nitrate-N relative to girdling. To test this hypothesis, we investigated the effects of clearcutting and girdling treatments on soil C and N fluxes with particular consideration to DOC and nitrate-N fluxes. Then, we also compared our results to those from the literature to analyze the factors regulating these fluxes under different forest management practices.

2. Materials and methods

2.1. Study design

Our study was conducted in a Japanese cedar plantation in Hongu, Wakayama Prefecture, Japan (N33°50′03.38," W135°47′04.39; 175 m a. s. L.). The stand characteristics (average age of the cedar plantation, tree height, and stand density) were 50 years old, 15.6 m, and 1400 trees ha^{-1}, respectively. The understory plants were shrub (*Camellia japonica* L.) and ferns (*Dryopteris sparsa* L.). The mean annual air temperature and annual precipitation were 15.3 °C and 2876 mm yr^{-1}, respectively. The soils of the study area are located on steep slopes (20°) and are derived from sedimentary rocks. Soils were classified as Typic Dystrudepts (Table 1; Soil Survey Staff, 2014). Clay contents increased with depth from the A horizon to the BC horizon, but most of the soil C and N distributed within the upper mineral soil (0–30 cm) in the profile (Table 1). The 30 cm depth (the boundary between B and BC horizons) corresponded to the bottom of rooting zone, as discussed later. In May 2005, we established 30 × 30 m plots with three treatments: clearcut, girdling, and an unharvested control. Timber and major logging residue were removed, but 2.9 Mg C ha^{-1} of slash (twigs and leaves) were left on the clearcut plot. Girdling caused slow tree dieback and the canopy was not open within the first year of the treatment, but all trees had died at the end of the second year. We monitored soil CO_2, DOC, and dissolved inorganic nitrogen (DIN; NH_4^+-N $+NO_3^-$-N) fluxes for 2 years following plot establishment.

2.2. Sample collection

Aboveground biomass was estimated using stem diameter at breast height, measured during an annual census, to regression equations provided in Shidei and Kira (1977). Circular litter traps of 60 cm in diameter were used to collect litterfall once per month in five replicates per each plot. Plant samples were oven-dried at 70 °C for 48 h, weighed, and milled. Then, C and N concentrations were determined using a CN analyzer (Vario Max CN, Elementar Analysensystem GmbH).

2.3. Soil and root respiration and soil heterotrophic respiration

Soil respiration rates were measured in five replicates once per month on each plot using the closed-chamber method, wherein collars with a diameter of 15 cm and a height of 15 cm were inserted just below the soil surface. Soil heterotrophic respiration rates were estimated using a trenching-root exclusion technique (Shinjo et al., 2006) in trenched plots, wherein collars with a diameter of 15 cm and a height of 40 cm were installed into the soil to a depth of 20 cm, severing the live roots that extended into the collars. After the tops of the collars were closed by plastic plates with gas-tight rubber, gases in collar headspaces were sampled 0, 10, 20, and 40 min, and were analyzed using an infrared CO_2 controller (ZFP9, Fuji Electric Instruments Co., Ltd., Tokyo, Japan). CO_2-C flux was calculated as the increase in CO_2 concentration in the headspace of the collars during the sampling period. Root respiration rates were calculated as the difference between the CO_2-C fluxes in the control and trenched plots. To analyze potential temperature or moisture dependency of CO_2-C fluxes, we examined a modified Arrhenius relationship between measured CO_2-C fluxes and the soil temperature and volumetric water content, expressed as:

$$F = A \times exp\left(-\frac{a}{RT}\right) \times \theta^{b} \tag{1}$$

where F (μg C m^{-2} s^{-1}) is the CO_2-C flux, A is a constant, T (K) is the absolute soil temperature, a (J mol^{-1}) is the activation energy, R (8.31 J mol^{-1} K^{-1}) is the gas constant, θ (L L^{-1}) is the volumetric water content in soil, and b is a coefficient. The equation can be rewritten in logarithmic form as:

$$lnF = -\frac{a}{RT} + b \times ln\theta + c \tag{2}$$

where c is ln A. The coefficients a, b, and c were determined from a stepwise multiple regression ($p = 0.05$) of F, T, and θ, using Sigma Plot software v. 14.5 (SPSS Inc., Tokyo, Japan). After determining coefficients from the regression equation, CO_2-C fluxes were simulated for a given period (i.e., 1 year) using the coefficients and data for T and θ. Similarly, the annual rates of soil heterotrophic respiration were calculated by summing the simulated rates of CO_2-C fluxes over 1 year.

2.4. Dissolved organic C and N fluxes in precipitation, throughfall, and soil solutions

Soil solutions were collected in each plot using a tension-free lysimeter beneath the O, A, and B horizons (depths of 0, 5, and 30 cm) in five replicates for the three treatment plots, respectively. The lysimeters were installed horizontally into small soil pits by inserting the plates (area of 200 cm^2) into precut openings and connecting the plates to collection bottles via tubing. Precipitation (clearcut plot) and throughfall (girdling and control plots) were collected using precipitation collectors, respectively. Samples were collected once or twice per month for one year in all the plots. To inhibit degradation of soil solution, $CuBr_2$ solution (0.05–0.10 mg L^{-1} Cu) was added in the collection bottles as a preservative. The bactericidal effects of this level of Cu ion were confirmed (Fujii et al., 2009). Sample solutions were filtered through a 0.45 μm filter (polypropylene, Whatman) and stored at 1 °C in the dark prior to analyses. The pH of the soil solution was determined with a glass electrode (HORIBA) and the concentrations of DOC and TDN were determined using a total organic C analyzer (TOC-V_{CSH}, Shimadzu, Kyoto, Japan). The concentrations of NH_4^+ and NO_3^- in the solution were determined by high performance liquid chromatography (HPLC; ion chromatograph HIC-6A, Shimadzu; shim-pack IC-C3 for NH_4^+, shim-pack IC-A1 for NO_3^-, conductivity detector CDD-6A). The concentration of DON was calculated by subtracting NH_4^+ and NO_3^- from the TDN concentration (DON = TDN – NH_4^+-N –NO_3^--N).

In tension-free lysimeter, soil water can be collected when soil on the plate is tentatively saturated by water. However, soil water potentials on the plate are higher than those of the adjacent drier soil region without the plate. This generates water flow out of plates along the gradient of water potentials and underestimates downward fluxes of soil water captured by collection bottles (Kosugi and Katsuyama, 2004). Thus, the fluxes of DOC, DON, NH_4^+ and NO_3^- from each soil horizon were calculated for each month by multiplying the estimated water flux by the concentrations of DOC, DON, NH_4^+, and NO_3^- in precipitation, throughfall, and the soil solutions. Water fluxes of precipitation and throughfall were measured using the precipitation collector with a 20-cm diameter funnel, while the half-hourly fluxes of soil water percolation were estimated by applying Darcy's law to the unsaturated hydraulic conductivity and the gradient of hydraulic heads at each depth. The one dimensional, vertical flow equation (Richards' equation) in the unsaturated soil zone is expressed as;

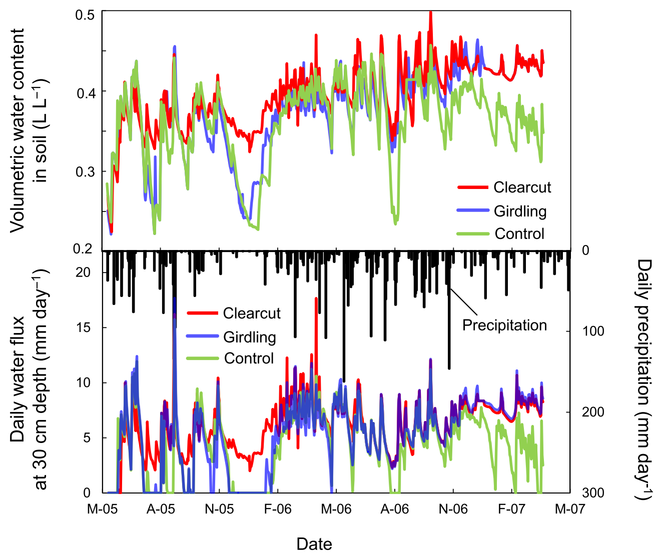

Fig. 2. Seasonal fluctuation of volumetric water content in the soil and the daily fluxes of precipitation and percolating water in soil at 30 cm depth in clearcut, girdling, and control plots.

$$C(h)\frac{\delta h}{\delta t} = \frac{\delta}{\delta z}\left[K(h)\left(\frac{\delta h}{\delta z}+1\right)\right] - S(h) \tag{3}$$

where C (m^{-1}) is the differential water capacity, t (day) is the time, Z (m) is the height, h (m) is the soil water pressure head, K (m day^{-1}) is the unsaturated hydraulic conductivity, and S (day^{-1}) is the sink term accounting for water uptake by plants and lateral water flow. The unsaturated hydraulic conductivity characteristic, described by Mualem-Van Genuchten functions (Mualem and Dagan, 1978; Van Genuchten, 1980), is expressed as:

$$K = K_s \times S_e^{0.5} \times \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{4}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (-\alpha h)^n\right]^{-m} \tag{5}$$

where S_e is the effective saturation, K_s (m day^{-1}) is the saturated hydraulic conductivity, θ_s (LL^{-1}) and θ_r (LL^{-1}) are the saturated and residual water contents, respectively, n is a fitting parameter, and $m = 1–1/n$. K_s and water retention curves were obtained experimentally for undisturbed soils sampled using 0.1 L cores. Based on the water retention curve, pressure head values were calculated from volumetric soil water content, monitored every 30 min with TDR sensors (CS615, Campbell Scientific) and data loggers (CR 10X, Campbell Scientific). The Mualem-Van Genuchten parameters were optimized and adjusted using Sigma Plot software v. 14.5 (SPSS Inc., Tokyo, Japan) to meet the water budget in the clearcut plot according to Klinge (2001). The daily water

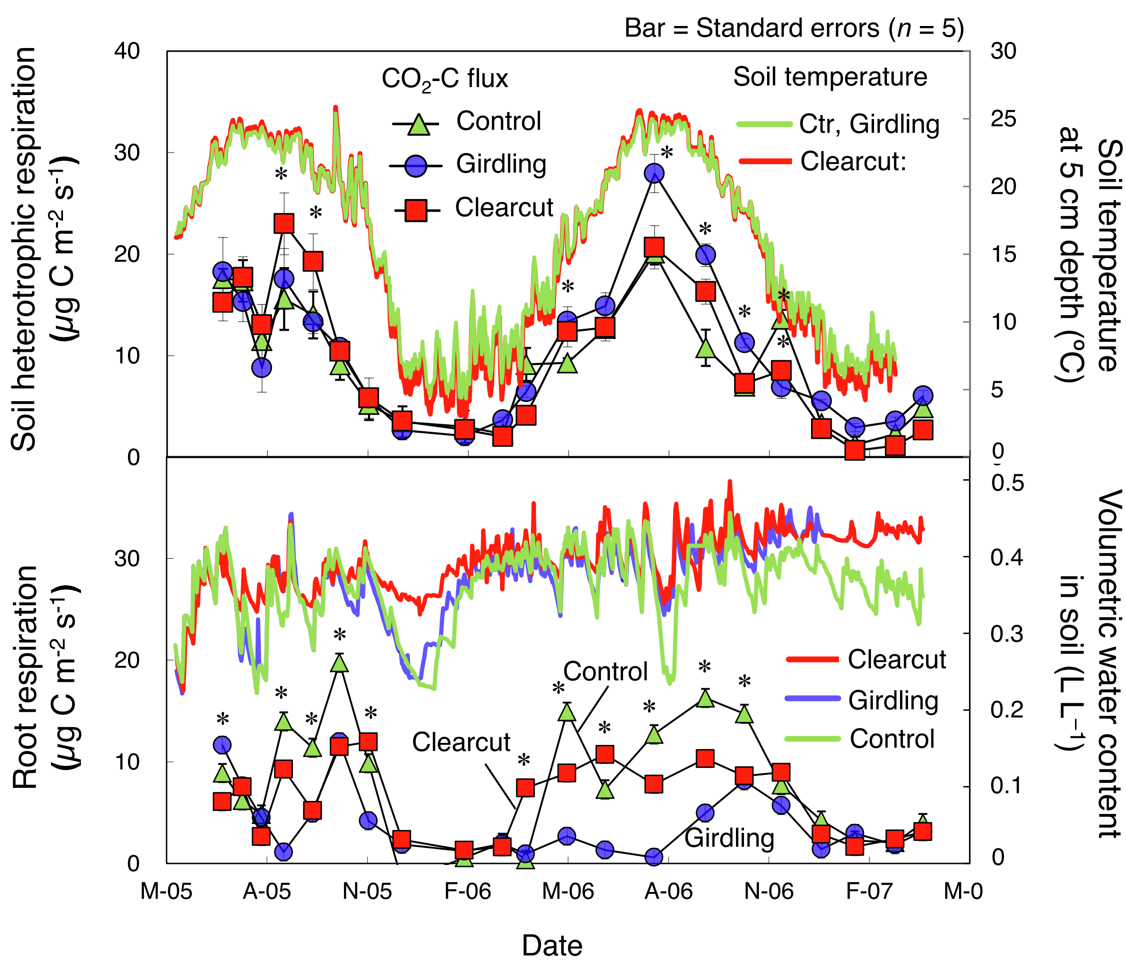

Fig. 3. Fluctuation in C flux of soil heterotrophic respiration and soil temperature (a) and C flux of root respiration and volumetric water content in soil at clearcut, girdling, and control plots (b). Bars indicate standard errors ($N = 5$).

Table 2
Parameters estimated by stepwise multiple regression to analyze temperature or moisture dependency of the CO_2 emission rates.

Plot	Fraction	*a*	*b*	*c*	*n*	R^2
Control	Soil respiration	651.8	0.8	30.8	21	0.92
	Soil heterotrophic respiration	783.3	1.1	36.3	21	0.92
Girdling	Soil respiration	782.7	1.3	37.0	21	0.94
	Soil heterotrophic respiration	723.4	–	32.6	21	0.93
Clearcut	Soil respiration	651.7	–	30.2	21	0.94
	Soil heterotrophic respiration	940.6	–	41.8	21	0.93

In the regression equation ($\ln F = -a/RT + b \times \ln\Theta + c$), F (μg C m^{-2} s^{-1}) is the CO_2-C fluxes, T (K) is the absolute soil temperature, *a* (J mol^{-1}) is the activation energy, R (8.31 J mol^{-1} K^{-1}) is the gas constant, and Θ (L L^{-1}) is the volumetric water content in soil, and *b* and *c* are coefficients.

fluxes at a depth of 30 cm (q_B) were estimated using the parameters of Mualem-Van Genuchten functions and the measured volumetric soil water content (Fig. 2). Monthly water fluxes were calculated by summing the half-hourly water fluxes. The water fluxes from the O and A horizons were calculated as the distributing water deficit (PT – q_B), depending on fine root distribution. Monthly ion fluxes were calculated by multiplying the water fluxes by the measured ionic concentrations in the throughfall and soil solutions for each month.

2.5. Statistical analyses

All results were expressed as mean ± standard error (SE). The Tukey's test was used to detect statistically significant differences between groups (soil horizons or treatments) at each sampling date. The effects of treatment and sampling time were assessed using repeated-measures analysis of variance (RM-ANOVA) for soil respiration rates and DOC, DON, and DIN concentrations. Pearson's linear correlation was used to assess the relationships between DOC and DON concentrations and between DOC flux and soil heterotrophic respiration rates. The differences in linear regression slopes of DOC flux related to soil heterotrophic respiration rates were tested using analysis of covariance between treatments. Statistical analyses were performed with Sigma Plot software v. 14.5 (SPSS Inc., Tokyo, Japan). In all cases, $P < 0.05$ was considered significant.

3. Results

3.1. Soil respiration carbon flux

The annual mean soil temperature increased by 0.4 °C in the clearcut plot, but no difference was found between the control plot and the girdling plot (Fig. 2). The temporal variation in soil heterotrophic respiration and root respiration rates in each treatment (Fig. 3) exhibited the significant ($P < 0.05$) interaction effect of treatments and sampling dates. Using multiple regression of soil respiration and soil heterotrophic respiration rates in Eq. (2), both soil respiration and soil heterotrophic respiration rates was expressed as a function of soil temperature and/or moisture (Table 2; Fig. 3). The annual C fluxes of soil heterotrophic respiration were the highest at the clearcut plot in the first year, among all plots (Table 3). In the clearcut plot, the annual C flux of soil heterotrophic respiration in the second year with no litter inputs was significantly ($P < 0.05$) lower than in the first year (Table 3). In the girdling plot, soil heterotrophic respiration rates in the second year were significantly ($P < 0.05$) higher than in the first year (Table 3; Fig. 3). The annual C flux of root respiration in the girdling plot was significantly ($P < 0.05$) lower, compared to the control and clearcut plot (Table 3). Soil C budgets indicated a loss in soil C in the clearcut plot, whereas C input and decomposition were nearly balanced in the control and girdling plots (Table 3).

3.2. Seasonal fluctuations in dissolved organic C and dissolved N in the soil solutions

There were the significant ($P < 0.05$) interaction effects of treatments and sampling dates for DOC, DON, DIN concentrations (Fig. 4). The DOC concentrations in the O and A horizon solutions collected in summer were significantly ($P < 0.05$) higher than in the B horizons in all plots (Fig. 4). Owing to a positive correlation between DOC and DON concentrations, DON generally followed the seasonal fluctuation pattern of DOC (Fig. 4). DOC/DON ratios in the A and B horizon solutions of the clearcut plot (7–17) were significantly ($P < 0.05$) lower than those of the control and girdling plots (10–34; Table 4). In all treatments, the DOC and DON concentrations decreased with soil profile depth (Table 4). By contrast, DIN (ammonium-N + nitrate-N) concentrations in the A or B horizons were significantly ($P < 0.05$) lower than those of the O horizon

Table 3
Stock and flux of carbon in soils at clearcut, girdling, and control plots.

Treatment		Control		Girdling		Clearcut	
C flux (Mg C ha^{-1} yr^{-1})		1st year	2nd year	1st year	2nd year	1st year	2nd year
Soil respiration		5.3 ± 0.1	5.8 ± 0.1	4.4 ± 0.1	4.3 ± 0.1	5.3 ± 0.1	5.2 ± 0.1
Root respiration[a]		2.3 ± 0.1 A	2.9 ± 0.1 a*	1.4 ± 0.1 B	0.9 ± 0.1 c*	1.6 ± 0.1 B	2.3 ± 0.1 b*
Soil heterotrophic respiration[a]	(a)	3.0 ± 0.1 B	2.9 ± 0.1 b	3.0 ± 0.1 B	3.4 ± 0.1 a*	3.7 ± 0.1 A*	2.9 ± 0.1 b
Litterfall	(b)	2.0 ± 0.5	1.9 ± 0.5	2.8 ± 0.1	3.1 ± 0.1	0.0	0.0
Root litter[b]	(c)	1.6	1.6				
C budget[c]	(d)	0.6 ± 0.5	0.6 ± 0.5	–0.2 ± 0.1	–0.3 ± 0.1	–3.7 ± 0.1	–2.9 ± 0.1
C stock (Mg C ha^{-1})							
Slash						2.9 ± 0.9	
Aboveground biomass		127 ± 22	131 ± 22	127 ± 22			
Fine root biomass	Total	5.6 ± 1.2		2.3 ± 0.5		1.9 ± 0.3	
	O horizon	1.6 ± 0.5		0.9 ± 0.1		0.8 ± 0.3	
	A horizon[d]	1.6 ± 0.5		0.8 ± 0.4		0.8 ± 0.1	
	B horizon[d]	2.5 ± 0.9		0.6 ± 0.2		0.3 ± 0.1	
Soil C stock	Total	64.1 ± 5.8		64.1 ± 5.8		64.1 ± 5.8	
	O horizon	3.8 ± 0.7		3.8 ± 0.7		3.8 ± 0.7	
	Mineral soil[d]	60.3 ± 5.8		60.3 ± 5.8		60.3 ± 5.8	

The results are the means ± standard errors of five replicates.
[a] The different uppercase letters (A, B) and lowercase letters (a, b) mean that mean values are significantly different ($P < 0.05$) between treatments in the first and second year, respectively. Asterisks (*) indicate a significant ($P < 0.05$) difference between the first and second years in each treatment plot.
[b] C input was calculated as the sum of litterfall and root litter (b = c + d). Root litter inputs were cited from Noguchi et al. (2007).
[c] C budget in soil was calculated as the difference between soil heterotrophic respiration and C input (e = b - a).
[d] The A horizon (0–5 cm), B horizon (5–30 cm), and the mineral soil (0–30 cm). Aboveground biomass and soil C stock was quantified before treatments.

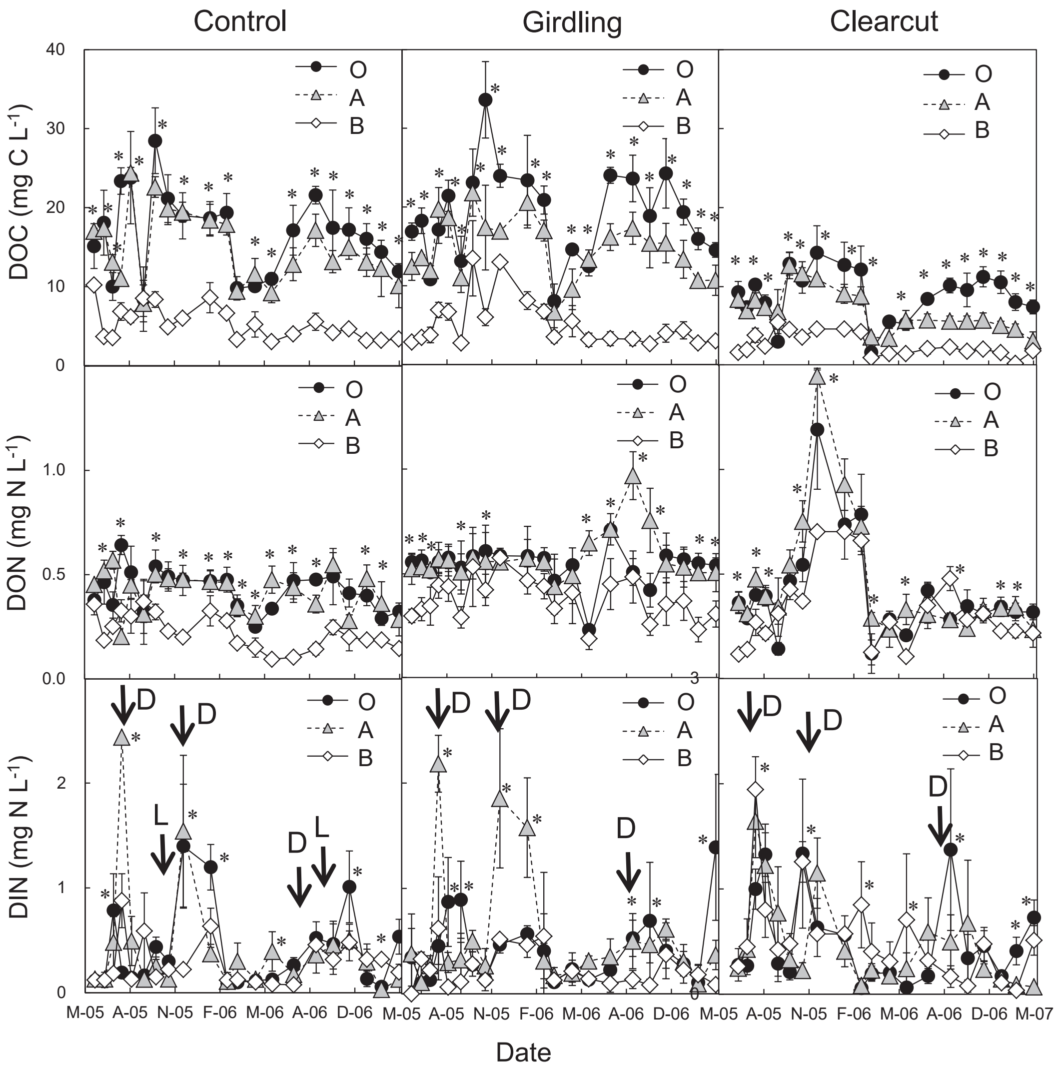

Fig. 4. Fluctuation in DOC, DON, and DIN concentrations in soil solution at clearcut, girdling, and control plots in cedar plantation. DOC, DON, and DIN represent dissolved organic carbon, dissolved organic nitrogen, and dissolved inorganic nitrogen (ammonium and nitrate), respectively. O, A, B indicates soil horizons. D and L indicate dry periods and litterfall events, respectively. Bars indicate standard errors ($n = 5$). Asterisks (*) indicate a significant ($P < 0.05$) difference between soil horizons for each sampling time (one-way ANOVA).

in the girdling and clearcut plots at most sampling dates (Fig. 4; Table 4). In the clearcut plot, nitrate-N concentrations in the B horizon were significantly ($P < 0.05$) higher than those of the O and A horizons (Fig. 4). Peaks in DIN concentrations were observed after litterfall in the control plot and after dry periods in all plots (Fig. 4).

3.3. Dissolved organic C and dissolved N fluxes in soil profiles

Based on minor (<5%) distribution of root biomass below the B horizon (<0.1 Mg C ha^{-1}) compared to root density in the organic horizon and the upper 0–30 cm mineral soil (Table 3), water and solute fluxes from the B horizon were regarded as those leached out of rooting zone in our study. Water flux in the B horizon was highest in the clearcut plot, followed by the girdling and control plots (Fig. 2; Table 5). The differences between precipitation and water flux from the B horizon [1199–1489 mm yr^{-1}, 1041–1352 mm yr^{-1}, and 831–1214 mm yr^{-1} in the control, clearcut, and girdling plots, respectively (Table 4)] were attributed to evapotranspiration (700 mm yr^{-1} estimated from Komatsu et al. 2008) and lateral water flow, including surface runoff associated with typhoon events, which was not evaluated in our study.

The DOC fluxes were the highest in the O horizon and decreased with depth at all plots (Table 5). The DOC fluxes also varied between treatments or between years (Table 5). In the girdling plot, the DOC fluxes from the O horizon in the second year were significantly ($P < 0.05$) higher than those of the first year, but there were no significant differences between years in the control and clearcut plots (Table 5). The DOC fluxes from the O horizon at each sampling interval were positively correlated with the respective soil heterotrophic respiration rates (Fig. 5). However, the slopes of DOC fluxes relative to soil heterotrophic respiration varied between treatments, with the lowest slopes in the clearcut plot, relative to the control and girdling plots (Fig. 5). Despite greater water flux, the percentages of DOC flux from the A horizon compared to CO_2 flux (soil heterotrophic respiration) in the clearcut plot (4.0–4.3%) were significantly lower than the other two plots (7.0–7.5% and 6.9–8.4% in the control and girdling plots, respectively).

The DON was a dominant N form (42–79%) in soil solution in the girdling and control plots, while nitrate-N was also a major N form (26–45%) in the clearcut plots (Table 5). The DIN fluxes from the B horizon were significantly ($P < 0.05$) higher in the girdling and clearcut plots than in the control plot (Table 5). The nitrate-N fluxes from the B horizon were highest in the clearcut plot (Fig. 6). The nitrate-N fluxes from the canopy were significantly ($P < 0.05$) higher in the girdling plot than in the other two treatments (Fig. 6). The nitrate-N flux from the B horizon in the second year was significantly ($P < 0.05$) higher than in

Table 4
The volume-weighted annual mean concentration of DOC and N in precipitation, throughfall, and soil solution in cedar plantation.

Treatment/ Horizon[a]	pH		Concentration: DOC		DON		NH_4-N		NO_3-N		TDN		DOC/DON[b]	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
			(mg C L^{-1})		(mg N L^{-1})									
Control														
TF	5.5	5.6	3.8	3.2	0.20	0.26	0.07	0.17	0.09	0.06	0.36	0.48	19 ± 1 bA*	12 ± 1 cA
O	5.4	5.6	16.8	16.8	0.43	0.44	0.21	0.29	0.11	0.10	0.75	0.83	39 ± 7 aA	38 ± 6 aA
A	5.3	5.4	15.8	14.0	0.47	0.45	0.20	0.28	0.11	0.11	0.78	0.84	34 ± 5 aA	31 ± 4 aA
B	5.3	5.2	5.6	4.5	0.27	0.19	0.16	0.21	0.06	0.05	0.49	0.46	21 ± 3 bA	23 ± 5 bA
SW	5.3	5.2	3.3	2.4	0.13	0.19	0.02	0.02	0.07	0.03	0.22	0.24	25 ± 2 b*	13 ± 1 c
Girdling														
TF	6.1	6.1	4.2	3.6	0.33	0.31	0.07	0.07	0.12	0.05	0.52	0.43	13 ± 1 bB	12 ± 1 bB
O	5.8	5.7	17.8	18.3	0.55	0.51	0.17	0.19	0.26	0.17	0.99	0.88	32 ± 6 aA	36 ± 6 aA
A	5.1	5.2	14.7	13.4	0.53	0.65	0.23	0.17	0.15	0.17	0.91	0.99	28 ± 4 aA*	21 ± 3 aA
B	5.2	5.2	5.8	4.0	0.39	0.39	0.25	0.09	0.03	0.13	0.67	0.61	15 ± 3 bB*	10 ± 2 bB
Clearcut														
P	5.7	5.8	2.0	2.0	0.15	0.18	0.11	0.07	0.06	0.04	0.33	0.29	13 ± 1 bB	11 ± 1 bB
O	5.6	5.5	8.7	8.3	0.44	0.31	0.16	0.16	0.21	0.22	0.81	0.69	20 ± 6 aA	27 ± 7 aA
A	5.4	5.3	7.3	5.2	0.48	0.31	0.18	0.09	0.25	0.18	0.91	0.58	15 ± 2 aB	17 ± 4 aB
B	5.0	5.4	3.4	1.9	0.38	0.28	0.18	0.09	0.45	0.20	1.01	0.57	9 ± 2 bC	7 ± 1 cC

[a] P and TF represent precipitation and throughfall, respectively. O, A and B represent soil horizons.
[b] All results are the mean ± standard error ($N = 5$). The different lowercase letters (a, b, c) mean that mean values are significantly different ($P < 0.05$) between horizons at each site, whereas different uppercase letters (A, B, C) indicate that mean values of each soil horizon are significantly different between treatments. Asterisks (*) indicate a significant ($P < 0.05$) difference between the first and second years in each treatment plot.

the first year in the girdling plot (Fig. 6)

4. Discussion

4.1. *Effects of clearcutting and girdling on soil respiration, dissolved organic C, and dissolved N*

The increased soil temperature and wetter conditions cause an increase in soil heterotrophic respiration especially in the first year (Figs. 2 and 3; Table 3). On the other hand, litter C inputs and soil heterotrophic respiration were balanced under girdled trees within the initial two years (Table 3). The smaller C loss by girdling could be related to the limited canopy opening, continuous litter inputs (Table 3), and small changes in microclimate (Fig. 2).

We found that stem girdling leads to the loss of cedar root uptake, as supported by the lower root respiration rates in the girdling plots (Fig. 3). This is consistent with the fact that girdling leads to a reduction in the allocation of photosynthate to the belowground and an associated decrease in root activity for N uptake (Högberg and Högberg, 2002). The loss of tree root uptake by girdling and clearcutting can lead to an increase in N leaching loss from the soil (Johnson and Edwards, 1979; Dahlgren and Driscoll, 1994; Fujii et al., 2010). The increased soil temperature due to canopy opening and wetter conditions also favored increased soil C loss and N release following clearcutting (Fig. 2). On the other hand, the higher root respiration rates in the second year in the clearcut plots (Table 3) support the growth of understory plants. This reduces nitrate leaching loss from the B horizon in the second year, compared to the first year (Fig. 6).

Clearcutting has been shown to cause a sharp increase in DIN concentration (Likens et al., 1970), but we found that DIN concentrations were regulated by dry periods (all plots) and litterfall events (girdled and control plots) in our study area (Fig. 4). As with DOC production in the O horizon, mineralization of organic N was primarily driven by soil heterotrophic respiration, which increased in summer (Figs. 4 and 5). In addition, dry-wet cycles can promote microbial biomass turnover and increase DIN concentrations in soil (Singh et al., 1989; Butterly et al. 2011). This effect was observed in the control plot soil, which tended to be drier, due to higher evapotranspiration by trees (Fig. 4). Generally, and within our study, fresh C inputs from litter help to maintain high DOC/DON ratios (>30), which were favorable for microbial N assimilation in the control and girdling plots (Table 4; Schimel and Weintraub, 2003). This is consistent with the fact that the nitrification potentials decrease with increasing soil C/N (Fukusima *et al.*, 2011). On the other hand, the reduction of fresh litter inputs led to a decrease in DOC/DON ratios (<30), which promoted the N oversupply in the clearcut plot (Table 4; Schimel and Weintraub, 2003).

4.2. *Comparison with reported soil C and N fluxes*

The effects of forest management practices on soil C and N fluxes may vary depending on original litter and soil properties, addition or removal of logging residue, growth of understory vegetation, and herbicide application (Johnson et al., 1995; Johnson and Curtis, 2001; Table 6). Increases in soil heterotrophic respiration following clearcutting have consistently been reported in the literature, but soil C loss was relatively low in our study (Table 6; Likens et al., 1970; Qualls et al., 2000; Piirainen et al., 2002). This may be related to the smaller increase in annual mean soil temperature (+0.4 °C) in our study relative to others (>+1.0 °C; Pumpanen et al., 2004; Kalbitz et al., 2004).

The observed DOC and DON fluxes from the O horizon (Table 5) fall

Table 5
The fluxes of DOC and N in precipitation, throughfall, and soil solution in cedar plantation.

Treatment/Horizon[a]	Water		DOC		DON		NH_4-N		NO_3-N		TDN	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
	(mm yr^{-1})		(kg C ha^{-1} yr^{-1})				(kg N ha^{-1} yr^{-1})					
Control												
TF	2094	2190	79 ± 3.9 cA	69 ± 3.5 cB	4.1 ± 0.2 bB	5.6 ± 0.3 bB*	1.5 ± 0.5 bA	3.7 ± 1.1 bA	1.9 ± 0.6 aA	1.2 ± 0.58 aA	7.6 ± 0.8 bB	10.6 ± 1.3 bB*
O	1819	1877	305 ± 37 aA	315 ± 28 aA	7.8 ± 0.9 aA	8.3 ± 1.0 aAB	3.7 ± 1.1 aA	5.4 ± 1.6 aA	2.1 ± 0.6 aB	1.9 ± 0.62 aB	13.6 ± 1.6 aA	15.6 ± 2.0 aA
A	1543	1711	243 ± 27 bA	240 ± 24 bA	7.2 ± 0.8 aA	7.8 ± 0.8 aB	3.1 ± 0.9 aA	4.7 ± 1.4 aA	1.7 ± 0.5 aB	1.9 ± 0.52 aB	12.1 ± 1.3 aA	14.4 ± 1.7 aA
B	936	1458	53 ± 5.3 dA	66 ± 9.3 cA	2.5 ± 0.3 cB	2.8 ± 0.4 cB	1.5 ± 0.5 bA	3.1 ± 0.9 bA	0.6 ± 0.2 bB	0.8 ± 0.17 bB	4.6 ± 0.5 cC	6.7 ± 1.0 cB
SW	936	1458	31 ± 1.8 e	35 ± 2.1 d	1.2 ± 0.1 d	2.8 ± 0.2 cB*	0.2 ± 0.1 c	0.3 ± 0.1 c	0.6 ± 0.1 bB*	0.4 ± 0.1 c	2.1 ± 0.2 d	3.5 ± 0.2 d*
Girdling												
TF	2209	2242	92 ± 4.6 cA*	80 ± 4 cA	7.4 ± 0.4 aA	6.9 ± 0.3 bA	1.5 ± 0.5 cA	1.6 ± 0.5 cA	2.7 ± 0.8 bA	1.1 ± 0.8 cA	11.6 ± 1.0 bA	9.6 ± 1.0 bA
O	1765	1997	314 ± 35 aA	366 ± 25 aA*	9.7 ± 1.5 aA	10.3 ± 1.5 aA	3.1 ± 0.9 aA	3.9 ± 1.2 aA	4.6 ± 1.4 aA	3.4 ± 1.38 aA	17.4 ± 2.2 aA	17.5 ± 2.4 aA
A	1369	1780	201 ± 22 bA	238 ± 26 bA	7.3 ± 0.8 aA	11.6 ± 1.3 aA*	3.1 ± 0.9 aA	3.0 ± 0.9 aA	2.1 ± 0.6 bB	3.0 ± 0.64 aA	12.5 ± 1.4 bA	17.5 ± 1.7 aA
B	1073	1616	62 ± 8.1 dA	64 ± 8.3 cA	4.2 ± 0.5 bA	6.4 ± 0.8 bA*	2.6 ± 0.8 bA	1.4 ± 0.4 bA	0.3 ± 0.1 cB	2.1 ± 0.1 bB*	7.2 ± 1.0 cB	9.9 ± 0.9 bA
Clearcut												
P	2425	2657	49 ± 2.4 cB	53 ± 2.6 cC	3.8 ± 0.2 cB	4.8 ± 0.2 bB*	2.7 ± 0.8 aA	1.9 ± 0.6 aA	1.5 ± 0.5 bA	0.9 ± 0.46 bA	8.0 ± 1.0 bB	7.6 ± 0.8 cB
O	1914	2307	166 ± 23 aB	191 ± 28 aB	8.4 ± 2.2 aA	7.1 ± 1.4 aB	3.1 ± 0.9 aA	3.6 ± 1.1 aA	4.0 ± 1.2 aA	5.2 ± 1.21 aA	15.5 ± 2.7 aA	15.9 ± 2.2 aA
A	1403	1957	103 ± 11 bB	101 ± 15 bB	6.7 ± 0.7 aA	6.1 ± 0.9 aB	2.6 ± 0.8 aA	1.8 ± 0.5 aA	3.5 ± 0.5 aA	3.4 ± 0.5 aA	12.8 ± 1.2 aA	11.4 ± 1.2 bB
B	1211	1826	41 ± 5.3 cA	34 ± 4.4 cA	4.5 ± 0.6 cA	5.2 ± 0.7 abA	2.2 ± 0.6 aA	1.6 ± 0.5 aA	5.5 ± 1.0 aA*	3.7 ± 0.4 aA	12.2 ± 1.3 aA	10.5 ± 0.9 bA

Flux[b]

[a] P and TF represent precipitation and throughfall, respectively. O, A and B represent soil horizons.
[b] All results are the mean ± standard error ($n = 5$). The different lowercase letters (a, b, c, d, e) mean that mean values are significantly different ($P < 0.05$) between horizons at each site, whereas different uppercase letters (A, B, C) indicate that mean values of each soil horizon are significantly different between treatments. Asterisks (*) indicate a significant ($P < 0.05$) difference between the first and second years in each treatment plot.

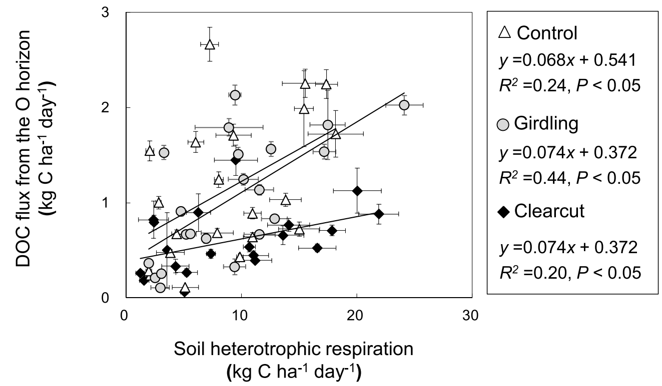

Fig. 5. Relationship between soil heterotrophic respiration and dissolved organic carbon (DOC) flux from the organic horizon. Bars indicate standard errors ($N = 5$).

within the range of previously reported values (100–482 kg C ha^{-1} yr^{-1} and 0.2–18.0 kg N ha^{-1} yr^{-1}, respectively, from Michalzik et al. 2001). By contrast, the decrease in DOC fluxes following clearcutting contrasts with values reported in the literature (Kalbitz et al., 2004; Table 5). This may be the result of a relatively small amount of residual logging debris, the depletion of new C substrates for DOC production, and the small increase in soil temperature in our study (Table 6). The increase in DOC fluxes in the girdling plot in our study (Tables 5 and 6) contrasts with other studies that have reported DOC decreases due to the loss of root exudate from girdled trees (Högberg and Högberg, 2002; Giesler et al., 2007). Higher litter inputs from the girdled trees might have increased DOC production in the O horizon (Tables 3 and 5). Although we did not assessed changes in the microbial community between treatments, forest management practices induce shifts toward bacterial dominance, following clearcutting, or fungal dominance, following the girdling of coniferous trees on boreal podzols (Baath 1980; Högberg et al., 2001; Kohout et al., 2018). Given that the leaching fraction of DOC is produced through the solubilization of recalcitrant litter by fungi, an increase or a decrease in DOC production (Table 5) might be related to a shift in the microbial community caused by girdling or clearcutting, respectively.

In our study, the fluxes of nitrate-N leaching following girdling and clearcutting were low (<5 kg N ha^{-1} yr^{-1}; Fig. 6) relative to the other studies (Table 6). This may be due to (i) increased growth in understory vegetation and (ii) the small soil C loss (Table 3). Small nitrate leaching and soil C loss could be related to slash retention and small changes in microclimate in our study, because retention of logging residue mitigates soil C and N losses (Tutua et al., 2019; James et al., 2021). Our observation is limited to the initial 2 years following clearcutting or girdling treatment, but greater litter inputs provided by dying trees in the girdled plots (Table 3) could retard a shift toward the lower DOC/DON ratios that favor microbial net N mineralization and nitrate leaching (Vitousek and Melillo, 1979). The continuous fresh litter inputs and growth of understory vegetation after disturbances may mitigate N leaching loss by increasing root uptake or microbial N assimilation.

5. Conclusion

Soil heterotrophic respiration rates, DOC, and nitrate leaching exhibited different responses to two forest management practices. Clearcutting increased soil heterotrophic respiration to cause soil C loss and nitrate-N leaching loss. On the other hand, high litter inputs from girdled trees and an increase in DOC flux from the organic horizon limit soil C loss and nitrate leaching following girdling. Effects of forest management practices on soil C loss and nitrate leaching loss could be variable, but the slash application in clearcutting and the slow dieback in stem girdling could mitigate soil C loss and contribute to maintenance

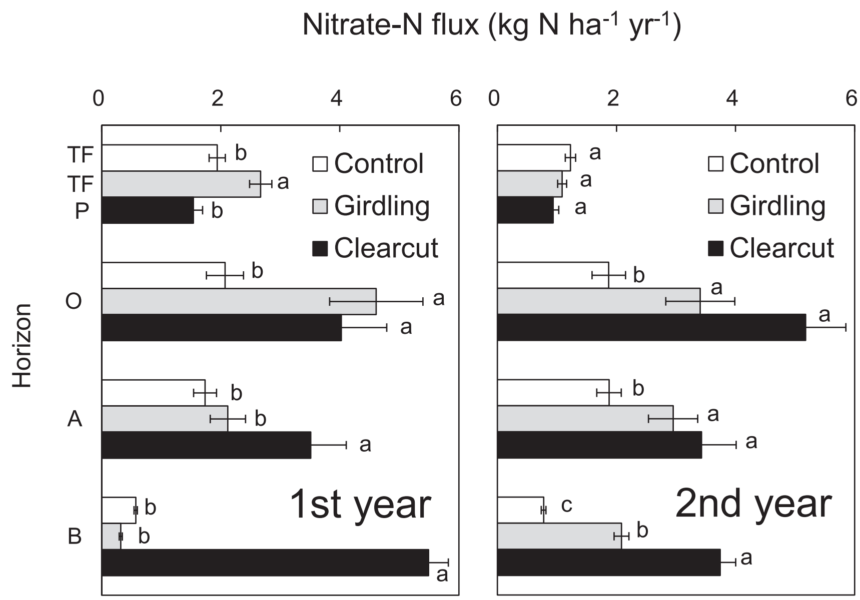

Fig. 6. Annual flux of nitrate-N in the soil profiles at clearcut, girdling, and control plots of cedar plantation. P and TF represent precipitation and throughfall, respectively. O, A, and B represent soil horizons. Bars indicate standard errors ($N = 5$). The same letters (a, b, c) indicate no significant ($p > 0.05$) differences between treatments.

Table 6
Effects of forest management practices on soil C and N fluxes.

Location	Vegetation	Logging residue	Soil heterotrophic respiration ($Mg\ C\ ha^{-1}\ yr^{-1}$)		DOC flux from the O horizon ($kg\ C\ ha^{-1}\ yr^{-1}$)		Nitrate-N export ($kg\ N\ ha^{-1}\ yr^{-1}$)			Data sources
		($Mg\ C\ ha^{-1}$)	Control	Clearcut	Control	Clearcut	Control	Girdling	Clearcut	
Japan	*Cryptomeria japonica*	2.9	3.0	3.7	305	166	0.9	0.4	4.7	Present study (1st year)
Finland	*Picea abies*	17.8	2.6	3.5	84	168	–	–	–	Piirainen et al. (2002), Pumpanen et al. (2004)
Germany	*Picea abies*				282	377	–	–	–	Kalbitz et al. (2004)
U.S., New York	*Tsuga canadensis*						2.5	6.6	–	York et al. (2003)
U.S., Wyoming	*Pinus contorta*						0.1	0.3	11.0	Knight et al. (1991)
U.S., Tennessee	*Liriodendron, Quercus* spp.						0.3	2-9[b] 0.88–25.43[c]	–	Edwards and Ross-Todd (1979)
U.S., New Hampshire	*Fagus grandifolia*	28.1	4.7[a]	5.6[a]	216	360	2.0	–	125.5[d]	Likens et al. (1970), Johnson et al. (1995)
U.S., West Virginia	*Quercus rubra*						0.6	–	3.0	Aubertin and Patric (1974)
U.S., North Carolina	*Liriodendron, Quercus* spp.	60.0	4.3	5.7	470	610	0.0	–	0.6	Swank and Waide (1980), Mattson and Swank (1989), Qualls et al. (2000)
U.S., Oregon	–						0.5	–	0.9	Gessel and Cole (1965)
Canada	–						0.9	–	6.7	Kimmins and Feller (1976)

[a] Whole soil respiration.
[b] Girdling, root sprouting permitted.
[c] Girdling, root sprouting prevented.
[d] Herbicide was applied.

of high DOC/DON ratios that limit nitrate leaching loss after disturbances.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Mr. Akihiro Deguchi for allowing us to conduct studies at the experimental sites. We are also grateful to Dr. Atsunobu Kadono, Dr. Soh Sugihara, Dr. Kenta Ikazaki, Mrs. Yoko Noro, Mr. Morihide Makino, and Mrs. Aya Makino for assistance with the field survey.

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