Incentives for carbon sequestration and energy production in low productivity collective forests in Southwest China

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Abstract

This paper develops three scenarios for the management of an existing, low productivity, collective forest plot in Southwest China: continuation of the status quo, transition to sustainable forest management (SFM), and conversion to a short rotation species for producing biomass for electricity generation. We examine how economic incentives vary across the three scenarios and how payments for CO2 sequestration and offsets affect incentives. We find that SFM is risky for forest managers and is highly sensitive to revenues from initial thinning; that carbon revenues can lower some of the risks and improve the economics of SFM; but that carbon revenues are effective in incentivizing management changes only if yield response to thinning is moderately high. Energy production from stemwood is too low value to compete with timber, even with revenues from CO2 offsets. However, conversion of existing forests into short rotation species for timber rather than energy is more profitable than any scenario considered here, highlighting the need for regulatory innovations to balance incentives for timber production with conservation goals. The results underscore the importance of improved public sector regulatory, planning, extension, and analysis capacity, as an enabling force for effective climate policies in China’s forestry sector.

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1. Introduction

Forests have the potential to play an important role in efforts to mitigate climate change, as a carbon sink, a primary energy source to offset fossil fuel use, and a source of wood products to offset more carbon-intensive building materials [1,2]. With its extensive forest resources, forests will be a key element in China’s national climate policy [3]. Discussion on the role of forests in climate policy in China has emphasized expanding forest area through afforestation and reforestation [3–5], and producing feedstocks for electricity and liquid fuels on fallow and marginal land [6,7]. Comparatively less has attention has
been given to the role that existing forests could and should play in climate change mitigation.

China’s forestry sector is currently in the midst of a longer-term reform process that will transition forest management from its historical emphasis on centralized administration and achieving production targets toward more decentralized incentive mechanisms, improving forest quality, and conservation [8,9]. Domestic and international climate policies will influence China’s forestry transition, with implications for forest and watershed conservation; timber size, composition, and quality; building materials; rural energy and development; and conventional energy supplies. Better understanding current incentives for forest management, and how policy influences the structure of those incentives, will be essential to ensure that climate policies are consistent with the multiple policy objectives that China’s central government has laid out for the forest sector [10].

This paper develops three scenarios for the management of an existing, low productivity, collectively owned forest plot in Southwest China, examining how economic incentives vary across the three scenarios and how carbon payments might affect those incentives. The three scenarios include continuation of the status quo, transition to sustainable forest management, and conversion to short rotation forestry for producing feedstock for electricity generation. The paper is organized as follows. Section 2 elucidates the historical context for understanding current forest management practices in China. Section 3 provides a detailed accounting of scenarios and methods. Section 4 describes the results. Section 5 closes with a discussion of broader policy implications for forest management in China.

2. Background

In ownership, management, and incentive structures, China’s forestry sector is unique. Historically, forest ownership was split between state-owned forests, managed by state-owned enterprises, and collectively owned forests, managed by township and village communities. China’s economic reforms, begun in the late 1970s, had a limited impact on state-owned and managed forests [8]. By contrast, over the 1980s management of a large portion of collective forests was devolved to individual households in an effort to improve incentives for forest production. By the early 2000s, collective forests accounted for around 60% of all forest land, with 80% of those managed by individual households [9].

After a brief and abrupt experiment with full timber market liberalization in 1985 resulted in extensive deforestation, the Chinese government instituted a national harvest quota system in 1986 [11] that has continued into the present. Actual harvests regularly exceed the quota by a large margin [8], which indicates the failure thus far of both market and regulatory institutions to give forest managers in China the incentives to manage for sustainability, either in terms of sustained yield or economic and environmental benefits more broadly defined.

Although China’s national forest cover has increased substantially over the past two decades—by 52%, or by 67 million hectares, from 1992 to 2008 [12,13]—forest productivity in China, and in particular productivity in collective forests, remains low [8,14]. Young and middle-aged trees account for the majority of forest removals [8], and as a result China’s domestic timber market is dominated by small and medium diameter logs [15]. Because of changing definitions and age structure, the severity of China’s forest productivity problem is difficult to assess using national inventory statistics. However, government initiatives to address the problem hint at its scale. In Yunnan Province, for instance, more than one quarter of the province’s 18.1 million hectare [12] of forest land was classified as medium- and low-productivity forest [16]. Improving forest quality and productivity is a priority for the State Forest Administration during the 12th Five-Year Plan (2011–2015) [14].

Low forest productivity has contributed to China’s sizeable forest products deficit. A paradigm shift toward forest conservation in China, including a ban on logging in most natural forests, led to a leveling off in domestic timber production beginning in the late 1990s [17]. Decreased production coincided with rapid growth in demand for forest products, which resulted in a surge in imports. Imports accounted for an average of 23% of China’s total industrial roundwood supply from 2001 to 2009, up from 14% in 2000 [17].

At the same time, rapid growth in energy demand and an emerging climate policy dialogue in China have led to greater consideration of forest-based energy feedstocks as alternatives to oil and coal. Policy support for forest-based biofuels in China has focused on biodiesel feedstocks, such as *Jatropha curcas*, but land availability [18] and costs [19] have proved to be significant obstacles. For biomass power, the Chinese government has, under discussion, an aggressive 30 GW capacity target for 2020 [20]. However, the feedstock source to provide such a large amount of power—30 GW is nearly equivalent to the entire installed generating capacity of Sweden—remains unclear. Agricultural and wood residues are the preferred feedstock but may not be available at sufficient scale. Low productivity forests, converted to short rotation energy forests, could provide a source of biomass, provided that conversion is done on a scale that does not compete with timber forestry. If sustainably harvested, forest biomass could be a high value low carbon energy source because more than 80% of electricity in China is generated by coal [21].

3. Methods: scenario development and calculations

The three management scenarios we consider in this paper, while certainly not exhaustive, represent three very different avenues for forest management. The business as usual (BAU) scenario is a continuation of the status quo. In the sustainable forest management (SFM) scenario, managers thin the forest plot and increase the sustainability, and the costs, of timber harvesting. In the forest-based biopower (FBBP) scenario, managers convert the forest plot to a short rotation species to produce biomass feedstock for generating electric power.

3.1. Initial conditions and description of management interventions

We assume that forest managers have a 30- to 35-year planning horizon and begin with a 10-year-old, one hectare pine forest plot that has a stand density of 40 m$^3$. Stand volume is based on...
an aggregate “Conifer” growth curve for Yunnan Province from Chen et al. [22] and growth curves for Yunnan Pine (Pinus yunnanensis) from unpublished surveys in collective forests by the authors. To overcome limitations on the availability of representative data on forest growth and management practices in China, we use a range of realistic assumptions that capture structural differences between the three management scenarios. These assumptions are described more qualitatively below and in tables in the Appendix.

Business as usual (BAU). Forest managers harvest timber on a continual basis rather than at the end of rotation, removing the best performing trees first. Timber sales are made every four years, and decline by 1 m$^3$ ha$^{-1}$ in each four-year period. All harvested wood is sold as small diameter (10–16 cm) logs.

Sustainable forest management (SFM). Forest managers conduct a major thinning to reduce stand density in year 11, removing 25% of year 10 volume, with thinnings every 4–5 years after the initial thinning that decline by 1 m$^3$ ha$^{-1}$ in each period. Half of the year 11 thinnings are sold as firewood, and half as small diameter logs. Subsequent thinnings are all sold as small diameter logs. Thinning ultimately leads to an increase in stand volume vis-à-vis the BAU scenario because the stand increment in the SFM scenario focuses on the best performing trees. Low (SFM-L), medium (SFM-M), and high (SFM-H) yield responses cases produce 45, 75, and 105 m$^3$ of biomass at the end of rotation. Forest managers leave 35 m$^3$ at the end of rotation for regeneration.

Forest-based biopower. Forest managers clear cut the pine forest in year 11 and replant with a fast growing alder that produces 112 m$^3$ of total biomass (80 m$^3$ of stem wood, 32 m$^3$ of residues) in an 8-year rotation. Managers conduct thinnings every four years. All wood biomass from the clear cut, thinning, and harvesting, including wood residues, is used as feedstock. To account for the difference in harvesting schedules between the FBBP and BAU and SFM scenarios, the FBBP planning horizon includes three rotation periods.

Fig. 1 shows illustrative growth curves for each management scenario. These curves are intended to show possible growth trajectories that are consistent with changes in stem volume in the different scenarios, but are not essential to the results.

### 3.2. Carbon sequestration and offsets

3.2.1. Carbon sequestration

Both the SFM and FBBP scenarios lead to an increase in above- and below-ground woody biomass relative to the BAU scenario. Assigning credit for carbon sequestration to forest managers requires an assumption that changes in management will be permanent. In the SFM scenario, this assumption is more plausible. In the FBBP scenario, given the short rotation period this assumption is less tenable. We assume that, given this uncertainty, forest managers in the FBBP scenario are not paid for any net carbon sequestration.

To make program design and administration more flexible and realistic, payments for carbon sequestration are assumed to be based on an incremental average annual carbon sequestration rate, calculated as the difference between the amount of carbon in above- and below-ground woody biomass at the end of a rotation period under a forest management intervention and the baseline (BAU), divided by the incremental rotation length.

\[
\text{iacs} = \frac{V^A \times \text{BCEF}^A(1 + R^A)\alpha^A - V^B \times \text{BCEF}^B(1 + R^B)\alpha^B}{T1}
\]

where iacs is the incremental average annual carbon sequestration rate (t ha$^{-1}$ year$^{-1}$); superscript A indicates the forest management intervention (SFM or FBBP); superscript B indicates the baseline (BAU) scenario; $V$ is the total stem volume at the end of rotation (m$^3$ ha$^{-1}$); T1 is the incremental rotation period (years), or 20 in the SFM scenarios and 8 in the FBBP scenario; BCEF is a biomass conversion and expansion factor (t m$^{-3}$ dry matter), assumed to be 0.8 for pine and 0.6 for alder; R is the ratio of below-ground to above-ground dry biomass, assumed to be 0.29 for pine and 0.46 for alder [24]; $\alpha$ is the fraction of dry wood (t C t$^{-1}$ dry matter), which we assume to be 50% for all species.

This approach omits changes in soil carbon. There is at least some evidence that sustainable forest management interventions increase soil carbon [25]. However, without a larger body of analysis to benchmark sequestration rates to species, growing conditions, and practices, accurately accounting for changes in soil carbon is more difficult than for woody biomass. Converting existing forest to short rotation trees could significantly reduce soil carbon, for instance, but the magnitude of soil carbon impacts depends on silvicultural techniques. We assume that, for lack of information, changes in soil carbon are not accounted for in carbon payments to forest managers.

3.2.2. Offsets

The FBBP scenario offsets CO$_2$ by displacing emissions from the average generation mix on the grid. CO$_2$ offsets are calculated as

\[
\text{EF}_y = \frac{1000}{11}
\]

$\text{EF}_y$ is the amount of CO$_2$ avoided by forest-based electricity generation in year $y$ (t ha$^{-1}$); $hv$ is the harvestable volume in year $y$ (m$^3$ ha$^{-1}$); $\rho$ is the basic wood density of the wood fuel (t m$^{-3}$ dry matter), assumed to be 0.44 t m$^{-3}$ for alder (see footnote 1); $HV$ is the lower heating value of the wood fuel (GJ t$^{-1}$ dry matter), assumed to be 17 GJ t$^{-1}$ for alder, 1000/3.6 converts from GJ to kWh; $\eta$ is the total net efficiency of the power plant burning the biomass (%), assumed to be 20% based on [26]; $\text{EF}_y$ is a projected grid CO$_2$ emission factor in year $y$ (kg kWh$^{-1}$), based on an estimated 2005 CO$_2$ emission

1 The biomass conversion and expansion factor (BCEF), which converts merchantable stem wood volume into total biomass (e.g., branches, foliage, twigs), is the product of a biomass expansion factor (BEF) and a basic density ($\rho$). BCEF = BEF $\times$ $\rho$. We use BEF values of 1.7 and 1.4, and basic density values of 0.48 t m$^{-3}$ and 0.44 t m$^{-3}$, for pine (based on Pinus yunnanensis) and alder, respectively. These values are from the CDM Project Design Document, “Small-scale Reforestation for Landscape Restoration," with data from the Chinese Academy of Forestry. The BEFs for pine in this document are high relative to the implied volume-volume BEFs (~1.1) in Fang et al. [23]. Fang et al. do not report BEFs for alder. The 0.82 t m$^{-3}$ BCEF value for pine compares with an IPCC default value of 0.75 t m$^{-3}$ for temperate pine at a growing stock level of 41–100 m$^3$ [24]. The IPCC Guidelines do not list a BCEF for a species comparable to alder.
factor of 0.72 kg kWh$^{-1}$ for the China Southern Power Grid (SPG) [27] that declines at a rate of 0.012% y$^{-1}$ [28].

### 3.3. Revenues and costs

Net revenues to forest managers in each scenario are

$$\pi = \left( \sum_{i=1}^{n} \left( \sum_{y=1}^{Y} \left( pw \right)_i \right) \right) \times \left( \sum_{y=1}^{Y} \left( hv \right)_y + \left( tv \right)_y + \left( cp \right)_y - \left( \sum_{y=1}^{Y} \left( cp \right)_y \right) \right) \times \phi$$  

(3)

$\pi$ is discounted, annualized profits ($\text{ha}^{-1}$ yr$^{-1}$); $Y$ is the final year in the planning horizon ($y$); $y_0$ is the age of the existing forests when the scenarios begin ($y$); $y$ is the year index, which begins at year 1; $pw_i$ is the wholesale price of wood type $i$ ($\text{m}^3$); $hv_y$ is the harvestable volume of wood type $i$ in year $y$ ($\text{m}^3$); $tv_y$ is the volume of thinnings of wood type $i$ in year $y$ ($\text{m}^3$); $cp_y$ are any carbon payments made in year $y$ ($\text{m}^3$); $\phi$ is the value discount factor, $\phi = \frac{1}{(1 + r)^{t}}$; $\pi$ is an annuity factor, $\phi = \frac{1}{r(1 - (1 + r)^{-t})}$.

#### 3.3.1. Wood types and wood prices

The subscript $i$ in Eq. (3) includes three types of timber, classified by diameter, an energy feedstock, and firewood. Wood prices for timber and firewood are straightforward, with assumed values shown in Table 1. Energy feedstock prices are less straightforward and are described below.

Energy feedstock prices are based on an implicit cost, calculated as a residual from the net revenues of a biomass power plant, or what the power plant can afford to pay for fuel after it has covered its capital, other operating, and transport expenses. In China, biomass power plants receive a feed-in tariff that is based on the base cost of desulfurized coal-fired generation, or the levelized cost of new coal generation plus a 2$\text{MWh}^{-1}$ desulfurization subsidy, plus a 54$\text{MWh}^{-1}$ subsidy specific to biomass. The residual price for energy feedstocks is the total feed-in tariff minus non-fuel costs, divided by the energy density of the fuel

$$pw_{EF} = \frac{P^b + S - CC}{\text{NED}} \times \left( 1 + \beta_{OM} \right) - c_{TR} \frac{P^w}{C2}$$  

(4)

$pw_{EF}$ is the wood price for energy feedstocks ($\text{m}^3$); $P^b$ is the base cost of desulfurized coal-fired generation, assumed to be 54$\text{MWh}^{-1}$ [29]; $S$ is the subsidy for biomass, 54$\text{MWh}^{-1}$, which is assumed to continue in some form throughout the planning horizon; $CC$ is an annualized capital cost, calculated as unit capital costs (UCC) multiplied by an annuity factor ($\phi$), $CC = UCC \times \phi$, with unit capital costs assumed to be 1550$\text{kW}^{-1}$ based on the approximately 1000–2000$\text{kW}^{-1}$ range of capital costs for recent biomass power plants in China, and $r$ and $t$ values for $\phi$ assumed to be 8% and 20 years, respectively.

$CF$ is the capacity factor of the power plant, assumed to be 0.7, higher than average capacity factors for thermal generators [30] in line with the Chinese government’s prioritization of renewable generation; $\beta_{OM}$ is the ratio of operations and maintenance costs to levelized capital costs (%), assumed to be 25% based on [26]; NED is the net energy density of the fuel ($\text{kWh m}^{-3}$), calculated as $ED = P \times HV \times 1000/3.6 \times \eta$ in Eq. (3); $c_{TR}$ is the cost of transporting biomass ($\text{t}^{-1}$ wet matter), assumed to be 7.75$\text{t}^{-1}$, based on typical medium-distance rural transport costs in Yunnan Province; $P^w$ is the moist

#### Table 1 – Prices for timber and energy feedstocks.

<table>
<thead>
<tr>
<th>Species and specification</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small diameter (10–16 cm DBH)</td>
<td>66$\text{m}^{-3}$</td>
</tr>
<tr>
<td>Medium diameter (16–20 cm DBH)</td>
<td>81$\text{m}^{-3}$</td>
</tr>
<tr>
<td>Large diameter (&gt;20 cm DBH)</td>
<td>96$\text{m}^{-3}$</td>
</tr>
<tr>
<td>Firewood</td>
<td>22$\text{m}^{-3}$</td>
</tr>
</tbody>
</table>

Sources: prices are an average between prices for Yunnan pine (Pinus yunnanensis) and David’s pine (Pinus armandii) in Baoshan Municipality (Changning County) in 2009; data are from the Baoshan Forestry Bureau. Firewood prices are based on household surveys by the authors in 2008.

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\(^2\) Throughout this paper, we use the average 2010 exchange rate of 1 US$ = 6.4554 yuan, from [http://www.oanda.com/currency/historical-rates/](http://www.oanda.com/currency/historical-rates/).
wood density of the wood fuel (t m\(^{-3}\) wet matter), which, assuming a moisture content of 50% and negligible shrinkage, would be 0.66 t m\(^{-3}\) for alder (see footnote 1).

3.3.2. Carbon payments
To calculate payments for sequestered carbon we use an average annual sequestration rate multiplied by the payment period.

\[
\text{cp}_y = \text{pc} \left( \text{PI} \times \text{iacs} \times z_y \times \frac{44}{12} + \text{os}_y \right)
\]  

(5)

\( \text{cp}_y \) is any carbon payment made in year \( y \) ($ ha\(^{-1}\)), \( \text{pc} \) is the price of carbon ($ t\(^{-1}\)); \( \text{PI} \) is the payment interval (y); \( \text{cs}_y \) is the average annual carbon sequestration rate in year \( y \), from Eq. (1) (t ha\(^{-1}\)y\(^{-1}\)); \( z_y \) is a dummy variable indicating whether a carbon payment is made in year \( y \); 44 and 12 are the respective masses of one mole of CO2 and C, \( \text{os}_y \) is the amount of CO2 offsets in year \( y \), from Eq. (2) (t ha\(^{-1}\)).

Payments for sequestered carbon and offset CO2 are assumed to be made every five years in the SFM scenarios, and every four years in the FBBP scenario. For example, with a carbon price of $5$ t\(^{-1}\) CO2 and an average annual carbon sequestration rate (iacs) of 1 t ha\(^{-1}\)y\(^{-1}\), in the SFM scenario (\( \text{PI} = 5 \)) forest managers receive a payment of $5 \times 5 \times 1 \times 3.67 = 92\$ $ ha\(^{-1}\) every five years. In the FBBP scenario, payments for CO2 offsets are assumed to be entirely passed through to the forest manager, and are made as the power plant purchases feedstock, which in the FBBP scenario occurs every fourth and eighth year.

3.3.3. Costs
We use four primary costs here: road building, planting, thinning, and harvesting (Table 2). Thinning and harvesting costs include all management costs, and, in the SFM scenario, the amortized costs of a cable logging system. We assume that unit costs are the same within each scenario (e.g., unit costs for SFM-M and SFM-H are the same). However, not all scenarios incur the same costs. For instance, in the SFM scenario we assume that forest managers must build roads in year 11, whereas roads are not required in the BAU and FBBP scenarios. The FBBP scenario requires a planting expenditure in year 11, whereas no planting is required in the BAU and SFM scenarios.

4. Results

4.1. Comparison of forest management scenarios without carbon revenues

The BAU, SFM, and FBBP scenarios generate significantly different net revenue streams, because of the timing and magnitude of revenues and costs. Fig. 2 shows annualized net revenues at different discount rates, excluding carbon revenues, for each scenario.

The BAU scenario provides forest managers with a regular source of profits, rising gradually at higher discount rates because the initial harvest is larger than subsequent harvests. Income stability from early and regular harvests explains the economic attractiveness of the status quo, as collective forests are typically managed by rural residents with high discount rates.

The SFM scenario requires upfront investment, has higher harvesting costs, and has a 20-year delay until a major harvest. Initial and, to a lesser extent, subsequent thinnings provide an additional revenue source, and revenues from the end of rotation harvest are several fold larger than in any year in the BAU. The net between these changes in costs and revenues is particularly sensitive to earnings from the initial thinning and the size of end of rotation harvest. If initial thinnings can only be sold as firewood, for instance, annualized profits are negative in all of the SFM cases at a discount rate higher than 17%.

The FBBP scenario requires upfront investment but reduces variable costs and generates a relatively steady stream of profits relative to the SFM scenarios. However, the FBBP scenario is generally not cost-effective relative to the BAU scenario at realistic discount rates, because of the low implicit value of wood used to generating electricity. After subtracting its other costs, the power plant is able to pay 28$ m\(^{-3}\) for biomass feedstock, a price only marginally higher than that of firewood. Improving the electrical efficiency of the plant to 30% would increase its feedstock price to 44$ m\(^{-3}\). However, given that forest managers can sell small diameter timber for 66$ m\(^{-3}\), it is impractical to expect managers to sell...
stem wood for energy rather than timber, even if the land is designated for energy forests.

4.2. Comparison of forest management scenarios with carbon revenues

Carbon payments significantly affect the economics of different forest management options, shifting the SFM and FBBP annualized profit curves up (Fig. 3). For the SFM scenario, carbon revenues increase the discount rate at which SFM becomes more cost-effective than the BAU and decrease the importance of sales of initial thinnings. Although carbon offset revenues markedly improve the economics of FBBP, at lower carbon prices they do not significantly bridge the cost differential between energy and timber. Each 10$ t\(^{-1}\) CO\(_2\) increase in the carbon price adds roughly 3$ m\(^{-3}\) to the price of energy feedstocks.

At carbon prices higher than 11$ t\(^{-1}\) CO\(_2\), the SFM-M case becomes more cost-effective than the BAU at a discount rate of 15% (Fig. 4), suggesting the potential of using carbon payments to incentivize SFM even when the yield response to thinning is only moderate. In the SFM-L case, however, much higher carbon prices would be needed to make SFM cost-effective, indicating the limits of carbon payments if not paired with the silvicultural support needed to improve the results of SFM interventions.

5. Discussion

The results raise a number of questions about barriers to SFM and the role of wood-based energy in China. SFM could be an effective way to match timber, rural development, and environmental goals, but encouraging adoption of SFM practices on a large scale is a challenge. Barriers to SFM in China may be as much institutional as they are economic. Transitioning an existing forest plot to SFM is inherently risky, because it replaces a relatively stable, secure source of income with one that requires an upfront investment and produces uncertain results. Regular carbon payments can reduce risk and provide incentives for thinning, but only to the extent that forests respond reasonably well to thinning. To ensure that SFM interventions are effective, forestry agencies will need to address the barriers that make existing forests less productive in the first place. Steps to removing these barriers range from regulatory changes, such as making it easier for forest managers to obtain permits for thinning, to extension support, such as field-based training on silvicultural methods for SFM and successful pilot projects that create wider demand for SFM extension services.

An additional challenge for SFM in China is how to find substitutes for non-marketed uses of wood, and in particular as a source of household energy, as these would become less available under SFM. With the assumptions here, a one hectare plot would generate 11 m\(^3\) of non-marketed harvest residues over the first 10 years, which is less than one year of firewood use for many rural households in mountainous areas in Southwest China [31]. SFM increases the opportunity cost of forest biomass, but in areas where firewood use is high support for SFM may need to be accompanied by complementary strategies to either reduce wood energy use or manage different forest plots for different uses. Successful strategies for reducing tension between SFM and non-market wood use would require some amount of local-level planning to anticipate and address potential conflicts.

If other solutions to rural energy needs can be found, harvest residues could also be freed up for other uses. The ability to sell harvest residues as an energy feedstock would significantly improve the economics of SFM, adding 48–60$ ha\(^{-1}\) y\(^{-1}\) in annualized profits at a 15% discount rate, and more than doubling profits from timber sales. However, because most (70–80%) harvest residues are generated at the end of rotation in the SFM scenarios, the logistics of securing wood feedstocks in young and middle-aged forests would likely prove too costly for biomass power plant developers. A more interesting possibility would be to co-locate biomass small-scale combined heat and power (CHP) units at timber processing facilities and allow these units to sell excess power to the grid. A number of biomass CHP plants have come online in China since 2008, but these all use agricultural residues as a feedstock. Introducing and scaling up wood-based CHP in the timber industry in China would first require identifying current obstacles, determining the conditions under which

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Fig. 3 – Annualized profits for forest management scenarios at different discount rates, with carbon revenues.

Fig. 4 – Annualized profits for forest management scenarios at different carbon prices. Note: annualized profits are calculated using a discount rate of 15%.
CHP is cost-effective, and, to the extent warranted, designing policy solutions. The results suggest that, while energy is not an economic use of stem wood biomass, converting existing low productivity forests to short rotation species would be highly profitable. Clear cutting existing forests and replanting with short rotation plantations generates higher profits than any of the scenarios considered here. Carbon payments can improve the economics of SFM vis-à-vis short rotation timber plantations, but high carbon prices are required at discount rates that realistically represent liquidity constraints and opportunity costs in rural China. For instance, at a 15% discount rate the SFM-H scenario would require more than 40$ t⁻¹ 𝑀𝐶𝑂₂ to match annualized profits from short rotation timber plantations. Large-scale clear cutting of existing forests, with no oversight of silvicultural practices, would most likely have disastrous environmental impacts. Balancing incentives for timber production with conservation goals will require incentive-based regulatory innovations that provide more flexibility than the current quota system, but still enforce environmental standards.

All of the challenges described above point to the need for improved regulatory, planning, extension, and analysis capacity at China’s State Forest Administration, particularly at a local level, as an enabling force. Although a system of carbon payments can help to provide incentives for more productive forest management, it does not obviate the need for, and indeed presupposes, stronger public sector capacity.

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Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.biombioe.2012.01.043.

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