The effects of thinning on carbon stocks and fluxes in a Chinese arborvitae plantation

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ABSTRACT

China has extensive areas of forest plantations that sequester and store large quantities of carbon. However, the rate of carbon sequestration by Chinese arborvitae (*Platycladus orientalis* Linn. Franco) is unknown. This research looks at carbon stocks and fluxes in forest vegetation, soil and litter seven years after thinning Chinese arborvitae in order to evaluate the effect of thinning levels on carbon sequestration. At 22 years, the plots were reduced from 5900 to 4100 and 3000 trees per hectare in three replicates. Carbon stocks of above-ground tree materials were lowest in the heaviest thinned plots and highest in the control plots. Above-ground shrub carbon pools were the opposite, i.e., largest in the heaviest thinned plots and lowest in the controls. Soil and litter carbon stocks were not affected by thinning treatment. Results suggest that thinning may positively affect vegetation carbon sequestration in the short term, an important observation for forest managers using thinning to optimize carbon sequestration capacity.

Key words: forest management, carbon sequestration, warm-temperate forest, soil respiration

Résumé

La Chine comporte de vastes étendues de plantation forestière qui captent et emmagasinent de grandes quantités de carbone. Cependant, le taux de séquestration du thuya de Chine (*Platycladus orientalis* Linn. Franco) n'est pas connu. Cette étude porte sur les stocks et les flux de carbone dans la végétation forestière, le sol et la litière sept ans après une éclaircie réalisée dans un peuplement de thuya de Chine afin d'évaluer les effets de l'éclaircie sur la séquestration du carbone. Les parcelles localisées dans des peuplements de 22 ans ont été éclaircies pour réduire le nombre d'arbres par hectare de 5 900 à 4 100 et 3 000, dans un dispositif à trois répétitions. Les stocks de carbone de la partie épigée des arbres étaient les plus faibles dans les parcelles les plus éclaircies et les plus élevés dans les parcelles témoins. Les stocks de carbone de la partie épigée des arbustes se sont comportés à l'inverse, c'est-à-dire, les plus élevés dans les parcelles les plus éclaircies et les plus faibles dans les parcelles témoins. Les stocks de carbone dans le sol et la litière n'ont pas été influencés par l'éclaircie. Les résultats suggèrent que l'éclaircie pourrait affecter de façon positive le stockage du carbone dans la végétation à court terme, une constatation importante pour les aménagistes forestiers qui utilisent l'éclaircie pour optimiser la capacité de séquestration du carbone.

Mots clés : aménagement forestier, séquestration du carbone, forêt tempérée chaude, respiration des sols

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Introduction

Detailed investigation of current carbon stock levels and sequestration potentials is required to understand the role of China's plantations in global carbon dynamics (Valentini *et al.* 2000, Hudiburg *et al.* 2009). In order to optimize forest carbon sequestration, it would be particularly beneficial to determine if specific management practices can modify carbon stocks of important tree species.

For instance, thinning as a management tool has been widely utilized to manipulate stand growth and timber yield (Hoover and Stout 2007). Thinning a densely stocked stand reduces its carbon stock and turns it into an atmospheric source of carbon initially (Dore *et al.* 2010), but it may gradually turn into a carbon sink with the rapid growth and enhanced photosynthesis of remaining trees. Thinning may influence overall ecosystem carbon sequestration by not only affecting tree growth but also microclimatic environments within the plantation, which alter soil CO₂ flux rates. In addition, thinned plantations are less vulnerable to wildfire (as fuel on the ground has been reduced), preventing carbon emissions through burning (Finkral and Evans 2008, Hurteau *et al.* 2008). Further, as a silvicultural tool, thinning has been widely used to moderate competition in favor of species/individuals of interest to increase tree production (Liu *et al.* 1992) and resistance to pests (Coyea and Margolis 1994), thereby achieving a more mature and stable forest structure within a shorter time period (Vargas *et al.* 2009).

Chinese arborvitae is a regionally representative species of the warm-temperate coniferous forests of China. Plantations of this species in the greater Beijing area cover about 26% (State Forestry Administration 2007). It is one of the most important species used for reforestation and afforestation in this region. The species is widely distributed as it tolerates nutrient deficiency and drought (Feng *et al.* 1999). As such, Chinese arborvitae offers a unique opportunity to test climate change mitigation through forest management practices.

It is well known that the productivity of Chinese arborvitae plantations may be greatly enhanced through thinning (Duan *et al.* 2010). Previous studies of these plantations identified management steps for optimal stand growth (Duan *et al.* 2010). However, the effects of thinning on carbon storage and fluxes are sparsely represented in the literature, but are in high demand to contribute to the knowledge base needed for enhanced forest carbon sequestration through management strategies. This paper reports on the effects of thinning of Chinese arborvitae plantations in the northern suburbs of Beijing seven years after treatment.

Methods

Study area

The research was conducted in 28-year-old plantations of Chinese arborvitae in the Shisanling area of Beijing (Fig. 1.). The site is a southeast-facing slope of 20% at an elevation of 900 m. It is under a temperate continental monsoon climate with a mean annual temperature of 4.8°C, an average annual precipitation of 610 mm and an average relative humidity of 66%. The soil is alluvial with a pH of 6.6 to 7.2 and 17% to 21% organic matter. The understory includes mountain-ash (*Sorbus pohuashanensis* [Hance.] Hedl.), honeysuckle (*Lonicera japonica* Thunb.), hazelnut (*Corylus mandshurica* Maxim.), spiraea (*Spiraea trilobata* Linn.), bushclover (*Lepedeza bicolor* Turcz.), painted maple (*Acer mono* Maxim.) and vervain (*Vitex negundo* Linn. var. *heterophylla* [Franch.] Rehd.).

Experimental design

Thinning treatments were based on different management objectives and resource availability in April 2004. The original density was 5900 trees per ha. Two thinnings were carried out to reduce stands to 4100 trees per ha (N4100 treatment) and 3000 trees per ha (N3000 treatment). The control of 5900 trees per ha was not thinned. The N4100 and N3000 treat-

Fig. 1. The site was located in the Changping area of northwestern Beijing (black circle) at 900 metres elevation, shown within the greater Shisanling ecoregion (shaded area)

ments represent the early rotation period and the late thinning, respectively, for this species. Plots were divided into three treatments and three replications. Each of the nine plots was 0.1 ha with a 20 m aisle between plots. The placement of each plot within the plantation was arbitrary and only established to avoid edge influence. Large slash piles were removed after thinning and the stands remained intact. Information on tree characteristics at the time of the first stand measurement in 2005 (one year after thinning) are summarized in Table 1.

Table 1. Stand characteristics (mean values [S.D.]) in 2005

Treatment	Average height (m)	Basal area (m ² ha ⁻¹)	Canopy height (m)	Standing volume (m ³ ha ⁻¹)
Control	6.07±0.67	19.83±1.31	4.28±0.69	61.91
N4100	6.50±0.40	16.02±2.01	4.75±0.33	45.82
N3000	5.68±0.78	12.44±1.82	4.32±0.50	34.14

Biomass estimation

Height and diameter at breast height (DBH) were recorded yearly for all trees with a DBH >3 cm in each plot at the end of each growing season in 2011. Standing volume including bark was calculated with volume functions (Chen *et al.* 1986). Tree biomass for each plot was determined using species-specific allometric equations based on tree height and DBH (Chen *et al.* 1986). Tree biomass (including stems, branches and bark), foliage and coarse roots >1 cm diameter were used. The total biomass for each plot was determined by adding all compartments for all trees. Average carbon content was approximately 50%.

The volume of dead wood (snags) and stumps (DBH >2.5 cm) were determined and their biomass calculated. Average density of woody debris was determined by weighing and dividing this value using water volume displaced (Tang *et al.* 2003). Average carbon content was around 50%.

Ten subplots (2 m × 2 m) were randomly selected from each plot to determine understory (hereafter referred to as shrubs) biomass for wood and foliage in 2011. All samples were harvested and used to measure biomass after oven-drying at 75°C for three days. The carbon fraction was estimated using a conversion factor of 0.50 based on carbon analyses (Fang *et al.* 2007).

Soil sampling

Fine roots (≤ 1 cm diameter) present in the top 20 cm of soil were sampled by using soil cores (7.5 cm diameter). In each plot, 15 regularly spaced soil core samples were taken each month from May to September in 2011. Fine roots were manually isolated from the sampled mineral soil cores, rinsed free of organic matter with deionized water and oven-dried at 70°C to determine dry weight. Fine roots of each plot were estimated using a modified maximum and minimum root core method (McClagherty *et al.* 1982). Additionally, the forest floor was sampled at 15 points within each plot by soil coring (5.5 cm diameter). All samples were dried at 75°C for three days and weighed. Oven-dried forest floor masses were converted to carbon using a factor of 0.5 (Law *et al.* 2001).

Within the plantations, five soil profiles for each plot were randomly located to cover possible variations of soil properties. Soil bulk density was sampled from each soil horizon (10 cm for each horizon, for a total of seven horizons). Mineral soil carbon content down to 70 cm was calculated in terms of bulk density and organic matter content was measured using the wet digestion method. Soil organic carbon stocks were estimated from organic matter using a factor of 0.58 (Fang *et al.* 2007).

Litter collection

In May 2010, five litter collectors were placed randomly within each plot in a regular pattern (1 m × 1 m). The collectors were square-shaped with wooden poles 0.5 m above the ground. Growing season litterfall was collected each month, while winter litterfall was collected once every two months. The last litter collection was made December 2011. One year's litter was collected from autumn 2010 to autumn 2011. The litter was dried at 75°C for three days and weighed. The oven-dried biomass was converted to carbon using a factor of 0.5 (Law *et al.* 2001).

Soil respiration

Soil respiration rate (Rs) was measured using a LiCor-6400 portable infrared gas analyzer coupled to a LiCor-6400-09 soil respiration chamber (LiCor Biosciences, Lincoln, NE, USA) for data collection and storage. Ground vegetation was removed before measurement in order to minimize disturbance. During measurements, the chamber sat on permanently installed PVC collars (10 cm diameter, 5 cm height) inserted 3 cm into the ground at least 20 days before measurement to ensure that the soil had recovered from the disturbances. For each plot, soil respiration was measured monthly at 10 points from May to September in 2011. On each occasion, all 120 spots were measured on three or four rain-free days to minimize effects of diurnal fluctuation. Soil temperature (Ts) and soil water content (Ms) near the chamber at 10 cm depth below ground was measured simultaneously with the Rs with a 6400 temperature probe (LiCor Biosciences, Lincoln, NE, USA) and a time domain reflectometer system (TDR, CS615 Campbell scientific, Logan, UT, USA).

Statistical analysis

For the Rs measurements, there were five samples within each plot and calculated based on average daily values each month. The thinning treatments effect on various carbon pools and Rs were tested using the interaction term of replicate and treatment as random error (ANOVA). If the effects of treatments were significant, means were further compared by Duncan's multiple range tests with a confidence level of $P < 0.05$. All tests were performed using SPSS v10.0 statistical software (SPSS Inc., Chicago, IL, USA). The Rs of repeated measurements in the same occasion was analysed in SPSS to assess the effect of time during the growing season.

Results

Carbon stock assessment

Wood (stem + branch) and foliage carbon stocks in the N4100 plots were some 74% of control plots, determined by above-ground tree carbon pools (Table 2). Similarly, total above-ground tree carbon pools were 54% of control plots in

Fig. 2. Litter production during one year.

Table 2. Distribution of tree and shrub carbon pools (t ha⁻¹) – mean values and (S.D.)

Item	Treatment		
	Control	N4100	N3000
Tree-stem (including bark)	20.42b (10.30)	15.03a (6.05)	11.12a (5.60)
Tree branches	11.00b (4.71)	8.30a (3.09)	5.69a (2.32)
Tree foliage	9.15b (2.37)	6.44a (2.15)	5.17a (1.61)
Shrub-branches	0.74b (0.23)	1.00a (0.19)	1.24a (0.31)
Shrub-foliage	0.16b (0.05)	0.42a (0.06)	0.59a (0.09)
Coarse root (R > 2 cm)	10.80b (4.02)	9.51ab (2.86)	7.80a (2.04)
Fine root (R > 2 cm)	0.0150a (0.08)	0.0124a (0.04)	0.0120a (0.05)
Stumps	3.66b (0.84)	2.73a (0.93)	2.06a (0.68)
Sum	55.95b (23.61)	43.44a (15.37)	33.68a (12.71)

Figures with different letters are significantly different (5% level). Respiratory fluxes are presented as the average of periodic measurements during the growing time in 2011 and were largely conserved between treatments.

Table 3. Soil carbon stocks and forest floor mass (t ha⁻¹) – mean values and (S.D.)

Item	Treatment		
	Control	N4100	N3000
Soil carbon stocks	52.52a (6.40)	53.32a (8.34)	46.50a (6.43)
Forest floor layer	17.28a (3.14)	18.81a (2.81)	23.34a (4.84)
Sum	69.80a (9.54)	72.14a (11.15)	69.84a (11.27)

Figures with different letters are significantly different (5% level). Respiratory fluxes are presented as the average of periodic measurements during the growing time in 2011 and were largely conserved between treatments.

the N3000 treatment. The response of above-ground shrub biomass to thinning was different from that of tree biomass. Above-ground shrub biomass in N3000-treated and N4100-treated plots was on average 2.0 times and 1.6 times higher than control plots, respectively.

Patterns in belowground coarse root biomass were similar to the above-ground tree biomass. The amount of fine roots decreased with thinning intensities but differences between treatments was not significant. Despite differences in the proportion of tree and shrub biomass among treatments, the

ecosystem-level wood : root : foliage biomass ratios were 60 : 25 : 15 among all treatments. The conservation of components at the ecosystem level was afforded by the shrubs on these plots having only marginally higher foliage fractions than the trees (0.31 and 0.19 for shrubs and trees, respectively).

Litter production

No significant effect of thinning was found on litter production over a one-year period (Fig. 2). Decreased amounts of litter were noted in treated plots. The difference between the control plots and the N3000-treated plots was about 0.22 t C ha⁻¹ a⁻¹.

Soil carbon stocks and forest floor

Table 3 shows the carbon stocks of forest floor and soil down to 70 cm. There were no significant effects of treatment shown in any soil layers.

Soil respiration

Daytime Rs during the growing season averaged 2.8, 4.5, and 3.5 μ mol CO₂ m⁻² s⁻¹ in the control, N3000 and N4100 treatment plots respectively (Table 4). No significant variation was observed in the treatments effect as well as measurement time (occasion). The seasonality of soil respiration was similar across all treatments. The lowest soil respiration occurred in the control plots while the highest was found in the N3000-treated plots, with the notable exception for July. Similarly, the lowest respiration fluxes occurred in May and the highest in August.

Discussion and Conclusions

Above-ground carbon pools

This study is one of the few to apply silvicultural thinning in Chinese arborvitae, warm-temperate plantations (Duan *et al.* 2010). The primary goal was to determine the consequences of thinning on carbon stocks

and fluxes in Chinese arborvitae plantations.

Generally, thinning leads to a decrease in volume increment per hectare (Slodick *et al.* 2005) and several studies have shown that thinning leads to decreased standing biomass per hectare (Hoover and Stout 2007, Campbell *et al.* 2009). Therefore, controls had the largest carbon pools. Thinning regimes significantly increased carbon pools from the understory. The magnitude of this response was dependent on residual stand density and thinning intensity. A high stand density will have limited light penetration and water availabil-

Table 4. Comparison of soil respiration rate (Rs), soil temperature (Ts) and water moisture (Ms) (mean and S.D.) during the growing period in 2011.

		May 15–18	Jun 25–28	Jul 20–23	Aug 13–15	Sep 15–18
Rs ($\mu\text{ mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$)	Control	1.12 (0.06)	1.92 (0.09)	2.92 (0.21)	5.59 (0.32)	2.50 (0.26)
	N4100	2.35 (0.13)	2.89 (0.16)	2.82 (0.22)	5.88 (0.42)	3.60 (0.31)
	N3000	3.23 (0.26)	3.89 (0.28)	3.47 (0.33)	7.90 (0.49)	4.08 (0.33)
Ts ($^{\circ}\text{C}$)	Control	17.31 (1.52)	19.20 (1.29)	21.07 (0.99)	24.49 (1.32)	15.33 (1.41)
	N4100	18.41 (1.25)	22.83 (1.43)	21.57 (1.32)	23.01 (0.98)	13.18 (1.26)
	N3000	22.73 (1.32)	23.13 (1.39)	23.26 (1.20)	25.10 (1.22)	14.21 (0.96)
Ms (%)	Control	5.73 (0.03)	7.57 (0.02)	6.79 (0.04)	9.40 (0.07)	6.52 (0.06)
	N4100	6.78 (0.04)	8.85 (0.04)	7.35 (0.05)	12.15 (0.08)	8.05 (0.05)
	N3000	9.10 (0.05)	9.66 (0.03)	9.47 (0.04)	14.41 (0.05)	9.91 (0.06)

ity, confining growth and accumulation to the understory. Understory vegetation gave a greater proportion of biomass to foliage indicating that compensatory responses of undergrowth to thinning may have an important impact on the carbon sink (Campbell *et al.* 2009). The increase in shrub carbon pools after thinning was smaller than either the amount of tree mass removed or left behind. Changes in forest structure may affect carbon allocation.

Litter

With differences in above-ground biomass, it might be expected that there would be more litter in the control plots. However, differences between thinning treatments were not statistically significant (Fig. 2). Litter was approximately 0.78 t C ha⁻¹ a⁻¹ to 1.00 t C ha⁻¹ a⁻¹ in the different treatments which is minor compared to the litter of highly productive pine forests in Beijing of 2.34 t C ha⁻¹ a⁻¹ (Fang *et al.* 2007). Additionally, thinning had no effect on the production of litter. This is consistent with Slodicak *et al.* (2005), who found no differences between the amounts of litter in unthinned controls and thinned plots in even-aged Norway spruce.

Soil

Variations in soil carbon may be attributed to litter and/or the decomposition of root systems (Slodicak *et al.* 2005). In this study, decreased soil respiration and increased litter production in control plots increased soil carbon but there were no significant effects on soil carbon due to thinning. The difference in litter produced in control and N3000 plots was 0.22 t C ha⁻¹ a⁻¹ and soil respiration averaged 1.70 $\mu\text{ mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$. Taking this difference over five months, the result is 6.40 t C ha⁻¹ a⁻¹. Högborg *et al.* (2001) found that 50% of soil respiration was root respiration. The difference in heterotrophic respiration was 3.20 t C ha⁻¹ a⁻¹. Increased litter and lower heterotrophic respiration in the two treatments (4.90 t C ha⁻¹ yr⁻¹) equals 8% of total soil carbon stocks in the control plots. Additionally, slash was removed after thinning. This indicates that changes in soil carbon stocks within a seven-year time frame may be too minor to detect.

Soil respiration

Average soil respiration varied between 1.12 and 7.90 $\mu\text{ mol CO}_2\text{ m}^{-2}\text{ s}^{-1}$ during the growing period, typical of Chinese

arborvitae (Yu *et al.* 2011). The apparent conservation of soil respiration across treatments is consistent with the findings of Vesala *et al.* (2005) and Campbell *et al.* (2009), who found that soil respiration was unaffected by thinning treatments in ponderosa pine (*Pinus ponderosa* P. Laws. ex Laws.) forests in the Sierra Nevada Mountains.

Previous research has reported increases in soil respiration after thinning (Gordon *et al.* 1987, Hendrickson *et al.* 1989). This may be affected by soil temperature, water content, undergrowth cover, tree root biomass and litter fall. All these will affect soil microbial respiration and root respiration. Soil temperature and moisture may explain temporal variation in soil respiration (Yu *et al.* 2011). Increased soil temperature (Ts) and soil moisture (Ms) may also enhance root growth of remaining trees, given that there is less below-ground competition for water and nutrients (Santantonio and Santantonio 1987, Van Lear *et al.* 2000) and photosynthetic rates (Gravatt *et al.* 1997, Peterson *et al.* 1997). Additionally, thinning increased above-ground growth. This increased root growth and photosynthesis in thinned forests will increase root respiration. Investigation of litter biomass showed no differences between treatments. Russell and Voroney (1998) also indicated the inability of soil organic matter and litter mass to explain soil CO₂ fluxes in a study of boreal aspen (*Populus tremuloides* Michx.).

In conclusion, increased thinning in 22-year-old Chinese arborvitae plantations reduced above-ground tree carbon pools but increased shrub carbon stocks seven years after thinning. Increased forest floor carbon pools were also found but no significant effects due to thinning could be determined.

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