Emission Inventories of Carbon-containing Greenhouse Gases in China and Technological Measures for Their Abatement

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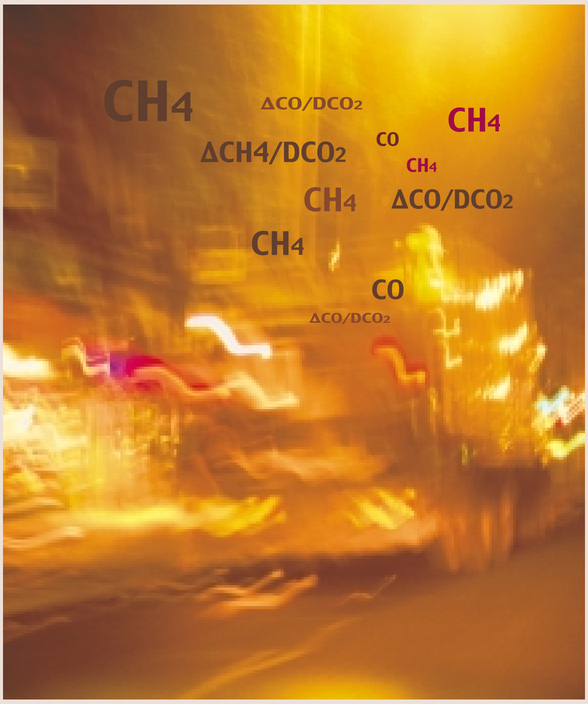
Abstract: The report summarizes surveys on carbon inventories and initiatives on sustainable carbon cycling taken by the Research Center for Eco-Environmental Sciences, where the authors work/worked. The first part of the report, which appeared in the preceding issue of this journal, deals with the concept of sustainable carbon cycling, the historic evolution of carbon cycling processes in China, carbon pool enhancement, value addition, carbon sequestration and carbon balance. This very paper, as the second part of the report, covers the results of carbon dynamics modeling, emission inventories of various carbon-containing greenhouse gases and their potential abatement measures.
Keywords: sustainable development; carbon cycle; carbon dynamics modeling; emission inventory

1 MODELING CARBON DYNAMICS

Sustainability of Chinese ecosystems is challenged by a series of stresses, including soil degradation, water eutrophication and sand storms. We, using a denitrification-decomposition (DNDC) model developed by the fourth author, conducted a modeling study to explore what is happening fundamentally in the Chinese agriculture by tracking coupled carbon and nitrogen biogeochemical cycles in the agro-ecosystems for China and the United States (Li et al., 2001; Li et al., 2004). Our results indicated a significant difference in soil carbon dynamics in these two large agricultural countries. In the year of 1990, the 95 million ha of Chinese cropland lost 54.2 Tg C, which was more than double of the carbon (26.7 Tg C) lost from the 141 million ha of the U.S. cropland. Model simulation also indicated that China's current agricultural management, especially crop residue treatment, led to loss in soil organic carbon, causing not only soil degradation (including desertification) but also "skewed" nitrogen biogeochemical cycle in China's ecosystems. Chinese soils generated 13.4 Tg inorganic N less than their counterparts in the U. S. annually, because of deficiency in soil organic matter. This fact partially explains why the Chinese farmers have to use much more synthetic nitrogen fertilizers (almost double) than the American farmers to support crop growth. The DNDC model predicted about 8.8 Tg N leached from the Chinese cropland vs. 2.1 Tg N from the U.S. cropland annually. Our findings related both soil degradation and water eutrophication to a same cause, namely, loss of soil organic matter due to the lack of crop residues returned to the cropland. For sustainable development, it would be crucial to set new policies to correct the long-term mismanagement of crop residues in China.

According to the statistical figures of a Sino-American joint study (Li et al., 2003), a significant part of crop residues was burned, only 25% of the above-ground residues (including collection loss) was returned to the fields, while the rest was used as animal feed and industrial material (e.g., pulp making). In contrast, the farmers in the U.S. return approximately 90%



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of crop residues to the fields by chopping their crop residues in the fields during the harvest time. In addition, overgrazing is common in the Chinese grassland. Decline in both grassland productivity and soil organic matter content has been observed in a wide region from Inner Mongolia to Qinghai. Since soil organic carbon (SOC) is a key factor dominating the most important soil physical and chemical properties, decreases in SOC would unavoidably accelerate soil erosion, desertification, and salinization. Sandstorms occurring in 2000 spring were related to soil degradation in the entire northern parts of China, and continued decrease in annual precipitation in the areas accelerated the desertification process.

These recently reported hazardous issues have demonstrated a common character, i.e., they occurred in an unprecedented large scale and caused severe economic and environmental damages. People began to ask if there is any way to correct the mismanagement in China. In the following sections, we present some of our demonstration efforts towards a less-polluting carbon cycle.

2 BETTER MANAGEMENT FOR THE REDUCTION OF METHANE EMISSIONS FROM PADDY FIELDS

Chinese rice paddy field is considered as an important contributor of increasing methane level in the atmosphere. Saas et al. (1999) estimated its methane emission to be 37.6% of the total in the world. Hence, methane emission is a worldwide concern. With the efforts of both foreign and Chinese scientists, emission data have been accumulated since 1990.

Decreased methane emissions from paddy rice may have contributed to the decline in the rate of increase of global atmospheric methane (CH_4) concentration over the last 20 years. In China, midseason paddy drainage, which reduces growing season CH_4 fluxes, was first implemented in the early 1980s, and has gradually replaced continuous flooding in much of the paddy area. We constructed a regional prediction for China's rice paddy methane emissions using the DNDC biogeochemical model (Li et al., 2002). Results of continuous flooding and midseason drainage simulations for all paddy fields in China were combined with regional scenarios for the timing of the transition from continuous flooding to predominantly mid-season drainage to generate estimates of total methane flux for the period of 1980-2000. CH_4 emissions from China's paddy fields were reduced over that period by 5 Tg CH_4 per year. Consequently, avoiding long-period flooding and shifting to drainage in winter and mid-season aeration could reduce the annual methane emissions from paddy fields. Such field practices are also favorable to increasing grain yield.

For better management, we need accurate agricultural census data. Large-scale assessments of the potential for food production and its impact on biogeochemical cycling require the best possible information on the distribution of cropland. This information can come from ground-based agricultural census data sets and/or spaceborne remote sensing products, both with strengths and weaknesses. Official cropland statistics for China contain much information on the distribution of crop types, but are known to significantly underestimate total cropland areas and are generally at coarse spatial resolution. Remote sensing products can provide moderate to fine spatial resolution estimates of cropland location and extent, but supply little information on crop type or management. We combined county-scale agricultural census statistics on total cropland area and sown area of 17 major crops in 1990 with a fine-resolution land-cover map derived from 1995 to 1996 optical remote sensing (Landsat) data to generate 0.5° resolution maps of the distribution of rice agriculture in mainland China (Frolking et al., 2001). Agricultural census data were used to determine the fraction of crop area in each 0.5° grid cell that was in single rice and each of 10 different multi-crop paddy rice rotations (e.g., winter wheat/rice), while the remote sensing land-cover product was used to determine the spatial distribution and extent of total cropland in China. We estimate that there were 0.30 million km^2 of paddy rice cropland; 75% of this paddy land was multicropped, and 56% had two rice plantings per year. Total sown area for paddy rice was 0.47 million km^2. Paddy rice agriculture occurred on 23% of all cultivated land in China.

3 STUDY ON GHG (CO_2, CH_4 AND OCS) EMISSIONS FROM BIOMASS BURNING

Biomass burning plays a crucial role in China. Biomass may become a sustainable fuel of the future. However, biomass burning is a major global source of many atmospheric pollutants. The species and quantities of gaseous and particulate emissions resulting in biomass burning depend not only on the type of ecosystems, the moisture of the vegetation, and the different burning practices (e.g., open versus enclosed combustion), but also on the stages of combustion (i.e., flaming versus smoldering stages). It is no longer valid to assume constant emission ratios for all fires.

There is particular concern about emissions from China because of her population growth, economic development and fuel shift (Zhuang, 1996). More crop residues are now disposed of in the fields by fire (Zhuang et al., 1996). During harvest seasons, particulate emissions from crop residue fires sometimes seriously reduce the visibility of nearby airports to such an extent that all flights have to be canceled. It is hoped that our study will contribute to the promotion of rational use of biomass in China.

In this paper, we describe the results of our study on biomass burning emissions in China. For the measurement of combustion emission factors, both dynamic and static combustion systems were employed. Samples of the above-ground components of typical Chinese tree, shrub, grass and crop species were collected and burned under flaming and smoldering stages in open and closed systems. The emission factors of CO, CH_4, N_2O and OCS were determined. Meanwhile, the Chinese forest and crop biomass inventories have been established, including the component and layer biomass of 16 main forest types and 4 eco-climatic regions as well as the major crops in China. Starting with our carbon pool inventory and emission factors, we made spatial distribution maps of trace gas emissions from the crop residue combustion, and preliminary estimation of emissions from forest fire as well. Finally, technological mitigation measures in China are evaluated to identify the gap for cleaner combustion of biomass.

● Emission Sources of Biomass Combustion

The major types of biomass burning in China are: direct combustion of fuelwood and agricultural residues for domestic heating and cooking purposes; combustion of biogenic residues and wastes in industrial boilers for steam or electricity generation; incineration of stubble and waste on croplands after the harvest; and accidental forest fire. Charcoal production and the subsequent combustion are also considered as a special type of biomass burning. A distinction should be made between open fires and enclosed combustion.

Open fires in forested areas

The occurrence and extent of forest fires in China have been summarized by us (Wang, 1996; Wang et al., 1996). On the basis of our forest statistical data, we quantified the biomass burned annually due to accidental fires in China. The contribution of the big boreal forest fire occurred in China in 1987 has been also estimated by us as a case study (Wang et al., 1996). We reported the damaged forest area was 1.14 million hectares on the basis of ground survey after the 1987 big Chinese fire. That value agrees quite well with Cahoon's result based solely on satellite measurements (Cahoon et al., 1994). The direct carbon release was estimated to be 18.8 Tg, according to our calculation. This implies that burning in boreal forests has been underestimated.

Emissions from agricultural residue combustion

The major agricultural residues used as fuels are cereal residues, woody crop residues and dung. Crop residue combustion in China plays a significant role in global emissions from all biomass combustion (Table 1). Up to now, insufficient attention has been given to agricultural residue combustion under small-scale semi-enclosed conditions in cooking stoves and space-heating fireplaces.

The availability of crop residues is estimated from the harvest or plantation areas and the annual yields of grains per unit area. Estimates of the amount of available crop residues found in the literature vary widely. Because of this variability, individual estimates in the literature should be examined carefully to establish their validity before using them. We have established an agricultural residue database for all the 2484 counties in mainland China (Zhuang et al., 1996). The values of annual yield and harvest area in our database were verified by occasional field sampling survey and by using remote sensing estimation results, whenever available. The total amount of crop residues available in China and the fraction used as fuels are listed in Table 2.

Table 1 Breakdown for rural household energy consumption in China

Fuel, Mtce*	1996[a]	1993[b]	1992 [b]	1991 [b]
Crop residues	120	153.5	135.5	164.1
Fuelwood	99	89.4	93.5	103.0
Coal	-	91.4	78.9	77.5
Electricity	-	12.9	11.2	11.6
Oil	-	2.9	1.4	1.3

Mtce stands for million tons of coal equivalent. Here we use a conversion value of 0.50 tce per ton of residues.
Sources: [a]SETC, 1997; [b]Zhuang, 1996

Table 2 Crop residues consumed in China as household fuel

	1979[a]	1987[a]	1992[b]	1993[c]	1996[d]
available residues, Mtce*	183.6	268.3	297.9	285.0	201
residues consumed as fuel, Mtce*	113.7	130.3	135.5	153.5	120
fraction of residues burnt, f	0.62	0.49	0.46	0.54	0.60

Mtce stands for million tons of coal equivalent.
(Sources: [a] Sinton, 1996; [b] Deng, 1994; [c] Deng and Zhang, 1995; [d] SETC, 1997)

The ratios of residue weight to grain weight of the major crops have been collected by us. In this paper we adopted the ratios for China's major crops compiled by Ma et al. (1987). The values of f fluctuate in the range of 0.46-0.62. In our computation, we have taken into account of the often neglected contribution of residue incineration in the field, and employed a value of 0.60 for f.

Accurate country-wide statistics about the open fires of crop residues are not available, About 8 Mt of crop residues were burned wastefully in 1992 (Wang, 1994). Since the total amount of crop residues amounted up to 595.7 Mt in 1992, it infers that 1.3% of crop residues was incinerated. In 1991, about 840 thousand tons of crop residues in Shijiazhuang, China were incinerated in the fields (NEPA, 1994). According to a Sino-Canadian joint survey (private communication), about 300 ha of crop residues in Beijing have been cleared in 1991. The total amount of above-ground biomass burned is 900 ton dry matter per annum. The above-ground biomass density has been found to be about 0.3 $kg \cdot m^{-2}$. It should be pointed out that some authors, estimating emissions from agricultural residue combustion, did not give the f values of Asian countries. They assumed that all the residues were burned as fuels. The inevitable errors resulting from uncertain f values cause considerably greater uncertainty than exclusion or inclusion of minor crops and vegetables.

Emissions from fuelwood combustion

A large fraction of the combusted fuelwood along with crop residues in the world is burned in household cooking and heating stoves. As we can see from Table 1, fuelwood ranks the second in the rural household energy sector of China. The total amount of traditional fuels is more than that supplied by hydroelectricity and oil.

Good forest biomass inventories are rare, especially in China. Because forested areas contain various species of different ages, it is much more difficult to quantify the forest biomass than the agricultural biomass. We established a comprehensive database on the forest biomass in China (Wang, 1996). The area data are combined with the detailed tree dry mass data to yield estimates of individual layers, sub-populations and the whole population. To separate those tree components, such as foliage, which can only be used as fuel, from merchantable stem wood, tree component biomass has been used for estimation of consumed biomass as fuel.

Emissions from animal and industrial waste combustion

Dry animal manure (dung) is a traditional fuel in Asian countries, but it is used as fuel only in the northwest part of China. Nevertheless, animal excreta are now used as a good material for biogas production. The dry manure produced per animal per year, and the livestock populations have been collected in our database. Among industrial wastes, bagasse from sugar industry and woody wastes from timber industry are the most important sources (Table 3).

Table 3 Fuelwood and bagasse production in China, including wood for charcoal

	Fuelwood production, $\times 10^3$ m^3				Bagasse, $\times 10^3$ tons			
Year	1990	1991	1992	1993	1990	1991	1992	1993
Production	188 477	192 235	196 088	199 996	15 322	18 105	23 117	20 841

Source: UN, 1995

● Emission Factors and Emission Ratios

The uncertainty about small-scale combustion emissions is partly due to uncertainty in the source intensity and partly due to uncertainty in the emission factors. Most of the published emission factor determinations have been designed to duplicate the conditions of large-scale open combustion. The emission ratios derived from cooking and heating stove emissions are quite different from large-scale open combustion. Cooking and space heating stoves account for most biomass fuels (wood, charcoal, crop residues, animal dung). Hence, more extensive measurements of emission factors for a range of fuels and combustion devices would be useful in reducing the uncertainty of emission inventories.

To simulate combustion with an insufficient or sufficient supply of air, we used both dynamic and static combustion systems, which are composed of combustion beds, ignition devices, an electric balance, temperature and flow rate sensors, sampling devices, NDIR, FID/GC, ECD/GC and FPD/GC analyzers, dataloggers, and a computer.

Samples of the above-ground components of typical Chinese tree, shrub, grass and crop species were collected and burned under flaming and smoldering stages in flowing and closed chambers. The emission factors or emission ratios of CO, CH_4, N_2O and OCS were determined (Tables 4-7). As a rule, twigs are much more difficult to be ignited than leaves, and thus the standard deviations are much larger.

Because of time and resource constraints, we have measured the emission ratios and factors only for a limited number of typical crop residues and foliage. Further determination of

Table 4 Emission factors of enclosed combustion of typical Chinese plants

Plants	Components	Molar emission factor(%)	
		CO	CH_4
East Liaoning oak (Quercus liaotungensis Koidz.)	twigs	6.99 ±.65	0.79 ±0.71
	leaves	10.27 ±.98	0.65 ±0.15
	litter	8.28 ±2.54	0.44 ±0.19
Asian white birch (Betula platyphylla Suk.)	twigs	7.09 ±2.17	0.84 ±0.46
	leaves	10.39 ±0.46	1.03 ±0.05
	litter	9.11 ±1.40	0.74 ±0.23
Chinese pine (Pinus tabulaeformis Carr.)	twigs	8.33 ±3.65	0.78 ±0.60
	leaves	8.12 ±2.32	0.52 ±0.25
Prince Ruprecht larch (Larix principis-ruprechtii Mayr.)	twigs	7.06 ±1.83	0.75 ±0.39
	leaves	8.96 ±1.52	0.95 ±0.09
Fritsch spiraea (Spiraea fritschiana Schneid.)	twigs	7.45 ±2.09	0.64 ±0.33
	leaves	9.26 ±0.07	0.95 ±0.02
Manchurian filbert (Corylus mandshurica Maxim.)	twigs	6.36 ±3.12	0.59 ±0.57
	leaves	7.44 ±1.10	0.77 ±0.17
Shrub lespesza (Lespedeza bicolor Turcz.)	twigs	4.97 ±1.98	0.43 ±0.40
	leaves	8.22 ±0.43	0.93 ±0.04
Hedin wormwood (Artemisia hedinii Ostenf.)		13.90 ±1.73	1.13 ±0.12
Tall oatgrass (Arrhenatherum elatius (L.) Presl.)		10.72 ±1.57	1.41 ±0.15

Source: Wang, 1996

Table 5 Emission ratios and emission factors under different stages of tree component combustion

Combustion stages	No. of samples	Emission ratio ±s.d.(%)		Molar emission factor ±s.d.(%)	
		$\Delta CO/DCO_2$	$\Delta CH_4/DCO_2$	CO	CH_4
Flaming	49	12.4 ±6.7	1.2 ±1.0	7.13 ±2.29	0.63 ±0.41
Smoldering	38	20.2 ±4.4	2.0 ±0.7	10.23 ±2.00	0.98 ±0.25
Overall	87	15.8 ±7.0	1.5 ±1.0	8.48 ±2.66	0.78 ±0.39

Source: Wang, 1996

Table 6 N_2O emission ratio and factor during straw burning in a flowing chamber

Combustion stage	Emission ratio ($\Delta N_2O/\Delta CO_2$) ±s.d. (%)	Weight emission factor ±s.d. (g of N per ton of dry stalk)
Flaming stage	(1.23 ±0.18) × 0-2 (n=26)	
Smoldering stage	(0.53 ±0.20) × 0-2 (n=16)	
Overall		151.2 ±4.06

Sources: Cao and Zhuang, 1994; Cao and Zhuang, 1996; Wang, 1996

Table 7 Emission factors of N_2O and OCS during crop stalk combustion in an enclosed chamber

Crop stalk	Weight emission factors ± standard deviation	
	N_2O (g of N per ton of dry stalk)	OCS (g of S per ton of dry stalk)
Maize stalk	107.6 ±7.4	2.75 ±0.23
Rice straw	69.8 ±4.83	1.80 ±0.12
Wheat straw	23.3 ±1.7	2.05 ±0.19

Sources: Cao and Zhuang, 1994; Cao and Zhuang, 1996 emission factors of other minor sorts of crop residues, as well as other species of foliage will be anticipated. Furthermore, we plan to perform field survey on forest fires and prescribed fire monitoring in the future. In order to make preliminary estimation of spatial distribution of trace gas emissions, we have to supplement our own data with data from the literature as indicated in Table 8.

Table 8 Emission Ratios Adopted during Estimation of Forest Fire Emissions

Layer	Eco-climatic regions	$\Delta CO/DCO_2$ (%)	$\Delta CH_4/DCO_2$ (%)	Reference
Tree	temperate	10.1±1.3	1.15 ±.4	Cofer et al. (1989)
Tree	warm temperate	16.1 ±.1	1.6 ±.0	Wang (1996)
Tree	subtropical	12.0	1.20	average value taken by Wang(1996)
Tree	tropical	7.9 ±.9	0.8 ±.3	Kauffman et al. (1992)
Shrub	warm temperate	15.5 ±.2	1.6 ±.9	Wang et al. (1998)
Litter	warm temperate	14.6 ±.9	1.0 ±.5	Wang et al. (1998)

Source: Wang et al., 1998

- Spatial Distribution of Emissions

Detailed and accurate emission inventories are essential for reliable model simulation of the behavior of important trace gases. In recent years, databases for the spatial and temporal distribution of emissions from biomass burning have been established. Hao et al. (1993) quantified the biomass burning sources in tropical Asia, Africa and America during the late 1970s with 5° × 5° resolution. Hao and Liu, (1994) updated their database with data in 1990 and upgraded it to a higher resolution of 1° × 1° . However, emissions from mainland China were not taken into account.

Starting from crop yields, cropped areas, and conversion factors of major crops, we have depicted a map of crop residues in China with a resolution of 1° × 1° (Zhuang et al., 1996). Multiplication of the above-ground biomass by the fraction of residue burned and the emission factors gives the spatial distribution maps of nitrous oxide and carbonyl sulfide from residue burning with the same resolution (Cao and Zhuang, 1994; Cao and Zhuang, 1996). It turned out that grids with the highest emissions are mostly centralized in the eastern part of China, particularly in the Northeast-China Plain, the North-China Plains, and the Yangtse estuaries. These are the major grain-producing areas.

Meanwhile, we established Chinese forest biomass inventories, including the component and layer biomass of 16 main forest types and 4 eco-climatic regions in China (Wang, 1996; Wang et al., 1996). With our carbon pool inventory and emission factors, we estimated trace gas emissions from forest fire on a provincial level (Wang et al., 1996).

4 TECHNOLOGICAL MEASURES TAKEN IN CHINA FOR CLEANER COMBUSTION OF BIOMASS

Mitigation of the associated emissions and conservation of biofuel can be substantial. Measures can be technological, economical, or legislative. Here we highlight only the technological options adopted in China to foster cleaner biomass burning. Regarding biomass combustion technologies, a variety of modern residue energy systems are either under the stage of development and demonstration, or currently available commercially. The outstanding economic feature of biomass utilization processes is the cost associated with harvesting the raw material. As a result of this limitation of supply at a site, a biomass utilization process should be economic on a small scale, so that the plant can be situated at the source of raw material supply. Capital investment should be low too. For this reason, the technologies selected in China suit the needs of a developing country. They can be divided into three categories: 1) improved household stove, ventilation, modified fuel systems; 2) modern boilers for power and steam cogeneration with gas emission control; 3) microbiological and chemical conversion of biomass into upgraded liquid or gas fuels (Zhuang, 1996).

Improved Household Stoves and Heating Bed -- "Kang"

Although improved biofuel-fired stoves have been disseminated in China since the last decade, their thermal efficiency is only about 20%. Out of these stoves with improved design but built by the farmers themselves (the total number of improved stoves is estimated to be 150 million), only one fifth can actually meet the above-mentioned "20% efficiency" requirement. Hence, there is still significant potential to raise the thermal efficiency further to 40%. Moreover, there are about 30 million families that have not used improved stoves yet. The thermal efficiency of un-improved stoves is usually only 10%. The new trend in this decade is the coming-out of commercialized ready-made versatile stoves for cooking, heating and hot water. Nevertheless, technological modification of biomass-fired stoves has emphasized fuel efficiency with little attention to emission control. Quantification of air pollutant emissions is needed.

A new feature is the high-efficiency ready-made heating bed, the so-called *Kang*, which is very popular in north China. Hot flue gases from cooking stoves pass through and heat up the hollow beds made of bricks or mud. Another labor-saving facility for space-heating is the so-called *burning pit*. Pulverized straw, stack and leaves are packed in a big concrete pit 1.2-1.4 m deep, and are burnt slowly with limited air supply. The pit has a metallic or ceramic top that serves as a heat-exchange surface.

The biomass in a pit can last for 2-3 months after each filling, so it is fuel-efficient and it reduces the labor intensity of housewives. Here again quantitative emission data are lacking.

Densification and Carbonization of Biomass Fuel

Densification of agricultural residues improves the residence time of fuel in stoves, and reduces the particulate emission as well. Evidently, the processing cost limits its dissemination. So the ultimate product of densified biomass is charcoal that can be sold at a much higher price, and enjoys a prospective market. However, the highly concentrated carbon monoxide emission has not been recovered and utilized.

Cogeneration

For small-scale heat and/or power generation, the main option is combustion/steam engine. The steam process for electric power generation from biomass is mature, well proven and commercially available. The capacity of each unit is generally in the range of 750-1500 kW. It is estimated that the total capacity in China was 800 MW in year 2000. The major fuels are sugarcane bagasse and rice husk. The process is of particular interest, since it may offer a better utilization of limited agro-residual resources and provides heat both for drying and electricity. However, the present utilization of biomass for electric power generation is exclusively restricted to sites where residual biomass is available at low or negative cost. On the other hand, there are about 200 biomass-fired boilers in operation solely for raw material drying purposes.

Airborne emissions are an unavoidable and undesirable consequence of biomass combustion. Dominant pollutants are carbon-, nitrogen-, sulfur-, and chlorine-containing trace gases, as well as particulate with adhered heavy metals. Cogeneration alone is not the ultimate means to reduce emissions to a satisfactory degree, hence some flue gas cleansing devices should be employed. It is especially important for particulate and organic pollutants including chlorinated polycyclic organic compounds. Unfortunately, the environmental impacts of biomass cogeneration are often overlooked.

Gasification

A more efficient alternative is to gasify the biomass and use the gas after scrubbing for power generation. The total number of small biomass gasifiers installed in China was reported to be about 800 units (SETC, 1997) in service for wood and agriculture products drying, among which there were no less than 130 units for rice husk gasification (CBETDC, 1992). The gas stream contains some dust and tar, which would cause operational problems. Adequate technical back-up and after-sales service is crucial for maintenance of such installations. This type of energy systems, totaled 800MW in capacity, could be cost-effectively applied for electricity generation in Guangxi and Guangdong, where coal and electricity are in short supply.

Biomass gasifiers are manufactured not only for power generation, but also for drying of tea and timber, and cooking, as indicated in Table 9. In recent years, large- and medium-sized gasifiers with gas supplying pipelines are demonstrated in Shandong to meet the cooking demands of a community of 200-5000 families. The raw materials used for gasification include rice husk, wood chips, saw dust, straw, stalks, twigs, and bark.

In Hainan, there is an alcohol factory with an annual output of 20,000 tons, using sweet potato as raw material to obtain alcohol fuel.

Table 9 Typical biomass gasifiers developed in China

End use	Gasifier diameter, mm	Power generated, $MJ \cdot h^{-1}$	Gasification intensity, $kg \cdot m^{-2} \cdot h^{-1}$	Status of development (Model)
Electricity generation	2,000	160 kW	150	About 30 sets (HY6250M)
Electricity generation	1,200	60 kW	150	About 100 sets installed
Steam production	1,100	2.9	250	Demonstration
Steam production	1,000	1.6	180	Demonstration
Steam production	900	1,490	200	Demonstration (ND-900)
Drying of timber	600	660	200	Commercialized since 1989 (ND-600)
Drying of tea	400	300	200	Demonstration since 1981 (ND-400)
Household gas range	280	42-50	30	Demonstration since 1986
Community gas pipelines	700	600	200	Commercialized since 1992 (XFL-600)
Prototype for electricity generation	200	2~5	398	Demonstration of stratified down-draft type

Sources: Zhuang, 1996; CBETDC, 1992

Biogas

Biogas produced from agricultural residues is a particularly important fuel source in China. About 8.02 million family-size biogas digesters are available. The annual biogas production is $1\ 630 \times 10^6$ Nm^3. The potential impact of biogas to the atmosphere is gas leakage. In view of financial reform in China, subsidies for installing family-size biogas digesters have been reduced. There is a shift towards medium and large community digesters, which are operated on commercial terms using more advanced technology. Consequently, in recent years about 600 community-size digesters have been built with a total annual productivity of 106×10^6 Nm^3. In addition to using biogas as cooking fuel, there are more than one hundred biogas-based power generation units with a total installed capacity of 3 400 kW.

Energy Forest Plantation

To meet the fuelwood needs of local communities, fast-growing trees are being planted in 100 counties where fuel is in short supply. According to the Bureau of Forestry, the area of plantation in a five-year period (1996-2000) is about 0.6 million hectares.

We have demonstrated the potential of agro-forestry ecosystems

in China (Wang and Feng, 1995), which are likely to be more efficient and practical than large-scale forest plantation.

CONCLUDING REMARKS

China has a long way to go to forge a more sustainable society by:

- shifting from direct combustion of coal to cleaner fuels, such as natural gas, coal gas and biogas;
- curtailing chemical fertilizers by organic fertilizers and genetic engineering;
- gradual substitution of chemical pesticides by biogenic ones.

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