Agricultural Residues

An Exciting Bio-Based Raw Material for the Global Panels Industry

by Jim L. Bowyer and Volker E. Stockmann

The use of agricultural residues as an industrial raw material is not new. Wheat straw chemical pulp was first produced in 1827, and wheat-based corrugating medium was commercially produced in the U.S. Midwest as recently as 1960. Interest in using crop residues to make building panels dates back to the early 1900s. A flurry of research in the mid-1970s and a more concerted effort in recent years have focused on this subject.

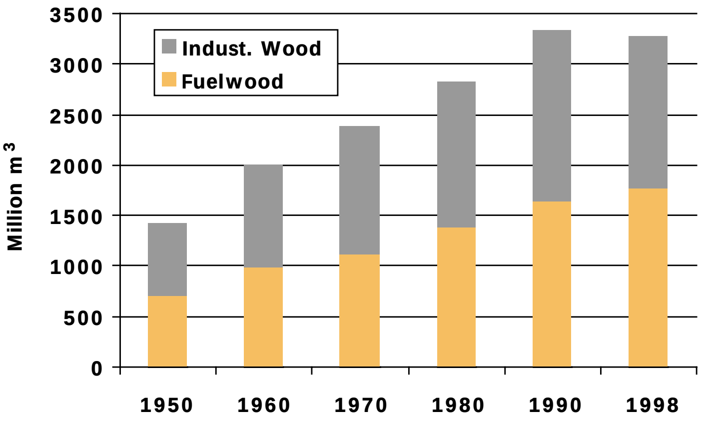
Today, panels made of straw from small-grain cereals (wheat, barley, oats, and oil seeds) and other crop residues are being commercially manufactured in a number of countries, including the United States. This fledgling industry is slowly emerging from a development phase and, assuming that several technical and economic issues can be resolved, appears poised for significant growth. This article examines the potential for further development of this industry.

Growing Demands, Shrinking Land Base

Rising Consumption

Currently, global consumption of wood approximates 3.23 billion m^3 annually, or 0.54 m^3 per capita per year. Of the estimated 3.22 billion ha of natural forests worldwide, some 1.56 billion are currently available for periodic harvest; of this, about 10 percent are managed. In addition to the natural forests, there are 0.14 to 0.15 billion ha of forest plantations available for harvest. Based on an estimated average annual growth globally of 1.5 m^3/ha (0.27 cords/acre) in unmanaged natural forests, 5.6 m^3/ha (1 cord/acre) in managed natural forests, and 15.0 m^3/ha (2.7 cords/acre) in forest plantations, the total net annual growth within the world's natural and plantation forests is estimated to be 5.1 billion m^3. Thus, given the current mix of natural and plantation forests, consumption of wood could grow another 40 percent while still maintaining a sustainable growth-to-harvest ratio. However, current trends suggest that this magnitude of increase in demand may occur within the relatively near term. Increased demand is driven both by expanding economies worldwide and by population growth.

Other than the decade of the 1990s, when global demand for wood actually declined (Fig. 1), worldwide consumption of wood throughout the 20th century expanded in parallel with population growth. Global consumption of wood declined in the past decade partly because Japan and a number of Asian countries experienced a deep economic recession. All of the decline in wood consumption was in industrial wood; fuelwood



Source: FAO (16).

Figure 1. Global Wood Harvest 1950 to 1998.

consumption continued to increase during this period. It remains to be seen whether per-capita consumption will rebound to previous levels as Japan and other parts of Asia experience economic recovery. In any case, substantial increases in global wood demand are expected. The Food and Agriculture Organization of the United Nations (FAO), for example, recently forecast a 26 percent increase in industrial roundwood demand, and a 15 percent increase in fuelwood consumption for the period 1996 to 2010 (17,18).

Falling Forest Area Per Capita

Not only is demand growth directly linked to population growth, but increasing population also has the effect of reducing the area of forestland on a per-capita basis. The historical record in this regard is dramatic (Tables 1 and 2). The United States currently has 2.7 acres (1.1 ha) of forest for each of its citizens. Worldwide, the current forest area is 1.4 acres (0.6 ha) per capita. Taking into account projected U.S. and global population for the year 2100 yields sobering numbers. By the end of this century, it appears that the United States will have only 1.3 acres (0.5 ha) of forestland per capita. Globally, the average will be only about 0.7 acres (0.3 ha). Moreover, these figures include all forestland; the area available for periodic harvest of timber will obviously be even less.

Will this kind of per-capita reduction in forestland allow wood production to keep pace with increases in population? A 1990 analysis by Sedjo and Lyon (39) presented a very optimistic view regarding adequacy of future wood supplies. A key conclusion of that analysis was that dramatic increases in industrial roundwood demand within developing nations were unlikely, primarily because large foreign debt burdens would limit economic expansion. Moreover, technological advances in growing and processing wood were expected to stretch the wood supply. Nonetheless, recent trends suggest that without significant changes, wood production will not rise at a sufficient rate to keep pace with population growth.

USDA Forest Service figures for 1992 show average net annual growth for all timberland[1] in the United States to be 44.2 ft.^{3}/acre (2.8 m^3/ha) (Table 3); the highest average rate of growth reported by ownership type was on industrial land, where annual growth was estimated at 60.9 ft.^{3}/acre (3.8 m^3/ha) (36). Global figures from FAO are less precise due to the enormity of the data collection challenge, but recent informal estimates of annual growth and total forest area suggest an average annual growth globally of 23.9 ft.^{3}/acre (1.5 m^3/ha) for unmanaged natural forests. Note that this global growth estimate includes all forestland, and not just commercial forestland as in the U.S. figures.

The average U.S. resident consumes 74.0 ft.^{3} (2.1 m^3) of roundwood annually (22) (Table 4). Worldwide, this figure is 19.0 ft.^{3} (0.54 m^3) (16,47). Using the current annual growth figures for the United States and the world in combination with consumption numbers indicates that each U.S. resident requires 1.7 acres (0.7 ha) of forest to provide annual wood needs and that each global citizen requires 0.9 acre (0.4 ha). However, the total area of forest per capita by the year 2100 is expected to be 1.3 acres (0.5 ha) and 0.7 acres (0.3 ha) for the United States and world, respectively. If it is assumed that only two-thirds of the total forest area is available for periodic harvest, then the area of harvestable forest per capita by the year 2100 is even less: 0.87 acres (0.35 ha) for the

Table 1.—Historical and Projected U.S. Forest Area Per Capita, 1785 to 2100.

Year	Population[a]	Forest Area		Forest Area Per Capita	
		(million acres)[b]	(million ha)	(acres)	(ha)
1785	3 million	1,044	423	348	141
1850	23 million	926	375	40	16.2
1910	77 million	730	296	9.5	3.8
2000	274 million	737	298	2.7	1.1
2100	571 million	737	298	1.3	0.5

[a] U.S. Census Bureau (46).
[b] Powell et al. (36).

Table 2.—Historical and Projected World Forest Area Per Capita, 1800 to 2100.

Year	Population[a]	Forest Area		Forest Area Per Capita	
		(billion acres)	(billion ha)[b]	(acres)	(ha)
1800	1 billion	11	4.5	11	4.5
2000	6.1 billion	8.5	3.4	1.4	0.6
2100	10 to 11 billion	8.5	3.4	0.7 to 0.8	0.3

[a] U.S. Census Bureau (47).
[b] Brown and Ball (10).

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[1] Only those lands capable of producing 20 ft.^{3}/acre/year (1.4 m^3/ha/yr.) and on which periodic harvest is not prohibited by law are included in the timberland figure. In 1992, some 490 million acres (198 million ha) of the total 737 million forested acres (298 million ha) in the United States were included in the timberland category.

Table 3.—U.S. Timberland Area, Net Annual Growth, and Average Net Annual Growth By Forest Area and Ownership Category, 1992.[a]

	Timberland area		Total net annual growth per year		Average net annual growth per year	
	(acres)	(ha)	(ft.^{3})	(m^3)	(ft.^{3}/acre)	(m^3/ha)
Total United States	489,555	198,200	21,626,155	549,305	44.2	2.8
National forest	84,661	34,276	3,292,997	83,642	38.9	2.4
Other public	46,833	18,960	1,963,122	49,863	41.9	2.6
Forest industry	70,455	28,524	4,289,540	108,955	60.9	3.8
Non-industrial private	287,606	116,440	12,080,496	306,845	42.0	2.6

[a] Powell et al. (36).

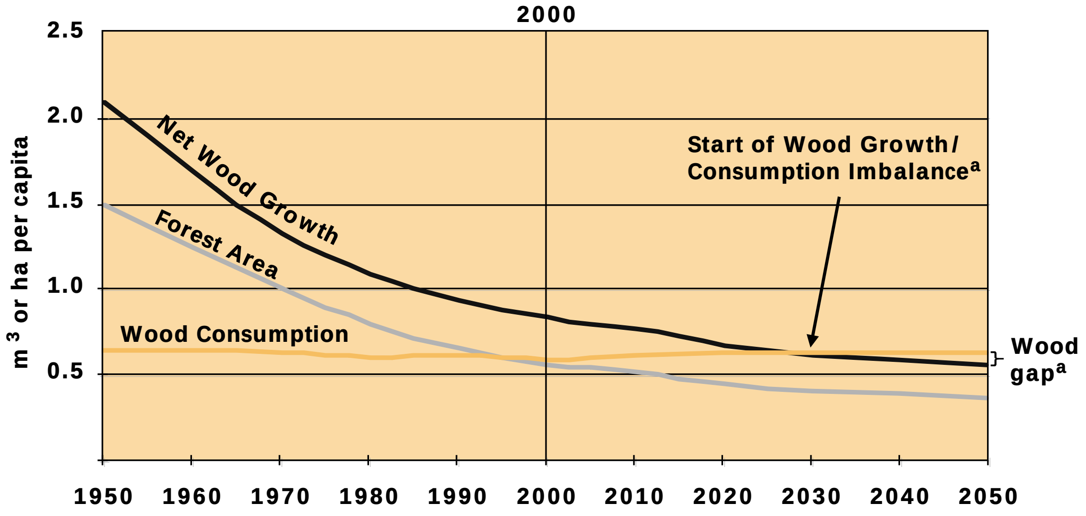
Table 4.—A Comparison of Annual Per-Capita Wood Consumption and Available Forest Area to Support That Consumption, 2000 and 2100.

		United States	World
Net annual forest	ft.^{3}/acre	44.2	21.4
growth (average)	m^3/ha	2.8	1.5
Per-capita consumption	ft.^{3}	74.0[a]	19.0
of wood (annual)	m^3	2.1	0.5
Forest area needed per	acres	1.7	0.9
capita to supply wood needs	ha	0.7	0.4
Forest area per capita - 2000	acres	2.7	1.4
	ha	1.1	0.6
Forest area per capita - 2100	acres	1.3	0.7
	ha	0.5	0.3

[a] Howard (22).

United States and 0.5 acres (0.2 ha) for the world as a whole. The net effect of these various factors is that supplying global needs for wood and fiber is becoming increasingly problematic. For example, were the world to continue to rely on the current mix of natural forests (95.8%) and plantations (4.2%), as well as the current level of management, the annual growth of wood would soon be insufficient to support current per-capita consumption (Fig. 2).

One solution to this problem would be to increase the intensity of management in the world's natural forests. However, an increase in management intensity in domestic and global forests today appears unlikely; societal pressures, including forest certification initiatives, are leading to increased areas of forest reserves and a lower intensity of management on those lands that are managed for timber production.



[a]Assuming present area and productivity of natural and plantation forests and current per-capita wood consumption.

Sources: Wood consumption, FAO (16); forest area, FAO (18), Mather (30); Net wood growth estimated based on average annual growth globally of 1.5 m^3/ha (0.27 cords/acre) in unmanaged natural forests, 5.6 m^3/ha (1 cord/acre) in managed natural forests, and 15.0 m^3/ha (2.67 cords/acre) in forest plantations.

Figure 2. Per-Capita Data for Forests and Wood.

Table 5.—Global Forest Area and Wood Production, 1999.

Forest Area	
Total area of natural forest [a]	3,221 million ha
Area of natural forest available for periodic harvest [a]	1,563 million ha
Plantation forests [b]	143 million ha
Wood Production	
Total roundwood harvest [c]	3,233 million m^3
industrial wood [c]	1,505 million m^3
fuelwood[c]	1,728 million m^3
Harvest from forest plantations [b]	417 million m^3
industrial wood [b]	331million m^3
fuelwood [b]	86 million m^3

[a] FAO (18).
[b] Brown and Ball (10).
[c] FAO (16).

Forest Plantations to the Rescue?

Since a general increase in forest management intensity is not likely, a second option for increasing the wood supply, which has received a great deal of attention in recent decades, is establishment of vast areas of high-yield forest plantations. The potential for increased wood production in such plantations is great. Currently, plantation forests comprise only about 4.2 percent of forests globally (up from 3.5 percent in 1995), but provide 21 to 22 percent of industrial wood, 4 percent of fuelwood, and 12 to 13 percent of annual wood production overall (Table 5). Forest plantations were estimated to cover about 306 million acres (123.7 million ha) globally in 1995; this had grown to about 353 million acres (143 million ha) by 1999. The current rate of establishment of such plantations is rapid (4.7 million ha/yr.) (10); some people are even predicting a glut of plantation wood in Asian and world markets by 2010 (28). Additional supplies of wood are likely to result from increased wood production on agricultural lands through expansion of agroforestry systems in many parts of the world (8,42). Both developments are largely taking place within the developing nations and most significantly in the tropical regions.

Despite the high current rate of forest plantation establishment, Sutton (45) suggests the likelihood of a significant gap between what society appears willing to have harvested from natural forests, and what an extension of current wood demand trends would seem to indicate for future wood consumption. If forest plantations are to fill this gap, it will require establishment of more than 247 million acres (100 million ha) of high-yield plantations beyond what exists today. Sutton points out that planting on this scale would require a huge global effort, noting that "it would require most of the world's land that is suitable for planted forests and which currently is surplus to food production, but which is not already in forest." Brown and Ball (10) recently examined several scenarios for creating new forest plantations, and concluded that establishment of 100 million ha of new plantations is "generally achievable in physical terms," requiring continuation of the 1995 planting rate through 2010 and a declining planting trend thereafter through 2050.

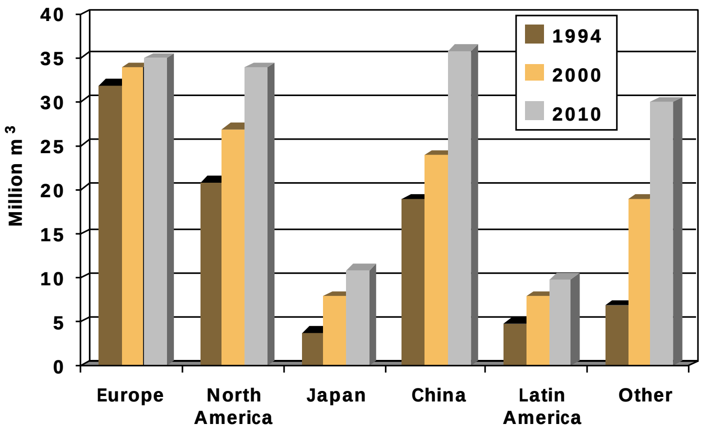
In monetary terms, an investment on the order of $100 to $150 billion ($U.S.) would be needed to create 100 million additional ha of plantations. Moreover, should reliance on forest plantations for wood supplies increase to the extent that some have forecast, significant dislocations of the present forest products industry, from developed to developing nations, would be likely, as manufacturing activity migrates over time to locations closer to the raw material base.

Fortunately, there is another potential source for significant quantities of lignocellulosic raw materials that can supplement wood from natural and plantation forests. That alternative involves the use of agricultural residues, e.g., stalks of wheat and other small-grain cereals, and perhaps even crop residues of corn, sunflower, or sorghum. Such residues are the focus of this article.

Spectacular Growth in Building Panels Demand

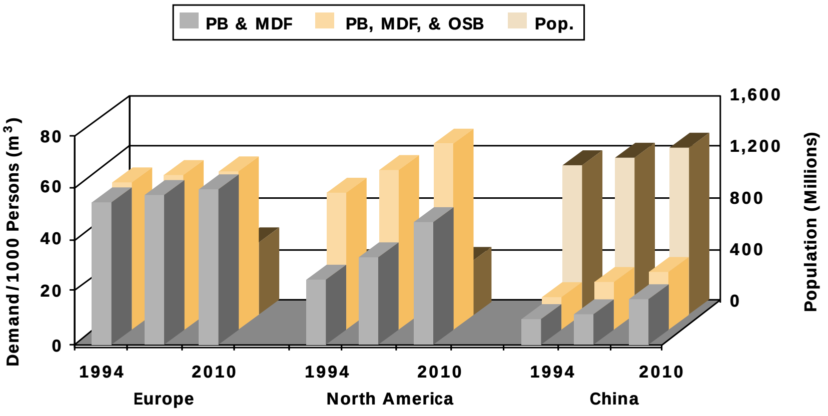
Per-capita consumption of structural and non-structural panels of wood is higher in western Europe and in North America than in other parts of the world. However, there is rapid growth in many countries, especially China (Fig. 3).

Due to the combined effects of population growth, economic growth, and end-user acceptance, the consumption of reconstituted wood panels is rising quickly in many regions of the world (Fig. 4). Rapid growth will likely continue through at least 2010. Particularly rapid demand growth is forecast for medium density fiber-



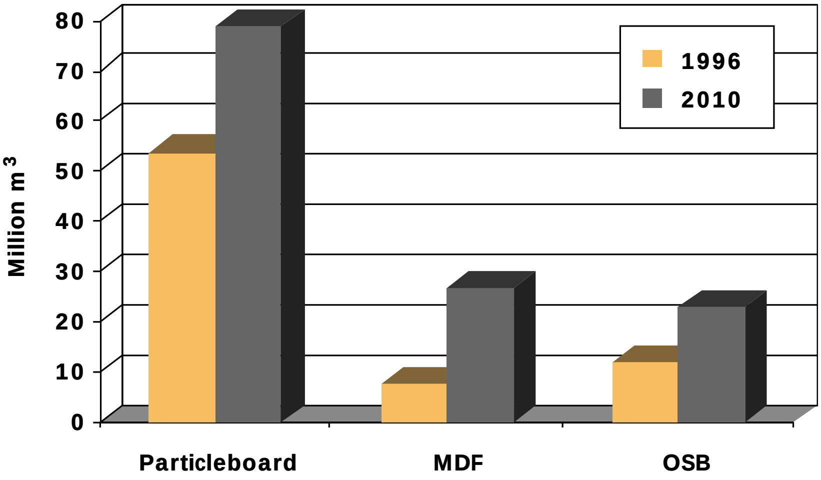
Source: FAO (16).

Figure 3. Regional Demand Growth - All Reconstituted Panels Combined.



Source: FAO (16)

Figure 4. Regional Per-capita Demand for Reconstituted Panels.



Source: FAO (17).
MDF data include dry-formed high density fiberboard.

Figure 5. Global Demand Growth for Reconstituted Panels.

board (MDF) and oriented strandboard (OSB), with consumption expected to double or triple during the period 1996 through 2010 (Fig. 5). Substantial growth in standard particleboard (PB) demand is likely as well. MDF and PB are largely "industrial" panels; they are converted by industry into end-use products such as furniture and cabinets. OSB, on the other hand, is largely a "construction" panel that has been substituting since the early 1980s for construction-grade plywood.

Agriculturally Derived Fiber as an Industrial Material

Fiber Crops

Agricultural crop residues have long been used for a variety of purposes, including fuel and a source of papermaking fiber. However, there are relatively few examples of crops other than trees having been planted specifically for the purpose of providing a source of energy or raw materials for industry. One exception is jute, a crop long cultivated throughout the world to provide the long fibers used in making cloth sacks and cordage.

During World War II, the United States was cut off from jute fiber suppliers in Asia, triggering a massive effort to develop fast-growing alternative crops, including kenaf (*Hibiscus cannabinus* L.), as a jute substitute (7). Cuba and Guatemala were involved in an intensive effort to find alternatives to jute, which resulted in development of a number of high-yielding varieties of kenaf. Subsequent work within the United States, which continued through 1960, led to additional varieties of this crop species.

In an initiative in the mid-1950s that was at first unrelated to the early work on kenaf, the U.S. Department of Agriculture (USDA) tried to identify crops that could help to expand and diversify markets for American farmers. The idea was to find new fiber crop species that contained major plant constituents different from those then available and to promote their potential for industrial use (32). It was agreed that work would focus on species that could replace crops in surplus, but not compete with them (7).

Because there was little in the way of historical knowledge from North America or elsewhere to build on, the USDA, in 1957, launched a massive crops screening program. As explained by Atchison (7) "... the emphasis was on studying fiber crops that could be used as raw materials for pulp and paper manufacture. More than 1,200 samples of fibrous plants from about 400 species were screened, taking into consideration all technical and economic factors involved. Based on the initial evaluation, the 61 most promising fibers were subjected to detailed pulping tests. By 1961, researchers had narrowed the list to six fibrous materials: kenaf, crotalaria, okra, sesbania, sorghum, and bamboo." After 2 more years of intensive work, kenaf emerged as the top candidate for further research into utilization options and technologies (26).

Over the next 15 years, kenaf was the focus of intensive research. Information was collected regarding technical and economic aspects of plant growth and harvest, storage, and conversion to pulp and paper products. Potential markets were also investigated. In 1978, perhaps concluding that as much had been done in the way of federally sponsored research as was practical, the USDA terminated funding for kenaf research. Atchison (7) notes that the decision affected not only kenaf research, but agriculturally derived fiber research in general. The USDA Peoria laboratory, for example, dismantled and sold its complete pilot-plant facilities for working on non-wood plant fibers shortly after the cut in funding was announced.

In the early 1990s, interest in alternative crops reemerged in the form of a new alternative crops initiative of the USDA (1) and research on industrial hemp funded by at least four state governments (49). Although the new federal effort is focused on potential energy and chemical crops, much of the state-funded research has been directed toward further investigation of the commercial potential of kenaf and of industrial hemp (*Cannabus sativa*), a species excluded from the earlier USDA alternative crops research. The primary impetus for all of these efforts appears to be the depressed farm economy throughout most of the United States.

Recent kenaf research has centered on harvesting and breakdown of stalks, technical and economic possibilities of substituting kenaf fiber for wood and other traditional materials in traditional products manufacture, and on development of niche markets. Pulp and paper and structural and non-structural composites are among the products being investigated (40). It appears that progress is being made in all areas of research. Investigation of industrial hemp is proceeding more slowly than of kenaf, in part because of the legal hazards and social stigma associated with marijuana, a different but closely related plant; in this case, most research and pilot studies are occurring in countries other than the United States, including Canada, France, and the Netherlands.

A common finding of various studies of both hemp and kenaf is that the highest and most commonly published yields are attainable only on the best agricultural land, and often only with intensive inputs. Yet, these are the same lands that will be needed in the future to ensure sufficient food supplies for a growing population. This reality raises a question as to whether annual agricultural crops planted specifically to produce non-food raw materials make sense over the long term.

Agricultural Residues

History

Whereas the use of annual crops planted specifically as a source of fiber is questionable from social as well as environmental perspectives, the same cannot be said for agricultural residues. These are by-products of food production that in many areas of the world currently represent a disposal problem. A case in point is the United States where regulations now prohibit the once-common practice of burning fields following harvest (13). The use of agricultural residues is both socially and environmentally attractive as long as volumes removed from the land do not compromise soil conservation.

The idea of using agricultural residues as an industrial raw material is not new. Paper was invented in China in A.D. 105, but it was not until about 1850 that wood began to be used as a principal raw material for papermaking. Early sources of fiber included flax, bamboo, various grasses, cereal straw, cottonseed hair, leaves, and inner bark of trees (23,31). Wheat straw chemical pulp was first produced in 1827 (33). Crop residues, such as bagasse (sugarcane residue), have long been used in making paper in China, India, Pakistan, Mexico, Brazil, and a number of other countries (35). Today, production of paper and paperboard from crop residues is on the rise, with the percentage of pulp capacity accounted for by non-wood fiber globally now close to 12 percent; this compares to an estimated 6.7 percent non-wood fiber in 1970. Wheat straw is currently estimated to account for over 40 percent of non-wood fibers, with bagasse and bamboo together accounting for another 25 percent (7).

U.S. research examining potential uses of crop residues as a papermaking raw material dates back to at least World War II (7). In the 1940s, 25 mills in the Midwest produced almost 1 million tons of corrugating medium annually from straw. By 1945, the Technical Association of the Pulp and Paper Industry (TAPPI) established an agricultural residues committee. Momentum in the non-wood fiber industry was lost following the war because of the high costs of gathering and processing straw, and the return to pulping of hardwoods on the part of the paper industry. The last straw mill in the United States closed in 1960. Today, however, new research is focused on the use of agricultural residues for paper and paperboard (5,24).

Panels of straw bonded by adhesive were first produced in Germany in 1905. The first published research on the possibility of manufacturing insulating board from crop residues appeared in the United States in the 1930s and 1940s (6,44). Investigation of the possibility of producing structural panels from such material appears to have begun in the 1970s (11,12,19,20). Considerable research activity in this regard has developed in the United States over the past decade, and a number of studies have demonstrated the technical feasibility of manufacturing structural panels from crop residues that meet commercial standards for such products (2,4,27,34,38,55).

A growing number of companies in North America have developed processes and are operating plants manufacturing panels from straw with a performance ranging from underlayment-grade PB to standard MDF. These developments continue. Douglas (13) recently described the situation, noting that "Agri-fiber in North America is starting to come out of the development phase and is beginning to compete in more than just commodity particleboard markets." Figure 6 depicts the announced annual capacities of the strawboard plants in operation and under development. The lengths of the bars in Figure 6 correspond to capacities expressed in m^3 (to convert m^3 to the U.S. customary MMSF, 3/4-in. basis, multiply by 565; for example, the Elie plant's

Table 6.—World Production of Selected Cereal Grains by Major Producing Countries, 1999.[a]

Country	Wheat	Barley	Oats	Total
	(1,000 mt)			
China	114,400	3,850	800	119,050
India	70,778	1,468	—	72,246
U.S.	62,662	6,136	2,122	70,920
Canada	26,850	13,196	3,641	43,688
Australia	21,269	4,360	1,503	27,132
U.K.	14,870	6,510	540	21,920
Ukraine	13,476	6,382	759	20,618
Argentina	14,500	400	385	15,285
Poland	9,051	3,401	1,446	13,899
Mexico	3,072	469	89	3,630
World	583,624	130,064	24,787	738,475

[a] FAO (15).

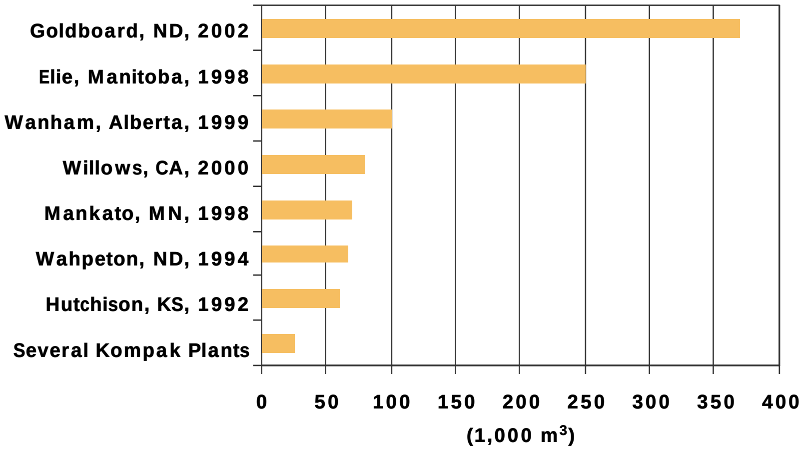
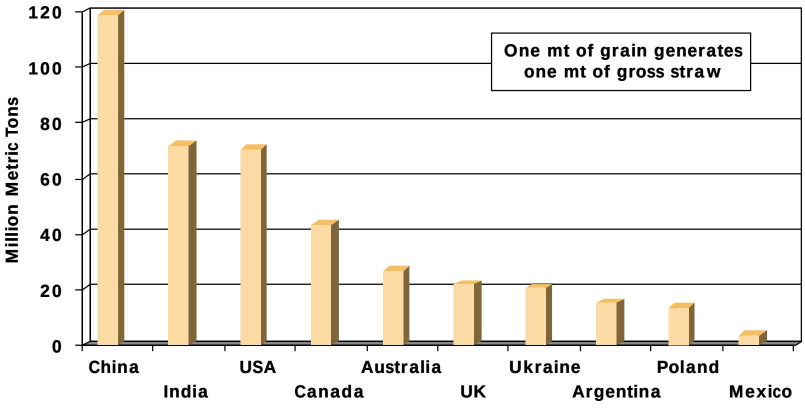


Figure 6. Announced Capacities of Strawboard Plants in North America.



Source: FAO (15).

Figure 7. Production of Cereal Grain by Country, 1999 (Wheat, Barley, and Oats).

announced capacity of 250,000 m^3 corresponds to 141 MMSF, 3/4-in. basis).

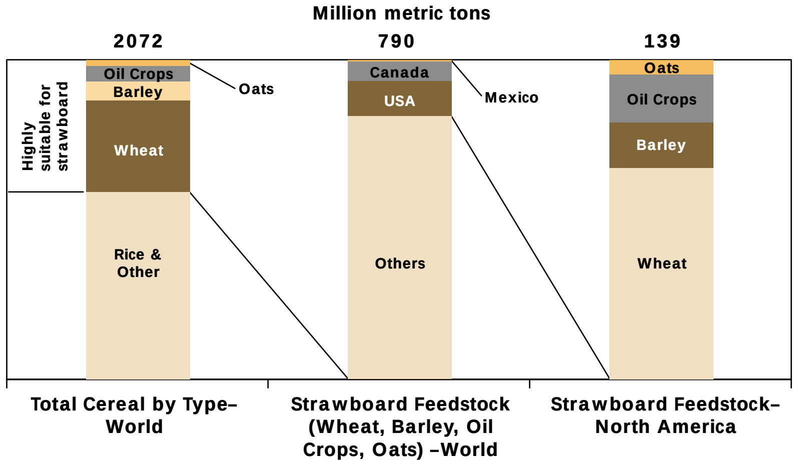
Potential Availability

The quantity of crop residues potentially available for use in manufacturing structural panels is quite large. It is important to recognize, however, that surplus residues are currently also under examination by the paper industry as a source of papermaking fiber, and by the U.S. Department of Energy and others as a potential biofuel (51).

Although a wide variety of crops might provide fiber for the panels industry, those that appear to be most compatible with current technologies are wheat, barley, and oats. Global production of these three crops alone totaled 738 million metric tons (mt) in 1999 (Table 6), with over 41 percent of production concentrated in China, India, the United States, and Canada (Fig. 7). As population rises in the coming decades, total production is likely to increase significantly, and perhaps as much as 40 to 60 percent.

North America (United States, Canada, and Mexico) together produced 118.2 million mt of wheat, barley, and oats in 1999, accounting for about 16 percent of world production; approximately 93 million mt, or 78 percent, of North American production of these three grains is accounted for by wheat (Fig. 8).

The ratio of wheat straw to grain production has been estimated by a number of investigators in recent years. Colorado State University Extension (41) estimates crop residues of 80, 50, and 40 pounds (36, 23, and 18 kg) per bushel for wheat, barley, and oats, respectively, at a green basis moisture content (MC) of 10 percent. Wheat, barley, and oats weigh about 60 pounds (27 kg), 50 pounds (23 kg), and 32 pounds (14.5 kg), respectively, when at 12 percent green basis MC (50). Using these weights in conjunction with the Colorado State University estimates of crop residues results in figures of 1.3 tons of wheat straw per ton of grain, 1.0 ton of barley straw per ton of grain, and 1.2 tons of oats straw per ton of grain. The Alberta Department of Agriculture (3) estimates residue volumes more conservatively, reflecting geographic differences and an assumption of only 80 percent recovery. Their estimate is 40 to 80 pounds (18 to 36 kg) per bushel for wheat, and 30 to 45 pounds (14 to 20 kg) per bushel for barley and oats; these numbers convert to 0.6 to 1.2 tons of straw per ton of grain for wheat, 0.6 to 0.9 tons of straw per ton of grain for barley, and 0.9 to 1.4 tons of straw per ton of grain for



Source: FAO (15).

Figure 8. Grain Production,1999.

oats. Another estimate from the grain-producing provinces of Canada and from the western United States, as reported by Wong (54), suggests production of from 0.8 to 1.8 mt of straw per mt of cereal grain produced. In this analysis, we have used a conservative figure of 1.0 mt of straw per mt of grain.

Much of the volume of crop residues is not available for new uses. In North America, about one-half of the straw produced is left on the field for soil conservation purposes (48,54). In addition, some is harvested, baled, and used to feed livestock. In other cases, livestock is grazed on fields in the several months directly following the grain harvest. In straw-rich regions, soil conservation and various agricultural uses may together account for about 60 percent of the total straw produced, leaving a surplus of 40 percent on average. However, in dry producing regions, such as much of Colorado, soil conservation concerns may dictate no straw harvest (21,29,41). Moreover, straw yields vary by growing season, with markedly lower production in abnormally dry years. For example, Russell (37) reports that in Montana, about 30 percent of the time, straw production is less than one-half of average production. Therefore one cannot rely on average surplus straw figures to determine the optimum capacity for a strawboard plant. Even considering these caveats, there is a significant volume of available straw. A simple calculation reveals the magnitude of the potential resource. Conservatively assuming a straw surplus of 15 percent instead of 40 percent (allowing for cyclical variation in straw production), but also assuming that surplus straw could be gleaned from all of the area on which wheat is produced in North America, yields the estimate shown in (Table 7).

Table 7.—Estimated straw surplus in North America, 1999.

		(million mt)
Wheat, barley, oats	(100%)[a]	118.2
Soil conservation	(50%)	59.1
Agricultural uses	(35%)	41.4
Surplus	(15%)	17.7

Requirement for 300,000 m^3 (170 MMSF, 3/4-in.) plant capacity:[b] = 300,000 mt.

Potential number of plants: 17.7/0.30 = 58 plants.

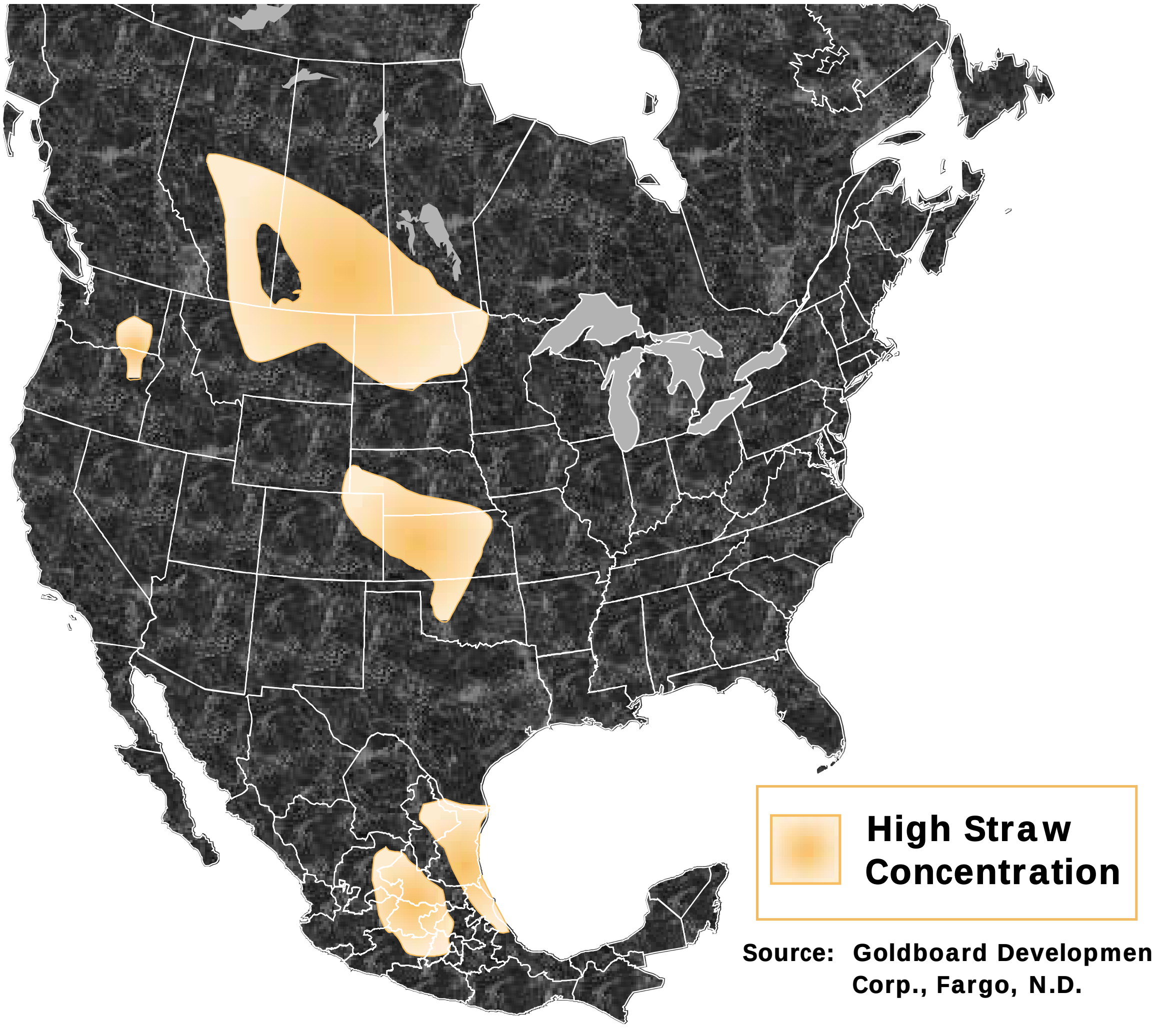
[a] Assuming 1 mt of straw for each mt of grain produced.
[b] Calculated assuming an average board density of 46.8 pcf (750 kg/m^3) and straw yield at 70 percent.

Another measure of magnitude is provided by comparing the 17.7 million mt of surplus straw (Table 7) with the quantity of wood currently used for structural panel manufacturing in North America. In 1998, the total weight of OSB, MDF, and standard PB produced in North America approximated 26.3 million mt, involving some 200 manufacturing plants (22).

By either measure, the quantity of crop residues available for panel manufacture is quite significant.

One question regarding straw availability is how much of the potentially available volume is sufficiently concentrated to allow for economic collection. As indicated in Figure 9, at least five regions have a high straw concentration: 1) central Alberta and the southern tier of Saskatchewan and Manitoba, North Dakota, and northeast Montana;2) Kansas and northwestern Oklahoma; 3) eastern Washington and Oregon; 4) the east Gulf Coast of Mexico from near Nuevo Laredo and Monterrey, south to the Veracruz area; and 5) the central plateau of Mexico, mostly north of Mexico City. Each of these regions could produce enough straw to supply several large strawboard plants.

Given the volume of straw, and especially wheat straw, produced annually in China, the potential for production of structural panels from agricultural residues is particularly large in that nation. This opportunity is magnified by the fact that China is a massive net importer of wood and is currently a net importer of 35 percent of the roughly 15.5 million m^3 of wood-based panels marketed there annually (16). Recent data show that China currently uses about one-third of gross crop residues for purposes other than soil conservation (25), a figure comparable to North America. Thus, using the same type of calculation as just presented (i.e., assuming a straw surplus of 15 percent and that surplus straw could be gleaned from all of the area on which wheat is produced), China could support as many as 60 panel plants, each with a capacity of 300,000 mt. This volume of potential production is equivalent to about twice the current annual consumption of wood-based panels within China. It is important to note, however, that this calculation assumes that all



Source: Goldboard Development Corp., Fargo, N.D.

Figure 9. Straw-Rich Regions in North America.

surplus straw will be used to produce panels, to the exclusion of additional production of straw-based paper or energy.

Because of the relatively small volume of wood-based panels now consumed annually within India (16), the potential for a straw-based wood panel industry is especially large. In India, surplus straw, if all was used to provide raw material for production of panels, would be sufficient to supply a quantity of panels equivalent to more than 75 times the current domestic consumption within India!

The Storage Issue

Because agricultural residues are produced over a 1- to 3-month period each year, storage of this material is a concern. Very large volumes need storage in order for processing facilities to be able to operate at a sufficient capacity to achieve economies of scale.

A study of opportunities in grass straw utilization, as reported by Ehrensing (14), concluded that covered storage was necessary and stated "providing storage facilities and holding stocks of raw materials to ensure uninterrupted supply to a mill will involve considerable investment. Estimated storage costs for grass seed straw in western Oregon range from $13.22 to $14.23 per short ton ($14.54/mt to $15.65/mt), assuming an average 6-month storage period. This figure includes costs of construction, interest, repairs, insurance, and straw losses." A similar estimate of storage costs ($14 to $15 per short ton), which included the cost of working capital tied up in stored fiber, resulted from a recent study of papermaking from kenaf (9).

Wagner (52) stated that there are a number of options for storing straw: 1) storage of all annual supply at the mill; 2) storage of a portion of the annual supply at regional storage facilities owned by a mill, with the rest stored at the mill; and 3) storage of a small portion of straw at the mill as a buffer supply with the rest stored at nearby farms. These options include storage within buildings, tarp-covered storage in farm fields or elsewhere, and uncovered storage at the farm, regional storage site, or mill.

Several sources have reported that to prevent degradation of straw bales, the bale moisture must be main-

Table 8.—A Comparison of Direct Costs for Wood and Straw MDF.

	Wood MDF		Straw MDF	
	($/MSF)[a]	(%)	($/MSF)[a]	(%)
Fiber furnish	96	(40)	65	(30)
Binder	58	(24)	73	(33)
Labor	29	(12)	29	(13)
Power	29	(12)	25	(11)
Operations and supply	29	(12)	29	(13)
	240[b]	(100)	220[b]	(100)

[a] 3/4-inch basis.

[b] These costs convert to $258 and $237 per 100 m^2 (19-mm basis) for wood MDF and straw MDF, respectively.

tained below 8 to 12 percent wet basis MC (32,53), as bales with higher moisture are reportedly susceptible to rot and spontaneous combustion. However, experience at Goldboard Development Corporation suggests that maintenance of bale MC at 18 percent green basis or less may be sufficient. All those reporting on this issue agree that storing hay at MCs above 20 percent will result in development of internal heating, mold, greater dry matter loss than if stored at a low MC, and discoloration. Not surprisingly then, high spoilage has been reported in Minnesota and Wisconsin for baled hay stored in ground contact (53). Losses of 22 to 23 percent were experienced by mid-June for fall-harvested stalks that were uncovered and in ground contact, compared to a 1 to 8 percent loss of bottom bales stored on gravel or inside a barn.

By covering outside-stored bales with a tarp, losses can be reduced by one-half or more (52). Estimates of the seasonal costs of tarped storage range from $2 to $6 per short ton. Estimates of the costs of tarp-covered storage are based simply on the cost of large tarps that last from 1 to 4 years. Costs of handling, land rent, or other factors are not included in these estimates. It is clear, however, that the costs associated with tarped storage are considerably less than the costs of storage within a dedicated structure (52). Cost savings, however, are likely to be tempered by higher straw losses than would be experienced with indoor storage.

Outdoor storage of uncovered bales is the most common practice of companies that are currently using agricultural residues. This practice is sometimes deemed satisfactory and sometimes unsatisfactory. For example, PrimeBoard is apparently satisfied with its practice of storing straw on bare clay soil and packing the bales into piles 50 bales long by 6 bales wide by 6 bales high. These bales are then left uncovered. Only the outer 6 to 12 inches reportedly show degradation from weather, even at the end of the storage season (43). The Isobord plant at Elie, Mont., has uncovered storage as well. Interestingly, Goldboard reports that aged straw makes better strawboard than fresh straw. Old straw requires less binder than fresh straw to achieve the same internal bond strength.

While some plants have reported satisfactory results with uncovered straw storage practices, significant problems have been reported by others. Such problems include substantial degradation and loss of straw late in the storage period and the development of wet pockets in bales that inhibit efficient processing of the baled straw.

It appears that the fiber storage issue may not be as problematic as it is sometimes perceived to be. This is, however, an area that has the potential to considerably impact mill operations and profitability, and thus one that must be addressed in planning.

Economics of Strawboard

It has yet to be consistently demonstrated that strawboard can economically compete with similar products made of wood. In an attempt to limit hauling distances and straw storage requirements, a number of North American strawboard manufacturing facilities built in the past decade are relatively small in size (Fig. 6). This strategy, however, has meant forfeiture of economies of scale. Largely because of this, many of the early plants are currently experiencing financial difficulties such that at least some are unlikely to survive over the long term.

Raw material costs for some composite panels appear to favor straw rather than wood-based products. Consider, for example, a wood-based MDF plant that would typically use a furnish composed of 50 percent sawdust and shavings and 50 percent pulp chips. Sawdust and shavings today cost about $45 per dry delivered short ton ($50/mt); pulp chips cost about twice that. The result is an average cost of furnish of $68 per short ton ($75/mt). Straw, on the other hand, can currently be purchased in the straw-rich regions for below $45 per dry delivered short ton ($50/mt). This provides roughly $36 per short ton ($40/mt) to farmers who stack bales at the edge of their fields, and allows $9 per short ton ($10/mt) for delivery to the mill site. If indoor straw storage is assumed, straw costs rise to about $60 per short ($65/mt). This current difference between the costs of delivered straw and the costs of sawdust and shavings bodes well for strawboard plants. Given growing pressure on wood supply and the very large reservoir of surplus straw, the costs of sawmill wastes are likely to escalate faster than the costs of straw.

A portion of the basic raw material cost advantage for strawboard is lost in binder cost because isocyanate, rather than urea- or phenol-formaldehyde, is needed in order to achieve desired properties in strawboard. Overall, though, operating costs tend to be lower for strawboard, assuming production facilities of like scale (Table 8).

Summary

Agricultural residues such as straw from wheat, oats, or barley are a potential source of bio-based raw material that could be used for industrial purposes. Although utilized by non-food industries in the past, such use has not been common for at least 40 years. Now, however, there is renewed interest in the possible use of agricultural residues for the manufacture of a variety of products, including paper and paperboard as well as structural and non-structural panels.

Agriculturally derived fiber is currently being utilized in North America as a raw material for manufacturing various kinds of panel products, including general-purpose PB. The industry is small, but growing. For the most part, this industry is based on crop residues rather than on fiber obtained from dedicated crops; growing needs for food worldwide are likely to dictate a continued focus on residues rather than on annual fiber crops.

Based on currently available volumes of surplus residues, the North American agrifiber industry could potentially grow to a size approximately two-thirds that of the present wood-based panel industry. The growth potential in China and India is also quite large.

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