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# An economic analysis of using crop residues for energy in China

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ABSTRACT. This study examines the economics of using crop residues to replace coal burning for energy in China in order to mitigate carbon emissions. About 60 per cent of the available crop residues are now used by rural households in China to replace coal so that the residues are already making a major contribution to controlling China's potential carbon emissions. Using the crop residues more efficiently in village or centralized facilities, shifting to crops with more residues, or growing energy crops can all further reduce carbon emissions. However, accounting for the costs of collecting, transporting, drying and storing crop residues and the foregone crop revenue, the study estimates that the marginal cost to remove more carbon emissions with crop residues will be high.

## 1. Introduction

One means to help limit the rising levels of carbon dioxide in the atmosphere is to use crop residues as a biomass fuel. By burning plant biomass for energy, one can displace coal and reduce $CO_2$ emissions. Since the emitted $CO_2$ from biomass burning will be re-absorbed by new biomass growth, using plant biomass for energy results in no net increase in atmospheric $CO_2$. Plant residues appear promising because biomass can be turned into energy with available conversion technologies, residues can be stored without major technical problems, and supplies are readily available.

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The potential to reduce carbon emissions in China by burning crop residues is enormous. China produces about 605 million tons of crop residues per year, 60 per cent of which are used as cooking and heating fuels in rural households (Li *et al*., 1998). That is, without any carbon policy at all, the current use of crop residues for energy in China already avoids substantial coal use.

In this paper, we calculate the amount of carbon emissions rural households are currently mitigating by burning crop residues rather than coal. We also examine additional activities that China could subsidize to further reduce carbon emissions using crop residues from prime agricultural land. China could encourage the crop residues currently used by rural households to be sent to village or centralized electric facilities. By 1995, only 0.8 of the 217 GW of electricity generation in China came from biomass, mostly sugarcane residues (Wang, 1997). China could increase the amount of residues available for energy by encouraging farmers to grow more residue-intensive crops. China could substitute energy crops such as trees for existing crops. Measuring the costs of collection, transport, drying, storage, and foregone crop revenue, we examine the economics of the above activities to substitute crop residues for coal in order to reduce carbon emissions. We estimate the marginal cost of reducing carbon emissions beyond the existing baseline.

In order to increase biomass use for energy purposes, several critical questions need to be addressed. First, how much crop residue per hectare does prime cropland generate in Chinese farms? Second, how much carbon from coal combustion can be displaced by crop residues per hectare? Third, what is the cost of using crop residues for domestic or commercial energy instead of coal? We present an analysis of this problem by doing a survey of current crop residues and associated costs in a single Chinese village. The village was chosen because its crop mix and yield are representative of prime cropland in eastern China. The paper then calculates how much additional carbon is mitigated with alternative biomass production and technology options and how much each option costs. We conclude with estimates of the marginal cost of abating additional carbon emissions using crop residues.

The paper reflects a first cut at the problem of using biomass to reduce carbon emissions in China. This paper looks at a single place, takes prices as given, and examines average conditions for two alternative conversion facilities. Ultimately, before China pursues a large-scale carbon mitigation program to use crop residues, additional analyses would be required to explore effects across the landscape and to resolve general equilibrium issues concerning how the carbon program would affect the prices of different crops.

## 2. Site selection

As there is scant published literature on the production and use of crop residues in China, we adopt a field survey approach. China contains 96 million hectares of cropland (CAY, 1999), most of which is concentrated in eastern China along fertile river valleys. A complete analysis of China's potential biomass supply would require careful sampling of sites throughout China. The specific site we study, Sunyang Village of Jiangsu province, is representative of prime cropland in eastern China. The crop mix and unit crop yield in this village are representative of the province as a whole.

Jiangsu province lies in the northern subtropics along the Yangtze River. The winter temperature is 0–5 degrees Celsius and the average annual temperature is 15 degree Celsius. The area has a frost-free period of 210–250 days and an annual precipitation above 1000 mm (APRC, 1995). It has a monsoon climate, warm in winter and hot in summer with four sharply differing seasons. The province belongs to one of the major agricultural production zones of China with prime agricultural land and rich water resources.

The advantage of studying a single site is that, at a modest cost, we have gathered careful information about farmer behavior and costs relevant to how biomass fuels are used. Obviously, an analysis of a single site is just going to be indicative of the promise of biomass programs and cannot be used as a definitive national estimate. We argue that although only a humble starting point, the study makes a serious contribution by providing at least a first estimate of biomass production potential and cost. Obviously, if this potential looks attractive enough to develop and the costs are low enough, additional studies exploring more sites, price changes, and more technical options would be justified.

## 3. Estimating current carbon avoidance

In this region, prime land supports two sets of crops, both a winter and summer crop. Table 1 gives the yield for each crop that is grown or can be grown in the village. Wheat is grown as the winter crop, and rice, cotton, and soybeans are the primary summer crops grown in the village. Corn is not grown in Sunyang Village but is grown elsewhere in the province. The crop yield data were taken from semi-official statistics kept by the village, and verified through interviews with local farmers. Proficiency in the local dialect allowed Ms Wang to communicate with different social groups, including farmers, cadre, and family heads, to win their cooperation in collecting statistical data and conducting interviews. The interview data were used when there were large discrepancies between village statistics and interview data.

Agricultural residue production is derived by multiplying the average grain yield by the residue to crop ratio (RCR). RCR is the ratio of the stover (the portion of residues above the ground) to grain weight and varies by crop species. Table 1 presents the reported RCR for each crop (Bernard and Kristoferson, 1985; RERPC, 1990). The table identifies the type of crop residues to be expected and the tons of residues generated per hectare. Given that there is both a winter and summer crop grown on each hectare, one must add the crop residues from wheat to the crop residues from the summer crop to get a total crop residue estimate per hectare per year.

How much crop residue is safe to be removed from the field for energy purposes is controversial. Recycling residues provides nutrients, helps prevent erosion, and enhances the soil carbon sink. Sampson *et al.* (1993) indicate that in general 50 per cent of agricultural residues can be removed from fields without affecting soil productivity. Changing from

Table 1. *Carbon currently mitigated by rural households per year*

| *Crop* | *Crop Yield (t/ha)* | *Residue type* | *RCR* | *Residue yield (t/ha)* | *Residue as fuel (t/ha)* | *TCEC* | *FSF* | *Coal (t/ha)* | *Carbon (t/ha)* |
|---|---|---|---|---|---|---|---|---|---|
| Rice | 7.5 | Straw | 1.0 | 7.5 | 4.5 | 0.46 | 0.5 | 1.04 | 0.73 |
| Wheat | 5.9 | Straw | 1.0 | 5.9 | 3.5 | 0.53 | 0.5 | 0.93 | 0.65 |
| Cotton | 0.9 | Stalk | 3.0 | 2.7 | 1.6 | 0.58 | 0.5 | 0.46 | 0.32 |
| Corn[a] | 5.9 | Stalk, cob | 2.0 | 11.8 | 7.1 | 0.56 | 0.5 | 1.99 | 1.39 |
| Soybeans | 2.6 | Stalk | 1.5 | 3.9 | 2.3 | 0.58 | 0.5 | 0.67 | 0.47 |

*Notes*: [a] As Sunyang does not grow corn, corn yield is taken from the provincial statistics (JPSY, 1996).
RCR = Residue to crop ratio;
TCEC = Total coal equivalent coefficient;
FSF = Fuel substitution factor.

conventional tillage to partial tillage or non-tillage, the latter of which China has begun to practice, could increase recoverable residues up to 58 per cent (Hall *et al*., 1993). Experimental research in Saskatchewan of Canada (Campbell *et al*., 1991) and in La Miniere of France (Balesdent and Balabane, 1996) show that carbon from roots contributes more to soil organic matter than the carbon from straw. Their research suggests that crop residues may be safely removed without detrimentally affecting soil productivity, provided adequate fertilization is practiced and tillage is reduced. Furthermore, Stumborg *et al*. (1996) estimate that 750 kg/ha of retained residue would be adequate for erosion protection in reduced tillage systems. When incorporated into soil, between 0 and 10 per cent of carbon in residues can be sequestered by soil mainly in the form of soil organic matter (Campbell *et al*., 1991; Duiker and Lal, 1999; Lal *et al*., 1999). In China, about 15 per cent of crop residues are being used as fertilizer or left on the field (Li *et al*., 1998). We assume that the current practice of leaving 15 per cent of crop residues in the field provides adequate fertilizer, soil protection, and soil carbon.

About 85 per cent of crop residues are currently collected, 60 per cent of the residues are used by rural households for energy to cook and heat their homes, and the other 25 per cent for animal feed and industrial raw materials (Li *et al*., 1998). Farmers use the crop residues for energy because the residues are easily collected and stored near their fields or homes. For most farmers, the cost of relying on the crop residues after accounting for their time inputs is still less than the cost of buying coal briquettes. Consequently, without any official carbon mitigation program in place in China, rural households are already substituting crop residues for coal in order to meet their personal energy needs.

In order to calculate the tons of coal that a ton of crop residue would replace, one needs to make two calculations. First, one must calculate the heat content of a ton of crop residue relative to the heat content of a ton of coal. The total coal equivalent coefficient (TCEC) measures the inherent heat value per ton of residue assuming that the residue has been dried to a 10 per cent moisture content. Given that the heat value of standard coal is 29.3 GJ/ton, TCEC measures the amount of coal that is needed for the same heat value as a ton of residue. In general, a ton of crop residue has the same heat value as 0.5 tons of coal (RERPC, 1990) (table 1). Second, one must also calculate the thermal efficiency of a household stove burning crop residues versus burning coal briquettes. Household stoves in rural China are notoriously inefficient from a thermal perspective. When the crop residue is burnt in self-built brick cooking stoves commonly seen in rural China, the thermal efficiency is around 15 per cent (Zhang *et al*., 2000; Wang and Feng, 2001). The thermal efficiency is around 30 per cent for coal briquettes used for cooking in China (WB *et al*., 1991). The fuel substitution factor (FSF) for household-use crop residues is therefore 0.5. One ton of crop residues used in cooking stoves effectively replaces only about 0.25 ($= 0.5 \times 0.5$) tons of coal briquettes.

Multiplying residues per hectare by 60 per cent, TCEC, and FSF, one can calculate the amount of coal per hectare that crop residues currently replace because of household use (shown in table 1). The most productive crop from a residue perspective is corn, which replaces about 2 tons of coal per hectare. Rice is second with 1 ton of coal per hectare and wheat follows closely behind. It is important to note that the average crop residue yield in Sunyang is about 13 tons/ha, double the national average of 6.4 tons/ha (= 605 million tons/95 million ha according to Li *et al*. (1998)). This can be explained by the high quality of the land and the practice of two croppings a year in Sunyang. We assume that only effectively irrigated farmland may match such quality, which amounts to about 50 million ha in China (CAY, 1999).

Multiplying the tons of coal by the tons of carbon that coal normally emits (0.7 tons carbon/ton of coal) yields an estimate of the carbon that is mitigated because the crop residues are burned in household stoves. As reported in table 1, prime agricultural land in China replaces substantial carbon emissions. The highest replacement rate, 2 tons/ha/yr, is associated with the annual rotation of growing wheat and corn. In Sunyang Village, the most profitable combination is growing wheat and rice, which replaces 1.4 tons of carbon per hectare per year. Using the average crop production for the village (35 per cent wheat, 44 per cent rice, 10 per cent cotton, and 7 per cent soybeans in terms of acreage (Wang, 2000); wheat is the only winter crop and the others are summer crops), the average carbon replacement is 1.3 tons/ha/yr. Given the average production in Jiangsu Province (32 per cent wheat, 34 per cent rice, 9 per cent cotton, 7 per cent corn and 10 per cent soybeans in terms of acreage (Wang, 2000)), the average carbon mitigated is 1.35 tons/ha/yr. Extrapolating this estimate to all of China's prime agricultural land (50 million ha) suggests that 65 million tons of carbon are currently being mitigated annually by rural households in China.

## 4. Additional carbon potential

The analysis to this point has focused on estimating the amount of carbon that households currently replace by burning crop residues instead of coal briquettes in their home stoves. In the following analysis, we wish to explore a number of alternatives that could potentially replace even more carbon emissions. We explore taking the 60 per cent of crop residues that rural households use for energy and devoting them to fueling either a village facility or a centralized electrical plant. We also consider growing a crop combination that produces more residue, wheat and corn, for either facility. Finally, we consider growing trees for energy on prime agricultural land. In all cases, these additional measures mitigate more carbon but also cost more. Without an official program to mitigate carbon, none of these measures are currently being done. The purpose of this analysis is to find out how much they would cost per additional ton of carbon removed.

We examine using the crop residue in a 100 kW village facility and a 40MW centralized electrical plant with available commercial or nearly commercial technologies. The village facility would be a trigeneration system that would make gas for cooking, provide hot water for heating, and generate excess electricity to sell on the grid (Henderick and Williams, 2000). A variation of such a system is under demonstration in China. The centralized facility could combine crop residues and natural gas to generate electricity. We assume that these new facilities would collect all the residues that are currently burned in household stoves. As seen in table 2,

Table 2. *Cost estimates to reduce carbon emissions above baseline per year*

| *Options* | *Residue as Fuel* (t/ha) | *FSF* | *Total C replaced* (tC/ha) | *Additional C replaced* (tC/ha) | *Lost grain revenue* ($/ha) | *Tree planting* ($/ha) | *Transport* ($/t) | *Collection, drying & storage* ($/t) | *Marginal cost* ($/tC) |
|---|---|---|---|---|---|---|---|---|---|
| *Household stoves* | | | | | | | | | |
| Wheat and rice | 8 | 0.5 | 1.4 | – | 0 | – | 0 | – | 0 |
| Wheat and corn | 12 | 0.5 | 2.1 | 0.7 | 137 | – | 0 | – | 196 |
| *Village facility* | | | | | | | | | |
| Wheat and rice | 8 | 0.57 | 1.6 | 0.2 | 0 | – | 4.8 | 0 | 192 |
| Wheat and corn | 12 | 0.57 | 2.4 | 1.0 | 137 | – | 4.8 | 0 | 195 |
| Forest on cropland[a] | 12.5 | 0.68 | 3.6 | 2.2 | 1138 | 28 | 2.4 | 2.7 | 559 |
| *Centralized facility* | | | | | | | | | |
| Wheat and rice | 8 | 0.86 | 2.4 | 1.0 | 0 | – | 9.6 | 0 | 77 |
| Wheat and corn | 12 | 0.86 | 3.6 | 2.2 | 137 | – | 9.6 | 0 | 117 |
| Forest on cropland | 12.5 | 0.94 | 5.0 | 3.6 | 1138 | 28 | 4.8 | 2.7 | 350 |

*Notes*: [a] The TCEC for firewood is 0.61(RERPC, 1990).
FSF = Fuel substitution factor;
C = Carbon;
tC = Ton(s) of carbon.

about 8.0 tons of crop residues are available for energy per hectare. Given that a 100 kW plant would need 600 tons of crop residues to operate two thirds of a year (Wang, 1997), the village facility would need residues from 75 hectares. Assuming that 75 per cent of the land is farmed, a circular area with radius of about 0.6 km could supply the village facility with what it needs. A 40-MW centralized facility would need approximately 240,000 tons of crop residues. This would require 30,000 hectares of cropland. Again assuming that 75 per cent of the land around the facility is cropland, supplies would have to be drawn from a circle of 10 km radius.

Moving this material from household use to village and centralized sites replaces more carbon because the crop residue can be converted to energy at a higher thermal efficiency and consequently replace more coal. The village facility is estimated to have an average electric efficiency of 20 per cent using crop residues (Henderick and Williams, 2000). The electric efficiency is about 30 per cent in a large commercial conversion facility using fuels from biomass plantations (Sampson *et al*., 1993). Given that the conventional pulverized coal–steam cycle technology has an average efficiency of 35 per cent, the FSF of crop residue vs. coal is 0.57 in the village facility and 0.86 in the centralized facility.

In table 2, we compare the amount of carbon that the village and centralized facilities will remove to what is removed by household use. Currently winter wheat and summer rice are dominant in Sunyang because it is the most profitable combination. The village facility would replace 1.6 tons of carbon per hectare and the centralized facility would replace 2.4 tons. Subtracting the baseline tons of carbon currently being prevented, this yields a net contribution of 0.2 tons of carbon/ha if the village facility is used and 1 ton of carbon/ha if the centralized facility is used.

We now calculate the marginal cost of mitigation by calculating the cost per ton of the additional carbon removed. This is the marginal cost of moving from the baseline where the residues are used by rural households to either the village or the centralized facility. We assume that the capital costs of the village and centralized facilities are similar to the capital costs of the coal facilities that they replace (Wang, 1997). Then the gross cost of straw at the facility is

$$
\begin{aligned}
C(\text{straw}) &= \text{collection–drying–storage cost} + \text{transport cost} + \\
&\quad\ \text{forgone crop revenue} \\
&= P(\text{collection–drying–storage}) + P(\text{tr}) + P(\text{crop}),
\end{aligned}
$$

and the gross cost of firewood at the facility is

$$
\begin{aligned}
C(\text{firewood}) &= \text{collection–drying–storage cost} + \text{transport cost} + \\
&\quad\ \text{forgone crop revenue} + \text{tree-planting cost} \\
&= P(\text{collection–drying–storage}) + P(\text{tr}) + P(\text{crop}) + \\
&\quad\ P(\text{planting}).
\end{aligned}
$$

The marginal cost of carbon avoided is the net cost of switching from burning coal to burning straw (firewood) at the facility divided by the additional carbon avoided, i.e.

$$= [C(\text{straw or firewood}) - P(\text{coal})]/\text{amount of additional carbon.}$$

Rural households currently collect, dry, and store crop residues at a price that is lower than buying coal briquettes. We consequently assume that this baseline activity is free in that the coal savings compensate the households for their time inputs. The cost of collection and transport for the villagers is quite low since they use the material in their homes adjacent to the fields. The transport costs to a village or central facility, however, will be higher. We rely on a limited market for straw established for nearby brick and tile kilns to determine the additional transport costs for the village and centralized facilities. We assume that the cost of village collection and transport of this material would be equal to the price that is currently paid by the kiln owners for the straw since it is also a nearby facility. The purchase price paid by kilns for crop residue is $4.8/ton of straw (1 US dollar = 8.28 Yuan in 1998). The cost per ton of straw is likely to be higher for the centralized facility than for the village facility because of the increased transportation cost and increased management effort required to sustain the cooperation of so many farms. However, there are no similar residue-related industrial activities in the region upon which we could base the estimate of the fuel transport cost for the centralized facility. In a phone interview, the local residents in Sunyang Village stated that truckers would probably be willing to transport the straw to the hypothetical central facility (no more than 10 km away) at a cost of double that for the village facility, that is, $9.6/ton. We take this value in our analysis.

There is a very small cost associated with drying and storing crop residues. Air drying is sufficient to reduce the moisture of crop residues to about 10 per cent, and involves little cost. We thus assume the cost of air drying is negligible. Proper storage measures may be needed to eliminate fire hazards as crop residues are prone to self combustion at such a low moisture. We assume covering crop residues with heavy ethylene film would effectively prevent fire hazards while maintaining a six-month supply. As with the household use, we assume that the cost of collection, drying, and storage is equal to the purchase price of coal.

Given the current crop combination of wheat and rice, the net cost of switching from burning coal to burning straw at the facility is

$$= C(\text{straw}) - C(\text{coal saved})$$

$$= P(\text{collection–drying–storage}) + P(\text{tr}) - P(\text{coal}), \text{ where } P(\text{collection–drying–storage}) = P(\text{coal})$$

$$= P\ (\text{tr})$$

That is, the only additional cost of the village and centralized facility is the extra transportation costs and management effort associated with collecting crop residues from many farms. The marginal costs are $192/ton (= 4.8*8/0.2) for the village facility and $77/ton (= 9.6*8/1) for the centralized facility. The additional efficiency gain of the centralized facility outweighs the increased transportation costs compared to the village option.

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In our next analysis, we consider growing crops that are more biomass intensive (i.e. produce more biomass per hectare per harvest). In this case, we consider moving from growing wheat and rice to growing wheat and corn. The net cost of straw includes not only the transport cost but also the forgone crop revenue. Table 3 presents the yields and revenues associated with growing different crops in this province. There exists a dual pricing scheme for grain in China: the state purchase price and the market price. The two prices are different but correlated (Huang, 1998). We use the state purchase price in these revenue calculations. The grain market is relatively new and characterized by significant government intervention in China. We therefore felt the market price was unreliable.

As can be seen in table 3, wheat and rice is the most profitable combination for farmers, earning $1,138 per hectare per year. Combining wheat and corn earns only $1,001 per hectare per year. Thus, by switching from rice to corn, the farmer is giving up $137 of net revenue per year. However, in return, the farmer grows an additional 4 tons of crop residue. As shown in table 2, if this additional crop residue were used by the household, it would replace 0.7 tons of carbon. The marginal cost of this additional mitigation is $196 (= 137/0.7) per ton. If all of this residue were sent to a village facility (with its higher thermal efficiency), it would replace one additional ton of carbon per hectare. Adding the cost of the extra transport and the income foregone, the marginal cost would be $195 per ton of carbon [= (137 + 4.8*12)/1]. If the residue were sent to the centralized facility, it would replace 2.2 additional tons of carbon with a marginal cost of $117 per ton of carbon [= (137 + 9.6*12)/2.2]. Crop switching would lead to more crop residue but it would cost $120 to $200 per ton of carbon. This does not include any additional fertilizer costs that might be required to sustain such high levels of production.

In our final analysis, we consider growing trees for firewood instead of crops. Although forest yields vary a great deal by location, it is generally assumed that trees would yield more biomass and energy output than byproduct crop residues on the same piece of land. In the mountains of Hengnan Count of Hunan Province in China, a firewood plantation of eucalyptus, poplar, or larch would yield 7.5 tons/ha/yr of biomass (WB *et al*., 1991). The mountains, of course, have a lower productivity than prime

Table 3. *Estimate of grain revenue per year*

| *Crop type* | *Grain yield* (kg/ha) | *Price* ($/kg) | *Gross revenue* ($/ha) | *Planting cost* ($/ha) | *Net revenue* ($/ha) |
|---|---|---|---|---|---|
| Wheat | 5,850 | 0.1328 | 777 | 375 | 402 |
| Rice | 7,515 | 0.1690 | 1270 | 534 | 736 |
| Corn | 5,865 | 0.1932 | 1133 | 534 | 599 |

*Notes*: 1. The exchange rate of the Chinese Yuan to US dollar used in this analysis was 1US$ = 8.28 Yuan in 1998.
2. As Sunyang does not grow corn, the corn yield is taken from the provincial statistics (JPSY, 1996). The yields for wheat and rice are field survey data.
3. Planting costs are obtained through interviews with farmers in Sunyang Village.

cropland. Estimates for Eucalyptus on high quality lands in Brazil suggest yields as high as 12.5 tons/ha/yr (Carpentieri *et al.*, 1993). We use the higher estimate of 12.5 tons/ha/yr in our analysis of prime agricultural land, recognizing its higher productivity.

The heat value of firewood is higher than crop residues so the fuel substitution factor of firewood vs. coal is higher. We estimate that a ton of firewood is equivalent to 0.68 tons of coal in the village facility and 0.94 tons of coal in the industrial scale facility. A hectare of forest would replace a total of 3.6 tons of carbon in the village facility and 5 tons of carbon in the centralized facility. This would represent an additional 2.2 tons of carbon in the village and an additional 3.6 tons in the centralized facility compared to the baseline.

Because firewood grows all year round, the trees will replace both the summer and winter crops. We assume that the trees would replace growing wheat and rice, the most profitable combination of crops. This would cost $1,138 per hectare. The forest plantation would also require planting and tending which we assume will cost about $28 per ha per year (WB *et al.*, 1991). The firewood will also need to be harvested and transported to the facility. We assume that harvest and transport costs for firewood are equal to one half of the same costs for crop residues per ton because of its higher volumetric density. In the United States, drying firewood with an unheated, forced-air system costs $11/ton, chipping costs $3.15/ton and storage costs $6.8/ton (Williams and Larson, 1993). Yang (1995) shows that less-sophisticated technologies are much cheaper to manufacture in China than in the US. Using Yang's cost conversion factor for relatively unsophisticated technologies, we estimate that the costs of chipping, drying and storage could be reduced to $2.7/ton for firewood in China. The net cost of firewood is sum of planting cost, transport cost, forgone grain revenue, and drying cost which is small but not negligible for firewood. The marginal cost to mitigate carbon using firewood in a village facility is $559 per ton {= [1138 + 28 + (2.4 + 2.7)*12.5]/2.2}. The marginal cost of mitigation using firewood in a centralized facility is $350 per ton of carbon {= [1138 + 28 + (4.8 + 2.7)*12.5]/3.6}. The cost of forestry is so high because the opportunity cost of the land is very high and forestry does not produce a lot more energy than crop residues.

## 5. Discussion and conclusion

The analysis estimates the quantity of carbon that is currently removed by rural households because they rely on crop residues rather than coal for cooking and heating. The analysis of Sunyang village suggests that rural households are mitigating about 1.3 tons of carbon per hectare per year. Given that there is about 50 million ha of prime (effectively irrigated) agricultural land in China (CAY, 1999), this amounts to an aggregate estimate of about 65 million tons of carbon annually. China currently emits about 800 million tons of carbon per year (NEPA *et al.*, 1994). Even without an official carbon mitigation program, crop residues eliminate a substantial fraction of China's total emissions.

We discuss several options (or the combination of them) that China could undertake to increase the amount of carbon mitigated using crop residues. China could organize village energy facilities or centralized electrical facilities to burn residues. These two options would increase the thermal efficiency associated with utilising crop residues for energy and consequently replace more coal. A third option is that they could shift to more residue-intensive crops. Finally, they could grow trees for energy on cropland and send firewood to the two facilities.

All of these options would increase the amount of carbon that residues mitigate. Shifting to a village facility would reduce carbon emissions another 0.2 tons per hectare. Shifting to a centralized electrical facility would reduce another ton of carbon per hectare. Shifting to growing wheat and corn rather than wheat and rice would eliminate another ton of carbon in the village facility and another 2.2 tons of carbon in the centralized facility. Finally, growing trees for energy would reduce another 2.2 tons of carbon per hectare in the village facility and 3.6 tons in the centralized facility.

The marginal cost of reducing additional carbon through these mitigation activities, however, is surprisingly high. The lowest marginal cost of the additional carbon saved is still as high as $77 per ton which can be achieved through utilizing the current residues at the centralized facility, followed by $117 per ton which belongs to the combined measures of crop shifting and centralized utilization. The other uses of crop residues at the household and village facilities result in a marginal cost of almost $200 per ton. These additional activities save only small amounts of additional carbon but entail substantial costs. Growing trees on prime agricultural land would cost between $350 and $559 per ton. The cost of replacing carbon by growing trees is so high primarily because of the opportunity costs of foregoing agricultural production on prime cropland. It is clear that prime agricultural land should not be diverted to growing firewood. Of course, growing trees for energy on wasteland that is not suited for crops is a different matter since the opportunity costs of the land would be much lower. The study did not examine this forestland alternative.

These results imply that there are few low-cost options for China to get more carbon reductions from their crop residues than they already do. Because rural households already substitute crop residues for coal, the residues already make a substantial contribution to reducing China's potential carbon emissions. For China to adopt a policy that would reduce carbon emissions even further would cost substantial resources.

One important issue that was not considered in this study concerns indoor air pollution. Current cook stoves in rural households have very low thermal efficiencies. Further, they are often not attached to chimneys or other ventilation systems that would remove the smoke from the interior. Indoor air pollution levels are quite high in many rural homes in China, causing serious health effects (Zhang *et al*., 2000). As their income increases, farmers are likely to switch from crop residues to coal briquettes or liquefied petroleum gas (LPG). China might seriously consider a modern village biomass facility primarily to address this health issue while retaining the carbon benefits. The health benefits would make these carbon mitigation strategies more attractive.

A complication of moving forward on the technological options in this paper is that there are also institutional barriers. The economics of both the village system and the centralized facility requires that the rural facility be able to sell the electricity produced to the utility grid. The electricity generated would far exceed the demand of rural households (Henderick and Williams, 2000). It is consequently necessary to sell the excess electricity on the market. The underdeveloped infrastructure and largely state-controlled power sector in China are not yet ready to allow this to happen especially in rural areas. If these systems became economically viable, the electrical system would have to be modernized and reformed so that the grid could take these new power sources.

The cost estimates in the paper depend on many assumptions. The data collection was limited to a single village. There is considerable uncertainty associated with the input parameters. The productivity of the land, the cost of different activities, the thermal efficiencies, and the fuel substitution factors are all uncertain. For example, in calculating the marginal cost of switching from coal to straw, we assume that the collection–drying–storage costs are equal to the price of coal. If such costs are much less than the price of delivered coal, then the net marginal cost of switching would be smaller. The estimates provided are unbiased but they are not necessarily accurate. A more extensive analysis would have to be conducted to get better estimates of the marginal cost of each activity. Further, prices are assumed to remain constant in this study. Any mitigation program that was instituted for the entire country would likely change prices and make these programs more expensive. These price changes would have to be taken into account.

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