Industrial Hemp (Cannabis sativa L.) as a Papermaking Raw Material in Minnesota: Technical, Economic, and Environmental Considerations[1]

by

Jim L. Bowyer[2]

May 2001

---

[1] Funding for this research provided by the Minnesota Environment and Natural Resources Trust Fund.

[2] Jim L. Bowyer is professor and Director of the Forest Products Management Development Institute, Department of Wood & Paper Science, University of Minnesota, 2004 Folwell Avenue, St. Paul, MN 55108.

Table of Contents

List of Tables

Abstract

Consumption of wood is increasing worldwide as demand for paper, structural and non-structural panels, and other products rise in response to population and economic growth. Interest in alternative sources of fiber is increasing as concerns about the adequacy of future supplies of wood fiber are growing.

One potential source of industrial fiber is agricultural crops, either in the form of residues of food crops or plants grown specifically for fiber. One species that has generated interest as a fiber source is industrial hemp (*Cannabis sativa* L.). This report focuses on the potential use of industrial hemp as a source of paper making raw material in Minnesota. Environmental implications of commercial scale hemp production are also examined.

Hemp has a number of properties that favor its use as a papermaking raw material. About one-third of the fiber of the hemp stalk, that from the outer layers or "bark," is quite long, a desirable quality for developing high-strength paper. Also, the proportion of lignin throughout the stalk is lower than in wood, a property that favors high pulp yields. Fiber from hemp bark has also been found by a number of researchers to be an acceptable raw material for use in contemporary papermaking, and it appears that hemp paper could be manufactured at a competitive price to paper made of wood pulp.

Despite the seemingly promising outlook for industrial hemp as a papermaking raw material, there are several issues that must be addressed if hemp is to become a viable fiber source in Minnesota. Among these are persistent problems related to economical bark/core separation, long-term fiber storage following harvest, and potential issues related to ongoing large-scale agricultural production of hemp. Other issues arise from the fact that hemp core fiber, which comprises 65 to 70 percent of stalk volume, has markedly different properties than hemp bark fiber, and generally less desirable properties than even the juvenile fiber of wood.

From an environmental perspective it makes little sense to promote the use of hemp over fiber produced in intensively managed forests or forest plantations. Although a given area of land will generally produce a greater quantity of hemp than of wood fiber, the fact that hemp is an annual crop requiring relatively intensive inputs, as compared to trees that are managed less intensively over longer harvest cycles, translates to substantial overall environmental impact from hemp production.

Context

Expanding Paper Demand

The global paper industry, as well as that of the United States, has enjoyed an extended period of rapidly rising demand (Table 1). Globally, consumption of paper and paperboard has expanded to more than 8.5 times 1950 levels, a period in which the world population expanded by 2.4 times. Growth in U.S. paper consumption has also been dramatic. Total U.S. paper consumption at the beginning of the new millenium is now four times that of 1950; the population of the United States grew by just over 86 percent during that 50-year period. Domestic demand for paper and paperboard is likely to rise 50 percent or more by 2050.

Growing paper demand is important to Minnesota in at least two ways:

- Demand for paper is increasing steadily in Minnesota with continued growth in the population and economy. Assuming the same per capita use of paper in Minnesota as nationally, paper consumption by Minnesota residents has increased four times since 1950. Considering the medium projection of population growth for the century ahead (U.S. Census Bureau, 2001), it is likely that paper demand will double again within Minnesota by the year 2100.
- Paper production is important to Minnesota's economy, and particularly the economy of Greater Minnesota. The current $4+ billion industry provides well-compensated employment to tens of thousands of industry employees and suppliers, as well as significant tax revenues to state and local government.

Table 1

U.S. and Worldwide Pulp and Paper Consumption vs. Population - 1950 to 2000

	United States			World		
Year	Consumpt. of paper & paperboard[a] (million mt)	Av. ann. inc. in paper consumpt. for prev.10 yr. (%)	Ann. pop. growth rate[b] for prev.10 yr. (%)	Consumpt. of paper and paperboard[c] (million mt)	Av. ann. inc. in paper consumpt. for prev. 10 yr. (%)	Ann. pop. growth rate for prev.10 yr[d] (%)
1950	22			38		
1960	31	4.5	1.7	77	7.3	1.7
1970	48	4.5	1.2	128	5.5	2.0
1980	59	2.1	1.1	170	3.1	1.8
1990	78	2.8	1.0	240	3.5	1.7
2000	96	2.3[e]	1.0[e]	317	3.1[e]	1.4[e]
2010	113	1.5	0.8	440	3.3	1.2

[a] Figures for 1950 and 1960 from the American Paper Institute (1984). More recent data from American Forest & Paper Association. Recovered Paper Statistical Highlights- 2000 Edition.

[b] Source: Calculated based on data from U.S. Bureau of the Census, U.S. Popclock Projection. 2001. http://www.census.gov/cgi-bin/popclock

[c] Source: FAO. 2001. Forestry Statistical Database. http://www.fao.org

[d] Source: U.S. Census Bureau, World Population Statistics (http://www.census.gov/ipc/www.worldpop.html)

[e] For previous 9-year period.

[f] FAO (1993)

The fiber supply situation in Minnesota is, however, becoming a limiting factor to industrial growth, as it is worldwide. John Krantz, the chief wood utilization specialist with the Minnesota Department of Natural Resources, recently commented on the Minnesota fiber supply situation, noting that while increased forest growth rates over the longer term will likely sustain current and planned harvest rates, the outlook in the relatively near term is less certain. A widely reported aspen age-class-imbalance could cause wood supply disruptions within the next several decades that could conceivably lead to closure of one or more oriented strandboard (OSB) mills (Krantz 2001).

Kaldor (1992) noted almost a decade ago that the combined effect of past and projected increases in paper demand could lead to a global shortage of virgin fiber shortly after the turn of the century. He further estimated that if future needs for papermaking fiber were to be met using wood fiber, approximately 25 million acres of tree plantations per year would have to be established beginning "now." Although Kaldor assumed 10-15 year cutting cycles in his calculations, rather than 4-5 year cycles now viewed as optimum for intensively managed plantations of fast growing hardwoods, it is nonetheless clear that concerted actions will be needed to ensure future supplies of fiber. Bold initiatives, including development of non-forest fiber sources, will likely be necessary to ensure sufficient industrial fiber for the future.

Increasing Pressures on Forests

Not only is demand for paper rising in response to population and economic growth, but increasing population is also steadily reducing the area of forest land on a per capita basis. The historical record in this regard is dramatic (Tables 2 and 3). The U.S. currently has 2.7 acres of forest for each of its citizens. Worldwide, the current forest area is 1.4 acres 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 U.S. will have only 1.3 acres of forestland per capita. Globally, the average will be only about 0.7 acres. 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 (1990) presented a very optimistic view regarding adequacy of future wood supplies. A key conclusion of that analysis was that dramatic increases in industrial wood demand within developing nations was unlikely, primarily due to large foreign debt burdens. Moreover, technological advances in growing and processing wood were expected to stretch the wood supply. Nonetheless, recent trends suggest that continued investment and technological development will be necessary to ensure that wood production will rise at a sufficient rate to keep pace with population growth.

Table 2
Historical and Projected U.S. Forest Area Per Capita – 1785-2100

Year	Population[a/]	Forest Area (million acres[b/])	Forest Area/Capita (million acres)
1785	3,000,000	1,044	348
1850	23,300,000	926	40
1910	77,000,000	730	9.5
2000	274,000,000	737	2.7
2100	571,000,000	737	1.3

[a/] U.S. Census Bureau, 2001. http://www.census.gov/cgi-bin/popclock/
[b/] Powell et al. (1993)

Table 3
Historical and Projected World Forest Area Per Capita – 1800-2100

		Forest Area		Forest Area/Capita	
Year	Population[a/]	billion ac.	million ha.[b/]	acres	hectares [c/]
1800	1 billion	11	4.5	11	4.5
2000	6.1 billion	8.5	3.4	1.4	0.6
2100	10-11 billion	8.5	3.4	0.7-0.8	0.3

[a/] U.S. Census Bureau. 2001. http://www.census.gov/cgi-bin/ipc/popclockw
[b/] Brown and Ball (2000)
[c/] One hectare = 2.47 acres.

U.S. Forest Service figures for 1992 show average annual growth per acre for all timberland[1] in the United States to be 44.2 ft^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 per acre. Global figures from FAO are less precise due to the enormity of the data collection challenge, but recent estimates of annual growth and total forest area suggest an average annual growth globally of 23.9 ft^3/acre for unmanaged natural forests. The global growth estimate includes all forestland, and not commercial forestland only as in the U.S. figures.

The average U.S. resident consumes 64.5 ft^3 of roundwood annually (Howard 1999). Worldwide, this figure is 21.2 ft^3. Using the current annual growth figures for the U.S. and the world in combination with consumption numbers indicates that each U.S. resident requires 1.5 acres of forest to provide annual wood needs and that each global citizen

---

[1] Only those lands capable of producing 20 ft.3/acre/year and on which periodic harvest is not prohibited by law are included in the timberland figure. In 1992 some 489,555 thousand acres of the total 736,681thousand forested acres in the United States were included in the timberland category.

requires 0.91 acres. Yet, the *total* area of forest per capita by the year 2100 is expected to be 1.3 acres and 0.74 acres for the U.S. and world, respectively (Table 4). 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 becomes even less - 0.87 acres for the U.S., and 0.5 acres 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.

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 growth (average)	ft^3/acre	44.2	23.9
Per capita consumption of wood (annual)	ft^3	64.5 [1/]	21.7
Forest area needed/capita to supply wood needs	acres	1.5	0.91
Forest area/capita - 2000	Acres	2.7	1.4
Forest area/capita - 2100	Acres	1.3	0.7

[1/] Ince (2000)

Minnesota is not immune to these kinds of problems. Population growth in combination with clearing of forests for a variety of reasons has reduced the area of forests on a per capita basis both indirectly and directly over the past five decades. An indirect impact of population growth has been the loss of about 15 percent of the forested area in Minnesota, almost totally due to urban expansion, over the past fifty years. Over the same time period, Minnesota's population has grown from 2.99 million to just under 5 million. The combined effect of these developments is that the forest area in Minnesota declined from 5.7 acres per capita in 1950 to 3.1 today. Projected population growth over the next century is likely to further reduce the area of forest per capita within Minnesota to only 1.6 acres, even assuming no further loss of Minnesota forests. As with the world and the United States as a whole, the steady decline of forests on a per capita basis, in combination with steady growth in demand for paper and other wood products, will make procurement of adequate supplies of wood and wood fiber more and more challenging in the decades to come.

One solution to this problem could be to increase the intensity of management in the world's natural forests, an option that is technically quite possible since only a fraction of the world's forests are actively managed using modern forest management tools. However, an increase in management intensity in domestic and global forests today appears unlikely; societal pressures are leading to increased areas of forest reserves and a lower intensity of management on those lands that are managed for timber production.

Other solutions to potential fiber supply problems might involve efforts to increase the area of forest plantations within Minnesota, the U.S., and globally, to expand recycling activity, to develop technology for using agricultural crop residues, or perhaps to move toward reliance on annual fiber crops, such as industrial hemp, as a source of industrial fiber.

Increasing the Area of Forest Plantations

Absent of a general increase in forest management intensity, an option for increasing the wood supply that 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 (including approximately 20 percent of pulpwood), 4 percent of fuelwood, and 12 to 13 percent of annual wood production overall. Forest plantations were estimated to cover about 306 million acres globally in 1995. The current rate of establishment of such plantations is rapid (11 to 12 million acres/year) (Brown and Ball 2000), and so much so that some are predicting a glut of plantation wood in Asian and world markets by 2010 (Leslie 1999). 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 (Beer 2000; Simons et al. 2000). Both developments are largely taking place within the developing nations and most significantly in the tropical regions.

Within the United States, plantations are also predicted to supply increasing quantities of wood fiber in the decades ahead. In fact, a recent estimate indicates that increasing volumes of plantation pine in the U.S. Southeast will provide sufficient pulpwood to provide for expected growth of the domestic paper industry through at least 2050 (Ince 2001).

Despite the high current rate of forest plantation establishment, Sutton (1999) reports that there is a significant gap between what society appears willing to have produced in natural forests, and what an extension of current wood demand trends would seem to indicate for future wood consumption. In order for forest plantations to fill the gap will require establishment of about 250 million acres of high-yield plantations by the end of this century 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 (2000) recently examined several scenarios for creating new forest plantations, and concluded that establishment of 250 million acres 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 US $100 to $150 billion will be needed to create 250 million additional acres of plantations worldwide. 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, are likely as manufacturing activity migrates over time to locations close to the raw material base.

Minnesota currently has approximately 16 thousand acres of hybrid poplar plantations (Krantz 2001), and perhaps 80 to 100 thousand acres of red pine plantations. While the productivity of these plantations is considerably lower than the most productive hardwood and softwood plantations globally, these stands are nonetheless currently important to Minnesota's wood supply, and even absent of additional plantation acreage, the relative importance of plantations is likely to increase in Minnesota in the decades ahead

Expansion of Recycling Activity

Increases in paper recycling over the past half-century have clearly served to reduce the consumption of virgin pulpwood in comparison to what consumption would have been in the absence of heightened recycling activity. Further expansion of recycling will further extend raw material supplies. However, recycling alone will not solve the potential wood fiber supply problem described above. Consideration of the current paper recycling situation in the United States provides a good example of the likely benefits and limitations of increased paper recycling.

In 2000, 45.0 percent of all paper used in the United States was collected for reuse. This amounted to 47.3 million tons of recovered paper. Recovered paper provided 37.8 percent of the U.S. paper industry's fiber in 2000 (AF&PA 2001). The difference between the wastepaper collection rate (45.0 percent) and the recovered paper use rate (37.8 percent) is largely traceable to the fact that the United States is the world's largest exporter of waste paper.

While paper recycling is extremely important, and a major contributor to reducing demand for virgin pulpwood over the past several decades, it is important to recognize that increasing recycling activity represents only one component of the fiber supply equation for the future. For example, if paper recycling in the United States were to be suddenly increased to the maximum level allowed by current technology (about 65 percent recycled content) this would have the effect of reducing demand for virgin fiber by only 12 to 13 percent. Moreover, when taking into consideration the time that will likely be required to move to the technological limit of recycling, and the population growth that will occur in the meantime, it is highly probable that demand for virgin fiber will continue to increase, even with aggressive recycling programs. Therefore, increased paper recycling alone will not be sufficient to ensure adequate fiber supplies in the future.

Potential Use of Agricultural Crop Residues

Fiber from agricultural crops has long been used for a variety of purposes, including fuel and a source of papermaking fiber. For example, 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, hemp, bamboo, various grasses, cereal straw, cottonseed hair, leaves, and inner bark of trees (Isenberg 1962, Miller 1965).

Wheat straw chemical pulp was first produced in 1827 (Moore 1996). Crop residues, such as bagasse (or sugarcane residue), have long been used in making paper in China, India, Pakistan, Mexico, Brazil and a number of other countries (Pande 1998). 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 (Atchison 1996).

U.S. research examining potential uses of crop residues as a papermaking raw material dates back to at least World War II (Atchison 1996). In the 1940s, 25 mills in the Midwest produced almost one 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 U.S. closed in 1960. Today, however, new research is focused on potential development of agricultural residue-based paper technology and industry development (Alcaide 1993; Jewell 1999).

In 1996, the Paper Task Force, a group of paper industry experts convened under the auspices of the Environmental Defense Fund and Duke University, and funded by several large U.S. corporations issued a report that included examination of the potential for commercial paper production from non-wood fiber. Cereal straws were among the fiber sources examined. It was concluded that 1) straw can be satisfactorily pulped, 2) that technology improvements are likely to improve pulp properties and reduce pulping costs, 3) that transport and storage of straw are factors likely to limit plant capacity (and thus perhaps to inhibit achievement of optimum economies of scale), and 4) that the most likely use of straw pulp was as an additive to wood pulp. Overall, the outlook regarding use of straw pulp was positive.

Any consideration of the quantity of crop residues that might be available for pulp and paper production must recognize that agricultural residues are also being actively evaluated as a potential source of raw materials for bio-based energy production and for manufacture of structural and non-structural panels. Although a wide variety of crops might provide fiber for the paper industry, commonly grown crops in the U.S. that appear to be the most promising source of fiber are the cereal straws: wheat, barley, and oats. In

1999 the United States produced just under 78 million short tons of wheat, barley, and oats. Approximately 78 percent of production of these three grains was accounted for by wheat. Minnesota produced 2.87 million tons of wheat, barley, and oats in 1999[2] (Minnesota Agricultural Statistics Service 2001).

The ratio of wheat straw to grain production has been estimated by a number of investigators in recent years. Such estimates approximate 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. When geographic differences are considered, and assuming that that less than 100 percent recovery can be attained, estimates of straw yield are often adjusted to more conservative values than those cited above. For example, a figure of 1.0 ton of straw per ton of grain is used is commonly used for wheat and other cereal grain crops.

It is recognized that much of the volume of crop residues is not available for industrial uses. In North America about one-half of the straw produced is left on the field for soil conservation purposes (U.S. Department of Agriculture 1994; Wong 1997). 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, such as northwest Minnesota, 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.

How significant, then, is the quantity of straw available for industrial use? 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 Minnesota yields the following estimate:

Estimated surplus straw in Minnesota - 1999:

		(million tons)
Wheat, barley, oats	(100%)[a/]	2.871
Soil conservation	(50%)	1.436
Agricultural uses	(35%)	1.005
Surplus	(15%)	0.430

[a/] assuming 1mt of straw for each mt of grain produced.

Based on total small grain production in Minnesota in 1999, the approximate quantity of surplus grain produced in the state was 430 thousand metric tons. This is theoretically

---

[2] Based on yields expressed in bushels from the Minnesota Agricultural Statistics Service (2001) and weights of 60, 50, and 32 pounds per bushel (@12 percent green wt. Basis moisture content) for wheat, barley, and oats, respectively.

enough to supply the total fiber needs of a paper mill the size of the new Potlatch mill in Cloquet, Minnesota.

Annual Fiber Crops as a Source of Industrial Fiber

There are relatively few recent 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 U.S. was cut off from jute fiber suppliers in Asia, triggering a massive effort to develop fast-growing alternative crops, including hemp, and kenaf (*Hibiscus cannabinus* L.), as jute substitutes (Atchison 1996). Hemp was actively promoted by the USDA in the early 1940s as a potential source of strategically critical cordage fiber (Hackleman and Domingo 1943; Robinson and Wright 1941; Wilsie et al. 1942, 1944; Wright 1941, 1942a, 1942b, 1942c, 1943). In fact, the United States government had supported the growing and use of hemp over a period of many decades (Anonymous 1890; Darcy 1921; Dewey 1901, 1913, 1927; Dodge 1897; French 1898; Humphrey 1919; Wright 1918). Although hemp production had been encouraged over many years, significant production of this crop did not occur until the war-related promotion efforts began. In the early 1930s, the total U.S. area planted to hemp varied from only 140 to 700 acres. The area planted doubled in 1936, remaining at 1,400 to 2,000 acres through 1940. Because of the jute shortage and government efforts to promote alternative crops, the acreage planted to hemp increased rapidly after 1940, reaching a peak of 178,000 in 1943 (Ash 1948); 46,000 of these acres were in Minnesota. As soon as the war ended, hemp production dropped dramatically, with the total acreage nationally down to 4,800 by 1946. Ash (1948) reported that hemp was mainly produced in the peak production years of the 1940s in Italy, Russia, Turkey, Yugoslavia, Hungary, China, Japan, Chile, and the United States. Within the U.S., primary producing states were listed as Illinois, Iowa, Indiana, Wisconsin, Kentucky, and Minnesota. As part of the effort to develop alternatives to jute, Cuba and later Guatemala were involved in intensive activity which resulted in development of a number of high yielding varieties of kenaf. It is not clear why kenaf, and not hemp, were the focus of those early efforts. In any event, subsequent work within the U.S., which continued through 1960, led to development of additional varieties of kenaf. Meanwhile, research on and promotion of hemp continued through the early 1950s (Black and Vessel 1945; Fuller et al. 1946a, 1946b; Lewis et al. 1948; Robinson 1952; Vessel and Black 1947)

In an initiative that was at first unrelated to the early work on kenaf, the U.S. Department of Agriculture set about in the mid-1950s 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 (McCloskey 1996). It was agreed that work would focus on species that could replace crops in surplus, but not compete with them (Atchison 1996).

Because there was little in the way of historical knowledge from North America or elsewhere in the world to build on regarding industrial raw material crops, the USDA, in 1957, launched a massive crops screening program. As explained by Atchison (1996) " the emphasis was on studying fiber crops that could be used as raw materials for pulp and paper manufacture. More than 1200 samples of fibrous plants from about 400 species were screened, taking into consideration all technical and economic factors involved. Hemp was among the plant species evaluated, although it was dropped from consideration early on in the screening process. Based on the initial evaluation, the 61 most promising fibers were subjected to extensive pulping tests. By 1961, researchers had narrowed the list to six fibrous materials: kenaf, crotalaria, okra, sesbania, sorghum, and bamboo." After two more years of intensive work, kenaf emerged as the top candidate for further research into utilization options and technologies (Kugler 1990). How much of this finding was influenced by the earlier work on kenaf is not clear, but in any event the stage was set for a renewed kenaf research effort.

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 (1996) 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 re-emerged in the form of a new alternative crops initiative of USDA (Abrahamson and Wright 2000), and research on industrial hemp funded by at least four state governments (U.S. Department of Agriculture 2000). 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, the latter having been 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 U.S.

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 (Sellers et al. 1999). It appears that progress is being made in all areas of research. Should kenaf emerge from current research and development efforts as a viable source of industrial fiber, it is farmers in the U.S. southeast, central, and northwestern coastal regions who stand to benefit. Because this crop is not suited for very cold climates (it can be grown as far north as southern Illinois), its further development would have only an indirect impact on Minnesota agriculture; an indirect impact could arise from the fact that kenaf crop yields are typically greater than those of hemp.

Investigation of industrial hemp has proceeded 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.

Hemp as an Industrial Fiber

The Nature of Hemp

Hemp is a herbaceous annual plant with a single, straight, unbranched hollow stem that grows over a 4 to 5 month growing season to a height of about one to five meters (3 to 19 feet) and a diameter of 10-60 millimeters (0.4 to 2.3 inches) (Robinson 1943; Ehrensing 1998). The stem is characterized by a relatively thin outer layer (referred to as bark or bast), and a wood-like core that surrounds a hollow center. The bast constitutes, on average, about 30 to 35 percent of the dry weight of the stem (De Groot et al.1999; Zomers et al. 1995), with the proportion of bark variously reported from 12 to 48 percent (Van der Werf 1994; Atchison 1998). The Paper Task Force (1996) estimated the bast fiber percentage at 30 percent. Primary bast fibers are highly variable in length, ranging from 10 to 100 mm (0.4 inch to 4 inches), with an average length of 20 to 40 mm. These fibers are thick-walled and rigid. Secondary bast fibers are reported as extremely short: about 2 mm or about 0.1 inch in length. The woody core makes up the remaining 65 to 70 percent of stem weight, and consists of short fibers that are reportedly a rather constant 0.50 to 0.55 mm in length (Table 5). These fibers are significantly shorter than even the juvenile fibers of most hardwood and softwood species.

Chemically, the bark fibers of the hemp stalk contain considerably more cellulose and holocellulose, and significantly less lignin than either hardwoods or softwoods. Hemp core, on the other hand, contains less cellulose than wood, about the same holocellulose fraction, and generally the same lignin content as hardwood species.

No definitive information regarding extractive or ash content of ash could be found in the literature. However, the ash content of kenaf, has been found to be about four times that of wood (Bowyer 1999). Regarding extractive content, although values have not been reported by contemporary researchers, an early report regarding hemp production suggests that this may be high. Robinson (1943) reported that " . . . during the process of retting [involving field aging of harvested stalks] the plants lost about 20 percent in weight in soluble and decomposed materials which leach out . . ."

Table 5

Physical Characteristics of Hemp and Wood

Characteristic	Hemp Bark		Hemp Core	Softwood	Hardwood
	Primary	Secondary			
Fiber length (mm)	10-100[a] (20)	2[a]	0.55[a]	2.5-5.5 [b]	0.8-1.9[b,c]
Juvenile fiber length (mm)				1.3-3.0[d]	0.8-1.3[e]
Alpha cellulose [f]	67^{+}/-5[a,g,h]		38^{+}/-2[a,g,h]	42^{+}/-2[i]	45^{+}/-2[i]
Holocellulose[f]	80^{+}/-1[a,g,h]		69^{+}/-3[a,g,h]	69^{+}/-4[i]	75^{+}/-7[i]
Lignin[f]	4^{+}/-2[a,g,h]		20^{+}/-2[a,g,h]	28^{+}/-3[i]	20^{+}/-4[i]
Extractives[f]				3^{+}/-2[i]	5^{+}/-3[i]
Ash content[f]				<0.5[i]	<0.5[i]

a De Meijer (1994)
b Panshin and deZeeuw (1980)
c Manwiller (1974)
d Haygreen and Bowyer (1996)
e Koch (1985)
f Expressed as a percentage of the dry weight
g Ranalli (1999)
h Kirby (1963)
i Thomas (1977)

The Narcotic Issue

As noted in a recent USDA report (USDA 2000), industrial hemp contains less than one-percent THC (delta-9-tetrahydrocannabinol), the psychoactive ingredient of marijuana. Varieties of industrial hemp currently cultivated in various countries generally contain 0.3 percent THC or less. In contrast, hemp grown primarily to obtain marijuana contain 1 to 2 percent THC (unselected strains) (Clarke and Pate 1994) to as much as 10 to 15 percent THC in the best modern varieties (USDA 2000; Clarke and Pate 1994). Thus, while it is technically possible to produce marijuana from industrial hemp, it is unlikely to be economical to do so.

The primary marijuana-related issue regarding the possibility of industrial hemp production is that marijuana and industrial hemp plants are distinguishable from one another only through chemical analysis (USDA 2000). The significance of this is that current marijuana interdiction activities of law enforcement agencies would become extremely difficult to impossible should growing of hemp become widespread . Therefore, legalization of industrial hemp production in Minnesota would effectively mean tacit approval of marijuana production within Minnesota as well.

Production of Industrial Hemp

Growth and Yield

Reported yields for hemp grown worldwide are highly variable, reflecting differences in plant varieties and climate. Shown in Table 6 are yields as reported in a number of studies conducted over the past 80 years. It is important to recognize that the highest yields are attainable only on the best agricultural land, and often only with intensive inputs. As Robinson (1943) put it "Hemp should be planted on the most productive land on the farmland that would make 50 to 70 bushels of corn per acre."

Comparisons of annual hemp yields with annual yields of wood in Minnesota stands of *Populus* species (Table 7) shows that reported annual production of dry biomass per hectare or per acre is roughly equal for hemp grown in various locations of the U.S. (1.1-4.0 t/ac./yr. - average 2.4 t/ac./yr.) and for *Populus* tree species grown in Minnesota and Wisconsin (1.4-7.4 t/ac./yr. - average 3.1 t/ac./yr.). Dry yields of hemp stalk and wood are also approximately equal, with average hemp and *Populus* yields reported at 2.2 and 2.0 t/ac./yr., respectively.

It could be argued that the reported hemp yields all occurred five decades or more ago, while the reported wood yields are much more recent. When Minnesota/Wisconsin poplar yields are compared to all hemp yields reported in Table 6, then annual hemp yields exceed wood yields by 70 percent.

Atchison (1998) urged caution when considering reported hemp yields, noting that yields obtained in practice are often lower than those obtained in controlled field trials. In Atchison's words " . . . in my review of the literature, I find that the maximum yield of dry hemp stalk, obtained anywhere commercially, amounted to about 3.0 tons/acre and of this amount, the hemp bast fiber represented only 750 kg/acre or only 25 % of the total dry weight. This was in Germany, where very little hemp is grown. However, in the U.S., the maximum commercial annual yield of dry hemp stalk obtained, during 1943 and 1944 when it could be grown legally during World War II, amounted to only about 1.98 metric tons/acre, of which only 495 kg/acre was bast fiber."

Tempering yield studies of the mid-20th century are more recent reports such as that of De Meijer (1993) who noted sufficient variation within *Cannabis* to allow genetic improvement leading to better yield and quality of fiber. He also indicated the possibility of breeding to improve resistance to pests. Hennink (1994) reported that heritability of bast fiber content is high, raising the possibility of increasing relative yield of this stalk component; he also found that bast fiber content is positively related to stem yield overall.

It is interesting to note that reported industrial hemp yields are significantly lower than reported yields of kenaf. In contrast to the figures indicated above, kenaf stalk yields of about 14 mt/ha (6.3 tons/acre) have been widely reported, placing average kenaf stalk yields at almost double those of hemp. This differential could severely disadvantage hemp producers should kenaf production become common in the United States.

Table 6
Reported HempYields By Location

	Dry Basis Yield of Biomass[a]					
	Combined		Stalk		Leaf	
Location	mt/ha	t/ac	mt/ha	t/ac	mt/ha	t/ac
Holland[b]	**7-10**	3.1-4.5	**4.5-7**	2.0-3.1	**1.4-2**	0.6-0.9
Holland[c]	**8.7-18.4 (14.9)**	3.9-8.2 (6.6)	**7.6-15.4 (12.7)**	3.4-6.9 (5.7)	1.5-3.1 (2.5)	0.7-1.4 (1.1)
Denmark[d]	**7.9**	3.5	7.0	3.1	0.9	0.4
Denmark[e]	**8.9**	**4.0**	8.0	3.6	0.9	0.4
Poland[d]	**6- 8**	2.7-3.6	5.3- 7.1	2.4 -3.2	0.7-0.9	0.3-0.4
France[d]	**7.9**	3.5	7.0	3.1	0.9	0.4
Italy[d]	**13**	5.8	11.6	5.2	1.4	0.6
Italy[e]	**15**	**6.7**	13.4	6.0	1.6	0.7
Netherlands[d]	**9-11.4**	4.0-5.1	8.0-10.1	3.6-4.5	1.0-1.3	0.4-0.6
Netherlands[d]	**10.5**	4.7	9.3	4.1	1.2	0.5
Netherlands[e]	**19.4**	**8.7**	17.3	7.7	2.1	0.9
Netherlands[e]	**9.4-13.6**	**4.2-6.1**	8.4-12.1	3.7-5.4	1.0-1.5	0.4-0.7
Netherlands[f]	**11.9-13.6**	5.3-6.1	10.6-12.1	4.7-5.4	1.3-1.5	0.6-0.7
Germany[e]	**3-10**	**1.3-4.5**	2.7 - 8.9	1.2-4.0	0.3-1.1	0.1-0.5
Sweden[e]	**8.7**	**3.8**	7.7	3.4	1.0	0.4
UK[e]	**5 - 7**	**2.2-3.0**	4.5 - 6.2	2.0-2.8	0.5-0.8	0.2-0.4
Canada[e]	5.6-6.7	**2.5-3.0**	5.0 - 6.0	2.2-2.7	0.6-0.7	0.3
U.S.[g]	4.0	**1.8**	3.6	1.6	0.4	0.2
U.S.[h]	4.5-4.9	**2.0-2.2**	4.0 - 4.4	1.8-2.0	0.5-0.6	0.4-0.3
U.S.[i]	4.0	1.8	3.6	**1.6**	0.4	0.2
U.S.[j]	9.0	**4.0 (fert)**	8.0	3.6	1.0	0.4
	5.9	**2.6 (no fert)**	5.2	2.3	0.6	0.3
U.S.[k]	2.4-9.0	**1.1-4.0 (2.3)**	2.2-8.0	1.0-3.6	0.2-1.0	0.1-0.4
U.S.[l]	6.5	2.9	5.9	**2.6**	0.7	0.3
Minnesota[m]	3.5-3.8	1.6-1.7	3.2-3.4	1.4-1.5	0.3-0.4	0.2
Average of Reported Yields	8.7	3.8	7.7	3.4	1.0	0.4
Average of Reported U.S.Yields	5.4	2.4	4.9	2.2	0.5	0.2

[a] Reported values in bold; all other values calculated using standard conversions. When not specifically reported, the stalk was assumed to constitute 89% of the dry weight of total biomass.

[b] Zomers (1995). Combined weight includes inflorescence (fallen leaves).

[c] Van der Werf et al. (1999). Reports of over 17 trials over a period of 6 years. Combined weight includes inflorescence (fallen leaves).

[d] Ranalli (1999). Reported yields from various studies by various researchers.

[e] Ehrensing (1998). Reported yields from various studies by various researchers.

[f] De Meijer et al. (1995). Yield using herbicides.

[g] Atchison (1998)

[h] Robinson (1935)

[i] Ergle et al. (1945)

[j] Jordan et al. (1946). Reported results from four different researchers.

[k] Robinson (1946). Reported results from eight trials in Nebraska, South Dakota, and Iowa.

[l] Wilcox (1943) as reported by Ash (1948). Average of 112 randomly selected farms in Illinois.

[m] Ash (1948). Figures reported included only bast fiber yield (830 pounds per acre in 1943, 900 pounds per acre in 1944). Stalk yields derived by dividing by 0.30 (the bast fiber fraction of the stem).

Table 7
Reported Average Annual Wood and Biomass Yields from Tree Plantations in the Northern Plains

	Dry Basis Yield of Biomass[a,b]							
	Total Biomass		Wood (Xylem)		Bark (Phloem)		Tops, Leaves, Branches .	
Location	mt/ha	t/ac	mt/ha	t/ac	mt/ha	t/ac	mt/ha	t/ac
Hardwoods.								
Hybrid Poplar/ND,SD, MN,WI[e]	3.6- 4.0	**1.6-1.8**	2.3- 2.6	1.0-1.2	0.4	0.2	0.9	0.4
Hybrid Poplar/MN,WI, MI[f]	7.5-16.6	**3.3-7.4**	4.9-10.8	2.2-4.8	0.8-1.7	0.4-0.8	1.8-4.1	0.8-1.8
Hybrid Poplar/WI[g]	**6.2-10.4**	2.8-4.6	4.0- 6.8	1.8-3.0	0.6-1.0	0.3-0.5	1.6-2.6	0.7-1.2
Quaking Aspen/MN[h]	3.2- 3.6	1.4-1.6	2.1- 2.3	**0.9-1.0**	0.3-0.4	0.1-0.2	0.8-0.9	0.4
Avg. of reported yields	6.9	3.1	4.6	2.0	0.7	0.3	1.7	0.8
Softwoods								
White spruce/Minnesota[g]	**4.2**	1.9	**2.9**	1.3	**0.6**	0.3	**0.6**	0.3

[a] Unless otherwise reported, bark is assumed to be 15% of total aboveground stem (wood + bark) weight in softwoods and 10% in softwoods.

[b] Unless otherwise reported tops, branches, and leaves are assumed to be 15% of total stem (combined weight) in softwoods, and 25% of total stem weight in hardwoods (Koch 1973; Young et al. 1963, 1965).

[c] Hansen (1992) -- 4-5 year rotation

[d] Ek et al. (1983) -- 3 year rotation

[e] Zavitkovski (1983) -- 9-10 year rotation

[f] Perala and Laidly (1989) -- 11 year rotation

[g] Rauscher (1985) -- 40 year rotation

Site Requirements

Hemp is said to grow best on fertile, well drained, medium-heavy soils and especially well on silty loams, clay loams, and silty clays (Robinson and Wright 1941). The crop is not limited to these kinds of soils, however, and can evidently thrive on a wide variety of soil types (Van der Werf 1994; Ranalli 1999). A soil pH of less than 5 has been reported to unfavorable to hemp production (Van der Werf 1994).

Climate Limitations

Apparently, climate conditions typical of the northern plains are favorable to hemp production, although short growing seasons and late spring frosts can pose risks to hemp producers. Robinson (1943) and Ree (1996) have reported that most fiber-producing varieties of hemp require a frost-free growing season of five months or longer to produce seed and approximately four months for fiber production. Van der Werf et al. (1999) addressed the issue of frost risk, noting that hemp seedlings can survive a short frost of -8 to -10^{o}C (+14 to +18^{o}F), whereas mature plants can handle brief exposures to temperatures as low as -5 to -6^{o}C (+22 to+23^{o}F). Compared to several agricultural crops common to Minnesota, frost resistance of hemp is reported to be comparable. For instance, Robinson (1943) noted that hemp will survive fall frosts better than corn. In comparison to sugar beet, fiber hemp is reported to be at less risk to frost during plant emergence, but more at risk for a longer period.

Aside from the issue of plant survival under frost, perhaps as important is the issue of fiber yield under different lengths of growing period. Van der Werf et al. (1999) pointed out that the dates of planting and harvest have large effects on potential stem yields of hemp. They noted, for instance, that a site producing a yield of dry stem matter of 17.1 mt/ha during a period from planting to harvest of April 15 to September 15 would yield 9 percent less if the crop were planted April 30, and 20 percent less if planting did not take place until May 15. Similar reductions occur if the harvest date is moved to an earlier date than mid-September. Lengthening of the time span between sowing and harvest has the potential to substantially increase dry matter yields, but as Van der Werf et al. point out, the possibility of increased yields must be weighed against the increased risk of frost damage.

With respect to rainfall and soil moisture requirements, hemp appears to require moist growing conditions early in the growing season, but well-drained soils for maximum production. Wright (1941) and Robinson (1943) report that hemp is very sensitive to drought conditions, especially early in the growing season until plants become well established. Reports regarding late season response to drought are varied. Some proponents of industrial hemp production report, for example, that hemp is a very drought tolerant crop. In contrast, virtually all early reports of hemp performance (Wright, 1941; Robinson, 1943), as well as more recent writings (Rosenthal 1993), indicate stunting of plant growth and substantial yield reduction under drought conditions.

Needs for Irrigation and Fertilization

Given the apparent susceptibility of hemp to damage from drought conditions, consideration of the potential for short-term irrigation may be warranted. In fact, an Oregon State University study (Ehrensing 1998) concluded that in the Pacific Northwest Region, " . . .hemp will almost certainly require supplemental irrigation . . ." In the absence of Minnesota specific agronomic research, the extent to which irrigation would be necessary locally is not known.

The literature regarding fertilization requirements for hemp consistently indicates a need for phosphate and potassium application at the time of planting, generally at a rate consistent with wheat production (Ranalli 1999; Rosenthal 1993; Van der Werf 1994). Jordan et al. (1946) reported results of fertilizer trials on hemp, noting stalk yield increases on the order of 26 to 100 percent, and bark fiber increases of 20 to 110 percent when applying 500 to 2,000 pounds of fertilizer (0-10-20, 0-20-20, 0-10-30) per acre. Although fertilization increased fiber yield, fiber strength was found to be reduced 8 to 13 percent. One of the most extensive discussions of fertilizer requirements for industrial hemp can be found in Walker (1990). Citing a number of contemporary authors (Kirby 1963; Berger 1969; Dempsey 1975), Walker points out that, despite claims to the contrary, fertilization of hemp is required, in part because hemp production removes large quantities of minerals from the soil.

To put requirements for fertilization into perspective, it is worth noting that all of the highest dry stalk yields reported by advocates of domestic hemp production are yields obtained with the benefit of fertilization.

Requirements for Pesticides and Herbicides

Van der Werf et al. (1996) acknowledge claims made by hemp advocates to the effect that hemp requires little or no pesticide and few to no herbicides, but then point out that hemp is not disease free. These authors specifically refer to the fungus *Botrytis cinerea*, commonly known as gray mold, and point out that this fungus can cause severe damage to hemp growing in the Netherlands in wet years. Pate (1999) explains that a number of fungal pathogens attack both hemp seeds and plants. MacPartland (1999) reports that at least 88 species of fungi are responsible for disease problems in hemp, but that only a few cause significant crop losses. MacPartland also identifies gray mold as having the potential to cause serious damage. He notes that high humidity at temperatures between 68 and 75°F can lead to epidemic levels of gray mold that can completely destroy a crop of hemp within one week. Root-infecting nematodes are also identified as a serious problem, and specifically in Canadian hemp. De Meijer et al. (1995) reported results of field trials in the Netherlands for the years 1987 through 1989. Attempts to grow hemp without applying herbicides resulted in crop yields that were 25 to 40 percent lower than yields obtained in subsequent years in which herbicides were applied.

MacPartland summarized disease and insect problems in hemp as follows: "Many current authors claim hemp is problem-free (Herer 1991; Conrad 1994; Rosenthal 1993). None of these authors has ever cultivated a fiber crop. In reality, hemp is not pest-free, it is pest tolerant; many problems arise in *Cannabis*, but these problems rarely cause catastrophic damage. However, diseases and pests cause small losses that may accumulate over time to significant numbers. Agrios (1988) estimates that 13 percent of fiber crops are lost to insects, 11 percent are lost to diseases, and 7 percent are lost to weeds and other organisms. In addition to these losses in the field, Pimental et al. (1991) adds another 9 percent in post-harvest losses. Add these numbers up and you reach 40 percent." MacPartland concludes with the observation that "As long as *Cannabis* continues to be grown in artificial monoculture, we will continue to need pesticides." It is clear that MacPartland uses the term "pesticide" to refer to both fungicides and insecticides.

Most reports suggest little need for herbicides with hemp production. However, this point needs a bit of clarification since some claims suggest that no attention to weeds is necessary. Wright (1942) notes that hemp is one of the best plants for smothering weeds, but cautions that the soil must be properly prepared prior to planting. He describes ideal planting preparation this way: "Early in the spring the soil should be worked up thoroughly and kept worked up to the very time hemp is seeded. He later reported (1943) that a corrugated roller used just before and just after seeding is a good way to get the seedbed in shape.

The net effect of pest-related problems and intensive demands placed on soil by hemp growth is that repeated cropping of hemp on the same site is not recommended. Robinson (1943) was one of the first to recommend that hemp should not be grown continuously on the same soil. He recommended that hemp be rotated in alternative years with corn. Rosenthal (1993) modified Robinson's recommendation, noting that hemp does best in rotation with other crops, including corn, wheat, oats, peas, alfalfa, and potatoes. He went on to say that hemp should be grown on a given field only one every two to three years. He also advised that "hemp cannot be grown on the same field continuously without fertilizer."

Harvesting

Traditionally, the harvesting of hemp involves cutting of stalks in the fall, often following chemical defoliation to promote pre-harvest drying. The hemp is laid down in a swath by mechanical harvesters and allowed, thereafter, to lay on the ground for 10 to 30 days (Robinson 1943). An on-the-ground storage period is important to the hemp fiber production process in that it promotes bacterial and fungal breakdown of pectins that bind fibers within the stems. Further drying of stalks also occurs during this period. The process is known as "retting" or "dew retting." Today, dew retting is a part of the harvest process in most hemp-producing regions.

In many ways the retting process is the Achilles heel of hemp fiber production, and is reported to have contributed to decline in hemp production and use in the 1940s. The idea of retting is to achieve partial rotting of the outer layers of the stalks, but to stop degradation at the proper time. Halting degradation requires that stems be dried to a green basis moisture content of 16 percent or less prior to baling. The process is, of course, highly weather dependent, and typically requires periodic turning of felled stalks in order to expose the entire stalk surface to microbial degradation (Walker 1990). Hessler (1945) reported on the effects of the retting period and retting conditions on fiber strength. He indicated that fiber strength is inversely related to the retting period and cautioned against excessive retting periods. He also indicated that retting over the winter season results in weak fiber.

An alternative to dew retting is water retting, a process which involves the laying of stalks in water (in tanks, ponds, or streams) for about 6 to 18 days. Ergle et al. (1945) indicated that water retting resulted in superior strength and quality of fiber as compared to that which is dew retted. Retting is reported to be significantly enhanced if the water is warm and/or laden with bacteria (Ranalli 1999).

Ranalli (1999) has commented at length on the retting process, noting that "Fiber extraction from fiber crops by traditional retting methods is highly polluting or carries high risks of crop failure and yields of varying fiber quality over the years. Nonpolluting processing techniques, which guarantee constant fiber qualities for industrial buyers are urgently needed." Ranalli further stated that "Water retting is unlikely to be viable on a modern farm as it is awkward, time-consuming, and produces an effluent that can be a source of pollution."

Walker (1990) also examined water retting in the context of textile fiber production, reporting findings that finer and better quality fibers are obtained from water or tank retting than from dew retting. He also noted that water retting is highly labor intensive as well as expensive, and described it as unsuitable for commercial scale adoption. A similar conclusion was reached by Ranalli regarding retting processes used with textile fiber production. He commented that "What is certain is that unless the problem of retting is overcome, it will not be possible to produce textiles from hemp economically in countries with temperate climates."

French investigators have tackled the retting problem and in recent years have developed an enzymatic retting process. The sequence begins with separation of hemp stalks into bark and core fractions using equipment long used for processing of flax. The outer bark fraction is then cut into one-foot-long segments prior to exposure to enzymes selected for their ability to break down pectins (Rosenthal 1994b).

Storage of Harvested Stalks

Perhaps because hemp is used commercially only on a small scale around the world there is little published information focused on the issue of stalk storage prior to processing. One of those who has commented on this issue (De Groot et al. 1999) notes that to totally supply the fiber needs of a modern kraft pulp mill would require the harvesting of about 250,000 acres each year. Pointing out that harvesting occurs over a brief span of time each fall, these authors conclude with the observation that "Consequently, large logistic problems must be solved (storage, transportation, guaranteed annual supply) and large investments must be made (apart from the start-up costs), before such a mill can be built for kraft pulp production using fiber hemp or any other fiber crop."

Given the general lack of information about storage of hemp stalks, it is informative to examine the literature regarding long-term storage of agricultural crop residues or annual crops in general. Because agricultural materials are produced over a one to three month period each year, storage of this material for use in an ongoing production operation is a concern. Intuitively, cereal straws and similar biomass materials should require covered storage to protect it from wetting from snow and rain. However, the volumes potentially requiring storage are quite large for processing facilities of sufficient capacity to achieve economies of scale.

A number of studies of the commercial potential for agri-based fiber have concluded that covered storage is necessary. For example, a study of opportunities in grass straw utilization, as reported by Ehrensing (1998), included the conclusion that "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, assuming a six-month storage period. This figure includes costs of construction, interest, repairs, insurance, and straw losses." A similar estimate of storage costs ($14-15/short ton), which included the cost of working capital tied up in stored fiber, resulted from a recent study of papermaking from kenaf (Bowyer 1999).

However, as noted by Wagner (1999), there are a number of options for storing straw, many of which do not involve construction of a building, or even covered storage. Options include: 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, 3) storage of a small portion of straw at the mill as a buffer supply with the rest stored at nearby farms, and 3) all annual supply is stored at the mill. Further 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 maintained below 8 to 12 percent wet basis moisture content (McCloskey 1996, Wilcke et al. 1998), as bales with higher moisture are reportedly susceptible to rot and spontaneous combustion. However, experience at an industrial firm that is currently using agricultural residues as a raw material for making medium density fiberboard suggests that maintenance of bale moisture content at 18 percent green basis or less is sufficient. All those reporting on this issue agree that storing hay at moisture contents above 20 percent will result in development of mold and internal heating, greater dry matter loss (than if stored at a low moisture content), and discoloration. Not surprisingly then, high spoilage is reported in Minnesota and Wisconsin for baled hay stored in ground contact. Losses of 22-23 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 (Wilcke et al. 1998).

By covering outside-stored bales with a tarp, losses can be reduced by one-half or more (Wagner 1999). Estimates of the seasonal costs of tarped storage range from $2-6/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 cost of storage within a dedicated structure (Wagner 1999).

All of these studies notwithstanding, the most common practice for currently operating agricultural residue-based industries involves outdoor storage of uncovered bales, a practice that is variously reported as satisfactory and unsatisfactory. Apparently satisfactory practices include those of another medium density fiberboard manufacturer in North Dakota which, for example, stores straw on bare clay soil, packing the bales into piles of 50 bales long by 6 bales wide, by 6 bales high. These bales are then left uncovered. Only the outer 6-12 inches reportedly show degradation from weather, even at the end of the storage season (Stern 1998). A similar plant in eastern Montana employs uncovered storage as well.

In contrast to the apparently satisfactory uncovered straw-storage practices referenced above, significant problems are also reported. Such problems include substantial degradation and loss of straw late in the storage period and development of wet pockets in bales that inhibit efficient processing of baled straw.

In short, it appears on the one hand that the fiber storage issue is not necessarily as significant as it is sometimes perceived to be. On the other hand, however, this is an area that has the potential to significantly impact mill operations and profitability, and thus one that must be carefully addressed in planning.

Industrial Hemp as a Papermaking Material

Technical Aspects of Hemp Paper Production

As previously noted, hemp stalks are composed of an outer layer of long bast fibers (also called bark fibers) that make up about 35 percent of stalk volume, and an inner core (also referred to as hemp hurds) composed of much shorter fibers. The viability of hemp as a papermaking material depends, in part, on the technical feasibility of using both the bast and core fibers, rather than simply one or the other.

De Groot et al. (1999) point out that the long bast fibers of hemp have been used for making paper ever since the invention of paper by the Chinese in 105 AD. They report, however, that little if any core fiber was used historically for papermaking, and that very little is used for this purpose even now. Supporting the observation about current use is a recent report (Dutton 1997) which indicated that France (a leader in commercial development of industrial hemp) had been exploring innovative uses for hemp hurds (hemp core), including such applications as insulation and cement additives. Van der Werf (Rosenthal 1994b) also recently reported on use of hemp in France, noting that a subsidiary of Kimberly Clark is manufacturing paper from both flax and hemp bark fibers. Core fibers, however, are reportedly being sold for alternative uses; use of core fibers for pet litter and for particleboard manufacture were identified. The fact that hemp core is being sold into relatively low value markets suggests lack of success in attaining commercial adoption of higher value applications such as papermaking fiber.

Johnson (1999) addressed the use of hemp as papermaking fiber, observing that " . . . current research has yet to yield a full-scale commercial pulping technology for anything beyond the high-cost, traditional specialty bast fiber pulps for high strength, thin applications such as bank notes, cigarette paper, and bibles. Though viable markets exist for specialty papers, demand is not increasing at a rate comparable to other wood-based, commodity grade paper (writing paper, fax and copier paper, newsprint, product packaging, etc.). To alleviate pressure on the timber industry or replace wood altogether in commodity-grade papers, high-yield and high-quality pulping technologies specifically for *cannabis* fiber - which would utilize all of the fiber (bast and core) in the stalk - would have to be developed."

De Groot et al. (1999) have extensively evaluated bast fiber as a papermaking raw material using a variety of pulping methods. Their findings indicate that industrial hemp bast fiber has a wide range of potential applications in modern papermaking. Specifically they reported that the properties of unbleached alkaline mechanical pulps made of hemp bast fiber were sufficient to warrant consideration for use in production of linerboard. Comparing unbleached hemp bast fiber mechanical pulp with softwood thermo-mechanical pulp, they found the hemp pulp to have higher tear strength, but higher density. They also found that properties of bleached alkaline mechanical pulp were such that this material could be used to replace bleached chemi-thermomechanical softwood pulp in printing and writing grade papers. Similar potential was found for replacement of northern softwood bleached kraft pulp with hemp bast alkaline peroxide mechanical pulp; in this case, tensile strength of the hemp pulp was found to be lower than that of the softwood pulp, while density and tear of the hemp pulp were found to be significantly better. Based on such studies, it is rather evident that from a technical point of view the outer bark (or bast) fibers of hemp are very acceptable raw materials for use in contemporary papermaking.

Recent pulping studies of hemp bast fiber clearly indicate why hemp bast fiber pulp has a long history of applicability in several specialty markets. It is less clear why hemp core fiber has failed to achieve market acceptance, particularly in view of apparently positive research findings over a period spanning the period 1916 to the present. De Groot (1999) makes reference to studies in the United States (Dewey and Merrill 1916), in Italy (Bosia 1975), in the Netherlands, and in Germany, noting that all of these studies have indicated that hemp woody core is a promising papermaking raw material (de Groot et al. 1999).

Zomers et al. (1995) evaluated pulping of both the bast and core fractions of industrial hemp using autoclaved organosolv pulping. These researchers found high yield, long fiber length, and high tear strength in bast fiber pulp, and concluded that such material would be ideal for use in paper products requiring high tear strength, stiffness, or bulk. The concluding observation in this case was that "this pulp may be interesting for use in printing, writing, or copying papers." Abdul-Karim et al. (1994) examined process variables associated with production of hemp dissolving pulp. They concluded that whole stalk hemp was a suitable raw material for production of cellulose derivatives. De

Groot et al. (1999) also extensively investigated hemp woody-core pulps. They found that brightness, burst, and crystallinity values are comparable with hardwood pulp and that the effects of beating on wood and hemp pulps is similar. They concluded that hemp woody-core pulp is comparable to hardwood pulps used in printing paper grades and that hemp core could be optimally produced so as to be a suitable component in pulp mixes for printing papers. Thus, recent technical evaluations of pulp made from the core of industrial hemp stalks have yielded very encouraging results. Pulp strengths comparable to commonly used hardwood and softwood pulps have also been obtained. Taken together, these studies suggest considerable potential for use of hemp core as a papermaking raw material.

While the previously cited research appears to indicate technical suitability of industrial hemp fiber for use in paper manufacture, all of these studies have examined pulp produced separately from either bark or core of hemp stalks. A relevant question, that has significant implications for pulping economics, is whether it is technically possible to pulp whole hemp stalks while obtaining acceptable paper properties. Zomers et al. addressed this question, finding that pulp made using the organosolv process from whole stems of industrial hemp yielded test paper strengths intermediate between commercial chemical hardwood and softwood pulps. However, noting severe reduction of the tear strength contribution of bast fibers, and in recognition of chemical and morphological differences between core and bast fiber, researchers recommended separate pulping of core and bast fiber. Results suggest that a pulp consisting of a blend of core and bast fiber, whether pulped separately or together in one operation, would yield a pulp with acceptable properties for many applications.

Given substantial differences in the hemp bark and core, differences in manufacturing processes needed to achieve optimum processing of the two fractions, and potential high-value specialty markets for the bast fiber fraction, it appears likely that bark/core separation would precede any commercial pulping of hemp. Thus, the costs of separation should be considered in any economic evaluation of hemp pulping.

Economic Considerations in Pulping of Industrial Hemp

An extensive discussion of the economics of U.S. hemp production can be found in the January 2000 USDA report *Industrial Hemp in the United States: Status and Market Potential*. This discussion focuses on probable returns to hemp producers visa- vis other potential crops, and is based on earlier assessments of hemp agriculture involving the states Oregon (Ehrensing 1998), Kentucky (Vantreese 1997), and North Dakota (Kraenzel et al. 1998). This discussion is not repeated here; instead, the reader is directed to pages 17 through 22 of the USDA report which is provided in full as Attachment A of this report.

The 1998 North Dakota evaluation of the feasibility of agricultural production of dual purpose hemp crops (hemp fiber and hemp seed) assumed values of hemp stalks of $40.44, $45.96, and $51.47 per short ton, and of hemp seed of $5.51, $6.16, and $6.80 pr bushel. The dollar values were converted from Canadian prices. The middle and highest estimates of value were shown to provide higher net returns to farmers than common crops such as spring wheat, feeder corn, malting barley, and confectionery sunflowers. It is interesting to note that the largest component of projected income comes not from the fiber of the stalk, but from the seed. As discussed earlier (see Site Requirements section), production of seed requires a growing season that is at least a full month longer than is needed for production of stalks alone (five months plus for seed vs. four months for fiber only). Thus, the much higher income projected from sales of both stalks and seed is associated with a significantly higher risk of early or late season crop damage.

Projected costs of hemp pulp were compared to costs of producing hardwood and softwood pulp. Economic comparisons were based on work of the Paper Task Force (1996) which examined costs of producing various kinds of pulp from wood and from kenaf. In assessing likely costs of producing hemp pulp, hemp stalk values equivalent to those derived in the North Dakota hemp evaluation report (Kraenzel et al. 1998) - $45.96 and $51.47 per short ton - were used. The highest of these two prices, ($51.47/short ton or $56.62/ metric ton), is almost exactly equal to the estimated price at which southern farmers could profitably deliver kenaf stalks to local paper mills (Bowyer 1999). Pulp costs were also examined using hemp stalk prices 20 percent above the highest value, or $61.76 per short ton.

Scenarios Evaluated and Basic Assumptions

Economic comparisons were conducted for three different scenarios:

1) Whole stalk TMP and CTMP pulping of industrial hemp was compared with TMP pulping of aspen and of white spruce.
2) Hemp bark (or bast) fiber chemical pulping and bleaching, and hemp core fiber chemical pulping and bleaching, were compared with chemical pulping and bleaching of aspen.
3) Whole stalk chemical pulping and bleaching of hemp was compared with chemical pulping and bleaching of white spruce.

Only differential costs were considered in the economic comparisons (i.e. costs that would be the same for the various alternatives being examined were not considered).

Assumptions that applied to all scenarios included the following:

- Hemp would be harvested once annually, with delivery of field-dried stalks to the mill (or to stalk storage areas) occurring over a four to six week period each year.
- A mill using hemp exclusively would need covered storage facilities sufficient to handle at least ten months of fiber requirements.

- Hemp fiber in storage would range from a one-month supply to a ten-month supply. On average, working capital equivalent to the delivered value to a five-month supply of fiber would be needed for a hemp mill.
- Wood in storage would range from a one-month supply to a three-month supply. On average, the working capital equivalent to the delivered value of a one and one-half month supply of fiber would be needed.
- Fiber losses in storage are the same for hemp and for wood. Alternatively, it was assumed that fiber losses for hemp in storage would be double that for wood.

Scenario One - Mechanical Pulping

Other than the costs associated with fiber storage, the primary issue in mechanical pulping is the cost of energy. The cost of energy assumed in this analysis is the industrial cost for electricity ($0.0456/kwh) as reported for Minnesota for the year 1999 (US Energy Information Administration 2001). When CTMP is employed, the costs of pulping chemicals are also significant. Projected costs for each system are presented in Table 8.

This analysis suggests that hemp TMP or hemp CTMP can be produced at 67-78 percent of the cost of producing hardwood TMP. This result is, of course, dependent upon the assumptions used in the study. Results are most dependent upon energy costs, with lower costs of energy more favorable to wood-derived pulps. However, even when using the lowest reported electrical energy cost nationwide ($0.027/kwh), the projected costs of producing hemp mechanical pulps are still at only 70-81 percent of the costs of producing mechanical pulps from wood. Results are also obviously sensitive to raw materials costs.

It is worthwhile considering that the figures presented in Table 8 do not include any costs that might be associated with covered storage of hemp fiber. If it is assumed that fiber must be stored under a roof once it is field dried, and if it is further assumed that a structure large enough to accommodate ten months of fiber needs would be needed, then capitalization costs associated with the drying facility could add as much as $14-15/odmt of pulp. Moreover, it is assumed in this analysis that fiber loss in storage is the same for both hemp and wood; if this is not the case, then a significant difference in fiber loss would obviously affect the relative cost of fiber. If, for example, hemp losses in storage were assumed to be as high as 20 percent, production costs for hemp mechanical pulps would rise to about 72-84 percent of costs associated with production of mechanical pulp from aspen. Adding in capitalization costs for a storage structure increases the estimated cost of producing hemp mechanical pulps to 78 to 90 percent of that of aspen pulp - still a substantial difference in favor of hemp.

Table 8
A Comparison of Differential Costs Associated With Various Types of Mechanical Pulp

(costs are expressed as dollars per o.d.m.t. of pulp)

	Hemp stalk value $45.96 per dry short ton		Hemp stalk value $51.47 per dry short ton		Hemp stalk value $61.76 per dry short ton		
Item	Whole Stalk Hemp TMP[a]	Whole Stalk Hemp CTMP[a]	Whole Stalk TMP[a]	Whole Stalk Hemp TMP[a]	Whole Stalk Hemp TMP[a]	Whole Stalk Hemp CTMP[a]	Aspen TMP
Delivered cost of fiber[b]	$ 55.56	$ 58.79	$ 62.22	$ 65.83	$ 74.65	$ 79.00	$ 82.22
Cost of working capital for stored fiber[c]	2.34	2.45	2.59	2.74	3.11	3.29	1.02
Process energy[d]	115.37	97.79	115.37	97.79	115.37	97.79	165.03
Process chemicals		7.89		7.89		7.89	
Total Costs	$173.27	$166.92	$180.18	$174.25	$193.13	$187.97	$248.27

[a] pulping yields for hemp were assumed to be the same as for kenaf - 91% and 86% for hemp TMP and hemp CTMP, respectively, and 95% for wood TMP as reported by the Paper Task Force (1996).

[b] Based on delivered costs as indicated for hemp and $70/cord (delivered) for aspen.

[c] Based on mill production of 750 tons per day, an average fiber inventory equivalent to 5 months production for hemp and 1 1/2 months production for wood, and a cost of capital of 10%.

[d] Based on power requirement of 1888, 1611, and 2472 kwh/ADT for hemp TMP, hemp CTMP, and aspen TMP, respectively (Paper Task Force, Table 9); power required assumed to be the same for aspen as for SYP. Power costs of $0.0456/kwh assumed (US Energy Information Administration 2001).

Scenario Two - Hemp Bark (or Bast) Chemical Pulping and Bleaching, vs Hemp Core vs. Spruce vs. Aspen Chemical Pulping and Bleaching

Other than costs associated with fiber storage, the primary economic issues in chemical pulping and bleaching are total energy costs and non-energy costs associated with bleaching.

This analysis was based on figures developed by the Paper Task Force (1996). Costs of fiber, energy, and chemicals assumed in this analysis are given in the column headings and footnotes to Table 9. It was further assumed in this analysis that the bast and core portions of hemp would be separated prior to pulping, and pulped separately. Costs of stalk separation and chipping of round pulpwood logs are shown in Table 10.

Based on the assumptions used in this study, bleached chemical pulps made from aspen or spruce are significantly less costly to produce than such pulps made from hemp; differences in production costs are projected to range from 24-34 percent. Costs of chipping in the case of wood, and fiber separation, in the case of hemp, need to be added to the costs shown in Table 9; as these costs are estimated to be roughly equal, they have been omitted from all calculations.

Adding fiber storage costs to the cost figures shown in Table 9 slightly widens the differences in projected production costs (Table 10).

Table 9

Projected Operating Costs for Hemp and Wood-Based Chemical Pulp Mills in Minnesota

(costs are expressed as dollars per o.d.m.t. of pulp)

	Hemp stalk value $45.96 per dry short ton		Hemp stalk value $51.47 per dry short ton		Hemp stalk value $61.76 per dry short ton			
Item	Hemp Core[a]	Hemp Bast[a]	Hemp Core[a]	Hemp Bast[a]	Hemp Core[a]	Hemp Bast[a]	Aspen[a]	Spruce[a]
Fiber[b]	$189	$253	$212	$283	$254	$340	$206	$253
Energy/chemicals[c]	212	199	212	199	212	199	143	153
Labor[d]	118	118	118	118	118	118	48	52
Operating Costs	$519	$570	$542	$600	$584	$657	$397	$458

[a] Based on figures from Paper Task Force (1996), Table 12.

[b] Based on delivered costs of hemp as indicated, and $70/cord (delivered) for aspen roundwood, $85 spruce roundwood, and assuming yield after pulping and bleaching of 44% for both aspen and spruce (Paper Task Force), 38% for hemp core (Table 5), and 67% for hemp bast fiber (Table 5).

[c] Used same energy and chemical costs as in Paper Task Force report (1966), inflated to reflect current energy and chemical prices. Energy prices obtained from the U.S. Energy Information Administration (2001). Chemical prices increased by multiplying by composite Producer Price Index, 1995-1999 [1.0064].

[d] Labor costs used in the Paper Task Force report were adjusted by inflating values 3% per year for five years.

If delivered costs for hemp are assumed to be as high as $61.76/admt, then the cost differences as indicated above become even higher - as much as 40 percent. Similarly, higher assumed costs of energy and chemicals would also increase the costs of hemp pulps relative to pulps made from wood.

Table 10
Projected Operating Costs, Including Fiber Inventory and Storage Costs for Hemp and Wood-based Chemical Pulp Mills in Minnesota

	(costs are expressed as dollars per o.d.m.t. of pulp)			
Item	Aspen	Spruce	Hemp core	Hemp bast
Fiber, energy, chemicals & labor[a]	$397	$458	$542	$600
Cost of working capital for stored fiber [bc]	2.00	2.41	7.51	5.50
Total Costs	$399	$460	$550	$600

[a] Based on delivered cost of hemp of $51.47 per dry short ton, and delivered costs of aspen and spruce pulpwood logs of $70 and $85/cord, respectively.
[b] Based on 300 ton/day hemp pulp mill and assuming hemp bast core separation and yield of 35% and 65% for bast and core, respectively. Also assumed 10% fiber loss of hemp in the separation process, and chemical pulping yield (bleached) of 67% for bast and 38% for core. Average fiber inventory equivalent to 5 months of production.
[c] Based on 1000 ton/day wood pulp mill with chemical pulping yield of 44%. Average fiber inventory equivalent to 1 1/2 months of production assumed.

As in the previous scenario, the figures presented in Tables 9 and 10 do not include any costs that might be associated with covered storage of hemp fiber. In this case, if it is assumed that fiber must be stored under a roof once it is field dried, and that a structure large enough to accommodate ten months of fiber needs would be needed, then capitalization costs associated with the drying facility could add as much as $22-31/odmt of pulp. Additionally, it was again assumed in this analysis that fiber loss in storage is the same for both hemp and wood, an assumption that if wrong would obviously affect the relative cost of fiber. For example, if it is assumed that hemp degradation in storage is double that of wood (10 percent vs. 5 percent) the result is an increase of about $10 to$14 per ton of hemp pulp. Larger differences in storage loss would result in proportional changes in relative costs of pulp made from wood and hemp.

Although the magnitude of the cost differences shown in Tables 9 and 10 are substantial, the picture looks quite different if it is assumed that self-generated energy could be sold to the regional energy grid, and that its use would therefore appropriately represent an expenditure equivalent to the opportunity costs. The effect of such an assumption is to make the apparent production costs of wood-derived chemical pulps about equal to those of hemp pulps (see Table 12).

Scenario Three - Whole Stalk Chemical Pulping of Hemp vs. Spruce vs. Aspen

Projected costs of chemically pulping and bleaching whole stalk hemp were derived from the calculated costs of producing hemp bark (or bast) fiber and hemp core fiber pulps. Averages of the earlier calculated costs, weighted by the percent of bark and core fiber within whole stalk hemp (35 and 65 percent, respectively), provided the production cost estimate (Table 11).

Table 11
Projected Operating Costs for Whole Stalk Hemp and Wood-based Bleached Chemical Pulp Mills in Minnesota[a]

	(costs are expressed as dollars per o.d.m.t. of pulp)		
Item	Aspen	Spruce	Whole Stalk Hemp
Fiber[b]	\$206	\$253	\$134
Energy, chemicals[c]	\$143	\$153	\$200
Labor[d]	\$ 48	\$ 52	\$118
Costs of working capital for stored fiber	2.00	2.41	5.58
Operating Costs	\$399	\$460	\$458

[a] Based on figures from Paper Task Force (1996), Table 12.

[b] Costs calculated using delivered costs for hemp of \$51.47/air dry (10%mc) metric ton (\$51.477/od short ton), for aspen pulpwood of \$70/cord, and for spruce of \$85/cord, and assuming yield after pulping and bleaching of 44% for both hardwood and softwood, 48% for whole stalk hemp.

[c] Used same energy and chemical costs as in Paper Task Force report (1996)), inflated to reflect current energy and chemical prices. Energy prices obtained from the U.S. Energy Information Administration (2001). Chemical prices increased by multiplying by composite Producer Price Index, 1995-1999 [1.0064].

[d] Labor costs used in the Paper Task Force report were adjusted by inflating values by 3% per year for five years.

Here, the estimated costs of wood and hemp derived pulps are very similar. As in the previous analysis, increases in the delivered cost of hemp or to changes in energy and/or chemicals costs widen the differences in the cost of wood and hemp pulps. Also as previously indicated, provision of covered storage for hemp stalks would add on the order of 5 percent to production costs (\$25-26/ odmt).

The one assumption that makes chemically pulped and bleached whole stalk hemp fiber economically attractive is the assumption that self-generated energy could be sold to the regional energy grid, and that its use would therefore appropriately represent an expenditure equivalent to the opportunity costs. As noted previously, the effect of such an assumption is to drive the apparent production costs of wood-derived pulps to levels about equal to those of hemp pulps (see Table 12).

Table 12
Projected Operating Costs, Including Operating Costs Associated with Self-Generated Energy for Whole Stalk Hemp and Softwood-based Chemical Pulp Mills in Minnesota

(costs are expressed as dollars per o.d.m.t. of pulp)

Item	Aspen	Spruce	Whole Stalk Hemp
Operating costs[a]	$399	$460	$458
Opportunity costs associated with self-generated energy[b]	160	160	10
Total Costs	$559	620	$468

[a] From Table 11.
[b] Based on an energy buyback rate of $0.22/kwh.

Environmental Aspects of Hemp vs. Wood Production

A number of proponents of commercial hemp production suggest a number of environmental advantages of hemp fiber, rather than wood fiber production. Clues as to likely environmental impacts of commercial hemp production in Minnesota can be obtained by examining conclusions regarding other annual crops. Kaldor (1992), for example, addressed environmental considerations related to kenaf production, saying simply that " . . . the purchasing public is becoming increasingly conscious and environmentally aware of the need to preserve forests." Wood and Angus (1976), writing about the situation in Australia, noted that if periodic clearcutting of forests is curtailed, then this would favor kenaf as a substitute for eucalypt pulpwood. However, they also noted that cultivation of kenaf may itself cause environmental problems, citing the need for energy-intensive nitrogen and phosphate fertilizers, irrigation water, and higher inputs of fossil fuel energy in farming.

A significant environmental disadvantage of any annual fiber crop as compared to tree plantations is the frequency of activity on the landscape (Bowyer 1995). Consider, for example, a hybrid poplar plantation that is grown to an age of 20 years before harvest. Site intervention would occur three to six times over the 20-year rotation (once or twice to prepare the site, once to plant, zero to two times to suppress competition, and once to harvest). Compare this with kenaf production as outlined by Scott and Taylor (1990): annual activities including chisel, disc, disc/herbicides/disc (2X), application of pre-plant fertilizer, bedding, seeding and planting, application of side-dressing, cultivation, and harvesting. Based on findings in this study, the hemp production sequence would be similar, involving four to six passes across a site prior to and during seeding, one pass to harvest, and potentially several passes associated with retting and periodic turning of stalks and stalk pick-up. Assuming this sequence of production steps, direct site impacts would occur 140 to 200 over a 20-year time span. This reality not only dramatically increases fuel requirements, but also greatly increases the risk of such things as soil erosion and impacts on water quality. It is, therefore, difficult to argue that hemp production is environmentally preferable to production of wood fiber, especially if about the same land area is required for production of hemp as for wood fiber. Environmental advantages appear questionable even if annual hemp yields are assumed to be as much as 70 percent greater than wood yields from poplar plantations.

Whereas the use of specific fiber crops such as hemp is questionable from a social perspective, 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. The use of these materials is both socially and environmentally attractive, as long as volumes removed from the land do not compromise soil conservation.

Summary

Even though paper recycling is steadily rising, expanding paper demand is placing increasing demands on the forests of the U.S. and the world. One strategy being widely pursued is to establish large areas of highly productive forest plantations. Planting initiatives have been highly successful, with an increasing portion of U.S. and world fiber needs coming from plantations covering a relatively small land area. It is possible that future wood and fiber needs can be completely supplied by forest plantations, although a substantial investment will be required to ensure sufficient increases in plantation area and technology development aimed at increasing annual fiber yields on each acre. Moreover, should expansion of plantations in Minnesota not keep pace with developments in the U.S. South or elsewhere, Minnesota’s paper industry is likely to face a declining market share.

Interest in alternative sources of fiber is growing as concerns rise about the state of the world’s forests. One potential alternative is hemp (*Cannabis sativa* L.). Hemp has a number of properties that favor its use as a papermaking raw material. About one-third of the fiber of the hemp stalk, that from the outer layers or "bark," is quite long, a desirable quality for developing high-strength paper. Also, the proportion of lignin throughout the stalk is lower than in wood, a property that favors high pulp yields. Hemp has a long history in the U.S., grows rapidly, and is suited to the climate of southern Minnesota. Significant increases in growth rates are thought possible through genetic improvement. Also, fiber from hemp bark has also been found by a number of researchers to be an acceptable raw material for use in contemporary papermaking, and it appears that hemp paper could be manufactured at a competitive price to paper made of wood pulp.

Despite promising attributes of industrial hemp, several factors suggest that development of an industrial hemp-based paper industry in Minnesota should not be pursued without very careful consideration.
Factors dictating caution include:

- Hemp growth rates are markedly lower than kenaf, another agricultural fiber currently being promoted as a papermaking raw material. The relatively slow growth rates of hemp could place Minnesota farmers at a considerable disadvantage to those several hundred miles to the south who could raise fiber crops of kenaf.

- Hemp crops are highly sensitive to early and late season frosts, a reality that could prevent reliable production of seed that is needed to make hemp production economically attractive to farmers.

- Although industrial hemp is not likely to be an economically viable source of marijuana, separation of industrial hemp from hemp grown as a narcotic is extremely difficult.

- Separation of bark and core portions of hemp stalks are thought by many to be necessary for optimum processing of hemp. However, retting, an integral part of the bark/core separation process, is reported to require substantial improvement prior to large-scale use of industrial hemp as a fiber source.

- Long-term storage of large volumes of hemp would be needed following harvest were hemp to become a principal papermaking fiber.

- In comparison to industrial fiber productivity in tree plantations, production of hemp fiber would likely result in significantly greater environmental impacts, even if it is assumed that annual hemp yields per acre would be as much as 70 percent greater than yields from poplar plantations.

Literature Cited

Abdul-Karim, L.A., Rab, A., Polyanszky, E., and Rusznak, I. 1994. Optimization of process variables for production of dissolving pulps from wheat straw and hemp. TAPPI Journal 77(6): 141-150.

Abrahamson, L., and Wright, L. 2000. The status of short-rotation woody crops in the U.S. Abstract in: Jandl, R., Devall, M., Khorchidi, M., Schimpf, E., Wolfrum, G., and Krishnapillay, B. (eds.). Proceedings, XXI World Forestry Congress, Volume 2- Abstracts of Group Discussions, Kuala Lumpur, Malaysia, August 5-12, p 9.

Agrios, G. 1988. Plant physiology (3rd ed.). New York: Academic Press, 804 pp.

Alcaide, L., Baldovin, F., and Herranz, J. 1993. Evaluation of agricultural residues for paper manufacture. Tappi 76(3): 169-173.

American Forest and Paper Association. 2001. Recovered Paper Statistical Highlights - 2000 Edition.

American Paper Institute. 1984. Wood pulp and fiber statistics. 47th ed. New York.

Anonymous. 1890. Experiments with commercial fertilizers on hemp. Kentucky Agricultural Experiment Station Bulletin No. 27, 11p.

Ash, A.L. 1948. Hemp – production and utilization. Econ. Botany 2: 158-169.

Atchison, J. 1996. Twenty-five years of global progress in nonwood plant fiber repulping. Tappi 79(10): 87-95.

Atchison, J.E. 1998. Update on global use of non-wood plant fibers and some prospects for their greater use in the United States. Proceedings: TAPPI North American Non-wood Fiber Symposium.

Beer, J., Ibrahim, M., Schlonvoigt, A . 2000. Timber production in tropical agroforestry systems of Central America. . In: Krishnapillay, B., Soepadmo, E., Arshad, N., Wong, A., Appanah, S., Chik, S., Manokaran, N., Tong, H., Choon, K. (eds.). Proceedings, XXI World Forestry Congress, Volume 1- Sub-Plenary Sessions, Kuala Lumpur, Malaysia, August 5-12, pp. 777-786.

Black, C.A. and Vessel, A.J. 1945. The response of hemp to fertilizers in Iowa. Proceedings: Soil Science Society of America 9: 178-184.

Bosca, I. 1999. Genetic improvement: conventional approaches. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 153-184.

Bosia, A. 1975. Hemp for refiner mechanical pulp. World Research and Development Paper No. 37, p. 41.

Bowyer, J. 1999. Economic and environmental comparisons of kenaf growth versus plantation grown softwood and hardwood for pulp and paper. In: Sellers, T. Jr., Reichert, N., Columbus, E., Fuller, M., and Williams, K. (eds). 1999. Kenaf Properties, Processing and Products. Mississippi State University, pp. 323-346.

Bowyer, J. and Stockmann, V. 2000. Agricultural residues- an exciting bio-based raw material for the global panels industry. Forest Products Journal 51(1): 10-21.

Brown, C. and Ball, J. 2000. World view of plantation grown wood. In: Krishnapillay, B., Soepadmo, E., Arshad, N., Wong, A., Appanah, S., Chik, S., Manokaran, N., Tong, H., Choon, K. (eds.). Proceedings, XXI World Forestry Congress, Volume 1- Sub -Plenary Sessions, Kuala Lumpur, Malaysia, August 5-12, pp. 377-389.

Clark, R.C. 1999. Botany of the genus *Cannabis*. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 1-19.

Clark, R.C. and Pate, D.W. 1994. Medical marijuana. In: Rosenthal, E. (ed.). Hemp today. Oakland: Quick American Archives, pp. 303-309.

Conrad, C. 1994. Hemp: lifeline to the future. Los Angeles: Creative Expressions Publications, 314 pp.

Darcy, G.H. 1921. Revolutionizing an industry: how modern machinery is minimizing hand labor in hemp production. Scientific American, June 4.

De Groot, B., Van der Kolk, J.C., Van Dam, J.E.G., Van 'T Riet, K. 1999. Papermaking characteristics of alkaline hemp-woody-core pulps. TAPPI Journal 82(7): 107-112.

De Groot, B., Van Roekel, G.J., Jr., and Van Dam, J.E.G. 1999. Alkaline pulping of fiber hemp. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 213-242.

De Meijer, E.P.M.. 1993. Hemp variations as pulp source researched in the Netherlands. Pulp and Paper 67 (7): 41-43.

De Meijer, E.P.M. 1999. Cannabis germplasm resources. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp.133-151.

De Meijer, E.P.M., Van der Werf, H.M.G., Mathijssen, E.W.J.M, and Van den Brink, P.W.M.. 1995. Constraints to dry matter production in fibre hemp (*Cannabis sativa* L.). European Journal of Agronomy 4(1): 109-117.

Dempsey, J.M. 1975. Fiber crops. Gainsville: University of Florida Press, pp. 46-88.

Dewey, L.H. 1901. The hemp industry in the United States. USDA Yearbook, pp. 541-554.

Dewey, L.H. 1913. Hemp. USDA Yearbook, pp. 283-346.

Dewey, L.H. 1927. Hemp varieties of improved type are result of selection. USDA Yearbook, pp. 358-361.

Dewey, L.H. and Merrill, J.L. 1916. Hemp hurds as paper making material. U.S. Department of Agriculture, Bulletin No. 404, 26 pp.

Dodge, R. 1897. Useful fiber plants of the world. USDA Fiber Investigations Report No. 9, pp. 106-111.

Dutton, L. 1997. The return of hemp. Building Concerns Newsletter, May/June, pp. 1-4.

Ehrensing, D. T. 1998. Feasibility of industrial hemp production in the United States Pacific Northwest. Oregon State University, Department of Crop and Soil Science, Extension and Experiment Station Bulletin 681 (May), 38pp.

Ek, A.R., Lenarz, J.E., and Dudek, A. 1983. Growth and yield of populus coppice stands grown under intensive culture. In: Intensive Plantation Culture: 12 Years Research. USDA-Forest Service, General Technical Report NC-91, pp. 64-71.

Ergle, D.R., Robinson, B.B., Dempsey, J.M. 1945. Malvaceous bast fiber studies. Journal of the American Agronomy Society 37(2): 113-126.

Food and Agriculture Organization of the United Nations (FAO). 2000. Agriculture statistical database. http://apps.fao.org/page/collections?subset=agriculture

Food and Agriculture Organization of the United Nations (FAO). 2000. Forestry statistical database. http://apps.fao.org/page/collections?subset=forestry

Food and Agriculture Organization of the United Nations (FAO). 1993. Forestry statistics for today and tomorrow. I/V0270Tri/1/6.93/1200.

Food and Agriculture Organization of the United Nations (FAO). 1999. State of the World's Forests. Rome: FAO.

French, H.T. 1898. Notes on flax and hemp. Oregon Agricultural Experiment Station Bulletin No. 54.

Fuller, W.H., Norman, A.G., and Wilsie, C.P. 1946. The retting of hemp I – field retting of hemp in Iowa. Iowa Agricultural Experiment Station Research Bulletin No. 342, pp. 833-891.

Fuller, W.H., Norman, A.G., and Wilsie, C.P. 1946. The retting of hemp II – Controlled retting of hemp. Iowa Agricultural Experiment Station Research Bulletin No. 343, pp. 893-924.

Hackleman, J.C. and Domingo, W.E. 1943. Hemp – an Illinois war crop. University of Illinois Circular No. 547, 8pp.

Hansen, E. 1992. Mid-rotation yields of biomass plantations in the north central United States. USDA-Forest Service, Research Paper NC-309.

Haygreen, J.G. and Bowyer, J.L. 1996. Forest Products and Wood Science - an Introduction (3rd ed.). Ames: Iowa State University Press, p. 104.

Henneck, S. 1994. Optimization of breeding for agronomic traits in fibre hemp (*Cannabis sativa* L.) by study of parent-offspring relationships. Euphytica (Netherlands) 78(1-2): 69-76.

Herer, J. 1991. The emperor wears no clothes (rev.). Van Nuys, California: Hemp Press, 182pp.

Hessler, L.E. 1945. Chemical and strength differences in dew-retted hemp fiber. Journal of the American Society of Agronomy 37(2): 146-155.

Hessler, L.E. 1947. The effect of fertilizers on the chemical composition and quality of dew-retted hemp fiber. Journal of the American Society of Agronomy 39(9): 812-816.

Howard, J. 1999. U.S. Timber Production, Trade, Consumption, and Price Statistics, 1965-1997. USDA-Forest Service, General Technical Report FPL-GTR-116.

Humphrey, J.R. 1919. Marketing hemp. Kentucky Agricultural Experiment Station Bulletin No. 221, pp. 26-43.

Ince, P. 2000. Industrial wood productivity in the United States, 1900-1998. USDA-Forest Service, Research Note, FPL-RN-0272.

Ince, P. 2001. Outlook for sustainable fiber supply through forest management and other developments in the U.S. pulp and paper sector. Proceedings: TAPPI International Environmental, Health and Safety Conference, Charlotte, North Carolina, April 22-25.

Isenberg, I. 1962. Fibrous raw materials and wood structure. In: Libby, C. (ed.). Pulp and Paper Science and Technology - Volume I. New York: McGraw-Hill Book Company, pp. 20-53.

Jewell, M. 1999. Sulfur-free pulping and chlorine-free bleaching of wheat straw for paper production. MS Thesis, University of Minnesota, Department of Wood and Paper Science.

Johnson, P. 1999. Industrial hemp: a critical review of claimed potentials for Cannabis sativa. TAPPI 82(7): 113-123.

Jordan, H.V., Lang, A.L., and Enfield, G.H. 1946. Effects of fertilizers on yields and breaking strengths of American hemp, Cannibus sativa. Journal of the American Society of Agronomy 38(6): 551-563.

Kaldor, A. F. 1992. Kenaf, an alternative fiber for the pulp and paper industries in developed and developing countries. Tappi 75(10): 41-145.

Kirby, R.H. 1963. Vegetable fibers: botany, cultivation, and utilization. New York: Interscience Publishers.

Koch, P. 1973. Whole tree utilization of southern pine advanced by developments in mechanical conversion. Forest Products Journal 23(10): 30-33.

Koch, P. 1985. Utilization of hardwoods growing on southern pine sites. U.S.D.A. - Agricultural Handbook No. 605, pp. 315-336.

Kraenzel, D.G., Petry, T., Nelson, B., Anderson, D.M., and Todd, R. 1998. Industrial hemp as an alternative crop in North Dakota. Agricultural Economics Report 402, North Dakota State University, Fargo, July 23, 22pp.

Krantz, J. 2001. Personal conversation with J. Bowyer, April 9. Krantz is Chief wood utilization specialist, Minnesota Department of Natural Resources.

Krotov, V.S. 1994. Hemp or wood: potential substitutes. In: Rosenthal, E. (ed.). 1994. Hemp today. Oakland: Quick American Archives, pp. 145-148.

Kugler, D. 1990. Non-wood fiber crops: commercialization of kenaf for newsprint. In: Janick, J. and Simon, J. (eds.). Advances in New Crops. Portland: Timber Press, Inc., pp. 289-292.

Leslie, A. 1999. For whom the bell tolls. Tropical Forest Update 9(4): 7.

Lewis, E.B., Card, D.G., and McHargue, J.S. 1948. Tobacco stalks, hemp hurds, and sorghum bagasse as sources of cellulose for making high quality paper. Kentucky Agricultural Experiment Station Bulletin No. 515, 14pp.

Mandolino, G. and Ranalli, P. 1999. Advances in biotechnology approaches for hemp breeding and industry. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 185-212.

Manwiller, F.G. 1974. Fiber lengths in stems and branches of small hardwoods on southern pine sites. Wood Science 7:130-132.

McCloskey, J. 1996. What about non-woods? Proceedings: TAPPI Pulping Conference.

McPartland, J.M. 1996. A review of *Cannabis* diseases. Journal of the International Hemp Association 3(1): 19-23.

McPartland, J.M. 1996. *Cannabis* pests. Journal of the International Hemp Association 3(2): 49, 52-55.

McPartland, J.M. 1999. A survey of hemp diseases and pests. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 109-131.

Merrill, J.J. 1916. Hemp. U.S. Department of Agriculture, Bulletin No. 404.

Miller, D. 1965. Kenaf – a potential papermaking raw material. Tappi 48(8): 455-459.

Minnesota Agricultural Statistics Service. 2001. http://www.nass.usda.gov/mn/

Moore, G. 1996. Non-wood fibre applications in papermaking. UK: Pira International.

Nieschlag, H.J., Nelson, L.A., Wolff, I.A., and Perdue, R.E. 1960. A search for new fiber crops. Tappi Journal 43(3): 193-201.

Pande, H. 1998. Non-wood fibre and global fibre supply. Unasylva 49(193): 44-50.

Panshin, A.J. and deZeeuw, C. 1980. Textbook of Wood Technology, 4th Ed. New York: McGraw-Hill Book Company, Inc., pp. 134, 170-171.

Paper Task Force. 1996. Non-wood plant fibers as alternative fiber sources for papermaking. Environmental Defense Fund, Paper Task Force White Paper 13.

Pate, D.W. 1999. Hemp seed: a valuable food source. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 243-255.

Pate, D.W. 1999. The phytochemistry of Cannabis: its ecological and evolutionary implications. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 21-42.

Perala, D.A. and Laidly, P.R. 1989. Growth of nitrogen-fertilized and thinned quaking aspen (Populus tremuloides Michx.). USDA-Forest Service, Research Paper NC 286.

Pimentel, D., McLaughlin, L, Zepp, A., Lakitan, B., Kraus, T., Kleinman, P., Vancini, F., Roach, W., Grapp, E., Keeton, W., and Selig, G. 1991. Environmental and economic impacts of reducing U.S. agricultural pesticide use. In: CRC Handbook of Pest Management in Agriculture, Vol. I (2nd ed.). Boca Raton, Florida: CRC Press, pp. 679-686.

Powell, D., Faulkner, J., Darr, D, Zhu, Z., MacCleery, D. 1993. Forest Resources of the United States, 1992. USDA-Forest Service, General Technical Report RM-234.

Ranalli, P. 1999. Agronomic and physiological advances in hemp crops. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp. 61-84.

Rauscher, H.M. 1985. Growth and yield of white spruce plantations in the Lake States. USDA-Forest Service, Research Paper NC-253.

Ree, J.H. 1966. Hemp growing in the Republic of Korea. Economic Botany 20: 176-186.

Robinson, B.B. 1935. Hemp. USDA Farmer's Bulletin No. 1935, 16pp.

Robinson, B.B. 1943. Hemp. Washington D.C.: U.S. Government Printing Office. Agricultural Research Administration, Bureau of Plant Industry, Division of Cotton and Other Crops and Diseases, 16 pp.

Robinson, B.B. 1946. Dew retting of hemp uncertain west of longitude 95°. Journal of the American Society of Agronomy 38(12): 1106-1109.

Robinson, B.B. 1952. Hemp (revised edition). USDA Farmers' Bulletin No. 1935.

Robinson, B.B. and Wright, A.H. 1941. Hemp - its production and use as a fiber crop. U.S. Department of Agriculture, Bureau of Plant Industry, Division of Cotton and Other Crops and Diseases, 9 pp.

Rosenthal, E. 1993. Hemp realities. In: Rosenthal, E. (ed.). Hemp today. Oakland: Quick American Archives, pp. 67-82.

Sedjo, R. and Lyon, K. 1990. The Long-Term Adequacy of Timber Supply. Washington: Resources for the Future, pp. 180-186.

Simons, A., Jaenicke, H., Tchoundjeu, Z., Dawson, I., Kindt, R., Oginosako, Z., Lengkeek, A., and DeGrande, A. The future of trees is on farm: tree domestication in Africa. In: Krishnapillay, B., Soepadmo, E., Arshad, N., Wong, A., Appanah, S., Chik, S., Manokaran, N., Tong, H., Choon, K. (eds.). Proceedings, XXI World Forestry Congress, Volume 1- Sub-Plenary Sessions, Kuala Lumpur, Malaysia, August 5-12, pp. 752-760.

Stern, B. 1998. Making paper from Montana's straw - a guide to making straw pulp a reality. Native Forest Network, Inc. Unpublished report.

Sutton, W. 1999. Does the world need planted forests? New Zealand Journal of Forestry (August), pp. 24-29.

Thomas, R.J. 1977. Wood: Structure and Composition. In: Wood Technology: Chemical Aspects, Goldstein, I.S. (ed.). Washington, D.C.: American Chemical Society, ACS Symposium Series 43, pp.1-23.

U.S. Census Bureau, 2001. U.S. population information. http://www.census.gov/cgi-bin/popclock/

U.S. Census Bureau. 2001. World population information. http://www.census.gov/cgi-bin/ipc/popclockw

U.S. Department of Agriculture. 1942. U.S. revives hemp growing. News release, May 24.

U.S. Department of Agriculture. 1994. Farming with high residue, for profit and erosion control. USDA, Soil Conservation Service, 1994-575-103. Bismark, ND.

U.S. Department of Agriculture. 2000. Industrial hemp in the United States: status and market potential. 38pp.

Wagner, N. 1999. Pulp Mill Feasibility Study . Unpublished paper, Department of Wood and Paper Science, University of Minnesota, St. Paul, MN. (March)

West, C.J. 1921. Hemp wood as a papermaking material. Paper Trade Journal (Oct. 13). [Abstracted by C.J. West]

Wilcke, B., Cuomo, G., and Fox, C. 1998. Preserving the value of dry stored hay. Minn./Wisc. Engineering Notes. University of Minnesota Extension Service, Winter. http://www.bae.umn.edu/extens/ennotes/enwin98/hayvalue.html

Van der Werf, H.M.G. 1994. A review of the literature - agronomy and crop physiology of fiber hemp. In: In: Rosenthal, E. (ed.). Hemp today. Oakland: Quick American Archives, pp. 123-138.

Van der Werf, H.M.G. 1994. Fiber hemp in France. In: In: Rosenthal, E. (ed.). Hemp today. Oakland: Quick American Archives, pp. 213-220.

Van der Werf, H.M.G., Van Geel, W.C.A., Van Gils, L.J.C., and Haverkort, A.J. 1995. Nitrogen fertilization and row width affect self-thinning and productivity of fibre hemp (*Cannabis sativa* L.). Field Crops Research 42: 27-37.

Van der Werf, H.M.G., Mathijssen, E.W.J.M., and Haverkort, A.J. 1999. Crop physiology of *Cannabis sativa* L.: a simulation study of potential yield of hemp in northwest Europe. In: Ranalli, P. (ed.). Advances in Hemp Research. New York: Food Products Press, pp.85-108.

Vantreese, V.L. 1997. Industrial hemp: global markets and prices. University of Kentucky, Department of Agricultural Economics, Lexington.

Vessel, A.J. and Black, C.A. 1947. Soil type and soil management factors in hemp production. Agricultural Experiment Station, Iowa State College of Agriculture and Mechanic Arts, Ames, Research Bulletin No. 352, pp. 384-424.

Walker, D.W. 1990. Can hemp save our planet? In: Rosenthal, E. (ed.). 1994. Hemp today. Oakland: Quick American Archives, pp. 83-108.

Wilsie, C.P., Black, C.A., and Aandahl, A.R. 1944. Hemp production experiments: cultural practices and soil requirements. Iowa Agricultural Experiment Station, Agricultural Extension Service, Iowa State College, Bulletin P 63, 46pp.

Wilsie, C.P., Dyas, E.S., and Norman, A.G. 1942. Hemp - a war crop for Iowa. Iowa Agricultural Experiment Station, Agricultural Extension Service, Iowa State College, Bulletin P 49, pp. 587-600.

Wisconsin Energy Statistics. 2000. http://www.doa.state.wi.us/depb/boe/publications/pdf_files/11_price.pdf

Wright, A.H. 1918. Wisconsin's hemp industry. Wisconsin Agricultural Experiment Station Bulletin 293, 46p.

Wright, A.H. 1941. A report on the hemp fiber situation in Wisconsin and the United States. University of Wisconsin, College of Agriculture, radio script, July 15.

Wright, A.H. 1942. Federal hemp plans. University of Wisconsin, College of Agriculture, news release, October 5.

Wright, A.H. 1942. Wisconsin helps U.S. meet hemp situation. University of Wisconsin, College of Agriculture, news release, April 17.

Wright, A.H. 1943. Producing hemp in Wisconsin. Department of Agronomy, College of Agriculture, University of Wisconsin, Madison. 5pp.

Wong, A. 1997. Agricultural fibre supply for pulp production. Vancouver: Agripulp, document AK 15346. Paper presented at Fiber Futures '97 Conference, Monterey, Calif., June 2. http://www.agripulp.com/home98/articles/ar07/ar07_1.htm

Wright, A.H. 1941. What about growing hemp? Extension Service of the College of Agriculture, University of Wisconsin, Madison. 5pp.

Young, H., Gammon, C., and Hoar, L. 1963. Potential fiber from red spruce and red maple logging residues. Tappi 46(4): 256-259.

Young, H., Hoar, L., and Ashley, M. 1965. Weight of wood substance for components of seven tree species. Tappi 48(8): 466-469.

Zavitskovski, J. 1983. Projected and actual biomass production of 2 to 10 year old intensively cultured Populus tristis #1. In: Intensive Plantation Culture: 12 Years Research. USDA-Forest Service, General Technical Report NC-91, pp. 72-76.

Zomers, F.H.A., Gosselink, R.J.A., Van Dam, J.E.G., and Tjeerdsma, B.F. 1995. Organosolv pulping and test paper characterization of fiber hemp. TAPPI Journal 78(5): 149-155.