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Change of Carbon Dioxide Budget during Three Years after Deforestation in Eastern Siberian Larch Forest

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Abstract

Aiming to investigate effects of deforestation on ecosystem carbon dioxide budget in a boreal forest, a long-term flux observation by means of the eddy covariance method was performed over growing seasons from 2001 to 2003 at a mature larch forest and an adjacent experimental cutover near Yakutsk, Russia. Net ecosystem exchange (NEE) of carbon dioxide was negative from June to August at the larch forest and five-month (from May to September) total exchange ranged from –81 to –126 gC m^{-2} (5 months)$^{-1}$. NEE at the cutover was positive over the observation, and was +296 gC m^{-2} (5 months)$^{-1}$ in the first year after the clear-cut, which was more than twice as large as NEE at the larch forest. NEE at the cutover decreased year by year, and the daily exchange became negative in short periods in the third year (2003), which is because of absorption by the recovered surface vegetation. Seasonal NEE at the cutover decreased to +87 gC m^{-2} (5 months)$^{-1}$ in 2003, which indicates a quick recovery of surface vegetation, however, a careful and durable monitoring of the recovery course of ecosystem carbon sequestration in relation to the succession of surface vegetation is indispensable.

Key words: Carbon dioxide budget, Deforestation, Larch forest, Eastern Siberia.

1. Introduction

Boreal forests are noted as big sinks of atmospheric carbon dioxide and a number of organized research programs have already been conducted aiming to evaluate the annual budget of carbon dioxide based on the eddy covariance technique. Siberian taiga is the largest forest biome in the world and its property of carbon exchange must have a prevailing effect on the global carbon cycle. Recently, results of long-term carbon dioxide flux observation in a spruce forest of European Siberia (Milyukova *et al.*, 2002), pine (Lloyd *et al.*, 2002), birch, mixed and spruce forests (Röser *et al.*, 2002) of central Siberia were published. Larch forest is the most common and dominant ecosystem of the eastern Siberian taiga, however, only a limited short-term observation at a larch forest in the region has been reported (Hollinger *et al.*, 1998). Another uncertainty on knowledge of carbon exchange of taiga ecosystems is an effect of forest disturbance such as deforestation and forest fire. The forest disturbance causes not only direct loss of carbon but also environmental changes of soil and vegetation that may induce significant deformation of ecosystem carbon dioxide exchange. This indirect effect has also not yet been investigated in Siberian taiga. In order to evaluate the annual ecosystem carbon dioxide budget of a larch forest in eastern Siberia and to investigate the effect of forest disturbance on it, a long-term carbon dioxide flux observation was carried out both in an intact larch forest and an experimental cutover.

2. Method

2.1 Sites

Observation sites were established in a mature larch forest located 25 km northwest of Yakutsk, Republic of Sakha, Russian Federation (62°19'N, 129°31'E), standing on continuous permafrost. The sites are located on a terrace of the left bank of the Lena River, the altitude was 200 m A. S. L. and the topography was flat except for thermo-karst depressions surrounding the forest stand. Ecological surveys of tree and ground vegetation were conducted at the stand for several years (Yajima *et al.*, 1998; Takahashi *et al.*, 2000). The dominant tree species of the stand was larch (*Larix gmelinii*), average tree height was 8.6 m, maximum tree height was 21 m and average tree density was 2,100 ha^{-1}. The forest floor was covered mainly with shrub and moss including *Vaccinum vitis-idea*, *Vaccinum uliginousum* and *Pyrola incarnate.* Soil texture was loamy and soil organic carbon content in the top 1 m layer was 13.2 kgC m^{-2} (Sawamoto *et al.*, 2003). Trees in a rectangular area of 140 m × 70 m,

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Table 1. Monthly NEE at the larch forest and the cutover. Unit is gC m^{-2} (month or 5 months)$^{-1}$.

	Larch forest			Cutover		
	2001	2002	2003	2001	2002	2003
May.	+12	+31	+22	+45	+45	+22
Jun.	−94	−87	−56	+62	-	+22
Jul.	−32	−61	−54	+79	+69	+29
Aug.	−11	−19	−30	+45	-	+5
Sep.	+17	+55	-7	+33	+34	+11
Total	−107	−81	−126	+264	(+240)*	+89

* Assuming that NEE of Jun. and Aug. are 86% of 2001.

path eddy covariance method using sonic anemometer-thermometers (Gill Instruments Ltd. model 1210R3) and infrared gas analyzers (Li-cor Inc. model 6262) except at the cutover site in 2003 in which an open path system including a Li-cor model 7500 analyzer was used. The sonic anemometers were installed at 21m and 1.5m above ground at the forest and cutover sites, respectively. Air was sampled at 0.1 m below the anemometer path and drawn to the gas analyzers at a flow rate of 5 l min^{-1} through thermally insulated and heated polyethylene tubes of 4 mm ID and 26 and 5 m long at the forest and cutover sites, respectively. Digitized signals from the analyzers and anemometers were recorded on PCs at sampling rate of 20 Hz. Global radiation (Kipp & Zonen model CNR-1), air temperature and relative humidity (Vaisala model HMP-45A) at 21m high in the forest and at 2 m high in the cutover, soil temperature (thermistor) at 0.05 m deep and rainfall (R. M. Young Company model 52202) were measured and recorded every 10 minutes on data loggers (Campbell Scientific Inc. model CR-10X). Carbon dioxide concentration at six heights in the forest was measured using a gas analyzer (Li-cor Inc. model 6262) and an airflow switcher in order to evaluate carbon dioxide storage change. The storage change at the cutover was evaluated using only the concentration at the eddy instrument height.

2.3 Calculation, quality control and gap interpolation of carbon dioxide flux

Carbon dioxide flux was calculated within 30-minute periods. A linear trend removal correction for carbon dioxide concentration and a time lag correction by the maximum covariance were applied before calculating the flux. The band pass covariance correction by sensible heat flux ratio in high and low frequency domains (critical frequency at 1 Hz) was applied only at the forest site to compensate the gas concentration dumping in the long sampling tube. For the open path system at the cutover in 2003, the WPL correction for air density fluctuation was applied.

Stationarity of the flux was examined by comparing covariance in a 30-minute period and average of the covariance in six 5-minute sub-periods, and those of which the relative difference exceeded 40% were eliminated. To examine the effective fetch, footprint distance of the surface fluxes from the towers was analyzed and the fluxes with the windward fetch shorter than 80% of footprint distance were eliminated.

Carbon dioxide flux in observation gaps owing to the maintenance stops, instrumental failures and quality control was interpolated. Net ecosystem exchange (NEE) of carbon dioxide N_e (gC m^{-2} s^{-1}) is a difference between ecosystem respiration R_e (gC m^{-2} s^{-1}) and ecosystem photosynthesis A_g (gC m^{-2} s^{-1}).

$$N_e = R_e - A_g. \tag{1}$$

R_e and A_g was estimated using their response to the environmental conditions.

$$R_e = R_0 Q_{10}^{(T-T_0)/10}, \tag{2}$$

$$A_g = \frac{A_{gmax} R_s}{A_{gmax}/\alpha + R_s}\ , \tag{3}$$

where, T is temperature (°C), T_0 reference temperature (°C), R_0 ecosystem respiration at temperature T_0 (gC m^{-2} s^{-1}), Q_{10} temperature sensitivity, R_s global radiation (W m^{-2}), A_{gmax} maximum ecosystem photosynthesis (gC m^{-2} s^{-1}) and α initial photosynthesis efficiency to R_s (gC J^{-1}). Air temperature at 21 m high and soil temperature at 0.05 m deep were used as T and T_0 at the larch forest and cutover, respectively. Coefficients R_0, Q_{10}, A_{gmax} and α were determined half monthly using complete datasets of environmental variables and the quality controlled flux applying the simple genetic algorithm (Goldberg, 1989), which is a simple and universal tool to optimize models. Linear dependence of Q_{10} and A_{gmax} on vapor pressure deficit was also considered because these coefficients were empirically found to decrease by drought.

3. Results and Discussion

3.1 Climate during the observation period

Summers of 2001 and 2002 were dry with rainfall of 89.6 mm and 79.6 mm between May and September, respectively. Especially in 2002, rainfall from May to the first half of July was quite light and the mean VPD was extremely high. By contrast, in 2003, seasonal rainfall was 226.8 mm, which was more than twice as much as the dry years. Air and soil temperature at 0.05 m deep reached the maximum in July. Air temperature at the two sites was not significantly different; however, soil temperature of the cutover was lower than the larch forest in May and higher from June to September. The maximum difference of half monthly mean soil temperature between the two sites exceeded 5 °C. An unusually cold climate in late May of 2003 held up the development of the larch needle and surface vegetation two weeks later than the ordinary year.

3.2 NEE at the larch forest

The monthly and seasonal NEE of carbon dioxide at the larch forest is shown in Table 1. The NEE varied greatly depending on both the phenology of larch trees and climatic conditions. Monthly NEE was positive in May and negative from June to August in the three years. The NEE in September was variable; it showed a large positive in 2002 when air and soil temperature was higher than in the other years, and negative in 2003 when needle fall began in middle September that was about two weeks later than the other years. The relationship between NEE and climatic conditions in mid-summer was somewhat more complicated. A severe drought in 2002 suppressed photosynthesis; nevertheless, monthly NEE of July was the largest in the three years, which indicates that ecosystem respiration as well as the photosynthesis was also suppressed by the draught.

The five-month total NEE of the larch forest was –107, –81 and –126 gC m^{-2} (5 months) $^{-1}$ in 2001, 2002 and 2003, respectively. Annual NEE was supposed to be ten or more gC m^{-2} larger (less negative) than the five-month total considering soil respiration during the winter season from October to April. The evaluated summer NEE of the larch forest was smaller than that reported in pine (–156 gC m^{-2} y^{-1}; Lloyd *et al.*, 2002), birch (–247 gC m^{-2} $summer^{-1}$; Röser *et al.*, 2002) and spruce forests (–290 gC m^{-2} $summer^{-1}$; Röser *et al.*, 2002) and similar to a mixed forest (–90 gC m^{-2} $summer^{-1}$; Röser *et al.*, 2002) in central Siberia. This difference was consistent with the smaller biomass of the larch forest (basal area 21 m^2 ha^{-1}) than the forests in central Siberia (basal area larger than 30 m^2 ha^{-1}).

3.3 NEE at the cutover

Seasonal course of daily carbon dioxide flux of the cutover is shown in Fig. 1, and monthly total NEE, daytime and nighttime mean fluxes are shown in Fig. 2. At the cutover, measurement in early June and August 2002 was not usable because of instrumental troubles caused when a fire attacked the site. Monthly NEE of the cutover was positive through the observation period. Seasonal change of the flux was similar to that of soil temperature and was at the maximum at late July in 2001 and 2003, and at early July in 2002. It also depended strongly on rainfall event, and was relatively small in rainless periods, for example late June and early July 2001, and late June and late July 2002. The maximum daily flux was 6.3 gC m^{-2} d^{-1} and emerged on 7 July 2002, last of three continuous rainy days.

In 2001, which was the first year after the clear-cut, the cutover was covered with shrub and moss that had once been a floor vegetation of the larch forest. However, They were not vital any more under the direct irradiance and high temperature. Generally, in this region, fireweed (*Chamaenerion angustifolium*), a pioneer species, covers the renewed surface caused by fires quickly. However, it could not invade the cutover because the remaining vegetation obstructed landing of the seeds. Daytime mean flux was slightly larger than nighttime mean flux in all months of 2001 reflecting difference of the soil temperature, and it indicated no signal of photosynthesis by the surface vegetation. A partial invasion of herbaceous species in the cutover was found in 2002 and they covered a large part of the cutover in 2003, which pushed down the daytime mean flux below that of nighttime from June to September in 2002 and 2003. Negative daily NEE was first recorded after the clear-cut in June 2003, and negative daily NEE appeared more than 20 days in 2003. The recovered photosynthesis at the cutover was also found in Fig. 3 showing the relationship between soil temperature, global radiation and carbon dioxide flux in the second half of July. In 2001, there was an apparent increase of the flux with soil temperature but no significant relationship between the flux and global radiation. In 2002 and 2003, radiation dependency of the flux became obvious and the temperature dependency vanished.

Five-month total NEE of the cutover was +264 gC m^{-2} (5 months) $^{-1}$ in 2001. It was more than twice of absorption at the intact larch forest in the same period. This suggests that the accumulated soil organic matter began to decompose quickly in the cutover. The high rate of carbon dioxide emission was consequent to the soil temperature rise by the clear-cut treatment. Seasonal NEE in 2002 could not be evaluated accurately because of the long observation gaps.

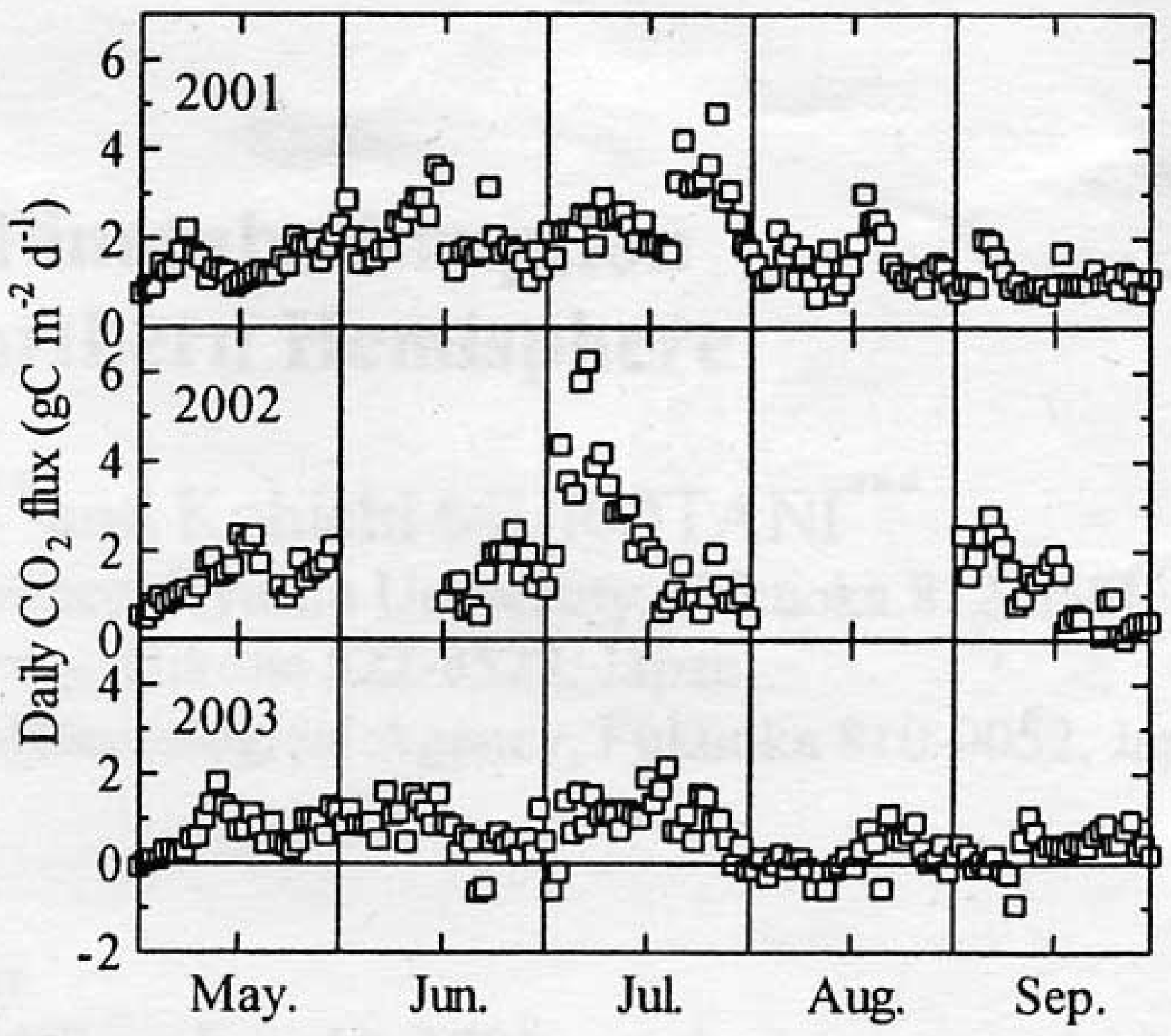

Fig. 1. Seasonal change of daily CO_2 flux at the cutover.

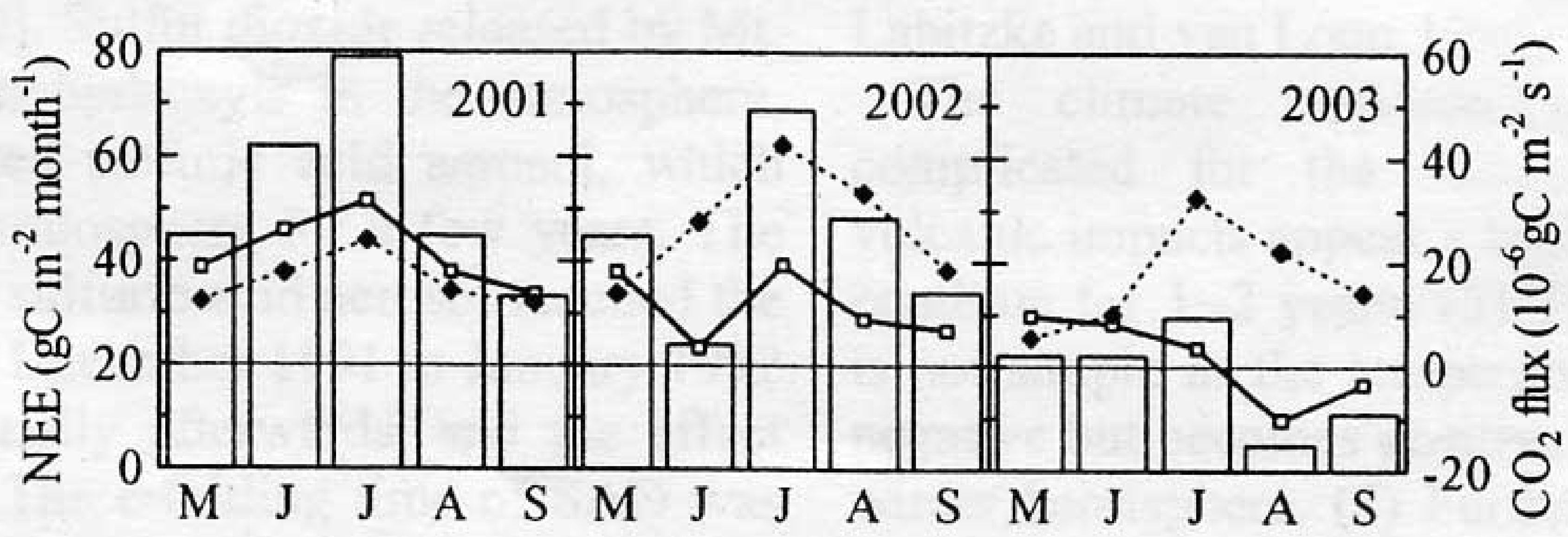

Fig. 2. Monthly total NEE, daytime and nighttime mean CO_2 fluxes at the Cutover; monthly NEE: bar (left axis), daytime and nighttime fluxes: solid and dotted lines, respectively (right axis).

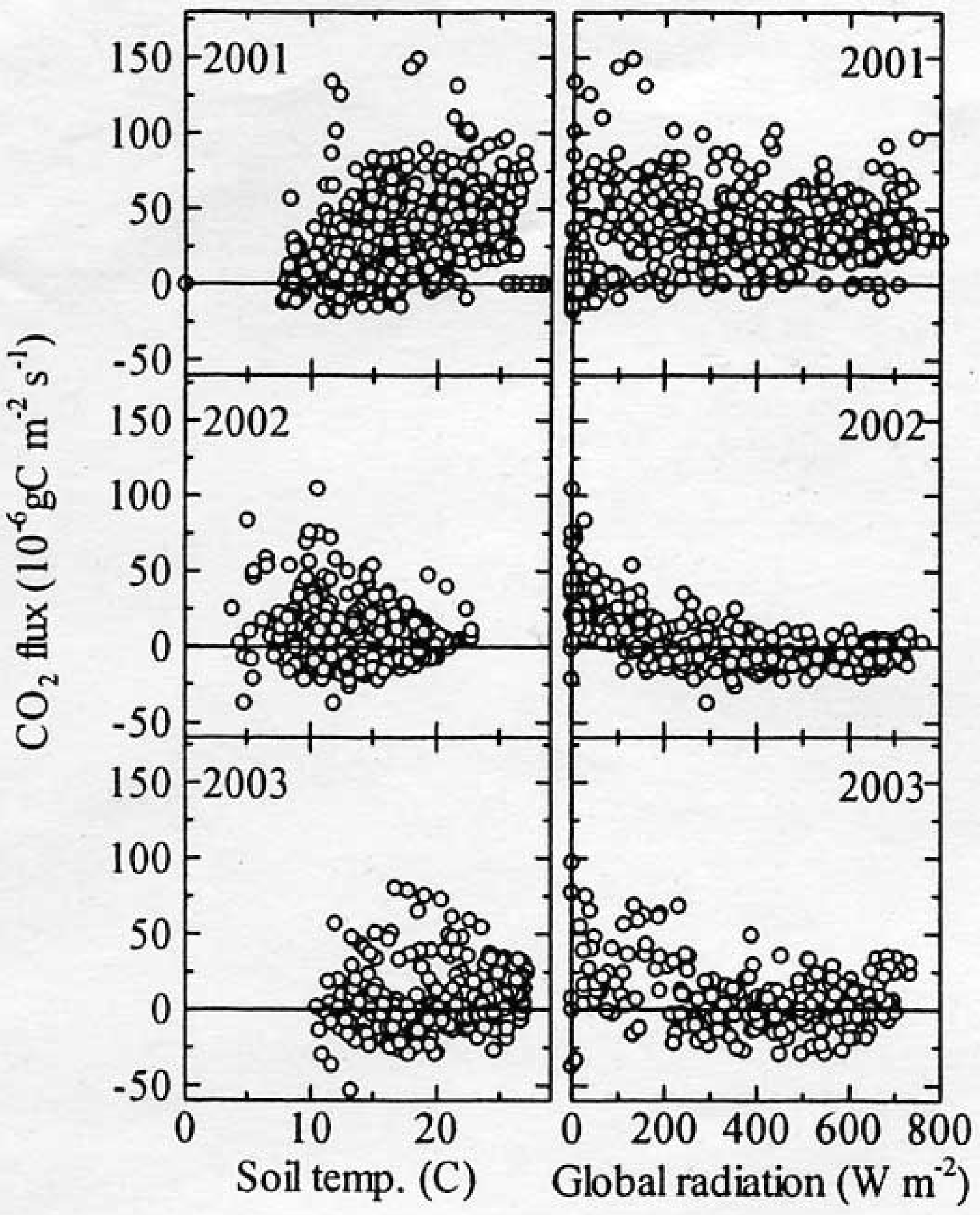

Fig. 3. Relationships between soil temperature at 0.05 m deep and CO_2 flux (left), and global radiation and CO_2 flux (right) at the cutover in the second half of July.

However, an estimation of +240 gC m^{-2} (5 months)$^{-1}$ may be reasonable assuming that NEE in June and August in 2002 was 86% of that in 2001, which was the observed ratio in July. The seasonal NEE greatly decreased to +89 gC m^{-2} (5 months)$^{-1}$ in 2003. It is not certain that this quick decrease of NEE is durable in future because the low NEE in 2003 should largely be due to the unusual wet climate that increased growth of the vegetation as can be seen at the larch forest. It may take the annual NEE at the cutover a few decades to become negative deducing from the fact that a burnt forest 10 years after a fire near the sites still showed a large annual emission (Machimura *et al.*, 2003).

4. Conclusion

Ecosystem carbon dioxide budget during the growing season was observed in a mature larch forest and a cutover in eastern Siberia. The intact larch forest absorbed carbon dioxide from 81 to 126 gC m^{-2} (5 months)$^{-1}$. By contrast, the cutover emitted 264 gC m^{-2} (5 months)$^{-1}$ in the first year after clear-cutting. NEE at the cutover decreased year by year according to recovery of the surface vegetation. Annual budget of carbon dioxide in disturbed forests depends both on course of the vegetation succession and the climate fluctuations year by year. Therefore, a careful and long-term monitoring of the carbon budget in relation to succession course of the vegetation is indispensable.

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References

Goldberg, D. E., 1989: *Genetic algorithms in search, optimization & machine learning.* Addison Wesley Longman, Inc., Boston, U. S. A., 412 pp.

Hollinger, D. Y., Kelliher, F.M., Schulze, E.-D., Bauer, G., Arneth, A., Byers, J. N., Hunt, J. E., McSeveny, T. M., Kobak, K. I., Milukova, I., Sogatchev, A., Tatarinov, F., Varlargin, A., Zieglerf W., Vygodskaya, N. N., 1998: Forest atmosphere carbon dioxide exchange in eastern Siberia. *Agric. For. Meteorol.*, **90**, 291-306.

Lloyd, J., Shibistova, O., Zolotoukhine, D., Kolle, O., Arneth, A., Wirth, C., Styles, J. M., Tchebakova, N. M. and Schulze, E.-D., 2002: Seasonal and annual variations in the photosynthetic productivity and carbon balance of a central Siberian pine forest. *Tellus*, **54B**, 590–610.

Machimura, T., Kobayashi, Y., Iwahana, G., Goto, K., Fukuda, M. and Fedorov, A. N., 2003: Seasonal variation of ecosystem carbon dioxide exchange over intact, burnt and cut larch forests in east Siberia. *Proceedings of the Tenth Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 2001*, 1-5.

Milyukova, I., Kolle, O., Varlagin, A., Vygodskaya, N. N., Schulze, E.-D. and Lloyd, J., 2002: Carbon balance of a southern taiga spruce stand in European Russia. *Tellus*, **54B**, 429–442.

Röser, C., Montagnani, L., Schulze, E.-D., Mollicone, D., Kolle, O., Meroni, M., Papale, D., Marchesini, L. B., Federici, S. and Valentini, R., 2002: Net CO_2 exchange rates in three different successional stages of the "Dark Taiga" of central Siberia. *Tellus*, **54B**, 642–654.

Sawamoto, T., Hatano, R., Shibuya, M., Takahashi, K., Isaev, A. P., Desyatkin, R. V. and Maximov, T. C., 2003: Changes in net ecosystem production associated with forest fire in Taiga ecosystems, near Yakutsk, Russia, *Soil. Sci. Plant Nutr.*, **49**, 493-501.

Takahashi, K., Hatano, R., Shibuya, M., Sawamoto, T., Yamamoto, G., Tsuno, Y., Isaev, A. P. and Maximov, T. C., 2000: Characteristics of ground vegetation at Neleger Alas. *Proceedings of the Eighth Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1999*, 77-82.

Yajima, T., Takahashi, K., Sasaoka, E., Hatano, R., Sawamoto, T., Ivanov, B. I., Isaev, A. P. and Maximov, T. C. 1998: Stand structure and biomass of Larix cajanderi forest in the Siberian taiga. *Proceedings of the Sixth Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1997*, 72-80.