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Effects of thinning and fertilization on soil respiration in a cottonwood plantation in Iceland

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Abstract

The main goal of this research was to determine the short-term effects of forest management practices (precommercial thinning and fertilization) on carbon efflux of a young black cottonwood (*Populus trichocarpa*) plantation in southern Iceland. Changes in leaf area index, tree growth, soil and air temperature were also monitored. Traditional precommercial thinning (50%) had little effect on soil temperature, but heavy thinning (80%) led to higher soil temperatures in spring and summer, but not much difference in winter. Thinning did not change foliage nutrient content or tree growth in the first treatment year. Effects on soil respiration were surprising; even if soil temperature was slightly higher and all organic material was left at site after precommercial thinning, soil respiration in the thinned stands was significantly lowered. Fertilization increased foliage nutrient content, but did not significantly change tree growth during the first growing season following spring application. It did however significantly increase soil respiration rate in the first treatment year. These results may be important when the effects of early forest management on carbon fluxes are modeled.

1 Introduction

Anthropogenic activities have increased greenhouse gas emissions, especially carbon dioxide (CO_2), yielding an annual accumulation of carbon (C) in the atmosphere at the rate of 2.8 $\mathrm{Pg\,C\,y^{-1}}$ (Fan et al., 1998). As a result, the surface air temperature has been rising steadily and it has been suggested that even more drastic changes will occur in the future (IPCC, 2007). Soil respiration is of particular importance as it is the largest terrestrial source of C to the atmosphere, contributing 80.4 $\mathrm{Pg\,C\,y^{-1}}$ (Raich et al., 2002). Hence, small changes in terrestrial soil respiration could have significant effects on atmospheric CO_2 concentration. Furthermore, a positive correlation has been demonstrated between temperature and soil respiration (Knorr et al., 2005a). Higher temperatures could therefore increase soil respiration to the atmosphere that further exacerbates global warming (e.g. Kirschbaum, 1995; Knorr et al., 2005a). However, it has been pointed out that this effect could be reduced through increase in primary production in nutrient limited ecosystems, as nutrient availability is expected to increase with higher temperature (e.g. Liski et al., 1999; Jarvis and Linder, 2000). At a hectare scale, similar changes occur when managed forests are thinned. The decreased leaf area index changes the microclimate at the forest floor which affects soil processes, such as decomposition and respiration activity (Siira-Pietikäinen et al., 2001; Hyvönen et al., 2007).

Soil respiration can be partitioned into two processes, metabolic activity of plant roots (autotrophic respiration) and the decomposition of dead organic material (heterotrophic respiration) (Ryan and Law, 2005). Autotrophic and heterotrophic respiration can respond independently to a number of factors, such as climate, soil type, forest type and human disturbances (Boone et al., 1998; Hanson et al., 2000; Knorr et al., 2005a; Olsson et al., 2005; Luo and Zhou, 2006). Probably because of the diverse and complex nature of these interactions, studies focusing on the effect of forest management practices on soil respiration have given ambiguous results. For instance, soil respiration has increased (Selmants et al., 2008), decreased (Tang et al., 2005; Sullivan et al., 2008) or stayed unchanged (Toland and Zak, 1994) following thinning. Fertilizer applications to forest soils have yielded similar responses, with reduction (Olsson et al., 2005), increase (Cleveland and Townsend, 2006) or no change (Castro et al., 1994) in soil respiration. Therefore, more work is needed to fully understand what are the general responses to such management practices.

It is of special interest to study the impacts of forest management on soil organic matter (SOM) in Iceland. Previous research has indicated that Icelandic forest soils can store twice the amount of C as aboveground woody biomass (Snorrason et al., 2002) and that the rate of C sequestration in SOM, fine roots and litter can be as high or higher than accumulation in woody biomass during the establishment phase after afforestation (Bjarnadóttir, 2009).

The aim of this study was to determine the short-term effects of precommercial thinning and fertilization on carbon efflux of a young black cottonwood (*Populus trichocarpa*) plantation in southern Iceland. Black cottonwood is the 2nd most used broadleaved tree species in afforestation in Iceland, following the native mountain birch (*Betula pubescens*). It was expected that precommercial thinning of a young broadleaved plantation would lead to higher soil respiration due to higher soil temperatures and increased litter input and that the size of the response would depend on the thinning intensity. Fertilization was expected to further increase soil respiration.

2 Material and methods

2.1 Site description

The experimental site is located in Gunnarsholt in southern Iceland (63°51′ N and 20°13′ W, elevation 78 m). In 1990 cuttings of a single clone of black cottonwood (*Populus trichocarpa* Torr. and Gray; Clone Idunn) were planted in an abandoned hayfield from which the sod had been removed in 1989. A total of 145 000 propagated cuttings were planted in 14.5 ha with 1 m spacing (stand density of 10 000 trees ha^{-1}). The Idunn-clone originates from the Copper River Delta region, Alaska (Lat 60–61°); an area with similar climate as Gunnarsholt (Sigurdsson, 2001).

A microclimatic station was installed at the centre of the site in 1989, where a range of climatic parameters, including air temperature, soil temperature and global radiation, were monitored (Aradottir et al., 1997). The soil is an Andisol (found only in volcanic areas) and silty loam in texture. The soil water potential is permanently close to field capacity, and water availability therefore not considered to limit tree growth at the site (Strachan et al., 1998). Organic carbon content of the A1 soil layer ranged between 1.8 to 2.4%, pH was 5.8 and cation exchange capacity (CEC) was 19 meq 100 g^{-1} (Strachan et al., 1998).

The most limiting environmental factor for tree growth at the site has been found to be nitrogen availability (Sigurdsson et al., 2001). The stand development was slow in the beginning, but after the saplings had overgrown the competing vegetation and the most active frost layer in 1997, the average annual height increment has been 33 cm. The average tree height, diameter at breast height and basal area across the whole plantation in autumn 2003 were 3.1 m, 2.7 cm and 5.9 m^2 ha^{-1}, respectively. More information about the climate, soil and other physical conditions at the site can be found in Strachan et al. (1998) and Sigurdsson (2001).

2.2 Experimental design

In June 2004, 24 plots were established in the experimental plantation, each 0.06 ha (25×25 m). The plots were arranged in a randomized block design with thinning intensity and fertilization as main factors. Treatments consisted of unthinned control (10 000 trees ha^{-1}), 50% thinned (5000 trees ha^{-1}) and 80% thinned (2000 trees ha^{-1}) on either unfertilized soil or where all macro- and micro-nutrients were applied in early June as 80 kg N ha^{-1} and with other elements in optimum proportions for black cottonwood (Linder, 1995; Sigurdsson, 2001). The treatments were entitled C-00, F-00, C-50, F-50, C-80 and F-80 for the three thinning intensities (00%, 50%, 80%) and two nutrient treatments (C and F), respectively. All thinned trees were left on the forest floor to decompose.

2.3 Leaf morphology and chemical analysis

To check if trees had increased their nutrient uptake following spring fertilization, youngest fully expanded leaves on top shoots were excised from 20 trees in each nutrient treatment in late-August 2004. The leaves were placed directly on ice and thereafter stored at –18°C to await further processing. Six leaves from each treatment were randomly chosen for morphological analysis, scanned on a pre-calibrated scanner and analyzed for area, length and width with the WinFOLIA image analysis program (WinSeedle, Regent Inc., Canada). Thereafter the leaves were dried at 85°C for 48 h and weighed. Specific Leaf Area (SLA; cm^2 g^{-1}) was then calculated for each leaf. The other leaves were used for chemical analysis. They were dried in the same way, ground and sent to the Centre of Chemical Analyses (Efnagreiningar Keldnaholti), ICETEC, Reykjavik, Iceland, where their total nitrogen was measured by Kjeldahl wet combustion on Tecator Kjeltec Auto 1030 Analyzer.

2.4 Growth measurements

At the start of the experiment, in June 2004, diameter at breast height (DBH) was measured for all trees in treatment plots. The results were used to randomly choose five ”mean trees” in each plot for further measurements of stature and growth. Additional measurements on those trees included height, length of the leader shoot, crown surface area, crown height and stem diameter at 50 cm height.

2.5 Leaf area index measurements

Leaf area index (LAI) of overstory trees was measured with a pair of LAI-2000 Plant Canopy Analyzers (LI-COR Inc., Lincoln, Nebraska) on an overcast day (only diffused light) in early August 2004. One instrument was placed outside the forest and the other was used to take readings of sky brightness at nine fixed points within each treatment plot. The sensor heads always faced north, a 180° lens cap was used and the calculations of LAI was limited to the hemispherical area above 23°, due to relatively small plot size.

2.6 Soil respiration measurements

Eight 5 cm deep PVC collars with 100 mm inner diameter were inserted ca. 3 cm into the soil surface in each treatment plot in early June 2004. Soil respiration was receptively measured from each collar with closed-chamber CIRAS gas analyzer (PP-Systems, Hitchin, Hertfordshire, UK) during the 2004 growing season. Each measurement lasted for 1.5 min and respiration rate was calculated by applying a linear function to the rise in CO_2 concentration that was measured once per 1.6 s. Measurement campaigns were carried out 22–30 June, 28 July, 16 August and 22 September. Soil temperatures at 5 and 10 cm depth were also simultaneously measured. On 28 July, only 3 out of 4 blocks could be measured due to instrument failure.

2.7 Climate and soil temperature measurements

Air and soil temperature were constantly monitored in the three thinning treatments by six HOBO dataloggers (Onset Computer Corporation, Pocasset, MA, USA) and sensors made out of copper-constantan thermocouples. Soil temperature was measured at 10 cm depth and air temperature at 50 cm height and stored as 30 min averages. Other climatic variables, including irradiance, air temperature, relative humidity, precipitation, wind direction and speed, were measured continuously and stored as 30 min averages at the central microclimatic station.

2.8 Data analysis

The effects of thinning and fertilization on different treatments were analyzed in the SAS statistical program (SAS system 9.1, SAS Institute Inc., Cary, NC, USA). Two-way ANOVA and ad-hoc pairwise Fisher's Least Significant Difference tests were used to test for treatment differences. When average soil respiration was analyzed, soil temperature at 10 cm depth was used as a covariate to adjust for temperature differences between treatments. Regression analysis was used to study the effects of thinning intensity on air and soil temperature.

3 Results

3.1 Leaf Area Index

Leaf area index (LAI) was on average 3.0 in the unthinned treatments in August 2004 (data not shown). The LAI was reduced by 51% and 84% in the 50% and 80% thinned treatments, respectively. No positive fertilization effects were noted on LAI at the end of the first growing season following spring fertilizer application (data not shown).

3.2 Nutrient status and leaf morphology

Nitrogen (N) concentration in leaves ranged between treatments from 18.5 to 32.8 mg N per gram leaf (Fig. 1). The spring fertilization had significantly increased N concentration in August ($P<0.001$). Effects of thinning on nutrient status were more subtle and not significant across unfertilized treatments. However, when compared across fertilized treatments thinning did have a negative effect on N concentration ($P=0.01$).

Mean leader shoot leaf size ranged from 8.5 to 19.9 cm^2 between treatments in the autumn (Fig. 2). Fertilization significantly increased leaf size ($P<0.001$) while thinning had a negative effect on leaf size ($P=0.002$). Specific leaf area (SLA) ranged from 74 to 85 $\text{cm}^2\ \text{g}^{-1}$ but no statistical difference was noted between treatments (data not shown).

3.3 Growth measurements

Diameter at breast height ranged from 3.4 to 3.8 cm at the end of the first growing season (data not shown). Neither fertilization nor thinning affected diameter growth in the first growing season. Other growth measurements gave the same results in the first year of treatments (data not shown).

3.4 Climate and soil temperature measurements

Annual irradiance, temperature and precipitation in 2004 was 2487 MJ m^{-2}, 4.9°C and 991 mm, respectively (Fig. 3). Mean monthly temperature ranged from –2.1°C (December) to 12.1°C (July) and monthly precipitation ranged from 13.7 mm (October) to 158.2 mm (March), but remained relatively stable throughout the growing season (Fig. 3). The average precipitation was 2.7 mm per day.

Air temperature at 50 cm height rose by 7% and 13% in the 50% and 80% thinned treatments, respectively (data not shown). This means that on a warm summer day of +18˚C in the unthinned treatments, the air temperature was +19.3˚C and +20.3˚C in the thinned treatments.

Thinning also increased soil temperature over the summer period, but the effects were more subtle than on air temperature (Fig. 4). The 50% and 80% thinned treatments had on average 1% and 7% higher soil temperatures, respectively, than the unthinned treatment (data not shown). Even though mean soil temperature did not increase as much as air temperature with thinning, there was a notable increase in within-day fluctuations of soil temperature in the thinned treatments (data not shown).

3.5 Soil respiration measurements

Soil respiration in the treatments generally followed soil temperature as it rose from spring until the middle of August and declined thereafter, while the unthinned fertilized treatment had maximum respiration rates in July (Fig. 5).

Seasonal average soil respiration between treatments ranged from 2.03 to 3.15 μmol CO_2 $m^{-2}s^{-1}$ (Fig. 6). Statistical analysis (Two-way ANOVA) revealed that thinning significantly lowered the soil respiration rate (P=0.004), when compared across fertilization treatments. The reduction of soil respiration with thinning intensity was more pronounced in the unfertilized treatment (Fig. 6), even if the interaction between thinning and fertilization was not significant (P=0.37).

Two-Way ANOVA also showed that fertilization significantly increased soil respiration (P=0.007), when compared across all three thinning treatments (Fig. 6). This was a valid observation for all thinning intensities, since the interaction term was not significant (C*F P=0.37). When the thinning treatments were compared individually, it was clear that the positive fertilization response increased with thinning intensity.

4 Discussion

4.1 Physical factors

The precommercial thinning increased average soil and air temperatures within the stand and increased the daily fluctuations in temperature. Such responses were to be expected as LAI and shading within the stand decreased (Aussenac, 2000; Thibodeau et al., 2000).

4.2 Responses of trees

Leaf N concentration in unfertilized plots (ca. 20 mg N g^{-1} dry weight in the youngest fully expanded leaf) revealed that the natural N supply was low and N was a limiting factor in tree growth. Sigurdsson (2001) found that N limited tree growth when dry weight leaf N concentration was below 30 mg g^{-1}.

No effects were noted on tree height and diameter growth in the first year of fertilization treatments. This slow growth response is in accordance with previous Icelandic forest management experiments (e.g. Óskarsson and Sigurgeirsson, 2001; Sigurdsson, 2001), where lag in fertilization response was observed. The only tree growth response in the first year was observed in the mean leaf size, which was significantly increased with fertilization. The average leaf size did, however, not increase as much in F-50 and F-80 compared to F-00. When trees grow in an environment where competition for light is high they often respond by growing larger and thinner leaves (Sigurdsson, 2001). Smaller leaf size in thinned fertilized treatments may show that competition for light was considerable in the unthinned plots and thinning was needed.

The negative response of leaf N to thinning intensity in the fertilization treatments was noteworthy, and maybe indicated more competitive understory N uptake with higher forest floor irradiance when tree LAI decreased or more immobilization of N by previously more temperature limited soil microorganisms. The latter was observed in a study by Thibodeau et al. (2000).

4.3 Soil respiration

The results of the present experiment did only partly support the hypothesis that was being tested. We predicted that soil respiration would increase with thinning intensity, due to higher soil temperatures and increased litter input. Thinning was, however, found to significantly reduce soil respiration during the first summer after treatments, and the reduction increased with thinning intensity. How can this be explained? Olsson et al. (2005) found that 63% of total soil respiration can be attributed to living tree roots in a Norway spruce stand in Sweden and similar results were recently reported by Korhonen et al. (2009) for Scots pine forest in Finland. Högberg et al. (2001) first demonstrated that in northern forest ecosystems an unexpectedly large proportion of the soil respiration consists of recently fixed CO_2 by canopy photosynthesis that has been translocated belowground and used by roots, mycorrhizae and exudation.

The thinning in the present study reduced tree density by ~50% and ~80%, leading to similar relative reduction in LAI. This should have reduced photosynthesis per area and the amount of respiring roots per area is likely to have reduced following the thinning. Therefore we believe the negative effects of thinning on soil respiration in our study to be the result of a reduction in the autotrophic root respiration and this effect was greater than any possible increase in heterotrophic respiration or understory root respiration. That the reduction of soil respiration increased with thinning intensity in the present study strongly supports this hypothesis. The present study therefore gives an example of strong autotrophic control of soil respiration for northern deciduous forest, but most other studies have been done in coniferous stands (Högberg et al., 2001; Olsson et al., 2005; Tang et al., 2005; Korhonen et al., 2009).

Our initial hypothesis that fertilization would increase soil respiration was supported by our findings. A recent meta-analysis by Knorr et al. (2005b) indicates that fertilization initially stimulates litter decomposition at sites with low ambient N deposition (<5 kg ha^{-1}year^{-1}) and for high quality (low-lignin) litters, whereas decomposition rates are generally reduced at sites with moderate levels of N deposition (5–10 kg ha^{-1}

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

year^{-1}). The N-decomposition in Iceland is low, or generally $<1.5\,\mathrm{kg\,N\,ha^{-1}\,year^{-1}}$ (Gíslason et al., 1996). Our results are therefore in accordance with previous findings on the initial fertilization response on soil respiration at higher latitudes, where the N-supply is a limiting factor in forest ecosystems (Hyvönen et al., 2007). It should, however, be stated that some recent studies have shown that the long-term fertilization in northern forests may decrease the rate of decomposition and soil respiration (e.g. Hyvönen et al., 2007).

Temperature and moisture have been found to play an important role in seasonal patterns of soil respiration (Ma et al., 2005). As was previously mentioned, the soil water potential has been found to be permanently close to field capacity at the present site (Strachan et al., 1998), and water availability was therefore not considered to limit tree growth or ecosystem processes. Therefore, temperature is likely the key determent of seasonality in soil respiration at the site, as was indeed indicated by similar seasonal fluctuations in seasonal soil respiration and temperature for all treatments.

5 Conclusions

It was expected that precommercial thinning and fertilization would have an immediate additive effect on soil respiration, due to higher soil temperatures and increased litter input. The data showed that fertilization indeed increased soil respiration, but thinning intensity decreased it. This occurred even though soil temperatures rose with thinning and all organic material was left at site. This response was interpreted as a signal from decreased autotrophic root respiration in the thinned stands; a response missing in most or all simulation models of the carbon cycle in managed forests. Hence, these results may be important when the effects of early forest management on carbon fluxes are modeled.

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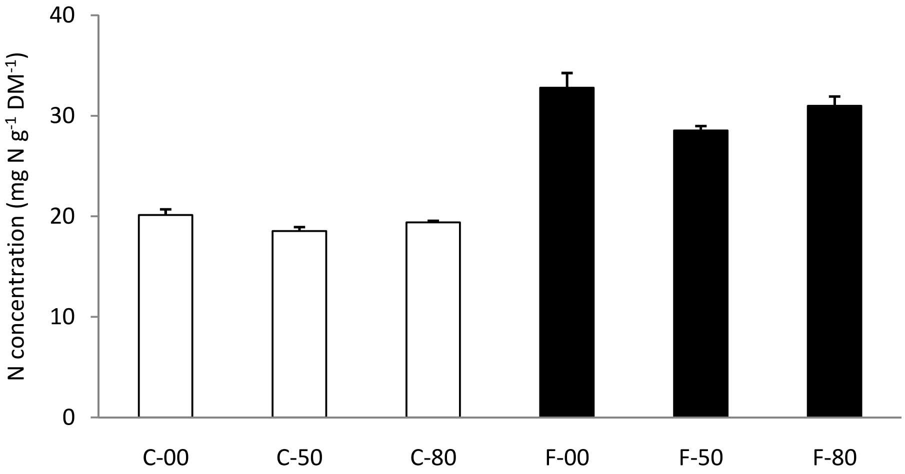

Fig. 1. Mean N concentration per g leaf in the youngest fully developed leaves of *Populus trichocarpa* canopy in August 2004 in unfertilized or fertilized (C or F) treatments with different thinning intensities (0%, 50%, 80%). Each bar represents an average ±SE of n=14.

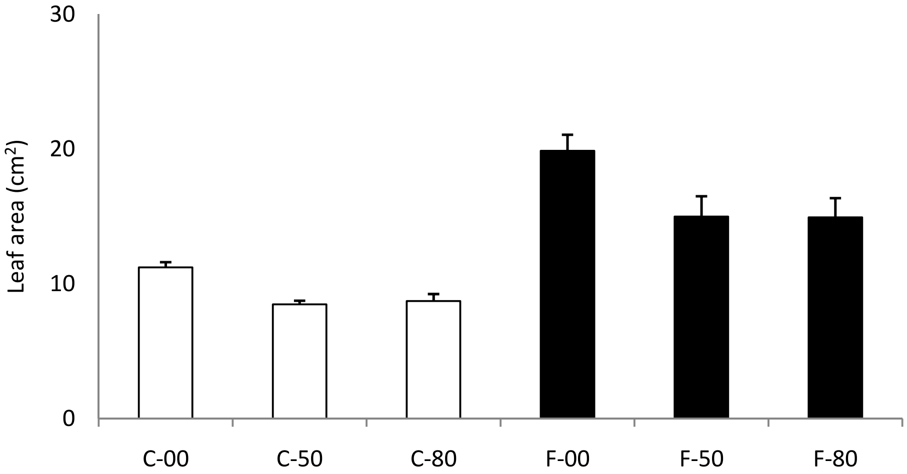

Fig. 2. Average leader shoot leaf size (cm^2) of *Populus trichocarpa* canopy in August 2004 in unfertilized or fertilized (C or F) treatments with different thinning intensities (0%, 50%, 80%). Each bar represents an average ±SE of n=6.

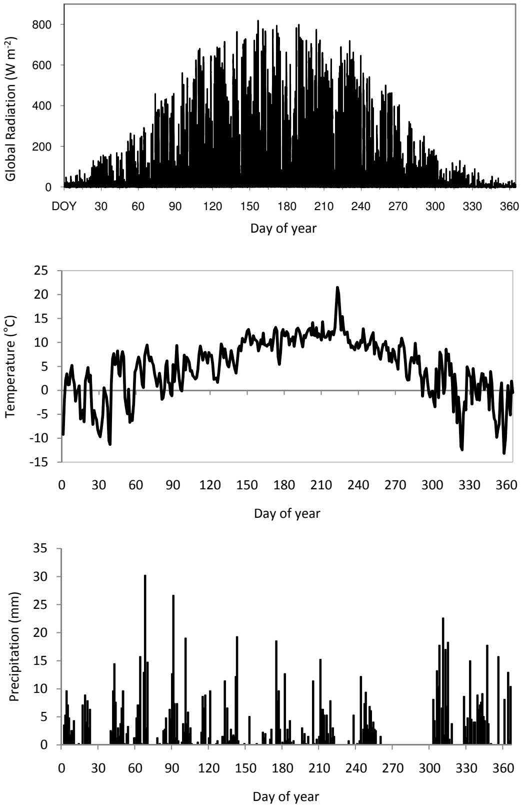

Fig. 3. Daily global radiation above canopy (top panel), mean daily air temperature (°C) at 2 m height (middle panel) and daily precipitation (bottom panel) measured in the *Populus trichocarpa* experimental plantation in 2004.

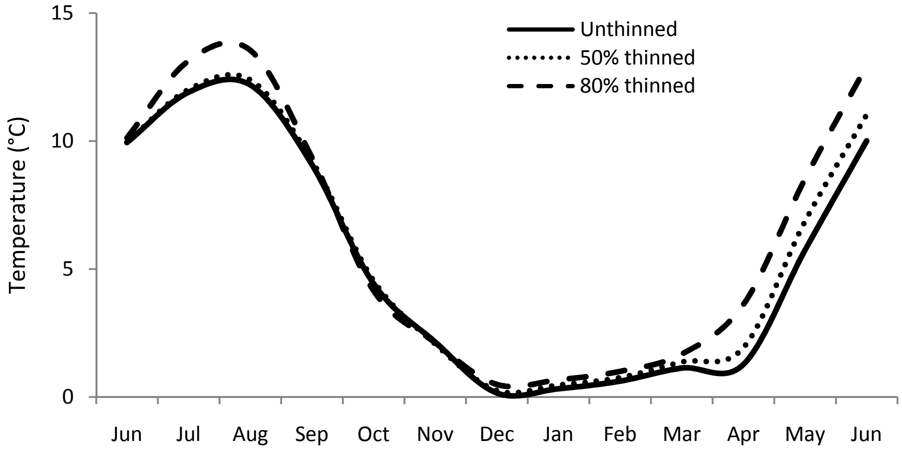

Fig. 4. Soil temperature (°C) in different thinning treatments at 10 cm depth over one year period from establishment. The measurements are averages of n=2.

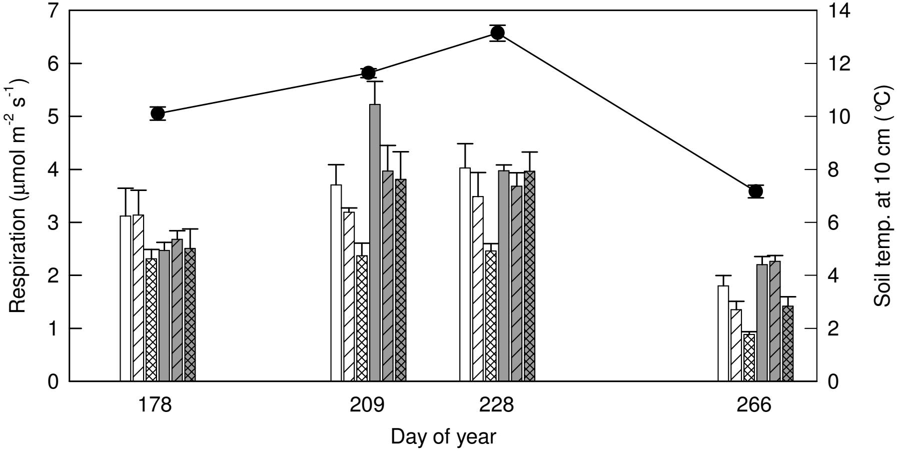

Fig. 5. Seasonal changes in soil respiration rates and mean soil temperature at 10 cm depth (line) of *Populus trichocarpa* plots in unfertilized (no fill) or fertilized (grey fill) treatments with unthinned (no pattern), 50% thinned (diagonally hatched) and 80% thinned (crosshatched) during the growing season in 2004 (22 June to 22 September) Each bar represents an average ±SE of n=4.

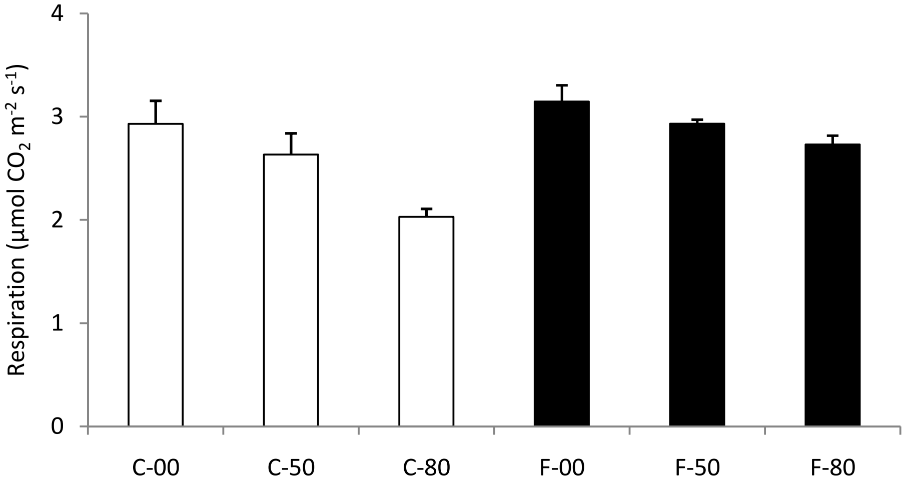

Fig. 6. Seasonal average soil respiration rate of *Populus trichocarpa* plots in unfertilized or fertilized (C or F) treatments with different thinning intensities (0%, 50%, 80%) during the growing season in 2004. Each bar represents an average ±SE of n=4.