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Bamboo: An Overlooked Biomass Resource?

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Environmental Sciences Division

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Contents

Page

Figures

Tables

Abstract

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Bamboo is the common term applied to a broad group (1250 species) of large woody grasses, ranging from 10 cm to 40 m in height. Already in everyday use by about 2.5 billion people, mostly for fiber and food within Asia, bamboo may have potential as a bioenergy or fiber crop for niche markets, although some reports of its high productivity seem to be exaggerated. Literature on bamboo productivity is scarce, with most reports coming from various parts of Asia. There is little evidence overall that bamboo is significantly more productive than many other candidate bioenergy crops, but it shares a number of desirable fuel characteristics with certain other bioenergy feedstocks, such as low ash content and alkali index. Its heating value is lower than many woody biomass feedstocks but higher than most agricultural residues, grasses and straws. Although non-fuel applications of bamboo biomass may be actually more profitable than energy recovery, there may also be potential for co-production of bioenergy together with other bamboo processing. A significant drawback is the difficulty of selective breeding, given the lack of knowledge of flowering physiology. Further research is also required on propagation techniques, establishment and stand management, and mechanized harvesting needs to be developed.

1. Introduction

It may be observed cynically that every 5–10 years a new “magic feedstock” appears on the bioenergy scene, a new Philosopher’s Stone about which great claims are made concerning its productivity, its ease of integration into existing markets for growing and fuel supply, its life-cycle analysis, and so on. Some of these novel candidate feedstocks may not be so new – they may have been considered and dismissed 20 years ago, or they may be already in widespread use outside the industrialized world. Bamboo is such a candidate, carrying with it a degree of Eastern mysticism: yet remarkably little is known about this entire sub-family of tall graminaceous plants, despite its everyday utilization, mostly for fiber and food, by about 2.5 billion people — over 40% of the world’s population.

This review evaluates bamboo as a potential bioenergy feedstock and tackles some of the myths and facts surrounding it — its “prodigious” productivity, its “disastrous” flowering, its multiple uses, etc. A limited range of bamboo species are characterized with respect to fuel quality, and a number of research recommendations are concluded.

2. What Is Bamboo?

Bamboo is the vernacular or common term for members of a particular taxonomic group of large woody grasses (subfamily *Bambusoideae*, family *Andropogoneae/Poaceae*). Bamboos encompass 1250 species within 75 genera, most of which are relatively fast-growing, attaining stand maturity within five years, but flowering infrequently. Dwarf bamboos may be as little as 10 cm in height, but stands of tall species may attain 15–20 m, and the largest known (e.g., *Dendrocalamus giganteus*) grow up to 40 m in height and 30 cm in culm (stem) diameter. Bamboos are distributed mostly in the tropics, but occur naturally in subtropical and temperate zones of all continents except Europe, at latitudes from 46° N to 47° S and from sea level to 4000 m elevation (IFAR/INBAR, 1991; Tewari, 1992). Asia accounts for about 1000 species, covering an area of over 180,000 km^2 (the size of Missouri, half the size of Germany, or about 2% of United States total land area). Most of this comprises natural stands of native species rather than plantations or introductions. China alone has about 300 species in 44 genera, occupying 33,000 km^2 or 3% of the country’s total forest area (Qiu et al., 1992). Another major bamboo-producing country is India, with 130 species covering 96,000 km^2 or about 13% of the total forested area (Shanmughavel and Francis, 1996). Other nations with significant bamboo production and utilization include Bangladesh, Indonesia, and Thailand.

The taxonomy of bamboos is still poorly understood, at least in part because of the infrequent flowering of many species (at intervals of 30–60 years). Major economic species include the following:

Dendrocalamus strictus – native to India. Solid culms, of greatest economic importance in India, where only about 10 out of more than 100 bamboo species are commercially exploited. Used mostly for paper-making and construction.

Dendrocalamus asper – thought to be native to Thailand. Thailand intends to propagate plantlets of this species since much of the present edible bamboo shoot production is from natural forests and not sustainable (IFAR/INBAR, 1991).

Thyrsostachys siamensis – native to Thailand. Used for construction in both rural and urban areas of Thailand; also cultivated for edible shoots.

Phyllostachys pubescens – sometimes described as *Phyllostachys edulis*. Originally from China, where it occurs extensively (20,000 km^2 or 60% of total bamboo cover); introduced to Japan about 1750. The largest of the *Phyllostachys* genus, this species is harvested for both poles and edible shoots throughout South-East Asia. This species requires a climate with precipitation of 1200-1800 mm, mean annual temperature of 13–20°C and monthly mean minimum temperatures no lower than freezing (Qiu et al., 1992).

Phyllostachys bambusoides – native to China, but extensively cultivated in Japan since 1866. The largest and most commercially valuable of this genus after *Phyllostachys pubescens*, producing good-quality wood. Hardier and more cold-tolerant than the latter (Chao, 1989). See Figure 1.

Figure 1. Experimental stand (clonal repository) of *Phyllostachys bambusoides*, cultivar White Crookstem, at the USDA-ARS/ University of Georgia Plant Genetic Resources Conservation Unit in Griffin, Georgia. Culm diameter is about 5 cm. Photograph taken August 1999 by G. R. Lovell, Bamboo Curator.

Bamboo has been neglected or ignored in the past by tropical foresters, who tend to concentrate on timber trees at the expense of traditional multi-purpose woody species such as bamboo and rattan (IFAR/INBAR, 1991). Literature on the dynamics and productivity of natural bamboo stands is meagre, and reports from plantation stands are almost non-existent (Shanmughavel and Francis, 1996). Bamboo has been used for handicrafts and building material in India and China for thousands of years, yet its potential contribution to sustainable natural resource management has only recently been recognized. Unfortunately, most bamboo is harvested from forest stands at a rate which exceeds natural growth, so current utilization is anything but sustainable (IFAR/INBAR, 1991; Tewari, 1992).

3. Commercial Applications of Various Bamboo Species

Many Asian species of bamboo have strong, light, and flexible woody stems, which lend themselves to applications as a construction material — one of the most notable modern uses being temporary scaffolding poles which are often seen surrounding the most modern of high-rise buildings in Asian countries. Bamboo utilization in South America is modest by comparison, except in certain local areas where indigenous species have been used for centuries, and where some Asian bamboos have been introduced (notably an international project for bamboo housing in Costa Rica). African use of bamboo is more limited and recent, since there are few native species except in Madagascar, although indigenous and introduced bamboo has been used in Kenya for soil stabilization, construction, and fuel (IFAR/INBAR, 1991) and in Tanzania for water pipes (Lipangile, 1987). Worldwide commercial bamboo utilization is reported to be 20 million tonnes per annum. It is unclear whether this figure represents dry weight or (more likely) harvested weight at about 15% moisture content — but this number is considered unreliable since about 80% of bamboo is used locally and statistics are hard to obtain. More than half of this amount is harvested and utilized by poor people in rural areas. Total revenues from bamboo and its products were estimated in the 1980s at $4.5 billion (IFAR/INBAR, 1991).

Approximately 1500 commercial applications of bamboo have been identified — mostly in Asia, except where noted below. They may be divided up into the following broad categories:

Construction and reinforcing fibers – these include agricultural and fishing tools, handicrafts, musical instruments, furniture, civil engineering (bridges, scaffolding poles), domestic building (house frames, walls, window frames, roofs, interior dividers).

Paper, textiles and board – (including rayon, plywood, oriented strand board, laminated flooring). Bamboo fibers are relatively long (1.5–3.2 mm) and thus ideal for paper production (El Bassam, 1998). Paper production in China dates back 2000 years, while in India, 2.2 million tonnes of bamboo per year are processed into pulp, making up about two-thirds of total pulp production (Adamson et al., 1978; IFAR/INBAR, 1991). At least eight North American suppliers are importing and marketing tongue-and-groove flooring made from laminated bamboo, which is said to be as hard, durable, and dimensionally stable as oak or other hardwood flooring (e.g., Plyboo America Inc., Kirkville, NY). Bamboo culms are sliced into strips, which are boiled to remove starch, dried, and laminated into solid boards using urea-formaldehyde adhesives. The boards may be treated with preservatives such as boric acid, before or after laminating, or both, and a darker amber color may be produced by pressure-steaming the bamboo to carbonize it. Although the adhesive tends to emit formaldehyde for a long time after production, the amount of urea-formaldehyde resin in a laminated product is much less than in a panel board product (Environmental Building News, 1999).

Food – bamboo shoots of a number of species are a well-known feature of Chinese and other Asian cuisine, generally imported into the United States in canned form (one estimate suggests 30,000 t/year in the early 1990s). Exports from Taiwan are worth $50 million annually, and those from Thailand $30 million, with much of this going to meet Japanese demand.

Combustion and other bioenergy applications – a preliminary literature search found no references to the use of bamboo as an energy feedstock, although anecdotal descriptions of bamboo as a fuel are commonplace. Molini and Irizarry (1983) proposed the use of bamboo as a fuel for power generation in Puerto Rico in preference to sugar cane, since its lower moisture content at harvest obviates the need for drying, but they provide few data in support of their case. Limited experience has been gained using de-lignified bamboo pulp as a substrate for ethanolic fermentation (Ram and Seenayya, 1991). Early work on preparing a diesel-like fuel from bamboo culms (Piatti, 1947) is cited by Tewari (1992); the process appears to have been the pyrolysis of “black liquor” from bamboo pulping, but does not seem to have progressed beyond the laboratory scale (Piatti, 1947).

4. Physiological Characteristics

Bamboos vary across a wide range of physiological characteristics, so the following information is merely illustrative, and mostly concerns the tall bamboos of likely interest as biomass resources. In general, bamboos can be classified as sympodial (clumped) or monopodial (spreading): Tropical bamboos are sympodial, whereas temperate species can be of either category (El Bassam, 1998). Although some bamboos can adapt to varying environments, most require relatively warm and humid conditions (e.g., mean annual temperature of at least 15–20°C and annual precipitation of at least 1000–1500 mm).

Shoot buds appear as swellings on the side of the underground rhizomes, which generally occupy the top 30-50 cm of soil and may spread for tens of metres. With the onset of warm spring weather, the bud lengthens and develops into a compact upright shoot which forms a sharp point and penetrates the ground surface. After emergence there is little radial growth of the shoot, with “growth” taking the form of massive elongation of internodes, as much as 0.5 m/week in the case of tall bamboos, until the shoot is the approximately the same height as the rest of the stand. At this point, sheaths are shed and leafy branches emerge from the internodes near the top of the shoot. Further growth over the next few years comprises thickening of the walls of the stem and increases in wood density (Sturkie et al., 1968). Compared with other tall flowering plants, this pattern of growth may give a misleading impression of high productivity – in fact, all that may be observed is an (albeit rapid) re-distribution of previously stored reserves.

The reported leaf area index of mature stands is generally high, e.g. 8.02 for *P. pubescens* (Qiu et al., 1992) and 11.6 for *P. bambusoides* (Isagi et al., 1993). Such a dense canopy may absorb up to 95% of incident solar radiation (Qiu et al., 1992).

The reported pattern of leaf fall for most bamboos is semi-deciduous, with leaves shed at the end of the growing season (e.g., *Bambusa sp*. growing at Auburn, Alabama; Sturkie et al., 1968) or during the following growing season. *P. pubescens* renews its leaves on a 2-year cycle, with most leaf fall taking place in the spring, beginning with the second growing season after shoot emergence. This biennial pattern of leaf renewal may be reflected in a biennial pattern of shoot emergence, with alternating “good” and “poor” years of new shoot production (Qiu et al., 1992).

The pattern of flowering in bamboos varies with species. A few (e.g., *Bambusa atra*, native to the Andaman Islands of the eastern Indian Ocean) are known to flower frequently, even annually. Others, such as *Bambusa vulgaris,* flower a few culms at a time. However, the majority — for example, *Dendrocalamus strictus* — display gregarious flowering, whereby an entire clump at one location produces flowers and then dies back over the course of 2–3 years. This happens typically every 30–40 years (more than 60 years in some cases), and is therefore observed quite rarely, so the physiology of flowering is still little understood. Clear-cutting does not appear to halt stand mortality, although some species can be induced to develop new shoots for a year or two before finally dying altogether. As a consequence of the rarity of flowering, the taxonomy of bamboos is still confused and based largely on vegetative features such as leaf anatomy, arrangement of vascular bundles in leaf sheaths and culms, etc. (Tewari, 1992).

A few genera (e.g., *Phyllostachys* and *Arundinaria*) have been reported to recover after flowering (Tewari, 1992). For example, *P. bambusoides* collected from China in 1926 and grown at Byron, Georgia, began to flower in 1989, but recovered with vigorous vegetative growth by 1993 (G. R. Lovell, pers. comm.). The threat of catastrophic flowering need not pose an economic problem for bamboo growers, as long as uneven-aged propagation material is maintained, and entire stands are replaced before they approach flowering age.

Unlike other highly productive members of the *Andropogoneae/Poaceae* family (e.g., sugar cane, switchgrass, miscanthus), the entire bamboo sub-family (*Bambusoideae*) lacks the C_4 photosynthetic pathway and anatomy (Jones, 1985). In the absence of this feature (which may lead to higher water-use and nutrient-use efficiencies under high light conditions), the maximum possible productivity of bamboos such as *P. pubescens* is unlikely to greatly exceed that of other bioenergy crops with C_3 photosynthesis such as short-rotation willow coppice.

5. Fuel Characteristics

5.1 Description of Samples

Nine bamboo samples were obtained from G. R. Lovell, Bamboo Curator for the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) at the University of Georgia Plant Genetic Resources Conservation Unit in Griffin, Georgia. Three different ages of three different bamboo species were sampled for analysis to determine the fuel characteristics of the bamboo samples in relation to other biomass feedstocks with potential for electricity and fuel production, and to determine how the fuel properties change as the plant grows under carefully controlled conditions. What follows is a description of each of the bamboos analyzed. All bamboo stands were established on Norfolk Loamy fine sand soils with slight slope (<5°), following their transfer from Savannah, Georgia, around 1978.

Phyllostachys nigra, cultivar Henon (Figure 2): These rhizomes originated in Nagasaki, Japan, and were obtained in 1909 from a Japanese bamboo grower by W. D. Hills, an agricultural explorer. This monopodial bamboo grows to a maximum height of 20 m with an 11-cm culm diameter, and is a much larger cultivar of the common black bamboo species whose culms do not turn black. It is cold hardy down to !20ºC, has dense dark green foliage and a gray waxy film on many culms that makes this species a striking ornamental plant. It also has straight, strong culms that make it useful for construction purposes. 1-, 2-, and 4.5-year-old samples of this bamboo species were obtained.

Phyllostachys bambusoides, cultivar White Crookstem (Figure 1): Rhizomes were collected near Yeunguk in the Lungtau Mountains of the People's Republic of China in 1926 by F.A. McClure, an agricultural explorer with the U.S. Bureau of Plant Industry. This monopodial bamboo grows to a maximum height of 11 m with a 5-cm culm diameter and is cold hardy to !18°C. This cultivar differs from the common form in having culms that are curved in a serpentine manner at the base. It also has deposits of white powder on the culms which persist and often completely obscure the

Figure 2. Stand (clonal repository) of *Phyllostachys nigra*, cultivar Henon, at the USDA-ARS/ University of Georgia Plant Genetic Resources Conservation Unit in Griffin, Georgia. Maximum culm diameter is about 11 cm, although this size has not been achieved in the stand pictured. Photograph taken August 1999 by G. R. Lovell, Bamboo Curator.

green color in older culms. One-, 2-, and 4.5-year-old samples of this bamboo species were obtained.

Phyllostachys bissetii (Figure 3): Rhizomes were collected from Szechuan Province, Peoples Republic of China, in 1941 by John Tee-Van of the New York Zoological Society. This bamboo grows to a maximum height of 7 m with a 2.5-cm culm diameter. With a cold hardiness of !23°C, it is one of the most cold hardy samples cultivated by the USDA-ARS and is the first to send up shoots in the spring. It is also the fastest growing and the most invasive. This bamboo is named after D. Bisset, the Superintendent of the USDA Plant Introduction Station at Savannah, Georgia, from 1924 to 1957. One-, 2-, and 4-year-old samples of this bamboo species were obtained.

5.2 Sample Preparation

The following preparation was performed to obtain samples which were representative of each bamboo stand. Each of the nine bamboo samples comprised 6–9 representative culms with 2–3 nodes. Culms were split into pieces 1.3-cm wide using a knife or wood chisel, and cut into blocks about 7.5-cm long to facilitate milling. Approximately one-half of each sample was processed whole, meaning that the nodes and internodes were milled together. The other half of the sample was separated into node samples and internode samples prior to milling. The node samples included the complete node plus less than one inch of culm on either side of the node. Each internode sample contained all of the pieces of culm not used in the node sample. Overall, 27 analyses were performed, representing whole bamboo, nodes, and internodes for each of the 9 samples listed earlier. Milling and homogenization was performed to assure that the chemical analysis was performed on material which represented that average of each sample. Samples were milled using a

Figure 3. Stand (clonal repository) of *Phyllostachys bissetii* at the USDA-ARS/ University of Georgia Plant Genetic Resources Conservation Unit in Griffin, Georgia. Culm diameter is about 2.5 cm. Photograph taken August 1999 by G. R. Lovell, Bamboo Curator.

Standard Whiley knife mill with a 2-mm screen. Material <2 mm was sieved for 5 minutes using a 20-mesh sieve. Any material >20-mesh was milled until it passed the 20- mesh screen. The <20-mesh material was homogenized by cone and quartered four times.

5.3 Fuel Analyses

The proximate, ultimate, and elemental ash analyses for the nine bamboo samples collected for this study are summarized in Table 1. The moisture contents of the samples ranged from 8–23% with no correlation between the amount of moisture and the sample or the age of the sample. The moisture content of the *P. nigra* and *P. bissetii* samples increased with age of the harvested plant, while the moisture content of the *P. bambusoides* sample decreased as the age of the harvested plant increased. The ash contents of all of the bamboo samples were 1% or less, and no correlation between ash content and bamboo sample or age of sample was apparent. Compared to other biomass feedstocks, these ash contents are comparable to what is found in woody biomass materials. Many herbaceous biomass materials, grasses, and straws have higher ash contents. The volatiles content of the bamboo samples ranged from 63–75% with no correlation between volatiles content and bamboo sample or sample age. The remainder of the bamboo samples was fixed carbon. The fixed carbon content of the bamboo samples ranged from 12–17% of the samples "as received." All of the bamboo samples had very similar higher heating values, ranging from 19.09–19.57 GJ/t on a dry basis (Tables 1 and 2). These heating values are comparable to, but slightly lower than, most woody biomass feedstocks and higher than most grasses and straws (Nordin, 1994). The carbon and hydrogen contents of the bamboo samples were all very similar, at about 52% C and 5% H. The variation in the nitrogen content of the bamboo samples was larger, ranging from 0.2–0.5%. From a combustion perspective, this is a very low N content and would be beneficial in terms of minimal fuel-bound nitrogen conversion to NO_x if bamboo were used as a boiler fuel. If bamboo were used as a co-iring fuel, this could offset some of the input fuel-bound N, because the bamboo samples tested here had lower N contents than many coals used for power production. Co-firing with bamboo may also have other NO_x benefits caused by differences in flame structure and temperature that reduce thermal NO_x formation. Likewise, the sulfur content of the bamboo samples is very low compared to coal, and like many woody biomass materials, is also lower than many herbaceous biomass feedstocks, grasses, and straws (Tables 1 and 2). Changes in the %C, %H, %N, and %S do not correlate with the different bamboo samples or maturity of the samples.

There does appear to be some variation in the composition of the ash between each of the bamboo samples and with the maturity of the individual species. The silicon content of the *P. nigra* samples appears to increase with the maturity of the sample and while the overall ash content of the 4.5-year-old *P. nigra* is lower than the younger samples, the silicon content of the ash is greater by a factor of 4. A similar increase in ash silicon content is also observed for the *P. bisetii* samples, and a more gradual increase for the *P. bambusoides* samples. The aluminum content of all the bamboo samples is very similar, and in all cases the amount of titanium in the samples was below the detection limits of the measurements. The iron oxide contents of the bamboo samples are also quite low. The amount of alkaline earth oxides, CaO and MgO, in the bamboo samples appears to increase as the bamboo plants mature. This is evident for all three samples. Conversely, the amount of alkali metal oxides appears to decrease as the bamboo plants mature. The amount of K_2O in the bamboo ashes ranges from 30–50%, however, the overall ash contents of the bamboo samples is low and this amounts to only 0.2–0.6% K_2O in the dry samples. The phosphorus content of the bamboo ashes is relatively high, however, given the low ash contents of the samples the phosphorus content of the dry materials ranges form 0.1–0.2%. The percentage of phosphorus in the bamboo ash appears to increase as the bamboo plants mature.

The low ash and chlorine contents of the bamboo samples make them attractive for use in biomass combustion applications for electricity production. As a feedstock for combustion applications, the potassium contents of these bamboo samples are also quite low. In fact, the alkali index of these samples (defined as kg alkali oxide per GJ energy content) ranges from 0.1–0.3, generally below the empirical limit of 0.17–0.34 kg/GJ known to cause adverse fouling and slagging in combustion systems (Miles et al, 1996; Baxter et al., 1998). Chlorine in biomass has been shown to increase the volatility of alkali metals during combustion (Dayton and Milne, 1996), and the low chlorine content of the bamboo samples suggests that the potassium that is present is unlikely to be volatile and therefore not problematic in terms of ash deposition. The low chlorine content of the bamboo samples means that burning them is unlikely to enhance high-temperature corrosion in biomass combustion systems.

Table 1. Fuel analyses for selected bamboo samples

	Phyllostachys nigra			*Phyllostachys bambusoides*			*Phyllostachys bissetti*		
	1 year	2 year	4.5 year	1 year	2 year	4.5 year	1 year	2 year	4.5 year
Proximate Analysis (% as received)									
Moisture	8.42	8.79	13.62	22.61	12.92	9.54	8.52	10.66	21.97
Ash	0.86	0.87	0.41	0.66	0.84	0.53	1.14	0.78	0.9
Volatiles	73.94	73.66	72.27	62.93	70.51	75.55	73.18	72.24	64.99
Fixed Carbon	16.78	16.68	13.7	13.8	15.73	14.38	17.16	16.32	12.14
Higher Heating Value (GJ/t dry basis)	19.57	19.48	19.27	19.49	19.53	19.09	19.42	19.50	19.51
Alkali Index (kg alkali oxide/GJ)									
Alkali Index (kg alkali oxide/GJ)	0.21	0.24	0.08	0.20	0.21	0.09	0.30	0.19	0.20
Ultimate Analysis (% dry matter)									
C	51.89	51.19	51.39	52.28	51.84	50.85	51.22	51.7	51.07
H	5.21	5.29	5.25	5.09	5.18	5.40	4.90	5.00	4.51
N	0.4	0.29	0.21	0.59	0.6	0.38	0.55	0.3	0.32
S	0.04	0.03	0.03	0.05	0.05	0.04	0.05	0.03	0.05
Cl	0.19	0.14	0.05	0.06	0.06	0.04	0.07	0.03	0.06
Ash	0.94	0.95	0.47	0.85	0.96	0.59	1.25	0.87	1.15
O*	41.52	42.12	42.61	41.10	41.33	42.75	41.98	42.11	42.91
Ash Elemental** (% dry matter)									
SiO_2	0.045	0.046	0.077	0.039	0.047	0.045	0.057	0.061	0.158
Al_2O_3	0.004	0.005	0.002	0.004	0.004	0.003	0.005	0.004	0.011
TiO_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe_2O_3	0.019	0.002	0.002	0.004	0.002	0.002	0.002	0.002	0.006
CaO	0.015	0.018	0.024	0.018	0.021	0.037	0.029	0.024	0.073
MgO	0.021	0.023	0.031	0.027	0.030	0.075	0.045	0.041	0.076
Na_2O	0.003	0.001	0.003	0.003	0.000	0.001	0.002	0.001	0.002
K_2O	0.415	0.475	0.158	0.378	0.411	0.180	0.578	0.371	0.382
P_2O_5	0.130	0.105	0.097	0.125	0.180	0.123	0.155	0.107	0.181
SO_3	0.028	0.024	0.011	0.018	0.022	0.019	0.052	0.025	0.033
Cl	0.034	0.027	0.003	0.009	0.008	0.002	0.025	0.006	0.007
CO_2	0.072	0.112	0.016	0.060	0.062	0.028	0.129	0.094	0.056
Undetermined	0.155	0.110	0.046	0.166	0.174	0.075	0.171	0.133	0.166
Ash Elemental (% ash, 600°C)									
SiO_2	4.74	4.89	16.30	4.61	4.87	7.64	4.52	7.04	13.74
Al_2O_3	0.40	0.56	0.42	0.42	0.42	0.48	0.43	0.49	0.99
TiO_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe_2O_3	2.06	0.23	0.42	0.43	0.16	0.39	0.16	0.25	0.48
CaO	1.59	1.90	5.06	2.17	2.17	6.34	2.33	2.74	6.35
MgO	2.22	2.44	6.66	3.12	3.10	12.70	3.62	4.71	6.62
Na_2O	0.27	0.15	0.71	0.35	<0.01	0.21	0.16	0.10	0.19
K_2O	44.20	50.00	33.60	44.50	42.80	30.50	46.20	42.70	33.20
P_2O_5	13.80	11.02	20.70	14.69	18.74	20.80	12.36	12.25	15.71
SO_3	2.94	2.51	2.32	2.13	2.27	3.18	4.17	2.93	2.83
Cl	3.63	2.87	0.59	1.10	0.84	0.26	2.03	0.65	0.58
CO_2	7.68	11.83	3.42	7.00	6.47	4.77	10.35	10.83	4.89
Undetermined	16.47	11.60	9.80	19.48	18.16	12.73	13.67	15.31	14.42

Table 2. Comparison of selected fuel properties of bamboo with other bioenergy crops

Fuel property	Bamboo (range of three *Phyllostachys* species)[a]	"Bamboo" (species not given)[b]	"Bamboo" (species not given)[c]	Miscanthus (*Miscanthus x giganteus*)[d]	Switchgrass (*Panicum virgatum*)[e]
Gross heating value (dry; GJ/t)	19.1-19.6	15.85	18.96	17.1-19.4	18.3
Moisture content (%)	8.4-22.6 (samples as received after shipping)	10.4 (at harvest?)	2.94 (after drying?)	15 (at harvest)	15 (at harvest)
Ash content (%)	< 1.0	3.98	2.04	1.5-4.5	4.5-5.8
Sulfur content (%)	0.03-0.05	N/A	0.15	0.1	0.12

[a] Present study.
[b] El Bassam (1998), Table 3.8, p. 30.
[c] C. E. Pugh, 1981, laboratory report for Northeast Louisiana University, cited in Woods (1996).
[d] Data for miscanthus from Scurlock (1999).
[e] Data for switchgrass from McLaughlin et al. (1996).
See also Nordin (1994) for a review of bioenergy fuel characteristics.

5.4 Wet Chemical Analysis

All bamboo samples were analyzed using American Society for Testing and Materials (ASTM) standard methods for whole biomass analysis, as listed:

ASTM E1690 Test Method for the Determination of Ethanol Extractives in Biomass
ASTM E1721 Test Method for the Determination of Acid Insoluble Residue in Biomass
ASTM E1756 Test Method for the Determination of Total Solids in Biomass
ASTM E1757 Preparation of Biomass for Compositional Analysis
ASTM E1758 Standard Method for Determination of Carbohydrates in Biomass by High Performance Liquid Chromatography

U.S. National Institute of Standards and Technology (NIST) Bagasse Standard Reference Material # 8491 was analyzed with each batch of bamboo samples, as a quality-assurance reference for the determination of extractives, lignin, and carbohydrates. Aqueous and ethanolic extractions were performed in duplicate on the milled, homogenized samples. Each extractives-free sample was analyzed in duplicate for lignin and carbohydrate content, giving a total of four separate determinations for each bamboo sample.

Table 3 shows the complete wet chemical analysis of the 27 bamboo samples. Total mass closure for all samples was greater than 99%, indicating that the analysis is complete and no significant biomass fractions were excluded. The values obtained are similar to those reported by Higuchi (1957) for samples of mature bamboo (Table 4). Direct measurement of the protein content of these samples was not performed, but the protein content can be estimated from the nitrogen elemental analysis (Phillips, 1939) and varies only slightly with age in the range 1.4–3.8%. Interference from acid-insoluble protein may introduce a slight additional error in the lignin analysis. The lignin values of 25–30% place bamboo at the high end of the normal range of 11–27% reported for non-woody biomass (Bagby et al., 1971), and more closely resemble the ranges reported for softwoods (24–37%) and hardwoods (17–30%) (Fengel and Wegner, 1984; Dence, 1992). This would suggest that bamboo should have similar physical properties and uses to conventional softwoods and hardwoods (Panshin and de Zeeuw 1980). Indeed, its high lignin content contributes to the relatively high heating value of bamboo, and its structural rigidity makes it a valuable building material. Similarly, the glucan contents of 40–48% compare to the reported cellulose content of softwoods (40–52%) and hardwoods (38–56%). Cellulose contents in this range make bamboo a useful feedstock for paper production and for processes that convert cellulose to fuels, chemicals, and other bio-based materials.

The average and standard deviation of 27 independent analyses of the standard reference material are shown at the foot of Table 3. The reproducibility and total mass closure indicate the precision that can reasonably be expected from these methods of analysis. Differences between bamboo samples smaller than the standard deviation of the reference material will not be significant. The average total mass closure for the National Institute of Standards and Technology bagasse reference samples was 99.5 ± 1.2%, indicating that no significant biomass fractions were excluded from the analysis.

The lignin, glucan, and xylan contents all showed variances with age comparable to the 1–5% reported for softwood (Panshin and de Zeeuw, 1980). There is a slight trend toward lower lignin with increased age (Table 3), although it is only significant in the 4- and 4.5-year old bamboo samples. This trend is confirmed by a slight increase in the independently determined glucan content. These changes occur in both the node and internode fractions, being only slightly more pronounced in the internode segments. However, the magnitude of the compositional differences is small and is not expected to result in significant variations in heating value or physical properties.

Differences between the composition of node and internode fractions are also small, 1–4%, and compare to those reported for the natural variance in wood (Panshin and de Zeeuw, 1980). The small differences in chemical composition between node and internode samples for these bamboo samples suggest that neither the number of nodes nor the length of internode segments would be critical to the utilization of bamboo for energy conversion, chemical production, or as a building material (Table 3).

6. Stand Establishment and Management

Since most bamboos flower very infrequently, plantation stands are usually established from vegetative material rather than from seedlings, although the latter approach is a possibility. Rhizome propagation involves cutting 30–50 cm lengths of rhizomes, 1–2 years old with nodes and buds present. However, low multiplication rates make it difficult to establish large plantations by this method (El Bassam, 1998). Older rhizomes, with fewer roots and buds present, do not propagate well (Sturkie et al., 1968). Adamson et al. (1978) used existing farm machinery (ploughs, etc.) to propagate bamboo from nursery fields. Rows of 2-year-old bamboo were cut at a height of about 2 feet (60 cm), the rhizomes dug up with a turning plough, and then the plants separated by hand. February (early spring in the U.S. Southeast) was the optimum time for propagating. Propagating from entire plants [about 6 nodes of stem material and a foot (30 cm) of attached rhizome] was more successful than propagating from rhizomes alone. Fertilization and weed control in nursery fields and young stands is desirable, but weed control with herbicides was preferable to disturbing the soil (Sturkie et al., 1968). Adamson et al. (1978) reported low multiplication rates (annual doubling): One hectare of 2-year-old nursery field was only enough to plant a 4-hectare stand. Traditional methods for propagation also include branch and stem cuttings and seedlings, where available (IFAR/INBAR, 1991).

In India, tissue culture techniques have been used for the rapid large-scale production of planting stocks from selected vigorous seedlings of *Dendrocalamus strictus* (Nadgauda et al., 1997). Cultured seedlings of several bamboo species have also been induced to flower and seed precociously using cytokinins and control of pH, suggesting that hybridization may be possible in the future. Nadgauda et al. (1997) review 34 published English-language reports of tissue culture in a variety of bamboo species.

Seven or eight years may be required after establishing a stand of tall bamboo before the culms are large enough and sufficiently “woody” to be harvested. Some weaker shoots may die back before reaching maturity. The ultimate stand height may not be achieved until 15–20 years (Sturkie et al., 1968). Adamson et al. (1978) agree that yields are likely to be low during an initial establishment period of up to 8 years.

Avoidance or control of flowering may comprise an important but yet undeveloped aspect of management, since this generally results in the die-back of entire stands. A few rhizome buds may remain viable, but the re-establishment of a new stand from surviving rhizomes or from seed would be required over the course of following 5–10 years. Bamboo re-growing after seeding requires thinning and selection of the strongest shoots (Sturkie et al., 1968).

Recommended fertilizer levels based on *Dendrocalamus* trials in India (cited in El Bassam, 1998) are N:P:K 100:50:50 kg/ha, similar to the levels suggested by Sturkie et al. (1968). Fertilization at the beginning of the growing season can result in up to a three fold increase in aboveground productivity (El Bassam, 1998).

Harvesting of traditionally grown bamboo is un-mechanized and labor-intensive. Traditionally, only the most mature poles (about 8 years old) are removed selectively, although it is feasible to harvest a range of ages of poles, sorting them later on the basis of density. Research in India suggests that clear-cutting does not significantly damage bamboo stands (El Bassam, 1998), so it may be possible to use machinery such as modified sugar-cane harvesters.

Some problems have been reported in restricting the spread of hardy monopodial bamboos (Sturkie et al., 1968).

Table 3. Wet chemical analysis of selected bamboo samples

Sample	Fraction	% ash	% Ethanol Extractives	% Total Lignin	% Glucan	% Xylan	% Mannan	% Arabinan	% Galactan	Total
P. bissetii 1 yr	whole	1.2	1.4	28.2	42.2	24.0	0.5	1.1	1.1	99.7
P. bissetii 1 yr	nodes	0.6	2.1	28.5	41.9	24.5	0.0	2.1	2.1	101.8
P. bissetii 1 yr	internodes	1.4	1.6	27.9	43.7	24.6	0.5	1.0	1.0	101.8
P. bissetii 2 yrs	whole	1.0	3.1	27.9	40.7	23.6	0.6	1.1	1.2	99.2
P. bissetii 2 yrs	nodes	0.7	1.9	28.4	42.3	25.7	0.0	2.0	2.1	103.1
P. bissetii 2 yrs	internodes	0.9	1.5	28.3	43.6	25.9	0.5	1.0	1.0	102.7
P. bissetii 4 yrs	whole	1.2	2.2	27.1	41.9	22.8	0.8	1.2	1.2	98.3
P. bissetii 4 yrs	nodes	0.8	3.0	27.0	41.3	23.3	0.0	2.0	2.0	102.3
P. bissetii 4 yrs	internodes	1.1	1.4	26.2	47.2	24.1	0.4	1.1	1.1	102.7
average		1.0	2.0	27.7	42.8	24.3	0.4	1.4	1.4	101.3
standard deviation		0.3	0.6	0.8	1.9	1.0	0.3	0.5	0.5	1.7
P. bambusoides 1 yr	whole	0.9	2.0	26.8	41.8	24.1	0.8	1.2	1.3	99.0
P. bambusoides 1 yr	nodes	0.3	1.8	27.0	40.9	23.9	0.7	1.3	1.3	97.3
P. bambusoides 1 yr	internodes	1.3	1.6	26.2	44.5	26.0	0.5	1.1	1.1	102.3
P. bambusoides 2 yrs	whole	0.9	1.9	26.8	40.8	24.1	0.7	1.2	1.2	97.5
P. bambusoides 2 yrs	nodes	0.4	1.6	27.4	40.3	24.9	0.8	1.3	1.4	98.0
P. bambusoides 2 yrs	internodes	1.3	1.3	26.2	44.4	27.0	0.4	1.2	1.2	102.9
P. bambusoides 4.5 yrs	whole	0.6	1.1	25.5	44.9	24.0	0.6	1.3	1.3	99.3
P. bambusoides 4.5 yrs	nodes	0.2	1.5	25.3	44.0	23.3	0.8	1.3	1.4	97.8
P. bambusoides 4.5 yrs	internodes	0.8	1.1	24.3	48.1	24.0	0.5	1.1	1.1	101.0
average		0.7	1.5	26.2	43.3	24.6	0.6	1.2	1.3	99.4
standard deviation		0.4	0.3	1.0	2.6	1.2	0.2	0.1	0.1	2.1
P. nigra 1 yr	whole	0.8	2.3	28.3	41.3	24.4	0.5	1.4	1.4	100.4
P. nigra 1 yr	nodes	0.2	1.7	27.9	40.7	23.1	0.7	1.4	1.5	97.2
P. nigra 1 yr	internodes	0.1	1.7	28.6	41.3	24.0	0.5	1.4	1.4	99.0
P. nigra 2 yrs	whole	0.8	2.2	27.8	42.7	24.2	0.6	1.2	1.2	100.7
P. nigra 2 yrs	nodes	0.9	1.4	27.9	42.8	24.6	0.6	1.3	1.3	100.7
P. nigra 2 yrs	internodes	0.6	1.6	27.5	43.1	23.4	0.5	1.2	1.2	99.0
P. nigra 4.5 yrs	whole	0.4	1.9	25.2	46.4	23.0	0.6	1.1	1.1	99.7
P. nigra 4.5 yrs	nodes	0.4	1.6	25.5	46.0	24.0	0.6	1.2	1.2	100.6
P. nigra 4.5 yrs	internodes	0.2	1.5	25.5	46.2	22.9	0.5	1.1	1.2	99.1
average		0.5	1.8	27.1	43.4	23.7	0.6	1.3	1.3	99.6
standard deviation		0.3	0.3	1.3	2.3	0.6	0.1	0.1	0.1	1.2
NIST reference material #8491 (bagasse)										
average		1.8	4.4	23.1	41.7	24.7	0.7	1.6	1.6	99.5
standard deviation		0.3	1.0	0.5	1.2	0.9	0.1	0.2	0.2	2.0

Table 4. Previous chemical analysis of bamboo

Species	% ash	% Ethanol-benzene extractives	% Lignin	% Cellulose	% Pentosan	Total
Phyllostachys heterocycla	1.3	4.6	26.1	49.1	27.7	108.82
P. nigra	2.0	3.4	23.8	42.3	24.1	95.61
P. reticulata	1.9	3.4	25.3	41.0	26.5	98.15

Data from Higuchi (1957).

7. Productivity of Bamboo in Asia and South America

As was suggested in Section 2, literature on bamboo productivity is scarce, with most reports coming from various parts of Asia. All the data reviewed here are reported as oven-dry biomass, and are summarized in Table 5.

Aboveground net primary productivity (ANPP), including leaf turnover, for *Phyllostachys bambusoides* in central Japan (latitude 35° N) was reported at 24.6 t/ha/year over a 6-year period (Isagi et al., 1993). Woody biomass increment, excluding leaf turnover, was 15.5 t/ha/year. Aboveground biomass of this mature stand (which last flowered 16-22 years previously) was 131 t/ha, of which 112 t/ha comprised culms. A related study on *Phyllostachys pubescens* in Japan found ANPP of 18.1 t/ha/year; although total NPP was high (33 t/ha/year), allocation to roots and rhizomes was substantial (Isagi et al., 1997). Aboveground biomass of this mature stand (age not given) was 138 t/ha (117 t/ha in culms).

Aboveground woody biomass increments averaging 7.7 t/ha/year (8.8 and 6.6 t/ha/year in 1986 and 1987, respectively) are reported for a semi-natural lowland stand of *Phyllostachys pubescens* in Zhejiang Province, China (latitude 30° N; elevation 100 m; mean annual temperature and rainfall, 16°C and 1800 mm). This mature stand, which was subject to harvesting of poles over 8 years old, had an aboveground biomass of 56 t/ha and a maximum height of 15-20 m (Qiu et al., 1992).

The ANPP of *Thyrsostachys siamensis* in Thailand (14° N; elevation 60 m; mean annual temperature and rainfall, 28°C and 950 mm) ranged from 1.6 to 8.1 t/ha/year according to site quality (mean 4.3 t/ha/year). Aboveground biomass of stands varied from 11–54 t/ha, with a mean value of 32 t/ha , and mean stand height ranged from 5.5 to 9.9 m (Suwannapinunt, 1983).

A tropical plantation of *Bambusa bambos* in southern India (approx. 11° N; elevation 540 m; mean annual temperature and rainfall, 31°C and 600 mm), grown from tissue culture stock with fertilization and irrigation, attained an aboveground biomass of 286 t/ha in its first 6 years. This is equivalent to an average aboveground productivity of 47 t/ha/year (Shanmughavel and Francis, 1996).

At a site in northern India (approx. 25° N; mean annual temperature and rainfall, 26°C and 830 mm), total NPP of *Dendrocalamus strictus* savanna was estimated at 15.8–19.3 t/ha/year.

Table 5. Reported maximum aboveground productivity of bamboo stands

Location (latitude, where available)	Mean annual temperature and precipitation, where available	Total ANPP* (maximum figure reported); t/ha/year	Aboveground wood productivity (average reported); t/ha/year	Special stand features (elevation, management) and other remarks	Reference
Southern India (11°N)	31°C; 600 mm	47.0	N/A	highland (540 m); fertilized and irrigated	Shanmughavel and Francis (1996)
Central Japan (35°N)	N/A	24.6	15.5		Isagi et al. (1993)
Japan	N/A	18.1	N/A		Isagi et al. (1997)
Georgia, USA (32°N)		N/A	9.1	"sustainable yield"	Adamson et al. (1978)
Central Chile (40°S)	4000 mm	10.5	6.2	montane (700 m)	Veblen et al. (1980)
Zhejiang, China (30°N)	16°C; 1800 mm	10.5	7.7	managed by harvesting	Qiu et al. (1992)
Alabama, USA (32 °N)		N/A	7.4	Probably fertilized	Sturkie et al. (1968)
Thailand (14°N)	28°C; 950 mm	8.1	N/A		Suwannapinunt (1983)
Northern India (25°N)	26°C; 830 mm	7.7	2.2		Tripathi and Singh (1994)
Central China (32°N)	1200 mm	4.5	3.1	montane (2750 m); ANPP* figure corrected for grazing	Taylor and Qin (1987)

*ANPP = aboveground net primary productivity
All data are reported as oven-dry biomass.

However, about half of total ecosystem NPP was accounted for by below ground turnover, and after accounting for other woody and herbaceous species, aboveground woody biomass increment of bamboo was only 2.2 t/ha/year for a mature stand and 1.1 t/ha/year for a recently harvested stand (Tripathi and Singh, 1994).

Veblen et al. (1980) estimated the biomass and productivity of a stand of montane *Chusquea culeou* in Chile (latitude 39.5° S, elevation 700m, annual rainfall 4000 mm). ANPP was 10–11 t/ha/year, and aboveground biomass about 160 t/ha, with a maximum stand height of about 9 m. Lower productivities and biomass are reported for montane forest understorey bamboos in central China (approx. 32° N) by Taylor and Qin (1987). Here, the most productive species, *Fargesia spathacea* (now renamed *F. robusta*), growing at 2500–3000 m elevation with annual rainfall of 1200 mm, had ANPP of about 3.6 t/ha/year (or 4.5 t/ha/year, corrected for grazing losses to giant pandas). Aboveground biomass was nearly 24 t/ha, with maximum stand height about 2.5–3.0 m.

El Bassam (1998) cites aboveground (air-dry) yields of native bamboo stands ranging from 1.5–2.5 t/ha/year for *Thyrsostachys siamensis* in Thailand to 10–14 t/ha/year for *Phyllostachys bambusoides* in Japan, and 18 t/ha/year for managed trial plots of *Dendrocalamus strictus* in India.

8. Limited Experience with Bamboo in the USA

Since there is a paucity of literature on United States experience with bamboos, most of the available information has been gathered together in one section covering history, applications, and productivity.

According to Sturkie et al. (1968) and Adamson et al. (1978) "oriental" bamboo was introduced to the U.S. in about 1860, and the former U.S. Department of Agriculture (USDA) collection at Savannah, Georgia, dates back to 1919. After a brief resurgence of interest in bamboo as a potential bioenergy crop during the 1970s, the Savannah station was closed around 1978, and the national collection (including 21 species of *Phyllostachys* and 17 other genera) is presently maintained at Byron, Georgia, with funding from the Agricultural Experiment Station at Griffin, Georgia (now the USDA Plant Genetic Resources Conservation Unit). The USDA concluded that many other crops would out-produce bamboo under the majority of U.S. conditions, and that most of the land not already used for food production in southern states such as Florida, was unsuitable for bamboo. However, large-scale trials were never conducted (G. R. Lovell, pers. comm.).

Interest in bamboo as a crop in Alabama dates back to the rise of angling in the 1930s and attempts by local growers to meet the demand for fishing poles (Sturkie et al., 1968). Trial plots of bamboo were initiated at the Agricultural Experiment Station, Auburn, in 1933, using nursery materials from the U.S. Plant Introduction Station at Savannah, Georgia. Development of the southeastern paper and pulp industry in the late 1950s and 1960s led to more extensive USDA trials at Camden, Alabama (latitude 32° N), but these were discontinued in 1965. Bamboos found in Alabama include *Bambusa sp*. from the Gulf Coast, *Phyllostachys sp.* (introduced "Japanese bamboo"), and the sole native *Arundinaria sp.* (sometimes described as two species; *A. gigantea* and *A. tecta*) which used to occur abundantly throughout the U.S. Southeast in stands known as "cane-brakes." Some hardy bamboos are reported to grow as far north as Pennsylvania (40–42° N), and *Phyllostachys bambusoides* is also known to grow in central northern California (40° N).

In the early 1960s, the USDA evaluated the paper-pulping characteristics of 21 bamboo species, including 5 tropical sympodial (clumped) bamboos from Puerto Rico (latitude 18° N). All were found to be suitable for papermaking using either the Kraft or the Raitt processes, with long fibers (1.4–2.3 mm) (Adamson et al., 1978). Some experience with applications of bamboo also appears to have been obtained at the Engineering Experiment Station, Clemson College, South Carolina (quoted in Sturkie et al., 1968).

Sturkie et al. (1968) report a cumulative aboveground “yield” of 121 t/ha dry matter (48 t/acre) for *Phyllostachys rubromarginata* at Auburn, Alabama (latitude about 32° N), for stands aged 14–20 years, or an average of 6.1–8.6 t/ha/year. These figures exclude leaf biomass, with branches accounting for 14% of aboveground dry matter. This *cumulative* yield is also reported as up to 54 short tons per acre (1 short ton = 2000 lb), which may account for some of the misleading figures quoted for bamboo productivity in the United States. The maximum productivity recorded for any natural ecosystem is 88 t/ha/year (for floodplain grass in the Amazon; Piedade et al., 1991), which is close to the maximum figure reported for crops (about 88–91 t/ha/year for aboveground yield of fertilized sugar cane; Alexander et al., 1982; Giamalva et al., 1984). Both of these examples represent roughly the maximum possible plant productivity with the advantages of C_4 photosynthesis and no nutrient limitations and are equivalent to about 39–40 short tons (35–36 imperial or long tons) per acre per year.

The most productive bamboo stand reported by Sturkie et al. (1968) was probably fertilized; recommended applications, assumed to be annual, were N:P:K 80:35:50 lb/acre (91:40:57 kg/ha). Other *Phyllostachys* species achieved lower annual yields (2.0–5.8 t/ha/year, or 0.8–2.3 t/acre/year, including up to 21% in the form of branches). In trials at Camden, Alabama (1959–1966, plots 65 m x 65 m, plants spaced 2.4 m x 2.4 m), *Phyllostachys bambusoides* outperformed *Pinus taeda* (Loblolly pine) by a factor of nearly 2:1 in terms of aboveground dry matter production over the first 7 years of growth (stems and branches, bark-free in the case of *P. taeda*), producing 12.4 t/acre (1.8 t/acre/year or 4.4 t/ha/year) compared with pine productivity of 7.1 t/acre (1.0 t/acre/year or 2.5 t/ha/year).

Adamson et al. (1978) found that shoot production of various *Phyllostachys* species at Savannah, Georgia (latitude 32° N), varied greatly between years in response to environmental factors. They estimated that sustained yields of over 4 short tons/acre/year (9.1 t/ha/year) were attainable for established stands of *P. bambusoides*. In trials with cutting this species on 5-, 6- and 7-year cycles, yields were 3.9–4.4 short tons/acre/year (9.0–9.9 t/ha/year), although one 3-year cycle produced 5.9 short tons/acre/year (13.5 t/ha/year). Newly established stands responded positively to N fertilizer, especially when applied in early spring.

9. Potential for New Applications in the Americas

Assuming that markets can be identified and established for domestically grown bamboo products (e.g., fresh or canned bamboo shoots, bamboo poles, bamboo flooring) there may be some commercial potential for certain bamboo species (notably *Phyllostachys spp.*) in the warmer, wetter parts of the United States As indicated by previous USDA interest, the U.S. Southeast is a likely candidate region, although the prevalence of frost in the southern Appalachian mountains may set a northern limit to the commercial growing of bamboo. Widespread growing for bioenergy production is unlikely, though, both for reasons of climate limitation and because bamboo productivity is no greater than, and in many cases less than, other candidate bioenergy crops.

Based upon the figures available from overseas, as well as the limited trials conducted in the U.S., intensively managed bamboo stands with fertilization may be capable of producing over 10 t/ha/year

(4 metric tonnes per acre per year), but a combination of variable soils and uneven management could significantly reduce this figure over large plantation areas. Nevertheless, bamboo appears to share a number of desirable fuel characteristics with other bioenergy feedstocks, including a low moisture content at the time of harvest (Table 2). The waste products from bamboo processing for other purposes may also be suitable for energy recovery using established biomass feedstock handling equipment.

Elsewhere in the Americas, notably Central America, there has been interest expressed in building upon local agricultural experience with management of bamboo stands, in order to provide fuel for conventional steam-generation power plants (Alger, Fielden, Wagner, pers. comms.). Under these conditions, the local skills base may prove more significant in determining project success than the potential productivity of the bioenergy feedstock.

10. Conclusions

Bamboo may indeed have potential as a bioenergy or fiber crop for niche markets, but little experience has been gained outside Asia since the 1960s in selecting well-adapted species/genotypes, or in estimating the productivity of the crop under U.S. conditions. Reports of high productivity appear to emanate from small-scale trials in the 1950s–1960s in Alabama, but there is little evidence overall that bamboo is significantly more productive than other candidate bioenergy crops. Bamboo has good fiber quality for papermaking, and it shares a number of desirable fuel characteristics with certain other bioenergy feedstocks, such as low ash content and alkali index. Its heating value is lower than many woody biomass feedstocks but higher than most agricultural residues, grasses, and straws. In common with certain other potential energy crops, non-fuel applications of bamboo biomass may be actually more profitable than energy recovery, although these other applications might be used as a means of supplementing the income of bamboo bioenergy growers. Alternatively, bioenergy might provide a market for utilization of waste materials from thinning/harvesting of bamboo stands grown for other purposes. Drawbacks include the near-impossibility of selective breeding, given the poor state of knowledge on bamboo reproduction.

Further research is clearly required on propagation techniques to increase multiplication rates, although recent studies in India appear promising. Large-scale trials are needed in order to develop recommendations for cost-effective establishment and stand management, and mechanized harvesting needs to be developed for countries with high labor costs. The economics of bamboo production require thorough evaluation, both for single-use and multiple-product scenarios.

11. Contacts for Further Information

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