

# SUSTAINABLE PRODUCTION IN SUBTROPICAL HYBRID POPLAR PLANTATIONS

J Dai<sup>1</sup>, C Welham<sup>2</sup>, L Cao<sup>1</sup> & F Cao<sup>1, \*</sup>

<sup>1</sup>Co-Innovation Center for the Sustainable Forest in Southern China, Nanjing Forestry University, Nanjing 210037, PR China

<sup>2</sup>Department of Forest Resources Management, University of British Columbia, Vancouver, BC V6T 1Z4, Canada

\*njfu\_caofuliang@163.com

Received May 2015

**DAI J, WELHAM C, CAO L & CAO F 2016. Sustainable production in subtropical hybrid poplar plantations.**

Little is known of the impact of harvesting intensity on long-term productivity in subtropical forests. We used a simulation model to evaluate whole-tree and stem-only harvesting, rotation length and planting density on hybrid poplar (*Populus* spp.) stemwood biomass and volume in subtropical China. None of the management scenarios could be sustained without fertilisation with N, the main nutrient considered in the model. Yield decline was a consequence of losses in N capital from leaching and harvest removals and was more severe in whole-tree harvesting versus stem-only harvesting. As nutrient capital was depleted, understorey competition also had increasingly negative impact on stemwood biomass. Total stemwood biomass declined with rotation length. Gains in productivity from delaying harvest were therefore not offset by reduction in harvest frequency. Rotation length and planting density were also important determinants of the differential in total stemwood biomass between whole-tree harvesting and stem-only harvesting. A majority of logs were generated in the 5–20 cm dbh (diameter at breast height) class. Volumes of large-diameter (> 20 cm dbh) logs were small on a per-rotation basis but compared favourably to natural stands when multiple harvests were summed over the long term. These poplar plantations will need to be fertilised and managed on a large scale in order to sustain continuous wood flow.

Keywords: Stemwood, volume, fertiliser, whole-tree harvesting; stem-only harvesting, FORECAST model

## INTRODUCTION

China is one of the world's leading countries in terms of total forest plantation area (FAO 2010). There is an expectation that plantations will be an important component of future wood and fibre supply (Hong 1985) and, over recent decades, the Chinese government has expanded its afforestation programme, particularly with poplar (*Populus* spp.) (Brown 2000). Many of these stands have reached a stage that harvesting is a commercially viable option, leading to the decision of when to harvest. Delaying harvest produces bigger trees that are utilised for sawnwood products and are economically more valuable (PRC 1984). Shorter rotations allow for more frequent harvesting but produce smaller logs. These logs (< 20 cm diameter at breast height (dbh)) are usually chipped and used in papermaking (PRC 1984). If rotations are too short, there is a risk that site nutrient capital may be depleted (Merino et al. 2005), leading to yield decline (Bi et al. 2007, Wang et

al. 2013). Harvest intensity is another important management decision in these plantations. In whole-tree harvesting, the entire aboveground component is removed and processed offsite which can result in high nutrient export and stock depletion (Bélanger et al. 2003, Merino et al. 2005, Thiffault et al. 2006, 2007). These effects can be ameliorated through stem-only harvesting, wherein harvest residues are retained onsite (Wei et al. 2003). Regardless of the harvesting method, only if rotations are sufficiently long can nutrient stocks be restored to pre-disturbance conditions without the addition of fertiliser (Tuskan 1998). A key issue in managing poplar plantations in China is how to generate high value logs over a time frame shorter than would occur if timber was sourced from primary forests and still sustain long-term production.

There are four main approaches that could be used to evaluate this issue, namely, long-term field trials, chronosequence studies,

retrospective analyses and simulation modelling (Wei et al. 2003). Modelling can be undertaken with historical bioassay and process-based models (Korzukhin et al. 1996, Kimmins et al. 2010). Historical bioassay models are based on empirical descriptions of growth and stand development in relation to management inputs. Constraints on available data undermine the utility of this approach in poplar plantations in China, particularly with respect to evaluating alternative management options. Process-based models describe a system in terms of its major state components and the processes dictating the transfer of energy, water, nutrients and biomass (Pretzsch 2009). They have the benefit of considerable flexibility in terms of the management activities that can be represented and are well designed for addressing cause and effect relationships (Korzukhin et al. 1996). A key limitation in many of these models, however, is representation of log size. In the stand-level forest ecosystem model, FORECAST (Kimmins et al. 1999, 2010), stemwood biomass of individual trees is simulated using index of size differentiation derived from calibration data. The model then determines annual stem growth by allocating net primary production across the size classes. This allows for the calculation of traditional yield components for individual trees and at the stand level.

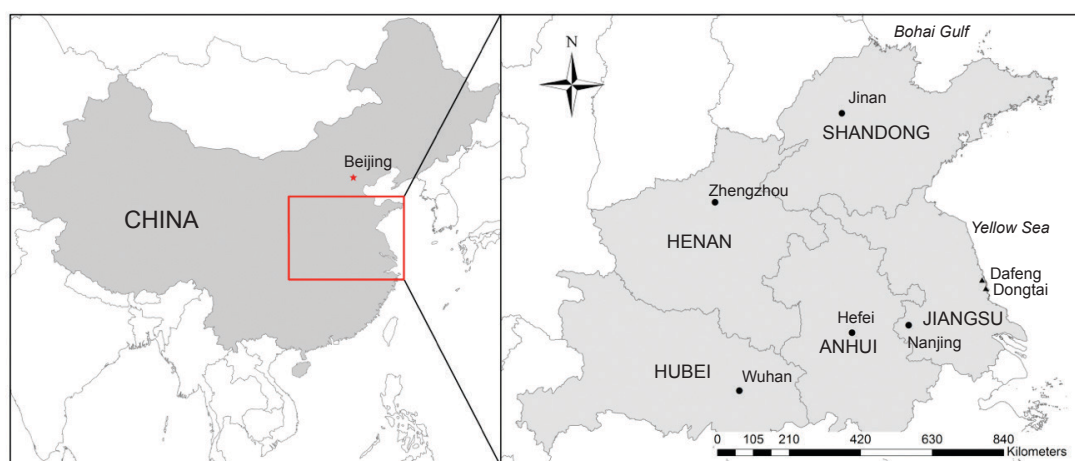
Here, we employed the FORECAST model to simulate yield in poplar plantations established in the subtropical region of north-east China. Model output was used to evaluate

the impact of harvesting intensity (whole-tree harvesting versus stem-only harvesting), rotation length (to a 30-year maximum), planting density (maximum 3000 stems ha<sup>-1</sup>), and fertilisation, on the relationship between stand biomass production and individual stem size. Most studies to date considered each of these factors separately but this analysis employed a factorial design in an effort to elucidate their joint interaction.

## MATERIALS AND METHODS

### Study area

Field data were derived from the 2240-ha Dongtai Forestry Farm, Jiangsu province, China (32° 52' N, 120° 49' E; Figure 1). The region has subtropical monsoon climate. Mean annual precipitation is 1050 mm and the mean annual air temperature is 14.6 °C, with an average of 2.5 °C in January and 27.7 °C in July. The annual frost-free period is about 220 days. Soil is a well-drained sandy loam with pH of 8.0–8.6, and total salt content of 1.1–2.1 g kg<sup>-1</sup>. The top 25-cm soil profile has a carbon–nitrogen ratio ranging from 17.5 to 29.8, and the ammonia and nitrate contents range from 17.4 to 20.9 mg kg<sup>-1</sup> and 3.1 to 4.1 mg kg<sup>-1</sup> respectively of dry soil (Fan 2014). A majority of the farm area (about 85%) is allocated to tree plantations. The main species are poplar (*Populus* spp. about 66% of the planted area), metasequoia (*Metasequoia glyptostroboides*) and ginkgo (*Ginkgo biloba*).



**Figure 1** Dongtai Forestry Farm, Jiangsu province, China

There were a total of 157 hybrid poplar plantations used in the study, occupying a total area of 1469 ha. Plantations were mixtures of clones I-69 (*P. deltoides*), I-72 (*P. xeuranmericana*) and I-35 (*P. deltoides*), established using 1-year-old rooted seedlings at densities that varied between 333 and 1500 stems ha<sup>-1</sup>. The oldest plantation originated in 1989 and was therefore 19 years old at the time of measurement. The youngest plantation was 3 years old. Rapeseed (*Brassica napus*) or wheat (*Triticum aestivum*) was sown in spring of the first three years in each plantation. Up to 750 kg ha<sup>-1</sup> year<sup>-1</sup> of undiluted urea (CH<sub>4</sub>N<sub>2</sub>O) was applied shortly after seeding but discontinued when crops were no longer seeded. Crops were harvested at the end of each growing season and all aboveground parts removed. Plantations were minimally hand-weeded in the years subsequent to when crops were no longer sown to reduce understorey competition.

A total of 157 (20 m × 20 m) plots were established in June 2008, one randomly located in each plantation. Dbh and height were measured within each plot for all trees with dbh > 5 cm. These data were used in a series of allometric equations to estimate above- and belowground biomass (Feng 2007):

$$\begin{aligned} W_{\text{stemwood}} &= 0.051(D^2H)^{0.823} \\ W_{\text{branch}} &= 0.103(D^2H)^{0.621} \\ W_{\text{foliage}} &= 0.003(D^2H)^{0.736} \\ W_{\text{stembark}} &= 0.006(D^2H)^{0.842} \\ W_{\text{root}} &= 0.005(D^2H)^{0.893} \end{aligned}$$

where W = dry weight (kg) and D and H = tree dbh and height respectively. Plot-level calculations were made from individual tree data and then expressed on a ha<sup>-1</sup> basis.

### The FORECAST model

FORECAST is a process-based stand-level ecosystem management model (Kimmins et al. 2010) and has been tested and applied in tropical and subtropical forests (Blanco & González 2010, Wang et al. 2013, Wei & Blanco 2014). The model employs a hybrid simulation approach in which the rates of key ecosystem processes are calibrated, in part, from empirical data (Kimmins et al. 1999, Seely et al. 1999, Wang et al. 2013). It can represent one or more tree and understorey

species, whose growth and survival depend on simulated competition for light and nutrients.

FORECAST employs a mass balance approach. It therefore outputs stand-level data on biomass of individual plant components (stemwood, branches, foliage, roots, etc.) as well as gross and merchantable volumes. Another key output variable is the stemwood biomass and dbh of individual tree. This component is simulated using an index of individual tree size, calibrated with data contained in the input file that describe the stem size frequency distribution for a given stand age. Stem-size distribution data may be inputted for up to 10 stand ages though only one size distribution is actually required. During a model run, net primary production in a given year is allocated across the distribution to calculate stem size increase in each time step; further details are provided in Kimmins et al. (1999). FORECAST can accommodate a comprehensive suite of management activities (Seely et al. 1999) and has been applied to a broad range of tree species (Blanco et al. 2005, Kimmins et al. 2010, Wei & Blanco 2014), including hybrid poplar (Welham et al. 2007).

### Model calibration and validation

FORECAST requires calibration data of biomass accumulation for each of the species to be simulated, along with associated soil variables (see Kimmins et al. (1999) for a complete list). When possible, poplar calibration data were derived from regional estimates but no data from the Dongtai site were used for calibration; the latter were reserved for model validation. Biomass values were calculated from height and dbh data in growth and yield reports (Sun et al. 2006, Xiao 2006) using the allometric equations reported above. Other local calibration data included stand densities (Tang et al. 2004, Xu & Chen 1994), photosynthetic efficiency (Qi & Chen 2011), litter decomposition rates and soil nutrients (Lu 2011). Additional variables are listed in Table 1.

Calibration data for wheat were derived, in part, from harvests conducted on the Dongtai farm. These data were supplemented with additional measurements from local (largely unpublished) sources and literature values (Cao 2004, Fang et al. 2005, Xie 2005) (Table 2).

**Table 1** (a) Vegetation parameters used in the hybrid poplar calibration data set, the associated N concentrations and their annual conversion to litterfall as well as the decomposition coefficient (k value) for each litter type and (b) soil parameters used in the calibration data set

Parameter <sup>a</sup>	N (%)	Litterfall (proportion year <sup>-1</sup> )	k value
(a) Vegetation parameter			
Sapwood	0.19	0.06	0.08
Heartwood	0.07		0.06
Live bark	0.9, 1.2, 1.35 <sup>c</sup>	0.1	
Dead bark	0.66, 0.76, 0.87		0.1
Live branches	0.7, 0.8, 0.9 <sup>c</sup>	0.04	
Dead branches	0.2, 0.25, 0.3		0.09
Live foliage	0.8, 0.9, 1.0 <sup>d</sup>	1	
Dead foliage	0.4, 0.45, 0.5 <sup>b</sup>		0.5 <sup>c, d</sup>
Live coarse roots	0.19 <sup>c</sup>	0.06	
Dead coarse roots	0.037		0.09
Live fine root	0.65, 0.7, 0.75 <sup>c</sup>	1.1	
Dead fine root	0.5, 0.55, 0.6		4
(b) Soil parameter			
	Value		
Soil cation storage capacity (kg N ha <sup>-1</sup> )	25, 50, 80 <sup>b, f</sup>		
Humus cation storage capacity (kg N tonne <sup>-1</sup> humus)	2.5 <sup>b</sup>		
Proportion active humus	0.8		
Active humus N (%)	1.5		
Passive humus N (%)	5		
Active humus mass loss (proportion year <sup>-1</sup> )	0.018		
Passive humus mass loss (proportion year <sup>-1</sup> )	0.001		
Precipitation N input (kg N ha <sup>-1</sup> year <sup>-1</sup> )	4.0 <sup>b, g</sup>		
Non-symbiotic N fixation (kg N ha <sup>-1</sup> year <sup>-1</sup> )	1.0 <sup>g</sup>		

<sup>a</sup>Values as per Welham et al. (2007), except as noted, <sup>b</sup>Qi & Chen (2011), <sup>c</sup>Lu (2011), <sup>d</sup>Wang (2012), <sup>e</sup>Yu et al. (2005), <sup>f</sup>Li et al. (2007) and <sup>g</sup>Wei et al. (2012)

### Creating the ecosystem starting condition

The first step in the application of FORECAST is to create the ecosystem starting condition (the ECOSTATE). The ECOSTATE reflects the buildup of soil organic matter in terms of its component litter and humus types and their stages of decomposition (Kimmins et al. 1999). FORECAST can simulate availability and competition for up to four nutrients. These simulations are focused on N, in part, because it is generally limiting throughout warm, humid subtropical China (Blanco et al. 2012), and relatively little is known about limitations and tissue concentrations of additional nutrients. In addition, N fertilization is widespread in China

ostensibly to correct deficiencies in this nutrient (Ju et al. 2009).

The ECOSTATE was created by simulating a 30-year period of site management prior to establishing the poplar plantations, as follows. In this period, wheat was sown annually at an initial ground cover in each year at 10%. For the first 29 years, wheat growth occurred with the nutrient feedback algorithm in FORECAST disabled. This meant that, in every year, nutrient demand was always satisfied and the crop was therefore able to achieve its maximum biomass, as dictated by the calibration data set. At the end of each year, the wheat was harvested. All biomass components except the seeds were left on-site in order to build up soil organic

**Table 2** FORECAST calibration data for wheat (*Triticum aestivum*)

Parameter	Value
Maximum aboveground biomass (kg ha <sup>-1</sup> )	9300
Maximum seed yield (kg ha <sup>-1</sup> )	4720
N (%)	
Live stem	0.71–1.34
Dead stem	0.51–1.00
Live foliage	1.87–2.69
Dead foliage	1.57–2.12
Live roots	0.38–0.62
Dead roots	0.35–0.53
Fruit	1.59–1.87

matter and its associated N capital. In the 30th year, nutrient feedback was turned on, which initiated nutrient competition, and potentially some limitation of biomass accumulation. The wheat was then planted and harvested as in the previous years. Note that atmospheric deposition was fixed at 4 kg N ha<sup>-1</sup> year<sup>-1</sup> in this and all simulations.

After implementing the setup protocol, the final soil organic matter and total available N (the amount of N accessible to plants) in the ECOSTATE file was 112.6 Mg ha<sup>-1</sup> and 438.4 kg ha<sup>-1</sup>, respectively. This compares favourably to measurements at the Dafeng Forestry Farm (33° 03' N, 120° 43' E), where Li (2012) reported 118.3 Mg ha<sup>-1</sup> for soil organic matter and 433.2 kg ha<sup>-1</sup> of available N. Dafeng is nearby to Dongtai and has similar soil and management regimes (Li 2012).

### Model scenarios

Poplar was planted in the model as 1-year-old seedlings at densities of 1000, 2000 or 3000 stems ha<sup>-1</sup>. These densities were considered sufficient to ensure full stocking but still have the potential to generate larger diameter logs (Hemery et al. 2005). Stands were permitted to grow for 10, 20 or 30 years before harvesting, except with the fertiliser scenario (see below) when a 5-year rotation was also added. Thirty years is considered the age after which senescence and decay begin to impact stand integrity. Any mortality incurred during stand development was left on site.

Two levels of harvesting intensity were simulated, whole-tree harvesting and

conventional, stem-only harvesting. Stem-only harvesting removed only stems and all other biomass components were left on site. With whole-tree harvesting, all aboveground biomass (stems, branches and foliage) was removed. Harvesting was assumed to occur during summer when foliage was present on the trees.

For purposes of analysis, harvested stemwood was allocated into three classes based on top (inside bark) diameter limits, namely, < 5 cm, 5–20 cm and > 20 cm. The smallest size class can be used for bioenergy (Mead 2001). The intermediate size class is considered suitable for pulping, while the largest diameter logs can be utilised as structural timbers (PRC 1984), the latter of which are of much higher value.

A second set of simulations was conducted with N fertilisation, using the same management regimes as described above and with the addition of a 5-year rotation. N was applied sequentially at a rate of 100, 150 or 200 kg N ha<sup>-1</sup> annually on a schedule designed to generate a level of stemwood biomass in subsequent rotations (i.e. after the first harvest) that was within 10% of the biomass produced in the first rotation. The application schedule was derived for each rotation using an iterative exercise in which fertiliser was applied in contiguous years and across rotations until sustained productivity was realised. Fertiliser was applied in the first year of planting and continued for either four or five years thereafter. Table 3 shows the total fertiliser added across the 120-year simulation period. In China, annual fertiliser application rates up to 600 kg N ha<sup>-1</sup> have been reported (Ju et al. 2009). Hence, the rates used in the simulations are not atypical.

**Table 3** Total nitrogen (N) added as fertiliser (kg N ha<sup>-1</sup>) across the 120-year simulation period, beginning with the second rotation

Planting density (stems ha <sup>-1</sup> )	Rotation length							
	5 years		10 years		20 years		30 years	
	WTH	SOH	WTH	SOH	WTH	SOH	WTH	SOH
1000	5450	2700	6600	5500	3300	2200	2000	1650
2000	8950	4450	8800	4750	4050	2250	2300	1950
3000	13,700	6800	9900	5300	4550	2650	2650	1850

WTH = whole-tree harvesting; SOH = stem-only harvesting

In the first rotation of all simulations, an understorey population of wheat was sown in conjunction with poplar at 10% cover density. This occurred only in the first three years of the plantation. An amount of 200 kg N ha<sup>-1</sup> was also applied in each of these years but not thereafter. The wheat was harvested annually and all aboveground biomass removed. In all other simulation years and subsequent rotations, wheat was sown at 1% cover density and simply harvested each year with all materials left on site. This protocol was designed to emulate anticipated natural ingress. Finally, a subset of runs was conducted with no understorey present to evaluate its competitive influence on poplar productivity. Poplar was established at combinations of 1000 and 3000 stems ha<sup>-1</sup>, harvested using whole-tree harvesting and stem-only harvesting at 10- and 30-year rotations respectively and with fertilisation in the first rotation only, as described previously.

### Assessing model performance

Model performance was assessed by comparing measured versus predicted trends in height, dbh, stemwood biomass and total tree biomass. Five performance assessments were undertaken (Wang et al. 2013): (1) the Pearson's correlation coefficient was calculated from linear regression of predicted versus observed values, (2) Theil's inequality coefficient, U (Theil 1966)—a zero value for U meant the model generated a perfect prediction; as values increased, model predictions became progressively worse (Bliemel 1973) and (3) modelling efficiency (Vanclay & Skovsgaard 1997). The modelling efficiency index generates a relative scale of the difference between predicted

and observed data. Modelling efficiency = 1 indicates perfect fit, while declining values indicate progressively poorer performance. The fourth and fifth assessments were calculations of average bias and mean absolute deviation respectively (Lo et al. 2011). Average bias was calculated to identify the overall directionality of the bias; positive and negative values indicate over- and under-estimate respectively. Mean absolute deviation was computed to determine overall magnitude of error.

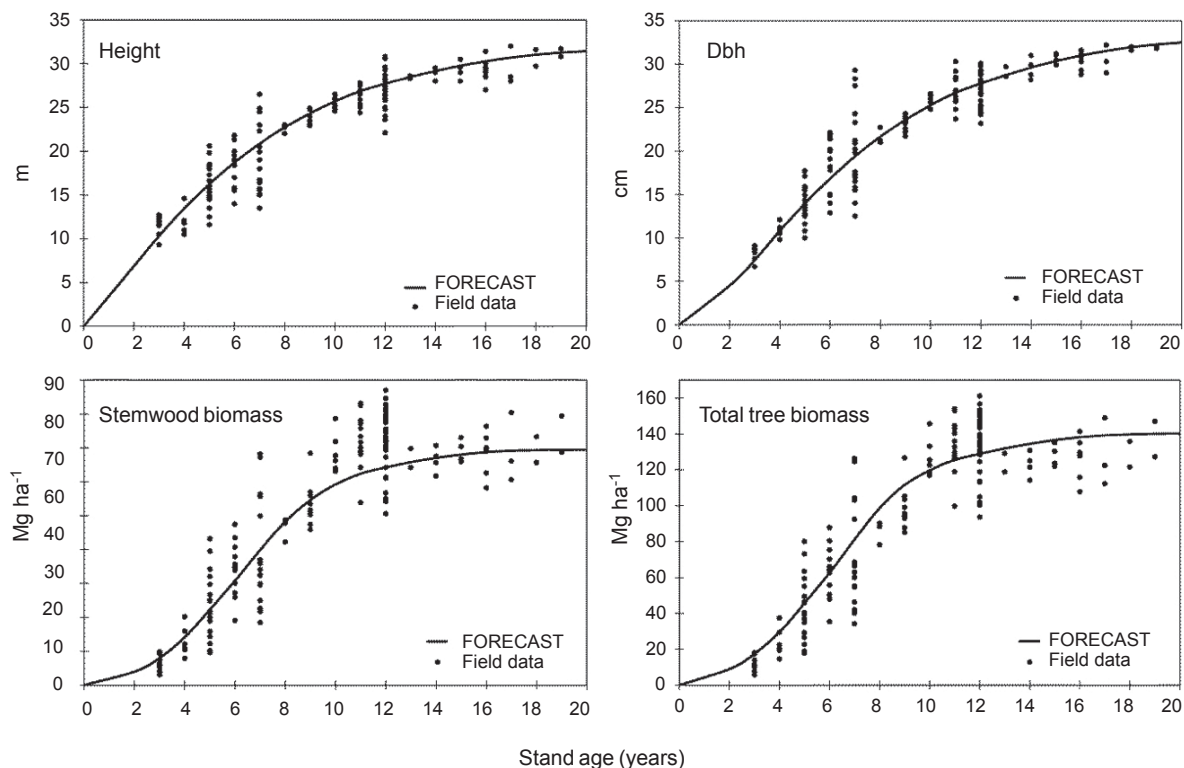
## RESULTS

### Model evaluation

FORECAST output constituted a good fit to dbh and height measurements as well as calculations for stemwood and total tree biomass (Figure 2). Pearson correlations (*r*) were 93% or higher (Table 4). Modelling efficiency (> 84%) and Theil's coefficient (< 0.18) highlighted overall fit of the model. Finally, average bias and mean absolute deviation were within acceptable limits (Table 4).

### Yield decline

First rotation stemwood biomass production varied from 2.7 to 13 t ha<sup>-1</sup> year<sup>-1</sup> (Table 5). Production increased with planting density and decreased with rotation length at a given density. With the exception of continuous N fertilisation, all scenarios showed evidence of yield decline, which was more severe at shorter rotations, and with whole-tree harvesting versus stem-only harvesting (Figure 3, Table 5). The N accumulated in as part of the ecosystem



**Figure 2** Height, diameter at breast height (Dbh), stemwood biomass and total tree biomass in poplar stands at the Dongtai Forestry Farm (n = 157); solid lines are predicted relationships from the FORECAST model

**Table 4** Model performance metrics in poplar plantations collected from the Dongtai Forestry Farm

Index	Height	Dbh	Stemwood biomass	Total tree biomass
Pearson's r	0.94	0.95	0.93	0.93
Modelling efficiency	0.86	0.90	0.84	0.85
Theil's coefficient	0.10	0.10	0.18	0.17
Average bias	-0.56	0.19	2.85	-2.64
Mean absolute deviation	1.72	1.65	7.76	13.70

Dbh = diameter at breast height

starting condition and the application of fertiliser contributed to an abundance of N in the first rotation (Figure 4). Without additional fertiliser, N availability diminished sharply in subsequent rotations and was always lower in whole-tree than stem-only harvesting. For a given harvesting system and planting density, average available N year<sup>-1</sup> was lower in the 10- versus 30-year rotation. For example, for the two rotation years, available N was 28.3 versus 42.2, and 45.9 versus 51.3 kg N ha<sup>-1</sup> year<sup>-1</sup>, for whole-tree and stem-only harvesting respectively at 3000 stems ha<sup>-1</sup> planting density (Figure 4).

Understorey competition was another factor influencing stemwood biomass production, with yield declines varying from 6 to 38% (Figure 5). The decline was more severe in stem-only harvesting than whole-tree harvesting, and at the lower planting densities.

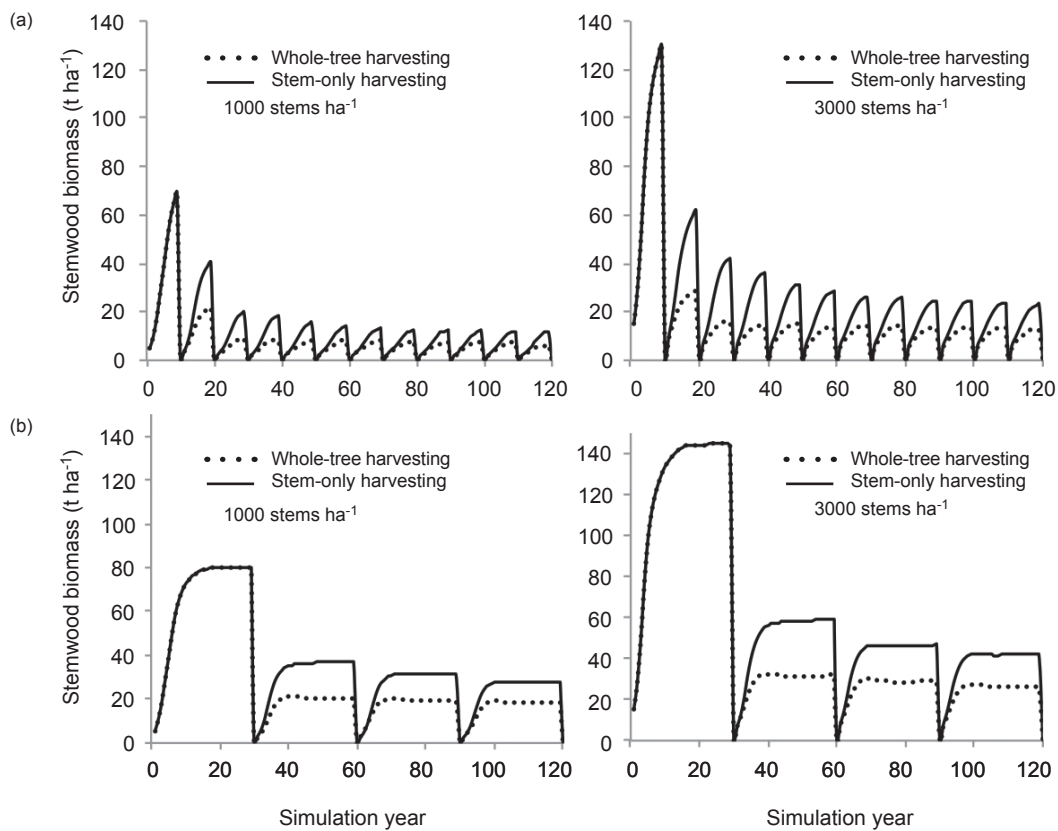
**Total stemwood biomass**

Total stemwood biomass harvested over the 120-year simulation period declined as rotation length increased (Figure 6). The decline was more pronounced with stem-only than whole-

**Table 5** Stemwood biomass yields ( $t\ ha^{-1}\ year^{-1}$ ) in the first and last rotations at three planting densities and 10-, 20- and 30-year rotations

Density (stems $ha^{-1}$ )	10 years			20 years			30 years		
	First	Last		First	Last		First	Last	
		SOH	WTH		SOH	WTH		SOH	WTH
1000	6.8	1.2	0.8	4.0	1.0	0.6	2.7	0.9	0.6
2000	10.6	1.8	1.1	5.9	1.4	0.8	3.9	1.2	0.8
3000	13.0	2.4	1.3	7.2	1.7	1.0	4.8	1.4	0.9

Last rotation yields are in relation to stem-only and whole-tree harvesting; WTH = whole-tree harvesting; SOH = stem-only harvesting



**Figure 3** Stemwood biomass for poplar stands planted at 1000 and 3000 stems  $ha^{-1}$  and harvested on either (a) 10- or (b) 30-year rotation over a 120-year simulation period

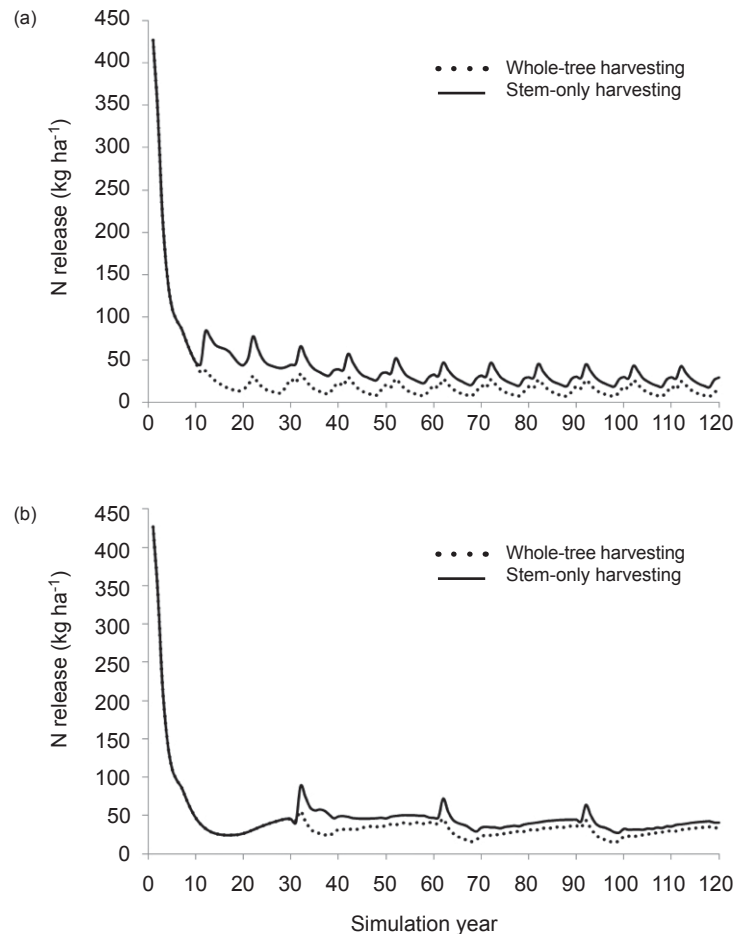
tree harvesting. For a given planting density and rotation length, whole-tree harvesting generated lower total stemwood biomass than stem-only harvesting. The difference was proportionately less as the rotation length increased. Increasing planting density always increased total stemwood biomass. Doubling the initial planting density increased the whole-tree and stem-only harvesting total stemwood biomass yields by

44 and 50% respectively, whereas at triple the initial planting density, yields increased by only 74 and 85% respectively.

**Stem size**

Total stem volumes from the first harvest ranged from 66–456  $m^3\ ha^{-1}$  (Figure 7). No large-diameter logs were produced on 5-year





**Figure 4** Nitrogen availability (N) for stands planted at 3000 stems ha<sup>-1</sup> (sph), and harvested on either (a) 10-year or (b) 30-year rotation, over a 120-year simulation period; dotted and solid lines denote whole-tree harvesting and stem-only harvesting respectively.

rotations but a maximum of 60 m<sup>3</sup> ha<sup>-1</sup> was produced at 1000 stems ha<sup>-1</sup> planting density and 30-year rotation. First rotation volumes were not good indicators of long-term (120-year) productivity. The highest total volume (4650 m<sup>3</sup>), for example, was generated on a 5-year rotation at 3000 stems ha<sup>-1</sup>. However, the greatest volume of large-diameter logs (423 m<sup>3</sup>) was produced at 1000 stems ha<sup>-1</sup> planting density and a 10-year rotation (Figure 7).

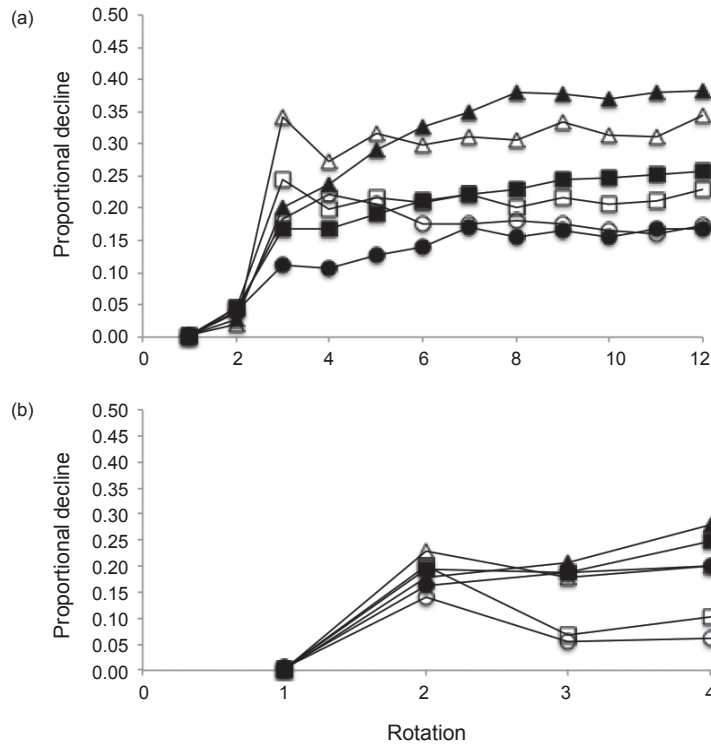
## DISCUSSION

### Yield decline

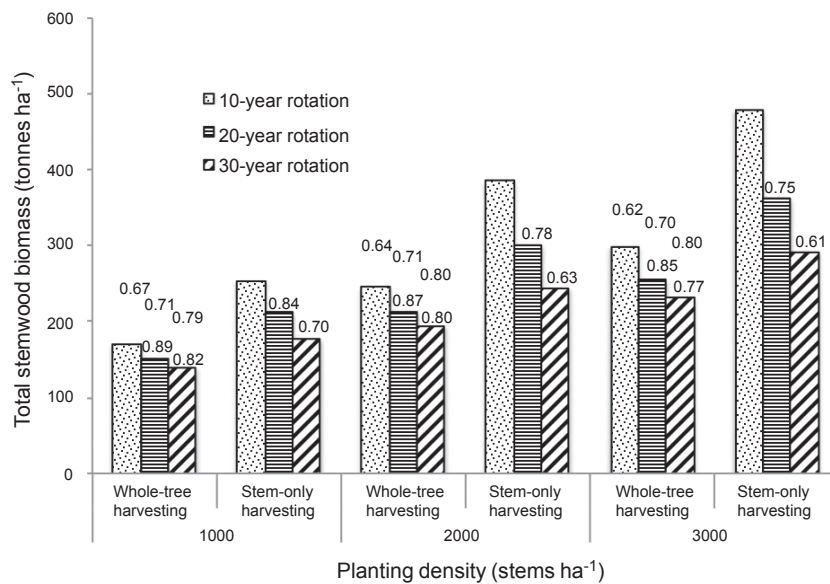
Yields from 2.2 to 13.5 t ha<sup>-1</sup> year<sup>-1</sup> are typical in intensively managed short rotation ( $\leq 5$  years) commercial plantations (Mitchell et al. 1999). In our systems, stemwood production in the

first rotation was within this range (Table 5). Without additional fertiliser, however, yields could not be sustained and indeed were much reduced in subsequent harvests, more so with whole-tree versus stem-only harvesting. Final yields were approaching stability but at values below 2 tonnes ha<sup>-1</sup> year<sup>-1</sup>. Productivity less than 7 tonnes ha<sup>-1</sup> year<sup>-1</sup> is considered uneconomical in short rotation systems (El Kasmoui & Ceulemans, 2012, Schweier & Becker 2013), which suggests that none of the management scenarios for poplar would be feasible without fertilisation.

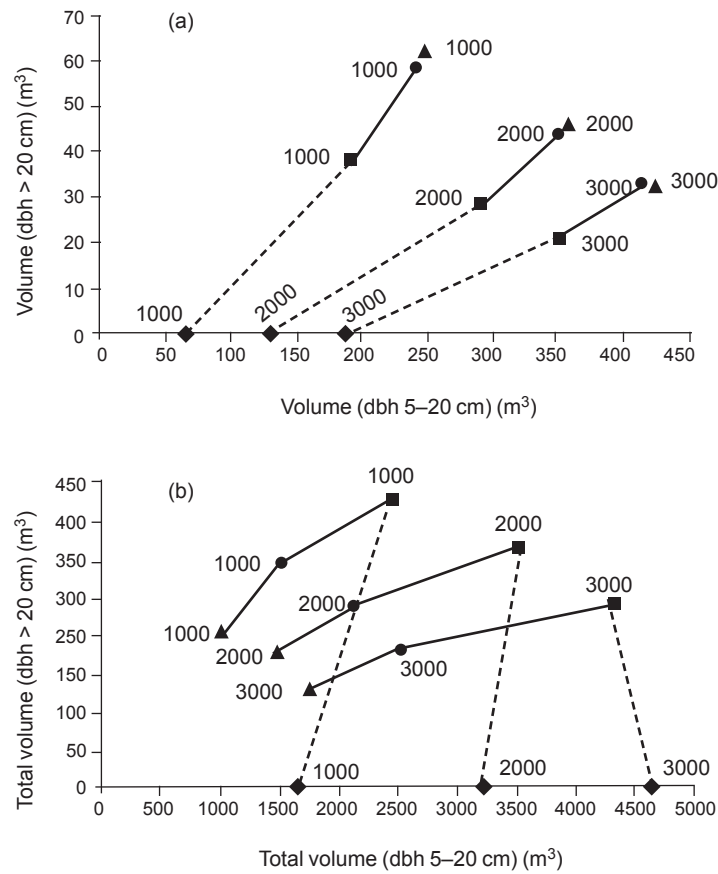
Nitrogen depletion is likely to be problematic in the subtropics and tropics. This is, in part, because the favourable soil moisture and temperature regime may stimulate nutrient cycling but high water fluxes introduce a risk of loss through leaching (Fang et al. 2008). In our simulations, yield decline was indeed partly



**Figure 5** Proportional decline in poplar stemwood biomass following understorey competition in (a) 10- and (b) 30-year rotations over a 120-year simulation period; open and closed symbols are whole-tree and stem-only harvesting respectively, with planting densities of 1000 (triangles), 2000 (squares), and 3000 (circles) stems ha<sup>-1</sup>



**Figure 6** Total stemwood across a 120-year simulation period for combinations of three planting densities (1000, 2000, and 3000 stems ha<sup>-1</sup>), three rotations (10, 20 and 30 years) and two harvesting intensities; sequential doublet numbers are the proportion of total stemwood biomass achieved at 20 and 30-year rotations respectively relative to the 10-year rotation, within a density–intensity grouping, sequential triplet numbers refer to the proportion of total stemwood biomass achieved with whole-tree harvesting relative to the associated value for stem-only harvesting at a given density



**Figure 7** (a) First rotation and (b) total volume over a 120-year simulation of small diameter at breast height (dbh) (5–20 cm) and large dbh (> 20 cm) logs; diamonds, squares, circles and triangles denote 5, 10, 20 and 30-year rotations respectively; values are the initial planting density (stems ha<sup>-1</sup>); total volumes were generated with the application of fertiliser in every rotation; dashed lines are added for clarity

a consequence of leaching losses. In the initial rotation, a large amount of N was available over the first five years, which is a typical response in land conversion (Kimmins 2004). Hybrid poplar grows quickly, has high tissue nutrient concentrations and is deciduous (Brown & van den Driessche 2005). Its nutrient demands are therefore high but given that stand biomass was not well developed at this time, N demand and uptake were small relative to supply (Welham et al. 2007). Similar conclusion was reported for fertilised willow (*Salix viminalis*) stands (Jug et al. 1999). One means of reducing leaching losses is by establishing a fast-growing perennial ground cover (Mc Laughlin et al. 1985, Welham et al. 2007). In these plantations, however, the understorey (combined with the poplar) had

only a relatively minor impact on N retention relative to what was released.

Harvesting in the first rotation was an additional factor in yield decline because of the amount of N capital contained within the harvested biomass. Yield decline in Chinese fir (*Cunninghamia lanceolata*) occurred in conjunction with a reduction in N capital that accompanied each harvesting event (Bi et al. 2007). Declines in two other species, *Phoebe bournei* (Wang et al. 2013) and *Pinus contorta* (Wei et al. 2000, 2003), were also attributed to biomass removals that led to a decrease in available nutrients, particularly N (Switzer et al. 1981). In Europe, fertile agricultural soils appear to be capable of supplying enough N to support two or three 5-year rotations of poplar

(Makeschin 1999). However, overall production was lower than occurred here (Hofmann-Schielle et al. 1999), which was reflected in lower export of N capital from harvesting (Jug et al. 1999).

### Harvest intensity

For a given rotation length and planting density, total stemwood biomass was always lower under whole-tree harvesting than stem-only harvesting. Stemwood had much lower N concentration relative to foliage and branches (Table 1) and when the latter were removed during whole-tree harvesting, there was higher export of N capital relative to stem-only harvesting. We estimated that the N removed in foliage and branches exceeded that from stemwood alone by a minimum of 1.78 (data not shown). A model for the long-term decline (whole-tree harvesting > stem-only harvesting) in biomass production of sub-boreal lodgepole pine forests showed that N removals under whole-tree harvesting exceeded stem-only harvesting by a factor of 1.9 (Wei et al. 2000, 2003)

Rotation length was an important determinant of the differential in harvest production between whole-tree harvesting and stem-only harvesting. In comparing the 10, 20 and 30-year rotations, total stemwood biomass after the 120-year simulation was about 35, 30 and 20% lower respectively in whole-tree harvesting than stem-only harvesting (Figure 6). Wang et al. (2013) reported a difference of 9.8% in aboveground carbon sequestration for whole-tree harvesting compared with stem-only harvesting in a 40-year rotation (over a 240-year simulation period) of *P. bournei* stands in subtropical China (Jiang et al. 2009). In cool and dry sub-boreal lodgepole pine forests, 40- and 60-year rotations had 12 and 10.8% decline in total biomass production for whole-tree and stem-only harvesting (240-year simulation period) respectively (Wei et al. 2000, 2003). Taken together, these results emphasise that if stands are to be managed on shorter rotations, retention of harvest residues (as per stem-only harvesting) should be utilised to protect fertility and minimise yield decline (Kimmins 1976, Jacobson et al. 2000). Nevertheless, for most forest types, maintaining long-term productive capacity at rotations of 60 years or less will likely require additional N inputs (Wang et al. 2013).

Total stemwood biomass declined with rotation length and gains in productivity from delaying harvest were therefore not offset by the reduction in harvest frequency. The relative benefit of harvesting on short rotation, however, also decreased with planting density and more so with stem-only harvesting than whole-tree harvesting. Typically, the impact of rotation length on forest productivity has been assessed after holding additional variables constant (Wei et al. 2000, Wang et al. 2013). As our results indicated, harvest intensity and planting density were important covariates.

Weed competition can negatively impact productivity, either directly (Walmsley et al. 2009) or in conjunction with site fertility (Bi et al. 2007, Welham et al. 2007). In our simulations, the addition of understorey reduced stemwood biomass production by as much as 38% but relative impact of competition depended on interaction between planting density, harvest intensity and rotation length (Figure 5). Short rotation harvesting triggers a loss of soil fertility, which is followed by associated reduction in tree growth that favours understorey growth because of reduced shading (Bi et al. 2007). There was evidence of competitive inhibition in our stands after the first rotation when nutrients became limiting and which was more severe at shorter rotations (Figure 5). Competition was also greater at lower planting densities suggestive of reduced understorey shading. However, this hypothesis did not explain why the understorey had stronger competitive effect in stem-only harvesting compared with whole-tree harvesting, given there was less N available in the latter. It may be that the very low nutrient levels triggered by whole-tree harvesting might depress tree growth sufficiently that understorey competition had relatively little additive impact.

### Volumes

If plantations are to be an effective substitute for harvesting in primary forests, they must be capable of supplying the same high quality products and in the amounts sufficient to be economical (Johansson & Lofgren 1985). These poplar systems demonstrated that significant volumes were produced at the first harvest on short rotation (Figure 7). However, ongoing fertilisation was required to maintain production.

Large-diameter logs are key features of many primary forests but they are usually the result of many decades of growth. In our case, large-diameter (> 20 cm dbh) volumes were small on a per-rotation basis but they compared favourably to natural stands when multiple harvests were summed over the long-term. Between 150 and 440 m<sup>3</sup> ha<sup>-1</sup> could be generated over a 120-year rotation. To generate a continuous and economical wood flow, these systems would need to be implemented on a large scale. This should not be problematic if volume of smaller diameter (5–20 cm) logs was also considered.

There was no benefit to extending the rotation length beyond 10 years, either in terms of generating larger logs or maximising harvested volumes (and biomass). The latter occurred in 5-year rotation (planting density 3000 stems ha<sup>-1</sup>) but only allowed for production of small-diameter logs. Doubling the rotation length to 10 years might be a favoured option because it generated large-diameter logs with only a small decline in total volume (Figure 7). Reducing planting density also favoured production of larger logs though there were minimum rotation lengths that constrained the effectiveness of this option.

## CONCLUSIONS

First rotation yields were not reliable indicators of long-term trends in these subtropical poplar plantations. Total production was very high when high planting densities were combined with short rotations but average tree size (diameter) was small. Planting at wider spacing can generate larger individual trees thus highlighting the inverse relationship between planting density and mean tree size. Stocking control and fertilisation (in our case, nitrogen) are essential if larger-diameter logs are to be produced on shorter rotational cycle.

## ACKNOWLEDGEMENTS

This research was supported by the China Forestry Public Research and Development Grant (No. 20104001).

## REFERENCES

ANONYMOUS. 1984. *Logs for Direct Use*. GB 142-1984. State Forestry Administration, Beijing.

- BÉLANGER N, PARÉ D & YAMASAKI SH. 2003. The soil acid–base status of boreal black spruce stands after whole-tree and stem-only harvesting. *Canadian Journal of Forest Research* 33: 1874–1879.
- BI J, BLANCO JA, SEELY B, KIMMINS JP, DING Y & WELHAM C. 2007. Yield decline in Chinese-fir plantations: a simulation investigation with implications for model complexity. *Canadian Journal of Forest Research* 37: 1615–1630.
- BLANCO J & GONZÁLEZ E. 2010. Exploring the sustainability of current management prescriptions for *Pinus caribaea* plantations in Cuba: a modelling approach. *Journal of Tropical Forest Science* 139–154.
- BLANCO JA, ZAVALA MA, IMBERT JB & CASTILLO FJ. 2005. Sustainability of forest management practices: evaluation through a simulation model of nutrient cycling. *Forest Ecology and Management* 213: 209–228.
- BLANCO JA, WEI X, JIANG H, JIE CY & XIN ZH. 2012. Impacts of enhanced nitrogen deposition and soil acidification on biomass production and nitrogen leaching in Chinese fir plantations. *Canadian Journal of Forest Research* 42: 437–450.
- BLIEMEL F. 1973. Theil's forecast accuracy coefficient: a clarification. *Journal of Marketing Research* 10: 444–446.
- BROWN C. 2000. *The Global Outlook for Future Wood Supply From Forest Plantations: Global Forest Products Outlook Study Working Paper Series No. GFPOS/WP/03*. Food and Agriculture Organization of the United Nations, Rome.
- BROWN KR & VAN DEN DRIESSCHE R. 2005. Effects of nitrogen and phosphorus fertilization on the growth and nutrition of hybrid poplars on Vancouver Island. *New Forests* 29: 89–104.
- CAO F. 2004. *Ecological Basis for Ginkgo Agroforestry Systems*. University of British Columbia, Vancouver.
- EL KASMI O & CEULEMANS R. 2012. Financial analysis of the cultivation of poplar and willow for bioenergy. *Biomass and Bioenergy* 43: 52–64.
- FAN H. 2014. *Effects of Soil Fauna on Litter Decomposition and N Mineralization Under Different Land Management Patterns in Northern Jiangsu Province*. Nanjing Forestry University, Nanjing. (In Chinese).
- FANG S, XU X, YU X & LI Z. 2005. Poplar in wetland agroforestry: a case study of ecological benefits, site productivity, and economics. *Wetlands Ecology and Management* 13: 93–104.
- FANG YT, GUNDERSEN P, MO JM & ZHU WX. 2008. Input and output of dissolved organic and inorganic nitrogen in subtropical forests of south China under high air pollution. *Biogeosciences* 5: 339–352.
- FAO (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS). 2010. *Global Forest Resources Assessment 2010*: FAO, Rome.
- FENG H. 2007. *A Study on Growth Characteristic and Biomass of Poplar Plantation*. Chinese Academy of Forestry, Beijing. (In Chinese)
- HEMERY GE, SAVILL PS & PRYOR SN. 2005. Applications of the crown diameter–stem diameter relationship for different species of broadleaved trees. *Forest Ecology and Management* 215: 285–294.

- HOFMANN-SCHIELLE C, JUG A, MAKESCHIN F & REHFUESS KE. 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. I. Site-growth relationships. *Forest Ecology and Management* 121: 41–55.
- HONG J. 1985. A brief account of forest tree improvement in China. *Forest Genetic Resources Information* 14: 2–6.
- JACOBSON S, KUKKOLA M, MÄLKÖNEN E & TVEITE B. 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management* 129: 41–51.
- JIANG X, XIAO F, YE J & GONG B. 2009. A study on the growth characteristics of *Phoebe boumei* in natural forests and plantation stands. *Acta Agriculturae Universitatis Jiangxiensis* 31: 1049–1054. (In Chinese)
- JOHANSSON P & LOFGREN K. 1985. *The Economics of Forestry and Natural Resources*. Basil Blackwell, Oxford.
- JU XT, XING GX, CHEN XP ET AL. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America* 106: 3041–3046.
- JUG A, HOFMANN-SCHIELLE C, MAKESCHIN F & REHFUESS KE. 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. II. Nutritional status and bioelement export by harvested shoot axes. *Forest Ecology and Management* 121: 67–83.
- KIMMINS JP. 1976. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. *Forest Ecology and Management* 1: 169–183.
- KIMMINS JP, MAILLY D & SEELY B. 1999. Modelling forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. *Ecological Modelling* 122: 195–224.
- KIMMINS JP. 2004. *Forest Ecology: A Foundation for Sustainable Forest Management and Environmental Ethics in Forestry*. Pearson-Prentice Hall, Upper Saddle River.
- KIMMINS JP, BLANCO JA, SEELY B, WELHAM C & SCULLAR K. 2010. *Forecasting Forest Futures: A Hybrid Modelling Approach to the Assessment of Sustainability of Forest Ecosystems and Their Values*. Earthscan, London.
- KORZUKHIN MD, TER-MIKAELIAN MT & WAGNER RG. 1996. Process versus empirical models : which approach for forest ecosystem management? *Canadian Journal of Forest Research* 26: 879–887.
- LI H, JIANG X, PAN J, LIAO Q, ZOU S & WU X. 2007. Distribution of soil cation exchange capacity—a case study of Lishui County, Jiangsu Province. *Soils* 39: 443–447. (In Chinese)
- LI Y. 2012. *Study on Light Utility Efficiency of Main Agro-Forestry Systems in North of Jiangsu Coastal Protective Forest*. Nanjing Forestry University, Nanjing. (In Chinese)
- LO YH, BLANCO JA, SEELY B, WELHAM C & KIMMINS JP. 2011. Generating reliable meteorological data in mountainous areas with scarce presence of weather records: the performance of MTCLIM in interior British Columbia, Canada. *Environmental Modelling and Software* 26: 644–657.
- LU X. 2011. *The Decomposition Characteristics of Litters From Poplar Plantations and its Effect on Soil Properties*. Nanjing Forestry University, Nanjing. (In Chinese)
- MAKESCHIN F. 1999. Short rotation forestry in central and northern Europe—introduction and conclusions. *Forest Ecology and Management* 121: 1–7.
- MC LAUGHLIN RA, POPE PE & HANSEN EA. 1985. Nitrogen fertilization and ground cover in a hybrid poplar plantation: effects on nitrate leaching. *Journal of Environmental Quality* 14: 241–245.
- MEAD DJ. 2001. Plantations, silviculture and bioenergy production. Pp 6–16 in Richardson J et al (eds) *Proceedings of the IEA Bioenergy Task 18 Workshop on Bioenergy from Sustainable Forestry: Principles and Practice*. 16–20 October 2000, Coffs Harbour.
- MERINO A, BALBOA MA, RODRÍGUEZ SOALLEIRO R & GONZÁLEZ JGÁ. 2005. Nutrient exports under different harvesting regimes in fast-growing forest plantations in southern Europe. *Forest Ecology and Management* 207: 325–339.
- MITCHELL CP, STEVENS EA & WATTERS MP. 1999. Short-rotation forestry—operations, productivity and costs based on experience gained in the UK. *Forest Ecology and Management* 121: 123–136.
- PRETZSCH H. 2009. *Forest Dynamics, Growth, and Yield*: Springer-Verlag, Berlin Heidelberg.
- QI L & CHEN Z. 2011. *Introduction of Poplar Silviculture in China*. Science Press, Beijing. (In Chinese)
- SCHWEIER J & BECKER G. 2013. Economics of poplar short rotation coppice plantations on marginal land in Germany. *Biomass and Bioenergy* 59: 494–502.
- SEELY B, KIMMINS JP, WELHAM C & SCULLAR K. 1999. Management models: defining stand-level sustainability; exploring stand-level stewardship. *Journal of Forestry* 97: 4–10.
- SUN Y, CHENG X & SHE G. 2006. Establishment of site index table for black poplar in Jiangsu province. *Journal of Nanjing Forestry University: Natural Sciences Edition* 36: 29#32. (In Chinese)
- SWITZER GL, NELSON LE & HINESLEY LE. 1981. Effects of utilization on nutrient regimes and site productivity. Pp 251–259 in Gessel SP, Kenady RM, Atkinson WA (eds) *Proceedings Forest Fertilization Conference*. 25–27 September 1979, Washington.
- TANG W, QI L, ZHENG L & LI H. 2004. Study on optimal management density of plantation for southern type of poplar. *Hubei Forestry Science and Technology* 24–27. (In Chinese)
- THEIL H. 1966. *Applied Economic Forecasting. Volume 4*. North-Holland Publishing Company, Amsterdam.
- THIFFAULT E, BÉLANGER N, PARÉ D & MUNSON AD. 2007. How do forest harvesting methods compare with wildfire? A case study of soil chemistry and tree nutrition in the boreal forest. *Canadian Journal of Forest Research* 37: 1658–1668.
- THIFFAULT E, PARÉ D, BÉLANGER N, MUNSON A & MARQUIS F. 2006. Harvesting intensity at clear-felling in the boreal forest. *Soil Science Society of America Journal* 70: 691–701.

- TUSKAN GA. 1998. Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? *Biomass and Bioenergy* 14: 307–315.
- VANCLAY JK & SKOVSGAARD JP. 1997. Evaluating forest growth models. *Ecological Modelling* 98: 1–12.
- WALMSLEY JD, JONES DL, REYNOLDS B, PRICE MH & HEALEY JR. 2009. Whole tree harvesting can reduce second rotation forest productivity. *Forest Ecology and Management* 257: 1104–1111.
- WANG W, WEI X, LIAO W ET AL. 2013. Evaluation of the effects of forest management strategies on carbon sequestration in evergreen broad-leaved (*Phoebe bournei*) plantation forests using FORECAST ecosystem model. *Forest Ecology and Management* 300: 21–32.
- WANG Y. 2012. *Decomposition and Nutrient Release of Mixed Residues in the Soil of Poplar-Crops Agroforestry System*. Nanjing Forestry university, Nanjing. (In Chinese)
- WEI X & BLANCO JA. 2014. Significant increase in Ecosystem C can be achieved with sustainable forest management in subtropical plantation forests. *PLoS ONE* 9: 1–14.
- WEI X, BLANCO JA, JIANG H & KIMMINS JPH. 2012. Effects of nitrogen deposition on carbon sequestration in Chinese fir forest ecosystems. *Science of the Total Environment* 416: 351–361.
- WEI X, KIMMINS JP & ZHOU G. 2003. Disturbances and the sustainability of long-term site productivity in lodgepole pine forests in the central interior of British Columbia—an ecosystem modelling approach. *Ecological Modelling* 164: 239–256.
- WEI X, LIU W, WATERHOUSE J & ARMLEDER M. 2000. Simulations on impacts of different management strategies on long-term site productivity in lodgepole pine forests of the central interior of British Columbia. *Forest Ecology and Management* 133: 217–229.
- WELHAM C, VAN REES K, SEELY B & KIMMINS H. 2007. Projected long-term productivity in Saskatchewan hybrid poplar plantations: weed competition and fertilizer effects. *Canadian Journal of Forest Research* 37: 356–370.
- XIAO J. 2006. *Studies on the Growth and Yield Models of Poplar Plantations in Southern Area*. Nanjing Forestry University, Nanjing. (In Chinese)
- XIE L. 2005. *Study on Soil Characteristics and Effects on Planted Crops of Different Agroforestry Types in the North Part of Jiangsu Province*. Nanjing Forestry University, Nanjing. (In Chinese)
- XU H & CHEN Z. 1994. Studies on the growth of poplar plantation of different spacings. *Forest Research* 7: 61–66. (In Chinese)
- YU C, LUO Z, CHEN W, LU J & CHEN F. 2005. Study on nutrition concentration and its accumulation seasonal change of young poplar. *Journal of Fujian College of Forestry* 25: 181–186. (In Chinese)