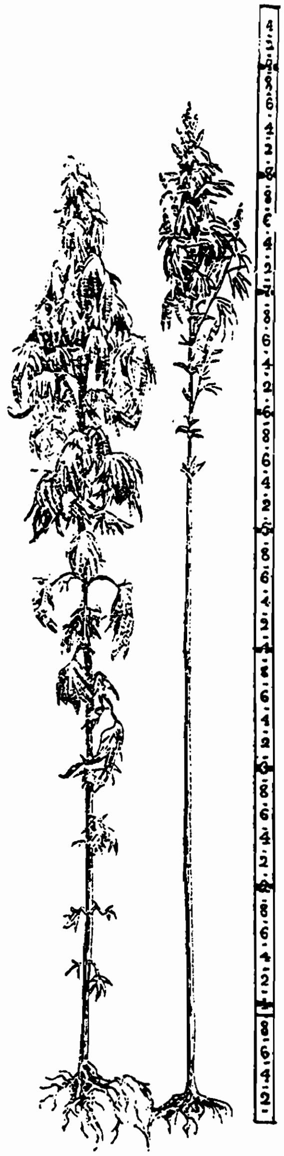
Station Bulletin 681
May 1998

Feasibility of Industrial Hemp Production in the United States Pacific Northwest


HEMP.

Agricultural Experiment Station
Oregon State University

For additional copies of this publication, write:

Publications Orders
Extension and Experiment Station Communications
Oregon State University
422 Kerr Administration Bldg.
Corvallis, OR 97331-2119

This report is printed on Vanguard™ Hemp, a product of the Living Tree Paper Company, Eugene, Oregon. It is 25 percent hemp, 25 percent cotton, and 50 percent post-consumer waste. The long fibers from hemp significantly improve and extend the recyclability of the post-consumer waste paper.

Cover: Hemp illustration from Oregon Agricultural Experiment Station Bulletin No. 54, May 1898, showing male (right) and female plants (left).

Agricultural Experiment Station
Oregon State University
Station Bulletin 681
May 1998

Feasibility of Industrial Hemp Production in the United States Pacific Northwest

Daryl T. Ehrensing
Department of Crop and Soil Science
Oregon State University

This report was prepared and printed with support from the Oregon Natural Resources Council, the Turner Foundation, and the Wallace Genetic Foundation.

CONTENTS

FEASIBILITY OF INDUSTRIAL HEMP PRODUCTION IN THE UNITED STATES PACIFIC NORTHWEST

SUMMARY:

For many centuries hemp (*Cannabis sativa* L.) has been cultivated as a source of strong stem fibers, seed oil, and psychoactive drugs in its leaves and flowers. Environmental concerns and recent shortages of wood fiber have renewed interest in hemp as a raw material for a wide range of industrial products including textiles, paper, and composite wood products. This report assesses the agricultural feasibility of industrial hemp production in the Pacific Northwest (PNW).

Hemp is an herbaceous annual that develops a rigid woody stem ranging in height from 1 to over 5 meters (3 to 19 feet). Hemp stalks have a woody core surrounded by a bark layer containing long fibers that extend nearly the entire length of the stem. Plant breeders have developed hemp varieties with increased stem fiber content and very low levels of delta-9-tetrahydro-cannabinol (THC), the psychoactive ingredient of marijuana.

Historically, hemp fiber was used mainly for cordage, but it can also be made into textiles, paper, and composite wood products. Demand for hemp cordage peaked in the late 1800's, and world hemp production has continuously declined since that time, except for brief increases during both World Wars. Hemp fiber has largely been replaced by relatively inexpensive natural and synthetic fibers.

Although hemp is well adapted to the temperate climatic zone and will grow under varied environmental conditions, it grows best with warm growing conditions, an extended frost-free season, highly productive agricultural soils, and abundant moisture throughout the growing season. When grown under proper conditions, hemp is very competitive with weeds, and herbicides are generally not required in hemp production. Although a number of insect pests and diseases have been reported on hemp, significant crop losses from pests are not common. High levels of soil fertility are required to maximize hemp productivity. Cultural requirements and production costs are quite similar to those of corn. Reported hemp yields range from 2.5 to 8.7 tons of dry stems per acre.

The climatic and soil requirements of hemp can be met in some agricultural areas of the PNW, however, hemp will almost certainly require irrigation to reliably maximize productivity in the region. The requirement for supplemental irrigation will place hemp in direct competition with the highest value crops in the PNW, limiting available acreage. Stem yields will have to be substantially higher than those previously recorded for hemp to be economically feasible in the PNW at current prices. It is unlikely that the investment needed to improve hemp production technology will be made until legislative restrictions are removed from the crop.

INTRODUCTION:

The decreasing availability and rising prices of local wood fiber resources have greatly increased commercial interest in agricultural production of alternative fiber sources in the Pacific Northwest. Production of industrial hemp has been proposed as a viable source of substitute raw material for a wide range of industrial products including paper and composite wood products. Although many popular publications have recently touted the revival of industrial hemp in the United States, a thorough analysis of the subject is essential to assess the feasibility of industrial hemp production in the Pacific Northwest.

Hemp (*Cannabis sativa* L.) has been grown for many centuries for the strong fiber produced in its stems. Hemp seed also contains a useful vegetable oil, and the upper leaves and flowers of some *Cannabis* varieties produce the psychoactive drug delta-9-tetrahydro-cannabinol (THC), the active ingredient of marijuana. Although these plants belong to a single species, the term hemp is often used to distinguish industrial fiber varieties from the drug varieties of *Cannabis*. Some confusion arises from the use of the term hemp, since the word hemp is used in association with strong fibers from many unrelated species. Among the many species commonly referred to as hemp are Manila hemp from *Musa textilis* (abaca), sisal hemp from *Agave sisalina* (sisal), ambari hemp from *Hibiscus cannabinus* (kenaf), and sunn hemp from *Crotalaria juncea* (Robinson, 1953; Montgomery, 1954). This study is concerned with true hemp, *Cannabis sativa* L.

This report is an attempt to assess the agricultural feasibility of industrial hemp production in the Pacific Northwest. The report will review the available literature on hemp botany, agronomy, and possible biological adaptation to the PNW. A preliminary analysis of hemp production costs will also be presented. While it is theoretically possible to obtain a permit to grow *Cannabis sativa* in the United States, restrictions imposed by the federal government have effectively prohibited production. This report will in no way attempt to deal with issues concerning *Cannabis* legalization.

BOTANY:

The hemp plant (*Cannabis sativa* L.) is an herbaceous annual belonging to the family Cannabinaceae. Among most botanists it is considered the only species in the genus *Cannabis*. As the plants mature a rigid, woody stem develops ranging in height from 1 to over 5 meters (3 to 19 feet). Uncrowded plants have many spreading branches, and the central stalk can grow 30 to 60 millimeters (1 to 2 inches) in diameter. When grown in thick stands, hemp stems are unbranched and without foliage except near the top and range from 6 to 20 millimeters (1/4 to 3/4 inch) in diameter. Stems of most varieties are hollow. Leaves are palmately compound with 5 to 11 pointed, serrate leaflets 50 to 150 millimeters (2 to 6 inches) long and 10 to 20 millimeters (3/8 to 3/4 inch) wide (Dewey, 1913). In light, well-drained soils primary hemp roots can reach depths of 2 to 2.5 meters (6.5 to 8 feet), and secondary root branches may grow 60 to 80 centimeters (2 to 2.5 feet) below the soil surface (Bocsa and Karus, 1998).

Hemp normally is dioecious having both staminate (male) and pistillate (female) plants, each with distinctive growth characteristics. Staminate plants are tall and slender with few leaves surrounding the flowers, while pistillate plants are short and stocky with many leaves at each terminal inflorescence (Figure 1.). Staminate plants senesce and die soon after their pollen is shed, while pistillate plants remain alive until the seeds mature. Relatively stable monoecious varieties have been developed through breeding and selection.

Figure 1. Pistillate (left) and staminate (right) hemp plants (Dewey, 1913).

Hemp seeds are smooth, nearly spherical achenes which range in color from light brown to dark gray and are often mottled. Seed size varies widely from 2.5 to 4 millimeters (1/10 to 3/16 inch) in diameter and 3 to 6 millimeters (1/8 to 1/4 inch) in length (Dewey, 1913). Thousand seed weights range from 8 to 27 grams. Seeds of monoecious fiber varieties average 16 grams per thousand while larger seeds from dioecious hemp average 21 grams per thousand (Dempsey, 1975). Hemp seeds usually contain from 29 to 34% oil. Hemp seed oil is similar to other common drying oils such as linseed, tung, and perilla and consists primarily of unsaturated fatty acids including approximately 54-60% linoleic (C18:2), 15-20 % linolenic (C18:3), and 11-13% oleic (C18:1) acid.

Hemp stalks have a hollow woody core surrounded by the vascular cambium (the growing tissue) and an outer ring of cells consisting of phloem, cortex, and epidermal tissue (the bark) (Figure 2). Fiber cells develop in bundles associated with the phloem (or bast).

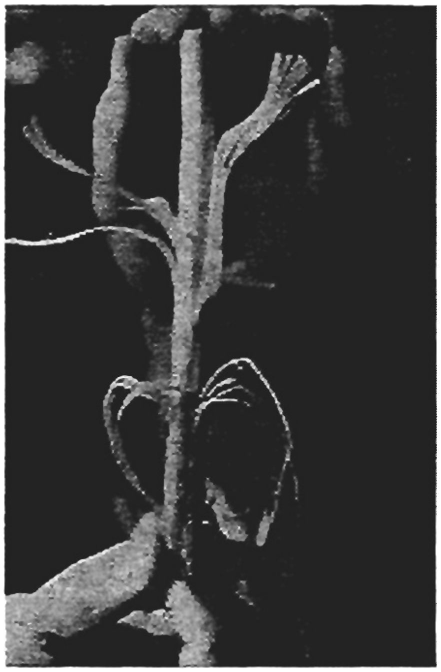


Figure 2. Hemp stems showing bark, secondary bast fibers, and woody core (De Meijer, 1993a). .

Hemp produces both long, coarse fibers which extend nearly the entire length of the stalk (primary bast fibers) and short, fine fibers which tend to adhere to the woody core (secondary bast fibers). Individual hemp fiber cells range from 0.20 to 2.16 inches (5 to 55 mm) long and 0.016 to 0.05 mm in diameter and are arranged in bundles to form the primary and secondary fibers (Montgomery, 1954). The proportion of bark in hemp stems varies from 14 to 48% depending on the genotype and plant height (Van der Werf et al., 1994).

HISTORY:

Although some authors contend that hemp originated in central Asia, most now agree that China was the original home of hemp (Dewey, 1913). Because the greatest diversity of hemp germplasm is found there, Vavilov placed the center of origin of hemp in China (Vavilov, 1992).

Cultivation and use of hemp for fiber predates written history. Chinese writings from the Sung dynasty (about 500 A.D.) state that the emperor Shen Nung first taught the people of China to cultivate hemp and make cloth around 2,800 B.C. Later Chinese texts indicate that hemp stalks were also used for fuel and the seeds for food and oil, but there are no early records of hemp production for drug use in China. According to Herodotus (about 450 B.C.) hemp fiber was used by the Thracians and Scythians beyond the Caspian Sea and was probably introduced to Europe during the westward Scythian migration around 1500 B.C. Hemp remained virtually unknown to the Greeks and Romans, however, until the beginning of the Christian era (Dewey, 1913). The earliest written record of hemp use in Europe states that "Heiro II, King of Syracuse (270 B.C.), bought the hemp used for the cordage of his vessels in Gaul" (De Candolle, 1886). By the sixteenth century hemp was widely distributed in Europe where it was cultivated for fiber and the seeds were cooked with barley or other grains and eaten. In 1537 Discorides named the plant *Cannabis sativa* and wrote of its use for cordage as well as its medicinal properties (Dewey, 1913).

As early as 1545 hemp was brought to the Western Hemisphere by the Spaniards who began cultivation in Chile (Husbands, 1909). Hemp was introduced to the United States in 1645 by the Puritans in New England as a fiber source for household spinning and weaving, but never became as important as flax in the region. Cultivation spread to Virginia and was well established in Pennsylvania before the American Revolution (Dewey, 1913). Hemp was brought to Kentucky in 1775 by settlers from Virginia and grew so well that a commercial cordage industry developed in Kentucky that lasted long after hemp cultivation was abandoned in the eastern states (Humphrey, 1919). The hemp industry flourished in Kentucky, Missouri, and Illinois between 1840 and 1860 due to strong demand for sailcloth and cordage, however, large imports of cheaper jute and abaca eventually displaced most domestic hemp (Dodge, 1897; Dempsey, 1975). With development of the cotton gin, the hemp industry quickly declined as cotton production rapidly increased in the South. Growth of the cotton industry did provide demand for hemp cordage and bagging to package cotton bales until iron ties were introduced in about 1865 (Dewey, 1913; Humphrey, 1919). During the late 1800's and early 1900's hemp production was tried in many other states, but from the end of the Civil War until 1912 virtually all hemp in the United States was produced in Kentucky (Wright, 1918). Domestic hemp production revived slightly in response to World War I, and fiber hemp was grown in several states including Kentucky, Wisconsin, California, North Dakota, South Dakota, Minnesota, Indiana, Illinois, Ohio, Michigan, Kansas, and Iowa (Wright, 1918; Dempsey, 1975).

There are no records that hemp was ever a commercial crop in Oregon, however, experimental crops were attempted in the 1890's (French, 1898) and in the 1930's. USDA researchers B.B. Robinson and E.G. Nelson planted many hemp trials in Oregon during the 1930's as part of an ongoing fiber crop research project. This included trials with high yielding varieties developed by the USDA such as Kymington, Chinamington, and Chington (Robinson, 1934; Robinson, 1935b; Robinson, 1936). In addition, a hemp breeding and selection program was established in Corvallis, Oregon to develop and test advanced lines. Results from the non-irrigated production trials were generally very poor with many crop failures due to lack of rainfall. Because of unsatisfactory crop performance and climatic conditions, the USDA hemp project based in Oregon and all seed produced were transferred to Madison, Wisconsin in 1937 (Nelson, 1937).

In 1937 the U.S. government passed the Marijuana Tax Act which placed all *Cannabis* culture under control of U.S. Treasury Department regulations. This act required the registration and licensing of all hemp growers with the federal government in an effort to restrict production of psychoactive *Cannabis* varieties in the United States. Additional legislation established penalties for production, sale, and possession of marijuana and hashish (Dempsey, 1975). Although many other countries also prohibited *Cannabis* cultivation, hemp production was not restricted in much of Asia, South America, eastern Europe, and in several countries in western Europe.

When World War II interrupted supplies of jute and abaca to the United States from the tropics, an emergency program was undertaken to quickly develop hemp as a domestically produced substitute. A special division of the USDA Commodity Credit Corporation contracted production of hemp planting seed and fiber. War Hemp Industries, Inc. constructed a number of hemp fiber processing mills in the midwest. Domestic hemp production peaked during 1943 and 1944 and declined rapidly after the war as legal restrictions on production were increased and supplies of inexpensive tropical fibers were reestablished. A small hemp fiber industry continued in Wisconsin, however, until 1958. Fiber hemp production in the United States has been negligible since that time (Ash, 1948; Dempsey, 1975).

ECONOMIC IMPORTANCE:

Because of their strength and durability, hemp fibers have been used for production of cordage and coarse textiles for centuries. In addition, hemp can provide raw material for pulp and paper manufacture, composite wood products such as particleboard and insulation board, and industrial products including geotextiles and nonwoven industrial fabrics. Hemp currently provides less than one percent of total world production of vegetable fibers (Table 1.) (FAO, 1996).

Use of hemp for marine cordage was largely replaced by abaca in the 1800's because abaca ropes are lighter and will float in water, are more resistant to damage from salt water without being tarred, and are less expensive than hemp due to lower labor costs in the tropics (Ash, 1948; Robinson, 1953; Dempsey, 1975). Relatively inexpensive synthetic (polypropylene) and natural (sisal) fibers have occupied most of the agricultural twine markets formerly served by hemp.

Hemp textile production is based primarily in Asia and central Europe. Korea has a long history of hemp fabric production, primarily for use as domestic clothing (Ree, 1966). In Italy, Hungary, and adjacent countries, water-retted fiber is prepared with great care to produce relatively fine yarns and soft fabrics resembling flax (Montgomery, 1954). These yarns and cloth are quite expensive compared to natural and synthetic fiber blends made from competing fiber sources largely due to the amount of hand labor involved in their production. A small novelty market based on hemp textiles imported from China and Hungary has been developing in western Europe and the United States since the late 1980's.

Table 1. World Production of Vegetable Fibers in 1,000 metric tons, 1992-96.

	1992	1993	1994	1995	1996
Cotton	18,090	16,861	18,560	19,814	18,812
Jute	3,525	3,411	3,165	3,080	3,080
Flax	592	572	572	559	561
Sisal	386	292	294	289	292
Coir	118	126	116	116	116
Abaca	107	104	107	111	111
Kapok	101	106	109	108	108
Ramie	75	79	71	70	70
Agave	66	65	65	66	66
Others	420	422	429	434	434
Cannabis Hemp	80	73	64	60	60
	--------	--------	--------	--------	--------
Total	23,597	22,151	23,692	24,749	23,752

Although many people are surprised to learn that paper can be made from nonwood fibers, wood-based papermaking is a comparatively recent development. Not until the mid-nineteenth century was the technology developed for converting wood into pulp suitable for paper. Hemp has a long history of use in papermaking and has normally been used to produce strong, thin specialty papers similar to those made from flax (Hurter, 1989). Traditionally, hemp fiber has been viewed as an inexpensive substitute for flax in paper production, however, in France hemp prices have been depressed by the availability of large quantities of flax tow, a byproduct of the fiber flax textile industry (Van der Werf, 1992). Woody hemp core has been shown to produce a mechanical pulp similar to those made from poplar (Dewey, 1913; Lewis et al., 1948; Bosia, 1975). Because hemp bark and core differ considerably in fiber length and chemical composition, they are generally processed separately to produce paper pulp. They also have very different market value. In 1992 the French market price for dry hemp bark was 2500 FF/metric ton (about \$500/ton), while hemp core was worth only 250 FF/metric ton (about \$50/ton) (Van der Werf, 1994). Since it has long been evident that forest resources may not be sufficient to supply the expanding pulp and paper industry, several studies have been undertaken to explore agricultural production of pulping fibers, including hemp (Nieschlag et al., 1960; Wood, 1981). In addition, there has recently been considerable increase in research activity on hemp pulping (De Groot et al., 1994; Laith et al., 1995; Van der Werf et al., 1994; Zomers et al.,1996). In the European and U.S. markets a number of companies are currently selling paper containing a minor percentage of hemp fiber (bark fiber), usually blended with other, less expensive agricultural residues. These have gained some market acceptance as ecologically friendly or "tree-free" products, but are at present considerably more expensive than wood-based paper. Larger scale production of hemp paper will undoubtedly lead to lower production costs.

Commercial manufacture of composite panelboard began early in this century. In both Europe and the United States, this industry was developed to use not only wood fiber but also a wide range of agricultural residues such as sugarcane bagasse, flax shives, corn stalks, and cereal straw. As a result, many of the technical details associated with making panels from agricultural fibers have been well known for decades (Atchison and Collins, 1976; Verbestel, 1978). Commercially acceptable three layer particleboards can be produced from woody hemp core using conventional equipment. Between 1950 and 1976 Siempelkamp & Co. (Krefeld, Germany) designed and built four particleboard plants using hemp core as their feedstock (Niedermaier, 1976). Production of composite panels from hemp or other agricultural fibers is largely a matter of economics and availability of raw materials.

Because of its low cost and availability in large quantity, wood fiber has long dominated paper pulp and composite panel production in North America and Western Europe, while agricultural fibers have only been important in countries with limited wood resources. Wood chip and sawdust prices in the PNW are extremely volatile and respond quickly to fluctuations in local and international wood fiber supply. Local prices range from less than $50 to over $100 per dry ton. A long-term trend of increasing wood fiber prices has been evident, however, for many years.

Recent shortages of wood fiber in the United States and the resulting high prices have renewed commercial interest in supplementing wood-based production with agricultural fibers from a variety of sources. Agricultural residues from cereal and grass seed production are widely available in the PNW in large quantities and at relatively low cost. Consideration of large-scale hemp production should also include analysis of the cost, availability, and performance of these inexpensive competing raw materials.

Another response to the price spike for wood fiber was the importation of large amounts of wood chips and logs from Canada, Siberia, and South America as softwood chip prices in the PNW exceeded $100 per ton. Large acreages of natural and plantation forests exist in these areas, and wood imports to the PNW can be increased rapidly in response to high market prices. Although cutting these offshore timber resources on a large scale is probably not sustainable over long periods of time, the availability of these resources may make development of fiber crops for commodity uses more difficult by placing a ceiling on wood fiber prices.

Woody core from hemp stems is highly absorbent material, and hemp core has been marketed as animal bedding and as an absorbent for oil and waste spill cleanup. It is also used in mixtures with lime and cement as a lightweight building material.

Historical and current estimates of the cultivated area planted to hemp are presented in Table 2 (FAO, 1996). For many years, until its breakup in 1991, the Soviet Union was, by a wide

Table 2. Estimated Area in Hemp Cultivation 1910 to 1996 in 1000 ha.

	Year or Period										
Region	1910	1925	1948-52	1969-71	1979-81	1988	1992	1993	1994	1995	1996
Asia											
China					123	53	18	18	17	17	17
Japan			4	1	0	0					
N. Korea			10	7	8	15	17	18	18	18	18
S. Korea			10	5	1	1	<1	<1	<1	<1	<1
Syria			4	1	0	0					
Turkey			12	8	9	4					
Europe											
Austria	23		0	0	0	0	0	0	0	0	0
Bulgaria	3	4	21	10	5	1	0	0	0	0	0
Czechoslovakia		12	5	2	1	<1	0				
France	14	5	5	0	3	3	4	6	6	6	6
E. Germany			4	2	0	0					
W. Germany			2	0	0	0					
Hungary	63	14	23	12	7	4	<1	<1	<1	<1	<1
Italy	79	112	58	1	0	0	0	0	0	0	0
Poland		43	14	16	3	3	<1	<1	<1	<1	<1
Romania	6	36	64	26	35	50	10	2	2	2	2
Russian Fed.							28	30	13	13	13
Spain	9	7	6	0	0	0	1	1	<1	<1	<1
Ukraine							6	5	3	2	2
USSR	653	858	558	202	140	100					
Yugoslavia	15		70	17	4	1	1	1	1	1	1
S. America											
Chile			4	4	4	4	4	4	4	4	4
N. America			1								
World Total	865	1091	875	314	343	239	89	85	64	63	63

margin, the largest producer in the world followed by Italy, Romania, Hungary, Yugoslavia, and Poland. The People's Republic of China is probably the largest current producer of hemp fiber, however, reliable figures on fiber hemp production in China are difficult to obtain. Although hemp production increased briefly during both World Wars in response to reduced availability of other fibers, production of hemp has continuously decreased since that time, particularly in countries with market economies. Decreased hemp production is also evident in countries where *Cannabis* production has not been limited by law such as Korea, China, Chile, eastern Europe, and France. This decrease occurred despite the fact that world trade of hemp fiber or finished products has not generally been restricted by law or unusual tariffs. In these regions hemp production decreased presumably because it could not compete economically with other lower priced raw materials or because growers could realize greater economic returns from other crops.

In 1988 the European Economic Community established subsidy payments for production of hemp seed in EC countries (Anon., 1988). In 1989 the EC established a direct subsidy program as well as rules covering production of fiber hemp production (Anon., 1989). These rules require registration of the area to be planted in advance, the use of seed from certified low-THC varieties, and testing of fields to determine THC content. Despite the inducement of substantial and direct subsidy to producers of approximately $400 per acre, no major increases in EC hemp production have been reported to date. Today hemp survives as a relatively minor crop in western Europe where only a few thousand hectares are grown annually. Western European hemp production is currently profitable only because of EC subsidies (Bocsa and Karus, 1998). Hemp production in France for the specialty paper market has remained relatively stable in recent years at about 6,000 hectares per year. Since the early 1990's hemp has also been produced on a small commercial scale in the Netherlands and southern England (approximately 1,500 ha per year), and experimental plantings have been made in other western European countries. Unfortunately, production estimates from these areas do not yet appear in international agricultural production statistics.

Current hemp development efforts in Western Europe include government and EC backed research programs in France, the Netherlands, and Germany. France has had an ongoing research program carried out by the Federation Nationale des Producteurs de Chanvre (FNPC) based near Le Mans for many years (Van der Werf, 1992). Since 1987 the Dutch government has supported active research on the feasibility of fiber hemp production in the Netherlands including germplasm collection and research on agronomy, crop physiology, plant breeding, harvesting, and pulping tests. Both of these programs are intended to explore the use of hemp as a nonfood crop for EC growers and a renewable raw material for pulp and paper production.

In the last several years small-scale experimental production of hemp has also been allowed under permits in Canada and Australia. Recently the Canadian government announced that commercial production of industrial hemp will be allowed in Canada beginning in 1998 under a permit system similar to the one used in Western Europe.

ADAPTATION:

Climatic Requirements

Hemp is well adapted to the temperate zone and will grow under a wide range of environmental conditions. Hemp grows best when mean daily temperatures are between 13° and 22° C (60°-80° F), but will endure colder and warmer conditions. Hemp grows quite well at relatively low temperatures, and young seedlings will tolerate some exposure to frost. Because of this, hemp can be planted earlier than corn in most areas and will develop a closed canopy early in the season allowing increased light interception and rapid growth (Van der Werf et al., 1995a). The best fiber producing hemp varieties require about 4 months without killing frost to produce fiber and about 5.5 months to mature seed (Dewey, 1913).

Moisture

Hemp requires abundant moisture throughout the growing season, particularly while young plants are becoming established during the first six weeks of growth (Dewey, 1913). After they are well rooted, plants can endure drier conditions, however, severe drought hastens maturity and produces dwarfed plants. Studies in Europe indicate that hemp requires 500-700 millimeters (20-28 inches) of available moisture for optimum yield, and that 250-300 millimeters (10-14 inches) of moisture should be available during the vegetative growth stage. These amounts include both precipitation and available soil moisture. In Europe hemp yield is strongly dependent on the amount of rainfall during June and July (Bocsa and Karus, 1998). Crop water use will, of course, vary depending on local soil, climatic, and cultural conditions.

Hemp has been grown successfully under irrigation in Turkey, Spain, and Chile (Dempsey, 1975). Since large-scale hemp production has generally been centered in areas with significant rainfall during the growing season, very little information is available regarding hemp irrigation.

Hemp is quite sensitive to soil moisture conditions. While hemp grows well on soils with high water-holding capacity, good soil drainage is also important to maximize hemp production. Commercial hemp fields grown in Iowa, Illinois, Minnesota, and Wisconsin in 1943 and 1944 had uneven growth and lower yields in slow-draining soils, and hemp plantings often failed or were abandoned in poorly drained fields (Vessel and Black, 1947).

Soils

Although it can be grown on a variety of soil types, hemp does best on loose, well-drained loam soils with high fertility and abundant organic matter (Dempsey, 1975; Van der Werf, 1991). Hemp should not be grown on poor soils (Robinson, 1952). Repeated attempts to cultivate hemp on heavy, low-lying soils have demonstrated that, while these soils may produce some large hemp plants, it is practically impossible to raise a good, even stand of hemp stalks that produce high quality fiber. "In Texas good crops of hemp have been produced on rich dark prairie soil, but on upland soils, subject to drought, the crop has proved a failure" (Dewey, 1901). "Fertile clay loam or silt loam soils, neutral or slightly alkaline, are best for hemp. It will not grow well in acid sandy soils, heavy clay, or gumbo soils, or gravelly soils that dry out quickly. On peaty marshlands the plants may grow large, but the fiber will be small in quantity and poor in quality" (Dewey, 1913). The most productive soils in the U.S. Corn Belt were recommended to maximize hemp production (Robinson, 1952).

Optimum soil pH for hemp production ranges from 5.8 to 6.0 (Bocsa and Karus, 1998).

AGRONOMY:

General agronomic practices for hemp production are well known and will be summarized below. Several extension publications were produced prior to and during World War II to educate growers about producing hemp (Robinson, 1935a; Wilsie et al., 1942; Hackleman and Domingo, 1943; Wilsie et al., 1944). As with most other agricultural crops, the technology employed to produce hemp and the timing and nature of cultural operations will be highly dependent on the end product for which the crop is produced. Hemp grown for high quality textile fiber may be handled much differently than hemp grown for paper or particleboard production. Hemp seed production for planting seed or oil is usually a specialized activity carried out on fields designated for seed production.

Hemp Varieties

As with any crop, the genetic background of hemp can have profound effects on crop productivity. Early European varieties of hemp were selections from indigenous populations and generally were grouped into northern and southern types (Hoffmann, 1961). Northern hemp is characterized by rapid early growth, early flowering, strong branching, and high seed yield. Southern types tend to be slow-growing, tall, late flowering, and have high yield and fiber quality and poor seed yield (Van der Werf, 1991). Selections from Asian hemp landraces and wild populations have also provided the basis for new hemp varieties (De Meijer, 1995).

In the United States, selections from imported Chinese fiber hemp strains made between 1903 and 1909 produced the first improved hemp varieties such as Minnesota No. 8 (Dewey, 1913). From 1913 to 1933 the USDA carried on an active fiber hemp breeding program based on crosses with Chinese germplasm which resulted in development of several high yielding varieties including Kymington, Chington, Arlinton, and Ferramington (Dewey, 1927). Unfortunately, seed stocks from this material were not maintained, and these varieties were lost.

More recent European breeding programs have produced a number of specialized hemp varieties for end uses such as pulp and paper, rope, textile fabrics, and oilseed production. Most hemp varieties are dioecious. Between 1940 and 1960 breeding programs in many countries led to the development of more uniform monoecious varieties (Dempsey, 1975). In the late 1950's F_1 hybrid varieties were developed in Hungary to exploit heterosis (hybrid vigor) in the species. Today fiber hemp breeding programs are continuing in France, the Ukraine, Hungary, Poland, Rumania, and China. An excellent review of the origin and current status of European hemp cultivars was recently published (De Meijer, 1995).

Since the 1920's, plant breeding efforts have more than doubled the fiber content of hemp stems from 12-15% to the current 25-33%. Selection for increased fiber content beyond this level was discontinued since further increases in primary bast fiber are accompanied by increased secondary bast fiber content, which decrease fiber quality for cordage and textiles (Hennink, 1994).

Considerable variation exists within hemp germplasm for levels of the psychoactive drug THC (De Meijer et al., 1992a). Although fiber hemp varieties generally contain much less THC than drug-types of *Cannabis*, a number of fiber hemp varieties have been developed that contain very low levels (less than 0.3%) of THC. Plants with less than 0.3% THC have been accepted by the EC as having no psychoactive properties, and approved varieties may be grown under the EC subsidy program. A list of low-THC varieties approved for use in the EC are included in the Organization for Economic Co-operation and Development (OECD) list of cultivars (Anon., 1996). A new French cultivar has recently been developed which reportedly contains no THC (De Meijer, 1995).

Although many hemp varieties are available, the full genetic potential of hemp has undoubtedly not been realized. The potential for increasing hemp productivity through genetic improvement is probably still substantial. Fiber hemp breeding efforts in North America continue to be impeded by legislative restrictions, and European hemp breeding appears to be limited primarily to state-supported programs in spite of a highly developed commercial seed industry throughout the region.

Seedbed Preparation and Planting

Hemp should be planted on well prepared land. The best crops are produced when fall or winter plowing is followed by preparation of a fine seedbed in the spring. Fertilizer is generally applied as a broadcast treatment in the spring just prior to final seedbed preparation (Dempsey, 1975). No records of banded fertilizer application or minimum-tillage planting of hemp have been found.

Optimum seeding dates vary with local climatic conditions, but are generally as early as possible after the danger of hard freezes has passed. This is usually after planting dates for spring grain and somewhat earlier than planting dates for corn (Robinson, 1952; Dempsey, 1975). In Kentucky, the best results were obtained when hemp seed was sown between March 15 and April 30; in Nebraska from April to June; and in California during February and March (Dewey, 1901).

Although hemp was formerly broadcast seeded and harrowed, almost all hemp is now planted with seed drills using row spacings from 8 to 18 cm (3 to 7 inches). Optimum seeding depth is 2 to 3 cm (3/4 to 1 1/4 inches). Historical seeding rate recommendations vary widely from

40 to 140 kg/ha (36 to 125 pounds/acre) (Dempsey, 1975). Current recommended seeding rates in western Europe range from 50 to 70 kg/ha (45 to 63 pounds/acre) (Kozlowski et al., 1995; Low, 1995). In general, high plant density results in a high quality hemp crop. Weeds are suppressed in high-density stands, eliminating the need for herbicides. Although plant density has little effect on total biomass yield of hemp, high plant density decreases the proportion of leaves and flowers and increases the proportion of stems. In addition, high density stands produce thinner stems with a higher percentage of bast fiber and less woody core in the stem tissue (lower core-to-bark ratio) (Van der Werf, 1991). Excessive seeding rates result in uneven plant size and high mortality of smaller plants (self-thinning).

Fertilizer

In addition to deep soils and adequate moisture, hemp requires substantial available nutrients to produce high biomass yields. Even the earliest investigators in the United States and Europe noted that only soils maintained in a high state of fertility produced good crops of hemp (Anon.,1890; Dewey, 1901 and 1913; Dempsey, 1975; Van der Werf, 1991). When rapid expansion of hemp production became necessary in the United States during World War II, very little information existed on the use of fertilizers on the crop, and several researchers began trials to determine the optimum fertilizer management in the Midwest. Hemp showed a good response to nitrogen, some response to phosphorus, and minimal or negative response to potassium in Iowa (Black and Vessel, 1945). Moderate yield increases from increased nitrogen levels were reported in Illinois and Wisconsin, but fiber quality was poor and increased nitrogen rates resulted in decreased fiber strength (Howard et al., 1946). In Illinois, nitrogen fertilizers increased stem and retted fiber yield, but produced coarse, weak fiber (Hessler, 1947). These trials have led to the popular belief that no fertilizer is required for hemp production, however, these trials were carried out on highly productive soils in the U.S. corn belt and did not account for nutrients available in the soil. Adequate nitrogen should be supplied to allow rapid growth of hemp while avoiding excessive levels which seriously affect fiber quality.

Research on fertilizer requirements of hemp have continued for years in many countries, and a summary of fertilization rates used in various countries is presented in Table 3 (Dempsey, 1975; Van der Werf, 1991 and 1992; Kozlowski et al., 1995; Low, 1995a). Over a wide range of soil and environmental conditions, hemp has been shown to require liberal fertilization for maximum production. Although nutrient uptake by hemp is high, a substantial portion of withdrawn nutrients are returned to the soil as leaves and roots, since only the stems are removed from the field. If the crop is retted in the field, nearly all soluble nutrients are washed into the soil during retting (Dewey, 1913).

Table 3. Hemp fertilization rates.

Country	Year	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
United States	1952	60	30	40
Spain	1955	60	100	70
Italy	1956	40-60	100	70
Netherlands	1957	100-200		
Rumania	1961	50-70	30-60	
Bulgaria	1964	120	90	60
Netherlands	1964	120	80	160-180
USSR	1965	150	90	120
Netherlands	1966	120	100	100
USSR	1966	120	90	90
Rumania	1966	50	100	
USSR	1968	120	90	90
South Korea	1968	100	60	80
USSR	1969	120	90	90
Italy	1975	75-150		
Denmark	1976	140		
France	1982	100-140	80-120	160-200
Poland	1995	90-120	70-100	150-180
United Kingdom	1995	120	100	160

Uniform stem size is desirable for industrial processing of hemp as well as for mechanical harvesting, and stem uniformity is affected by nitrogen fertilization. High levels of nitrogen fertility (200 kg/ha) increased variability in both height and weight of hemp stems compared to moderate (80 kg/ha) nitrogen rates (Van der Werf et al., 1995c). High nitrogen fertility levels were also associated with decreased bark content of hemp stems (Van der Werf et al., 1995a).

Weed control

When grown under favorable conditions, hemp is very competitive with weeds, and no herbicides are generally used in fiber hemp production. Many authors have commented on the exceptional ability of hemp to suppress weed populations (Dewey, 1901 and 1913; Robinson, 1935; Dempsey, 1975, Van der Werf, 1991). Weed suppression with minimal pesticide use is potentially one of the greatest agronomic and environmental benefits of growing hemp in rotation with other crops. Thick stands of hemp have been reported to suppress aggressive weed species including quackgrass (*Agropyron repens*) (Wright, 1918), bindweed (Robinson, 1935a), and yellow nutsedge (*Cyperus esculentus*) (Lotz, 1991). The use of hemp to suppress weed populations may offer conventional and organic growers an effective alternative to current weed control practices. Recent commercial experience in the U.K. has shown that with proper timing of planting, weeds can be almost completely suppressed during the hemp growing season. Uneven stand establishment or planting too early, which may lead to stunting of hemp seedlings by cool weather, can allow spring weeds to compete with hemp (Low, 1995b). Weed suppression by hemp is the result of direct competition with weeds during the hemp growing season, however, and weeds will begin to grow again after the hemp crop is harvested. Residual weed suppressing compounds have not been reported in the soil following hemp production.

Several climbing weeds have sometimes caused harvesting problems with hemp including black bindweed (*Polygonum convolvulus* L.), vetch (*Vicia* sp.), and morning glory (*Convolvulus sepium* L.) (Dempsey, 1975). Morning glory is a particular problem in hemp seed production because its seed is the same size as hemp and is very difficult to separate by screening (Robinson, 1935a).

Insects, Diseases, and other pests

Insect and disease pests have generally not been considered agriculturally significant problems in industrial hemp production, and pesticides are not commonly used in hemp production. This does not mean that hemp is free of pests or that there is no potential for pest problems with hemp.

Significant insect damage to hemp fields is apparently rare despite reports of nearly 300 insect pests associated with the crop. Most serious among these are the European corn borer (*Ostrinia nubilalis*) and the hemp borer (*Grapholita delineana*). Feeding by these stem boring insects causes formation of stem cankers which weaken hemp stalks. Heavy infestations of European corn borer cause collapse of the entire plant. In addition, stem borer entry holes provide openings for fungal attack of the stems. Hemp borers also destroy the upper parts of the plant by eating hemp leaves and seed. Hemp seedlings can be completely destroyed by many species of cutworms prior to stand establishment. In cooler regions, slugs cut off seedlings and shred older plant leaves. Many other insects attack hemp roots, stems, leaves, and flower parts but generally cause only minor damage (McPartland, 1996b).

Although a number of plant diseases have been reported on hemp, major disease outbreaks are uncommon. The most important disease of hemp is gray mold, caused by the fungus *Botrytis cinerea*. This disease attacks hemp stems under conditions of cool to moderate temperature and high humidity. In severe cases *B. cinerea* can completely destroy a *Cannabis* crop within a week. Hemp canker, a fungal disease caused by *Sclerotinia sclerotiorum* (Lib.) Mass., attacks hemp stems resulting in wilt and stem breakage (McPartland, 1996a). Under cool, wet growing condition in the Netherlands, severe hemp yield reductions were recently reported due to *B. cinerea* and *S. sclerotiorum*. Fungicide applications every 10 to 14 days were required to keep the crop disease free (Van der Werf et al., 1991). Seed and soil-borne diseases such as *Pythium* and *Fusarium* are commonly controlled by seed treatment with fungicides prior to planting (Robinson, 1943; Dempsey, 1975). Many other minor diseases have also been reported on hemp (McPartland, 1996a).

Several species of nematodes are known to infest hemp including the southern root knot nematode, *Meloidogyne incognita* (McPartland, 1996a), and, more rarely, the northern root-knot nematode, *Meloidogyne hapla* Chitwood (Norton, 1966). De Meijer has identified significant variation for resistance to *M. hapla* among accessions in the *Cannabis* germplasm collection in the Netherlands which may allow breeding resistant lines (De Meijer, 1993b). The bulb or stem nematode (*Ditylenchus dipsaci* [Kuhn] Filipjev) has been reported in Italy, Germany, Russia, and North America. Nematodes generally appear to be a minor problem in hemp production.

Two groups of parasitic plants are known to attack hemp. Broom rape (*Orobanche ramosa*), a parasitic annual plant that attacks hemp roots as well as tomato and tobacco, is one of the most serious pest problems associated with hemp production (Dewey, 1901; Robinson, 1935; Dempsey, 1975; McPartland, 1996a). Infected plants usually die before reaching maturity. The Hungarian varieties V7 and Kompolti V-7L are resistant to broom rape. Most monoecious varieties are apparently susceptible, however, the monoecious Russian variety Juzanna Odnodmnaja is reportedly resistant (Dempsey, 1975). In addition, five species of dodder (*Cuscuta spp.*) have been reported to infest above ground *Cannabis* tissue (McPartland, 1996a).

Birds feed voraciously on *Cannabis* seeds. Many bird species have been reported as pests in hemp, and their feeding can lead to substantial crop losses (McPartland, 1996).

Although hemp is comparatively free of major pests, introduction of new crops to the region and their increased production may result in unforeseen pest problems. High-density planting, increased fertilizer use, and irrigation have often increased incidence of pest problems in other crops, and such problems should be anticipated with intensive hemp production.

Harvest

When grown for the highest quality fiber, hemp is harvested when the staminate plants have finished flowering, but before seed has matured. This is sometimes referred to as "technical maturity" (Van der Werf, 1991). Early in this century and during World War II, horse or tractor drawn harvester-spreaders were used to cut hemp stems and lay them in windrows on the ground for field retting (Figure 3). A second machine was later used to gather and tie field dried stem bundles for pickup and delivery to the mill.

Figure 3. Cutting hemp near Waupun, Wisconsin (Wilsie, 1942).

A similar harvest system is still found in Europe using more modern, specialized equipment. These systems are designed to maintain the parallel alignment of hemp stems throughout harvest and processing in order to maximize the recovery of long textile fibers from the stems. Because it maintains the alignment of hemp stalks during handling, this equipment has limited harvest capacity per day. Additional innovation in harvesting equipment and practices is still needed to improve the efficiency of long fiber production. In southern Europe, fiber harvest usually occurs in late July and early August, while in northern France and the Netherlands harvest is in late August and September (Van der Werf, 1991).

It is possible to harvest unretted stalks using modified forage or sugar cane harvesting equipment as has been done for kenaf (Wood et al., 1978; Quick et al., 1980). Recent harvests in western Europe have used conventional forage harvesters to chop and windrow hemp for field retting (Figure 4). Once retting is complete, the crop is treated much like a hay crop. After turning with hay rakes or tedders and field drying, the crop is harvested with large round or square balers. This type of harvest system has the advantage of using efficient, readily available equipment, but does not maintain stem orientation and precludes the production of long fiber with traditional fiber separation machinery. This harvest method is currently being used in Europe for production of tow for the paper industry, but could also produce short fiber for spun or nonwoven textiles.

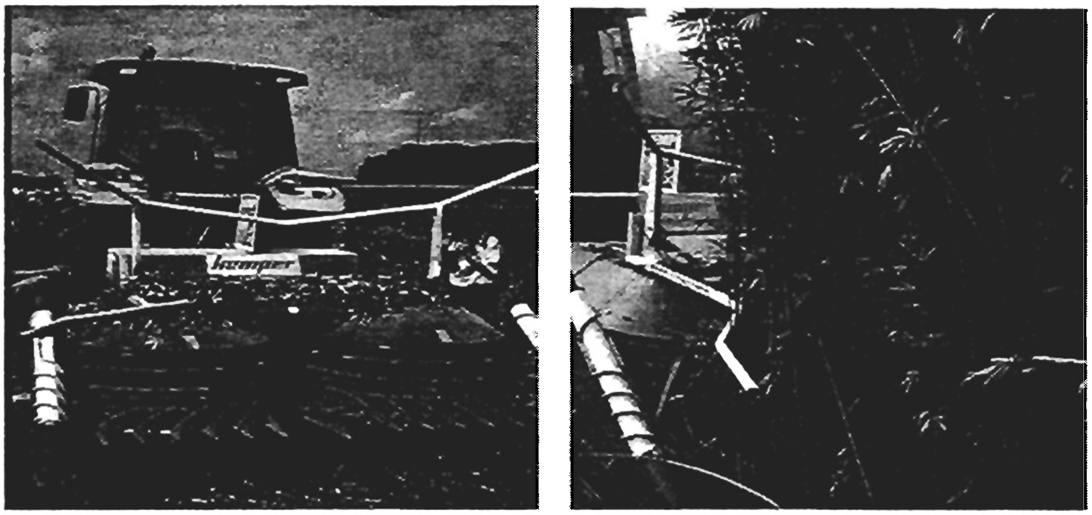


Figure 4. A modern European forage chopper (left) cutting and windrowing hemp (right) (Leson, 1996).

Fiber yield continues to increase after flowering until biological maturity (seed maturity) is reached and the plants senesce and die (Van der Werf, 1991). Stem fiber tends to become somewhat coarser and weaker, however, as the seeds mature and the stems become more lignified. End products such as paper or particleboard may not demand the same fiber qualities needed for textiles and, as a result, may not require retting and complete fiber separation. This may allow later harvest, which will result in greater total biomass yield and may include some mature seed as another byproduct. Late harvests will increase weather risks since the moisture content of hemp, like most other crops, must be below 15% before baling to avoid microbial breakdown in storage. In the PNW it may also be possible to extend the harvest season into winter east of the Cascade Mountains by directly harvesting dry stems after the crop has been killed by frost and allowed to dry while still standing. This will not work in the mild winter areas west of the Cascades due to heavy winter rainfall.

Another approach to extending harvest timing is the use of anaerobic storage for wet or green-chopped hemp employing the same equipment and techniques used for silage production. Preliminary tests of anaerobic storage of hemp have been completed in the Netherlands. After field decortication and ensilage, bark and core fractions were separated by water flotation (bark sinks while core material floats). Additional research is needed to determine the effect of anaerobic storage conditions on fiber strength (Huisman et al., 1995). While this method may work well for wet process manufacturing such as paper production, it is not well adapted for dry process composite board production.

Retting

If hemp fibers are to be made into cordage, textiles, or high quality industrial products, the fibers must be separated from the stalk. Retting is a microbial process which breaks the chemical bonds that hold the bast fiber bundles together. This partial rotting of the stem allows easy separation of individual fiber strands and the woody core and is common to all bast fibers used in high quality textiles, including hemp. Without retting, hemp fibers tend to break if stems are bent or broken (Robinson, 1935). Since it is a biological process, retting requires both available moisture and temperatures warm enough for microbial action to occur. The two traditional types of retting include water retting, in which plant stems are immersed in water (rivers, ponds, or tanks), and field or dew retting, in which the crop is spread in the field where rain and dew provide the moisture for retting.

Water retting produces fiber of greater uniformity and higher quality than can be produced by field retting, but is very labor and capital intensive. In addition, water retting requires large volumes of high quality water that must be cleaned before discharge after the retting process is complete (Fuller et al., 1946b). The vast majority of hemp fiber currently used in textiles is water retted in China or Hungary. Water retting has been largely abandoned in countries where labor is expensive or environmental regulations are enforced.

Field or dew retting has been used extensively with hemp because it is inexpensive, has been mechanized, and does not involve the use or treatment of water. In this process (Figure 5.) stems are cut, laid in the field in thin swaths, and left exposed to the weather for retting.

Figure 5. A field of retting hemp (Wilsie et al., 1944).

Turning the swaths is often needed to ensure uniform retting, especially if moisture is uncertain. Field retting may take as little as 1 to 2 weeks during warm, humid weather conditions, but usually requires 4 to 5 weeks. In colder climates, hemp is sometimes left for the winter under snow, however, the crop can be over-retted by thaws and must be picked up quickly in the spring (Wright, 1918). Knowledge of local climatic conditions is essential to estimate the risks involved in field retting (Fuller et al., 1946a). Control of the factors affecting field retting is very difficult, and fiber quality from field retted stems can vary greatly with environmental conditions during retting (Hessler, 1945). Field retting in areas without dependable moisture can be quite risky (Robinson, 1946). Excessive moisture can cause overretting in which the retting organisms attack the fiber cellulose resulting in loss of fiber strength. Weather must also be dry enough once retting is completed to allow sufficient drying that the stalks can be baled and stored.

The use of irrigation systems to supply moisture for field retting may add some measure of control to this process but will, of course, add to the cost of production and limit production to irrigated fields.

Considerable research effort has been directed toward improving retting efficiency by artificial culturing and use of the microorganisms responsible for retting or the direct use of retting enzymes in both water and field retting systems. While these systems have in some cases been technically successful, their economic viability has yet to be proven.

Fiber Separation

Breaking is the first step in mechanical separation of the fiber from the stalks. Dried stalks are passed between fluted rollers to crush and break the woody core into short pieces (known as hurds) which partially separate from the long fiber in the process. The remaining hurds and fiber are separated in a process called scutching. In the modern process, fiber bundles are gripped between rubber belts or chains and carried past revolving drums with projecting bars that beat the fiber bundles, separating the woody core and broken or short fibers (tow) from the remaining long fiber. The long fiber (line fiber in the trade) comes from the machine clean and ready for combing (Figure 6.).

Retting, breaking, and scutching are the traditional methods of preparing hemp line fiber and tow for twisting into twine or rope or for spinning into yarn. Although partially mechanized, these basic processes are functionally identical to the ancient hand methods. These processes are time consuming and require skilled workers as well as considerable investment in capital equipment.

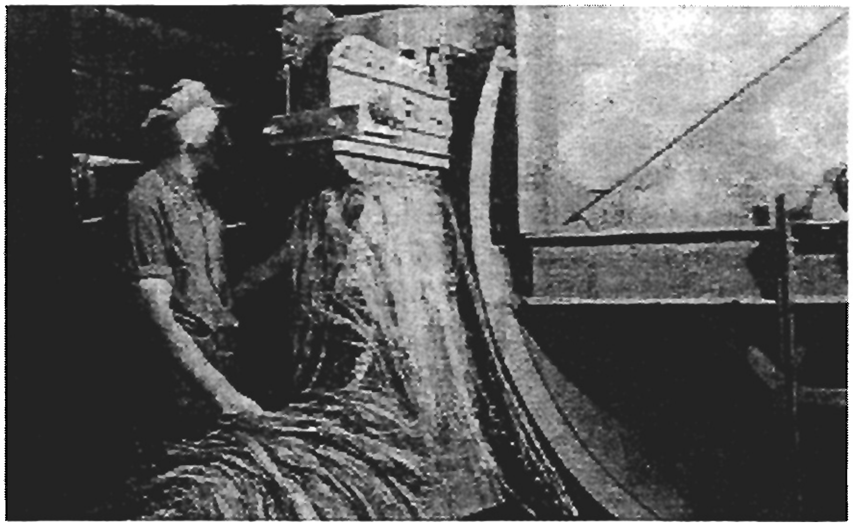


Figure 6. Hemp fiber emerging from the scutcher (Dempsey, 1975).

It is also possible to mechanically convert virtually all of the bark fiber directly into tow using commercially available flax breaking and tow processing and cleaning machinery. This eliminates the traditional long fiber scutching process and allows processing of randomly oriented baled straw. Compared to long fiber scutching machinery, tow processing equipment usually has higher throughput, requires fewer and less skilled workers, and can be purchased at somewhat lower initial cost. The main disadvantage of a tow processing system is that all of the stem fiber, including the long fiber, is cut into short lengths. Several European manufacturers produce short fiber processing machinery (Gschoßmann, 1995; Charle, 1996).

Research has been under way in Europe for many years to investigate methods of bast fiber separation that do not rely on traditional retting and scutching. Steam explosion is an old method of fiber separation that is now under study in Germany for use with hemp. In this process, raw material (usually decorticated fiber) is impregnated with alkali or detergent solutions, subjected to steam pressure for a period of time (1-30 minutes), and the fibers are then blown apart when the pressure is released. Fibers are then washed, rinsed, dried, and carded before spinning (Nebel, 1995). A fiber separation method using the energy of ultrasonic waves to separate individual bast fibers has also been developed in Germany. In this technique, green (unretted) or partially retted straw is mechanically broken between rollers, washed to remove dust and soluble components of the stem, and subjected to ultrasonic treatment under water. Fibers are separated by the very high local pressures created by collapse of gas bubbles formed in the liquid by the ultrasonic waves. The fibers are then washed, dried, and carded to remove the remaining woody core (Zimmer and Kloss, 1995). Both methods are appealing in that they move bast fiber processing closer to an industrial process and minimize weather and material handling problems associated with retting. Both processes, however, produce only short fiber. Precise control of process parameters is critical with either technology to obtain consistent results and avoid fiber damage. Neither of these technologies has yet moved beyond laboratory or pilot scale trials, and the costs and throughput of commercial machinery is not known.

Yield

Yield is one of the most important parameters to consider in assessing the feasibility of any crop, and also one of the more complex. Reported yields for hemp vary widely, and some care must be taken when studying yield figures. Differing units of measurement can cause significant misunderstanding of results. European authors generally report total above-ground dry matter in tonnes/ha, that is, metric tons (1 metric ton = 1,000 kilograms) per hectare (10,000 square meters). Those using the English system of measurement report yield in tons/ac, usually short tons (1 short ton = 2,000 pounds) per acre (43,560 square feet). Initial excitement over apparent high yields reported in metric units often evaporates once the conversion is made to more familiar units. Stems, leaves, and seeds combine to make up total hemp biomass above ground. For cordage or textile use, hemp fiber may be extracted from the stem, but only a portion of the stem is fiber. In addition, most of the leaves senesce and fall off the plant and are returned to the soil by the time flowering begins. Most modern authors are also careful to report dry matter rather than fresh (green) weight. Moisture content of the crop will, of course, be directly related to yield, and field dried weight can be much different from oven-dry weight.

Agricultural researchers from many countries have reported wide variations in hemp yield. In the United States, farmers' dry stem yields ranged from 2 tons/acre to 12.5 tons/acre, but averaged 5 tons/acre under good conditions (Dewey, 1913). Early reports from Germany (1919) indicate that dry stem yield of hemp varied from 3 to 10 tonnes/ha (1.3 to 4.5 tons/acre). In over 11 trials conducted in Sweden from 1959 to 1963, the stem yield of the variety Fibrimon 21 averaged 8.7 tonnes/ha (3.8 tons/acre). In Denmark, Fibrimon 21 averaged 8.9 tonnes/ha (4 tons/acre) in 8 trials from 1965 to 1969 (Van der Werf, 1991). Yields in France typically range from 8 to 10 tonnes/ha (3.6 to 4.5 tons/acre). In Italy, yields as high as 15 tonnes/ha (6.7 tons/acre) have been reported. Trials in the Netherlands from 1987 to 1989 recorded yields of 9.4 to 13.6 tonnes/ha (4.2 to 6.1 tons/acre) of dry stem matter (Meijer et al., 1995). A yield of 19.4 tonnes/ha (8.7 tons/acre) was recently reported in the Netherlands using a late maturing Japanese landrace (Van der Werf et al., 1995b). Most of these yields are based on harvests from small plots, and average yield attained by commercial growers may be somewhat lower. Recent commercial production in the southern U.K. has produced average dry matter yields of approximately 5 to 7 tonnes/ha (2.2 to 3 tons/acre) on several thousand acres over several years (Low, 1995a and 1995b). Experimental production during 1995 and 1996 in Ontario, Canada yielded 2.5 to 3 tons/ac (Kime, 1996).

Several approaches to increasing hemp yield are under investigation in Europe. Earlier planting may improve productivity by promoting earlier canopy closure, increasing the total amount of light interception during the season. This may be possible due to the ability of hemp to grow at lower temperatures than crops such as corn, but will increase the risk of frost injury. Optimization of planting density and rates of fertilizer application will help to reduce stand losses through self-thinning. Development of hemp cultivars with lower lignin content in the stem could improve both efficiency of cellulose synthesis and quality of stem dry matter for paper production. The use of late flowering varieties may increase stem yield by prolonging the period of vegetative growth and reduce the diversion of photosynthetic products to flowers and seed (Meijer et al., 1995).

Fiber hemp has not been produced in the PNW, even on a research scale, in many decades. For this reason, the harvestable yield of modern fiber hemp varieties under conditions in the region is unknown. The only way to reliably determine the potential of hemp in the PNW is through field testing over several years at multiple locations under commercial production conditions.

Transport and Storage

Unprocessed hemp biomass, like agricultural residues or other fiber crops, is very bulky material, and the costs of transportation and storage are a major consideration in the large-scale use of these products, regardless of their end use. The low density of stem core material from bast fiber crops, including hemp, is a major factor limiting their utilization in pulping. An inexpensive method of increasing their density is required to reduce transportation costs and ease handling in the mill (Wood, 1981).

Unlike wood fibers such as Douglas fir, which are resistant to microbial breakdown and can be stored outdoors, hemp will require protection from the elements to maintain quality, particularly if grown in high rainfall areas of the PNW. Even in low rainfall areas of the intermountain region, hay and straw are commonly stored under cover to reduce spoilage due to weather. 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 ton, assuming a six month storage period. This figure includes costs of construction, interest, repairs, insurance, and straw losses (Mackey et al., 1991). Costs should be comparable for hemp straw. As with other agricultural fiber crops, losses of dry matter and quality should be expected in storage. These factors will affect the cost and quality of the end products.

Seed Production

Since hemp grown for fiber is usually harvested before the female plants flower, production of planting seed or oilseed involve somewhat different crop management. In general hemp seed production requires a warmer climate and a five to six week longer growing season than hemp fiber production to allow time for seed maturation (Bocsa and Karus, 1998). Historically, hemp seed planted for fiber production in the U.S. Midwest was produced primarily in Kentucky.

Hemp seed production fields are planted on much wider row spacing and at much lower seeding rates (10-24 kg/ha) than fiber production fields to encourage development of large, branching plants that seed heavily (Dempsey, 1975). Row spacing wider than 40 centimeters (16 inches) promotes branching and increases seed yield, particularly during drought conditions. At low plant densities common in seed fields, the hemp crop may not suppress weed growth, and cultivation or herbicides are often used to control weeds in traditional European hemp seed production. Tall, heavily branched hemp plants are difficult to harvest with conventional combines, and in many countries hemp planting seed is still harvested by hand. Maximum expected seed yield using these practices is 1,000 kg/hectare (893 lb/ac). In Europe the hemp stalks left after seed crop harvest are either burned or chopped and then worked into the soil in countries where field burning is prohibited (Bocsa and Karus, 1998).

In some countries hemp is grown as a dual-purpose crop which is harvested for both seed and fiber when seeds are near maturity. In France, hemp seed is directly combined around the 15th of September using a combine set to cut 1.5 meters (5 feet) above ground level. The combine cuts the upper stems and threshes the seed in the field. The remaining crop is cut using a mower-conditioner and baled after field drying. Seed yields using this system range from 600 to 1000 kg/ha (536 to 893 pounds/acre) (Van der Werf, 1992).

In Hungary, dual-purpose hemp is planted on 20, 30, or 40 centimeter (8, 12, or 16 inch) row spacing at high enough plant density (20 seeds per meter or 7 seeds per foot of row) to ensure weed suppression. Narrow row spacing also helps to promote relatively uniform seed maturation. Seed is harvested with a combine harvester modified to cut higher off the ground than normal grain combines as in the French production system. Axial-flow combines are particularly well adapted for threshing and cleaning hemp seed. After seed harvest the stems are cut, field retted and dried, and then baled. Maximum expected seed yield from dual-purpose is 1000 kg/ha (893 pounds/acre), and dry hemp stalk yield is typically 4.5-6.7 tonnes/ha (2-3 tons/acre) (Bocsa and Karus, 1998).

Fiber from seed crops is usually rather coarse and weak compared to crops grown for fiber only (Ash, 1948; Dempsey, 1975). This is caused by the increasing lignification of hemp stems as the plants mature beyond flowering (Bocsa and Karus, 1998). As a result, fiber from hemp seed production fields is often used only for relatively low value products such as pulp and paper production, and hemp stalks from seed production fields usually have a lower market price than those from fiber production fields.

Since latitudes in the PNW are similar to those in Europe, it may be possible to produce seed crops of some hemp varieties in the region. Reliable seed production of the more desirable (later maturing) fiber varieties in the PNW may not be practical due to the interference of fall rains with seed harvest operations.

CLIMATE AND SOILS OF THE PNW:

The Pacific Northwest lies between latitude 42° to 49° north, approximately half way between the equator and the north pole. The regional climate is characterized by relatively dry, warm summers and cool winters with a distinct winter precipitation pattern. Climatic variation in the PNW is primarily attributable to the Cascade Mountain range which separates the high rainfall areas of western Oregon and Washington from the more arid intermountain region and creates a major barrier to the moderating influence of the Pacific Ocean. West of the Cascades and in areas influenced by marine air (primarily along the Columbia River Gorge), annual precipitation totals are relatively high, temperature ranges are low, and the frost-free growing season is generally long (ranging from 240 to 300 days). In the rain shadow of the Cascades and the intermountain region, total precipitation is low, seasonal temperature ranges are greater, and the duration of the frost-free growing season is highly variable (from less than 30 to 120 days), except for the Columbia and Snake River borderlands. Mean dates for last spring and first fall killing frost in the PNW are shown in Figure 8. Regional average annual temperature and precipitation patterns are shown in Figure 9 (Jackson and Kimmerling, 1993).

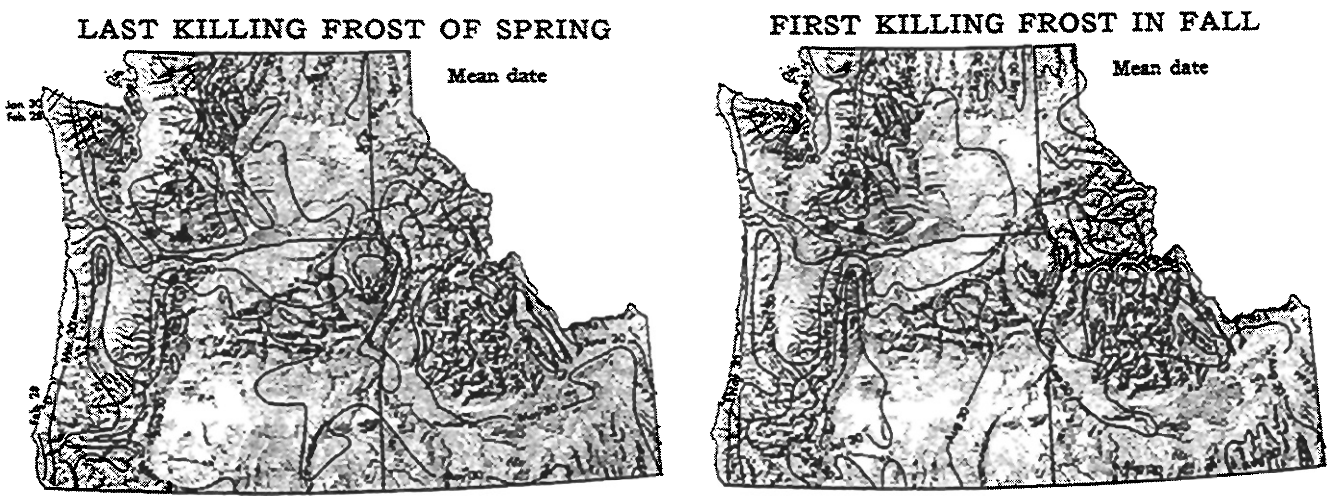


Figure 8. Mean annual dates of killing frost in the Pacific Northwest (Jackson and Kimmerling, 1993).

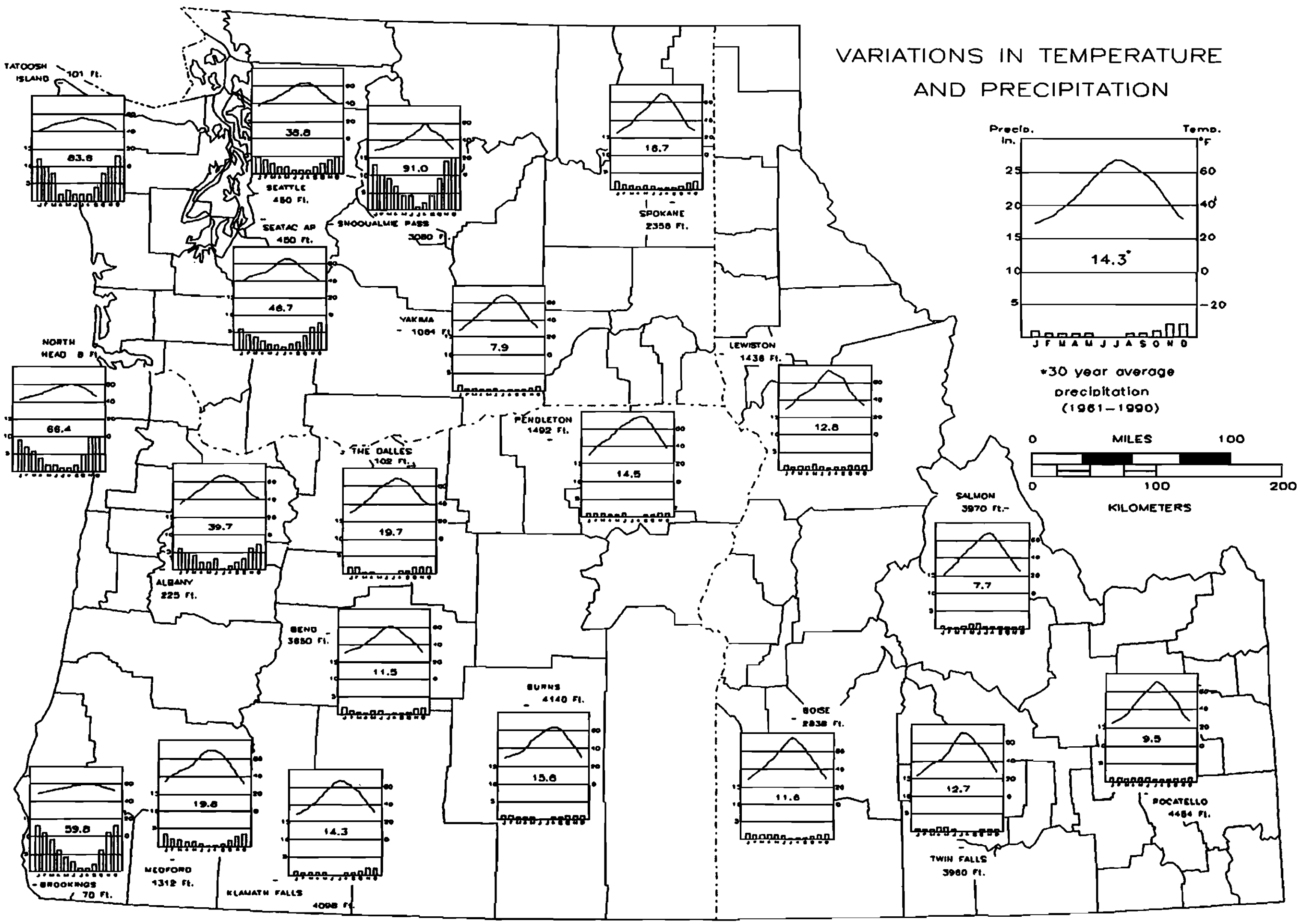


Figure 9. Precipitation and mean temperature in the Pacific Northwest. At each location monthly mean temperature (°F) is shown by the line graph and mean monthly precipitation (inches) is shown by the bar graph (Jackson and Kimmerling, 1993).

Agriculture in the Pacific Northwest is extremely diverse, due to the wide range of climate, soils, water availability and topography in the region. Approximately 29% of the land area of the region is devoted to agriculture, and about 42% of agricultural lands are cultivated cropland. Over 33% of PNW cropland is irrigated by diverted surface water or pumped groundwater (Table 4). Following the rapid expansion of irrigated acreage by

Table 4. Cropland area in the Pacific Northwest in acres (1992 Census of Agriculture).

	Irrigated	Non-Irrigated	Total	% Irrigated
Idaho	3,260,006	3,041,856	6,301,862	51.7
Oregon	1,622,235	3,415,529	5,037,764	32.2
Washington	1,641,437	6,357,982	7,999,419	20.5
Total PNW	6,523,678	12,815,367	19,339,045	33.7

new water system development in the 1950's and 60's, cropland acreage in the region has now stabilized at about 20 million acres. Under pressure from urban and commercial uses, a great deal of land is being converted from agriculture to non-farm uses despite laws intended to protect agricultural land in Washington and Oregon. These cropland losses are most frequent on highly productive soils within commuting distance of metropolitan centers. Future additions of cropland in the region will probably depend on new irrigation development, an unlikely prospect in the face of current water deficits throughout the PNW.

POSSIBLE HEMP ADAPTATION TO THE PNW:

Because of its requirement for an extended frost-free growing season, hemp could be grown most reliably in the existing agricultural areas of the Columbia and Snake River basins and in the lowland areas between the Coast Range and the Cascades from the Rogue Valley in the south to Puget Sound in the north (Figure 10). Since it is primarily adapted as a summer annual, industrial hemp will almost certainly require supplemental irrigation to maximize productivity in the PNW. Cultural requirements should be similar to those currently used for production of field, silage, or sweet corn in the region; however, hemp can generally be planted somewhat earlier than corn, possibly extending the growing season by several weeks. Early experience in the United States indicated that hemp grows well in areas where corn produces high yields. This generally agrees with results from other countries.

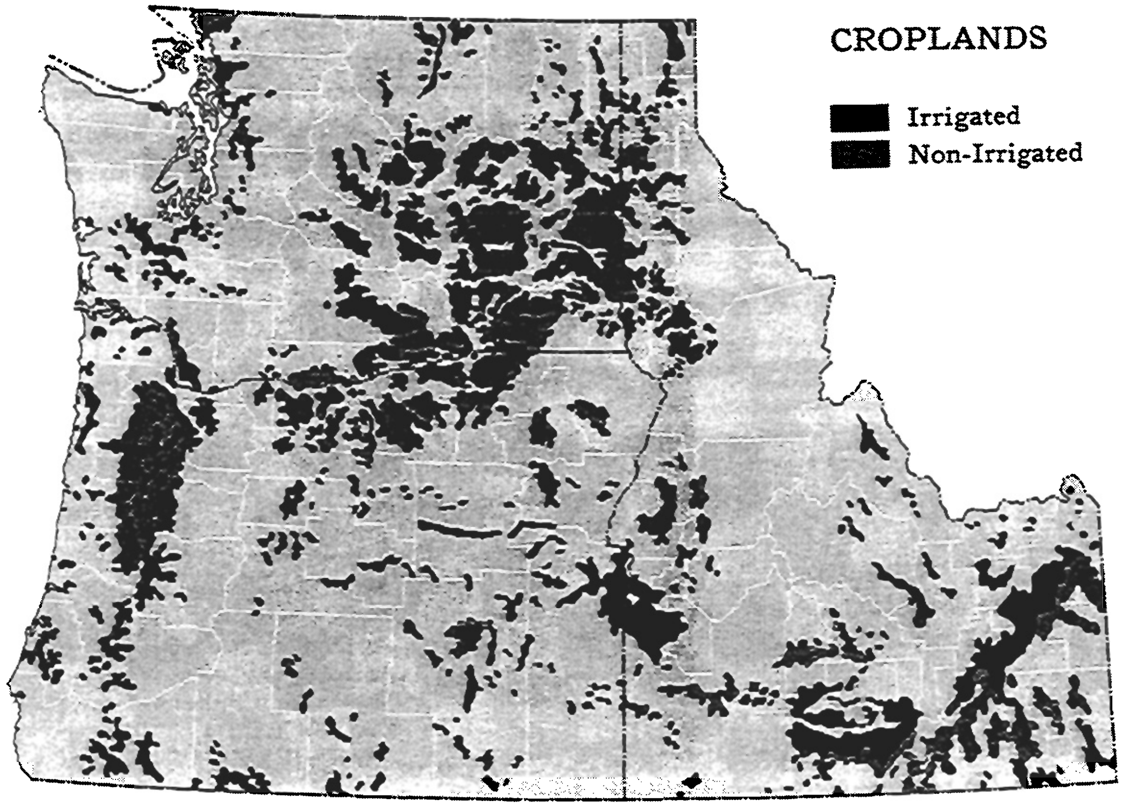


Figure 10. Distribution of irrigated and non-irrigated cropland in the PNW (Jackson and Kimmerling, 1993).

Using corn as a model, the areas of current corn production in the PNW (Figure 11.) are probably also the areas of maximum expected hemp productivity.

Due to the distinct winter rainfall pattern in the PNW, hemp production without supplemental irrigation will probably not be economically feasible. While well-established hemp is somewhat drought tolerant, both yield and fiber quality are reduced by drought stress. With early spring planting, it may be possible to grow hemp using available soil moisture and rainfall in some areas west of the Cascades, much like spring cereal grains. Risks associated with such production will be high and yields may be quite variable from season to season. Erratic crop performance in non-irrigated hemp trials in Oregon during the 1930's provide evidence of this risk. The lack of summer rainfall may put PNW growers at a significant disadvantage compared to growers in areas with regular summer rainfall such as the U.S. midwest and western Europe. Severe yield reductions or crop failure have been reported with hemp under drought conditions, and moisture is also required for field retting. Reliable irrigation can, however, reduce weather risks associated with rainfed production. Irrigation is not only an additional economic cost of production, but is also an environmental concern, especially considering recent controversies surrounding agricultural water use and increasing demand for in-stream water rights in the PNW.

FIELD CORN FOR ALL PURPOSES

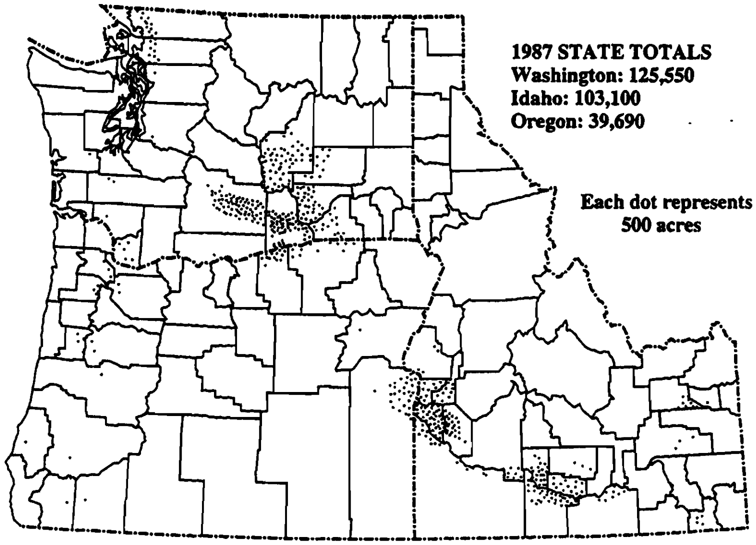


Figure 11. Distribution of field corn production in the PNW (Jackson and Kimmerling, 1993).

Unless industrial hemp production is extremely profitable, it is unlikely that more than a small percentage of the total available acreage will be devoted to its production in preference to higher value crops. Hemp may, however, provide an excellent rotation for traditional crops to avoid outbreaks of insect and disease problems or to suppress weeds.

HEMP PRODUCTION BUDGET:

Net return to growers of industrial hemp will depend on several factors including cost of production, yield, and the market value of the harvested crop. Many of the production costs for industrial hemp will be quite similar to other crops grown in the region. Table 5 is a possible industrial hemp production budget that was developed using typical costs associated with irrigated field corn in the Pacific Northwest (Cross and Smith, 1991). These include not only the variable production costs such as tillage, seed, and fertilizer; but also the fixed costs including insurance and amortization of equipment costs.

As with any cost analysis, many assumptions have been made to produce this budget, and a different set of assumptions will produce different results. In this example, production practices were chosen to maximize stem dry weight yield for production of composite

Table 5. Industrial Hemp Production Budget

	Gross Yield (tons/acre)	Hemp Price ($/ton)		
Assumptions:	5	$75.00		
Variable Costs			$/acre	$/ton dry wt.
Cultural				
Tillage and Planting			$40.00	$8.00
Hemp Seed (25 lb/ac @ $1.36/lb)			$34.00	$6.80
Fertilizer (600 lb/a 16-16-16 @ $250/ton) + Application			$85.00	$17.00
Irrigation			$62.00	$12.40
Total Cultural			$221.00	$44.20
Harvest				
Forage chopper ($3.00 / ton)			$15.00	$3.00
Raking ($1.50 / ton)			$7.50	$1.50
Baling, Large Square Bales ($9.80 / ton)			$49.00	$9.80
Loading and Trucking ($3.00 / ton)			$15.00	$3.00
Total Harvest			$86.50	$12.80
Miscellaneous				
Operating Capital Interest			$29.78	$5.96
Pickup			$7.68	$1.54
Farm Truck			$6.34	$1.27
General Overhead			$20.00	$4.00
Total Miscellaneous			$63.80	$12.76
Total Variable Costs			$371.30	$69.76
Fixed Costs				
Land Rent			$150.00	$30.00
Insurance - Machinery & Equipment			$3.00	$0.60
Irrigation System - Depreciation & Interest			$44.00	$8.80
Machinery and Equipment - Depreciation & Interest			$48.00	$9.60
Total Fixed Costs			$245.00	$49.00
Total Production Cost			$616.30	$118.76
Gross Income			$375.00	$75.00
Net Projected Return			**($241.30)**	**($43.76)**
Break-Even Yield (tons/ac), Total Variable Cost			4.95	
Break-Even Yield (tons/ac), Total Cost			8.22	

wood products or paper. While these are relatively low value end uses, they may also take advantage of existing regional production facilities. Maximizing production of high quality textile fiber would require alteration of some practices such as increasing seeding rate (and plant density) to produce more slender plants with higher fiber content, but may produce lower overall dry matter yield. The assumed dry matter yield of 5 tons/acre is consistent with the higher average yields reported in western Europe using well-adapted hemp cultivars. Currently the price for baled, dry hemp stems proposed by an Oregon hemp composite manufacturer is $50 per ton. This is similar to prices currently paid for whole stalk kenaf in the southeastern U.S. (Noblitt and Bitzer, 1995). Since PNW wood chip prices have been rising over the past decade, and this trend is expected to continue; the assumed price of $75 per dry ton was used for this analysis. The assumed cost of hemp seed is the average of prices reported for commercially available European hemp varieties, however, the cost of shipping from Europe was not included (De Meijer, 1995). The cost of locally produced, open-pollinated seed may ultimately be somewhat less than the assumed cost in this model, however, seed from well-adapted, elite lines or hybrid seed will probably cost more. Fertilizer application requirements can vary widely over the region depending on many factors, and a moderate application rate was chosen. Harvest costs are based on current cost of operating silage corn harvesters (8 to 10 tons of dry matter per acre) as well as local cost of raking and baling hay and grass seed straw. Crop storage costs have not been included in this budget, and should be added if on-farm storage is anticipated. In addition, no costs associated with retting, such as additional irrigation, are included. Trucking costs are based on relatively close proximity to storage and processing facilities. While some of these costs may be covered by the hemp processor rather than directly by the grower, all costs of production will ultimately be reflected in the price buyers can pay for the raw material.

The purpose of this budget is to provide a worksheet that will allow growers and researchers to evaluate the economic potential of hemp under their local conditions. Costs, particularly fixed costs, can vary widely among growers depending on their particular farming operation. Land prices in the PNW are quite high compared to some other regions and are increasing rapidly under the pressure of urban growth. Growers in summer rainfall areas of North America will have lower costs without the requirement for irrigation but may be at greater risk of yield reductions due to moisture stress. From this preliminary budget, however, it is apparent that either hemp yield or hemp prices must be substantially higher than current assumed levels for hemp to be economically viable for PNW growers.

Since both hemp yield and price may be quite variable depending on production conditions and the value of the end product, net return to the grower at various yield and straw price levels is shown in Table 6. Yield levels in this table represent a range from relatively low productivity that might be expected using poorly adapted germplasm under less than optimal conditions to high productivity that can result from growing well-adapted varieties under good conditions. Price levels span the range from current low prices for competing raw materials (wood chips) through very high prices that may be experienced during raw material shortages. Other assumptions in the spreadsheet did not change.

Table 6. Net return per acre from hemp production at various price and yield levels.

Yield (tons/ac)	Price ($/ton) 50	75	100	125
3	(431.70)	(356.70)	(281.70)	(206.70)
4	(399.00)	(299.00)	(199.00)	(99.00)
5	(366.30)	(241.30)	(116.30)	8.70
6	(333.60)	(183.60)	(33.60)	116.40
7	(300.90)	(125.90)	49.10	224.10

Production of high value specialty products from hemp may allow buyers to offer higher farm gate prices for unprocessed hemp. Higher raw material prices will obviously improve the economic outlook for hemp production. Higher quality end products usually require more stringent quality control in all phases of raw material production, storage, handling, and processing compared to bulk commodities, which may increase costs.

Current demand for hemp seed as a source of oil and as a food ingredient is strong, and bulk hemp seed prices are quite high ($0.45/lb). Dual-purpose (oilseed and fiber) hemp production may increase grower returns by providing income from both seed and straw sales. Possible net returns from dual-purpose hemp production at various seed yields and prices are shown in Table 7. Returns were calculated using a spreadsheet similar to the

Table 7. Net return per acre from dual-purpose hemp production at various seed price and yield levels. Straw yield is assumed as 2.5 tons/acre at $75/ton.

Seed Price ($/lb)	Seed Yield (lb/acre) 500	750	1000
0.30	(255)	(181)	(106)
0.35	(231)	(143)	(56)
0.40	(206)	(106)	(6)
0.45	(181)	(68)	45
0.50	(156)	(31)	94
0.55	(131)	7	144

one used in the previous example. The cost of combine seed harvest ($20/acre) was added to the variable costs. Hemp straw yield was assumed to be 2.5 tons/acre with a price of $75 per ton. Other assumptions were identical to those used previously.

From this analysis it is apparent that both high seed yield and high seed prices are required to provide positive returns to growers from dual-purpose hemp production. Hemp seed prices in the upper range shown in Table 7 may be justified for some high value end products, however, most current hemp seed buyers are actively seeking lower priced sources of bulk seed. Hemp stalks harvested following seed production are generally highly lignified and contain lower quality fiber than stalks from fiber production fields. As a result, stalks from dual-purpose hemp production usually sell for a lower price than stalks from fiber production fields and are unlikely to contribute substantial additional net returns to growers.

CONCLUSIONS:

Industrial hemp production has recently been the subject of increasing study around the world. In the PNW, regional paper and wood products companies are becoming more interested in agricultural fiber sources to meet their raw material needs. Hemp is one among many possible agricultural products that could supplement or replace fiber currently supplied by foreign and domestic wood species. Although production of many products is technically possible using hemp, acceptance of hemp by industry will depend on the specific properties required for particular end products as well as price and availability of hemp as a raw material. Several factors must be considered when assessing the feasibility of industrial hemp production in the Pacific Northwest.

1. Hemp is a summer annual crop that is well adapted to warm growing conditions, an extended frost-free season, highly productive agricultural soils, and ample moisture through the growing season. Previous research and experience indicate that hemp is well adapted to growth in the corn belt of the U.S. Midwest. The temperature and soil requirements of hemp can probably be met in the existing agricultural areas of the Columbia and Snake River basins and to a lesser extent in the lowland areas between the Coast Range and the Cascades from the Rogue Valley to Puget Sound.

2. Because of the predominantly winter rainfall pattern in the PNW, industrial hemp production will almost certainly require supplemental irrigation throughout the region to maximize production. The requirement for irrigation will increase production costs and require that hemp be grown on some of the most productive soils in the region, in direct competition with the highest value crops in the PNW. The use of surface or ground water for irrigation also carries environmental costs that must be considered.

3. Current industrial hemp production in Western Europe is economically feasible primarily as a result of substantial direct subsidy of production by the EC. Since government subsidy of industrial hemp is extremely unlikely in the U.S., a thorough understanding of

hemp production practices and costs is essential to determine the viability of fiber, seed, or dual-purpose hemp production.

4. Total biomass yields will need to be substantially greater than those previously recorded in other countries for industrial hemp to be economically feasible in the PNW at current prices. Since growing hemp, even for research purposes, remains under severe legal restrictions, direct measurement of crop performance using current agricultural technology has not been undertaken, and hemp yields under PNW growing conditions are unknown. Higher yields may be attained by improvements in genetics and cultural practices, but these will require considerable investment of time and resources. Although some high-value end products such as specialty papers or textiles may allow a higher price for hemp stalks, the costs associated with fiber separation and processing may preclude a substantial increase in the raw material price to the grower. Even when these factors are considered, PNW growers may remain at an economic disadvantage compared to Midwest growers who have lower land costs and can produce hemp using available summer rainfall rather than irrigation.

5. Innovation in harvesting equipment and materials handling is still required to improve the feasibility of hemp production. One of the greatest limitations of annual fiber crop production on a large scale may be the relatively short harvest interval imposed by the onset of fall rains throughout the PNW. This limitation may prove particularly challenging for production of hemp seed or later maturing fiber hemp varieties in the region. The logistics of handling the volume of material required to replace even a small portion of the wood fiber resources currently being used are far from trivial.

6. Even if hemp is brought into commercial production in the region, it will occupy only a portion of the limited irrigated acreage available in the PNW. As a result, hemp will only provide enough raw material to meet a small portion of current fiber demand in the region.

7. Significant quantities of agricultural residues such as cereal and grass seed straw are widely available in the region as by-products of existing agricultural enterprises. Grain and grass seed production levels have been quite stable over many decades, and straw from these crops is available at relatively low cost throughout the PNW. While straw will compete with hemp as a primary raw material for paper or composite wood products, there may be opportunities to improve the properties of straw-based products with the addition of hemp fiber.

There is little doubt that industrial hemp can be successfully cultivated in some areas of the Pacific Northwest. Application of agricultural technology such as intensive plant breeding and improvements in harvesting technology could increase hemp yield and enhance production efficiency. Development of these improvements will take time and resources. Until legislative restrictions are removed from hemp, it is unlikely that investments in improved production technology will be made or that the required industrial infrastructure will be developed.

REFERENCES:

Anon. 1890. Experiments with Commercial Fertilizers on Hemp. Kentucky Agricultural Experiment Station Bulletin No. 27, 11p.

Anon. 1988. Council Regulation (EEC) No 3698/88) of 24 November 1988 laying down special measures for hemp seed. Official Journal of the European Communities 31: L325.

Anon. 1989. Commission Regulation (EEC) No 1164/89 of 28 April 1989 laying down detailed rules concerning aid for fibre flax and hemp. Official Journal of the European Communities 32: L121.

Anon. 1992. Census of Agriculture.

Anon. 1996. List of Cultivars Eligible for Certification 1995. Organisation for Economic Co-operation and Development, Paris.

Ash, A.L. 1948. Hemp - Production and Utilization. Econ. Botany 2: 158-169.

Atchison, J.E. and T.T. Collins. 1976. Historical development of the composition panelboard industry including use of nonwood plant fibers. TAPPI Non-Wood Plant Fiber Pulping Progress Report No. 7, 29-48.

Black, C. A. and A.J. Vessel. 1945. The response of hemp to fertilizers in Iowa. Soil Sci. Soc. Amer. Proc. 9: 178-184.

Bocsa, I. and M. Karus. 1998. The Cultivation of Hemp. Hemptech, Sebatopol, CA.

Bosia, A. 1975. Hemp for refiner mechanical pulp. World Research and Development Paper Number 37, 41.

Charle, F. 1996. Flax tow and hemp working line "CHARLE". Proc. 4th European Regional Workshop on Flax, Rouen, France, 173-176.

Cross, T. and B. Smith. 1991. Irrigated Corn Enterprise Budget. Oregon State University Extension Enterprise Budget EM 8458, 4 p.

De Candolle, A. 1886. Origin of Cultivated Plants. D. Appleton and Company, N.Y.

De Groot, B., J.E.G. van Dam, R.P. van der Zwan and Klaas van't Riet. 1994. Simplified kinetic modelling of alkaline delignification of hemp woody core. Holzforschung 48(1994) 207-214.

De Meijer, E.P.M., H.J. van der Kamp, and F.A. van Eeuwijk. 1992a. Characterisation of *Cannabis* accessions with regard to cannabinoid content in relation to other plant characters. Euphytica 62: 187-200.

De Meijer, E.P.M. 1993a. Hemp Variations as Pulp Source Researched in the Netherlands. Pulp and Paper, July, 1993, 41-43.

De Meijer, E.P.M. 1993b. Evaluation and verification of resistance to *Meloidogyne hapla* Chitwood in a Cannabis germpalsm collection. Euphytica 71:49-56.

De Meijer, E.P.M. 1995. Fibre hemp cultivars: A survey of origin, ancestry, availability and brief agronomic characteristics. Journal of the International Hemp Association 2(2): 66-72.

Dempsey, J.M. 1975. Fiber Crops. University Press of Florida, Gainesville, 46-88.

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

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

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

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

FAO. 1996. United Nations Food and Agriculture Organization Annual Production Statistics, Rome.

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

Fuller, W.H., A.G. Norman, and C.P. Wilsie. 1946a. The Retting of Hemp. I. Field retting of hemp in Iowa. Iowa Agricultural Experiment Station Research Bulletin 342, 833-891.

Fuller, W.H., A.G. Norman, and C.P. Wilsie. 1946b. The Retting of Hemp. II. Controlled retting of hemp. Iowa Agricultural Experiment Station Research Bulletin 343, 893-924.

Gschoßmann, J. 1995. Hemp decomposing technology of the company Gebr. Bahmer Maschinenbau GmbH. Proc. Bioresource Hemp Symposium, Frankfurt, Germany, 290-301

Hackleman, J.C. and W.E. Domingo. 1943. Hemp an Illinois war crop. University of Illinois Extension Circular 547, 8 p.

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

Hessler, L.E. 1945. Chemical composition and strength differences in dew-retted hemp fiber. Jour. Amer. Soc. Agron. 37: 146-155.

Hessler, L.E. 1947. The effect of fertilizers on the chemical composition and quality of dew-retted hemp fiber. Jour. Amer. Soc. Agron. 39: 812-816.

Hoffmann, W. 1961. Hanf, *Cannabis sativa* L. Handbuch der Pflanzenzuchtung, Band V, Paul Parey, Berlin.

Howard, V.J., A.L. Lang, and G.H. Enfield. 1946. Effects of fertilizers on yields and breaking strengths of American hemp, *Cannabis sativa*. Jour. Amer. Soc. Agron. 38: 551-563.

Huisman, W., E. de Maeyer, and L. Frerichs. 1995. Harvest and storage of hemp. Proc. Bioresource Hemp Symposium, Frankfurt, Germany, 268-277.

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

Hurter, A.M. 1989. Some economic considerations in the implementation of a non-wood pulp and paper project. Proceeding Tappi Pulping Conference, 677-690.

Husbands, J.D. 1909. USDA Bureau of Plant Industry Bulletin 153, 42.

Jackson, P.L. and A.J. Kimerling. 1993. Atlas of the Pacific Northwest. Oregon State University Press.

Kime, G.G. 1996. Personal communication. Hempline, Inc., Ontario, Canada

Kozlowski, R., B. Jaranowska, J. Tymkow, J. Mankowski, P. Baraniecki, and L. Grabowska. 1995. Breeding, cultivation amd application of hemp in Poland. Proc. Bioresource Hemp Symposium, Frankfurt, Germany, 58-68.

Laith A.A., A. Rab, E. Polyanszky, and I. Rusznak. 1995. Optimization of process variables for production of dissolving pulps from wheat straw and hemp. Tappi Journal 77(6).

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

Leson, G. 1996. Personal communication. Nova Institute, Cologne, Germany.

Low, I. 1995a. UK Hemp Production. Proc. Bioresource Hemp Symposium, Frankfurt, Germany, 106-108.

Low, I. 1995b. Personal communication. Hemcore Ltd, Essex, England.

Lotz, L.A.P. 1991. Reduction of growth and reproduction of *Cyperus esculentus* by specific crops. Weed Research 31: 153-160.

Mackey, J.E., F.S. Conklin, J.E. Simonds, and M.L. Taylor. 1991. Opportunities in Grass Straw Utilization. CH2M HILL, Corvallis, OR.

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

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

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

Montgomery, B. 1954. The Bast Fibers. In: H.R. Mauersberger (ed.), Matthews' Textile Fibers, Sixth Edition, John Wiley & Sons, New York, 257-359.

Nebel, K.M. 1995. New processing strategies for hemp. Proc. Bioresource Hemp Symposium, Frankfurt, Germany, 312-316.

Nelson, E.G. 1937. Report of the Breeding and Agronomic Work with Fiber Flax. Oregon State Agricultural Experiment Station, 4-5.

Niedermaier, F.P. 1976. Technology, engineering, and machinery for manufacturing panelboard from non-wood materials. TAPPI Non-Wood Plant Fiber Pulping Progress Report No. 7, 49-66..

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

Noblitt, C. and M. Bitzer. 1995. Kenaf's potential as a new crop for tobacco farmers and as a forest-saving resource for the pulp and paper industry in the Southeast. AFSEE Alternative Fiber Research Project Report, Eugene, OR.

Norton, D.C. 1966. Additions to the known hosts of *Meloidogyne hapla*. Plant Disease Reporter 50:523-524.

Quick, G.R., I.M. Wood, and W.H. Rawlins. 1980. Application of a forage harvester for harvesting kenaf for paper-pulp production. Journal Australian Institute of Agricultural Science 46: 170-174.

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

Robinson, B.B. 1934. Report of the Breeding and Agronomic Work with Fiber Flax. Oregon State Agricultural Experiment Station, 23-24.

Robinson, B.B. 1935a. Hemp. USDA Farmers' Bulletin No. 1935, 16 pp.

Robinson, B.B. 1935b. Report of the Breeding and Agronomic Work with Fiber Flax. Oregon State Agricultural Experiment Station, 14-15.

Robinson, B.B. 1936. Report of the Breeding and Agronomic Work with Fiber Flax. Oregon State Agricultural Experiment Station, 7.

Robinson, B.B. 1946. Dew retting of hemp uncertain west of longitude 95°. Jour. Amer. Soc. Agron. 38: 1106-1109.

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

Robinson, B.B. 1953. Abaca, a cordage fiber. USDA Agricultural Monograph No. 21, 130 pp.

Van der Werf, H.M.G. 1991. Agronomy and crop physiology of fibre hemp. A literature review. Center for Agrobiological Reseach Report 142, Wageningen, The Netherlands.

Van der Werf, H.M.G. 1992. Fibre hemp in France. Report of a visit to the Federation Nationale des Producteurs de Chanvre. Center for Agrobiological Research, Wageningen, The Netherlands

Van der Werf, H.M.G., J.E. Harsveld, A.T.M. Bouma, and M. ten Cate. 1994. Quality of hemp (*Cannabis sativa* L.) stems as a raw material for paper. Industrial Crops and Products 2(1994):219-227.

Van der Werf, H.M.G., K. Brouwer, M. Wijlhuisen, and J.C.M. Withagen. 1995a. The effect of temperature on leaf apppearance and canopy establishment in fibre hemp (*Cannabis sativa* L.). Ann. Appl. Biol. 126: 551-561.

Van der Werf, H.M.G., M. Wijlhuisen, and J.A.A. de Schutter. 1995b. Plant density and self-thinning affect yield and quality of fibre hemp (*Cannabis sativa* L.). Field Crops Research 40: 153-164.

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

Vavilov, N.I. 1992. Origin and Geography of Cultivated Plants. English Edition, Cambridge University Press, 316-366.

Verbestel, J.B. 1978. Particles of non wood materials for particle board. TAPPI Non-Wood Plant Fiber Pulping Progress Report No. 9, 61-72.

Vessel A.J. and C.A. Black. 1947. Soil type and soil management factors in hemp production. Iowa Agricultural Experiment Station Research Bulletin 352, Iowa State College, Ames, Iowa, 384-424.

Wilsie, C.P., C.A. Black, and A.R. Aandahl. 1944. Hemp Production Experiments Cultural Practices and Soil Requirements. Iowa Agricultural Experiment Station Bulletin P63, Iowa State College, Ames, Iowa, 46pp.

Wilsie, C.P., E.S. Dyas, and A.G. Norman. 1942. Hemp A War Crop for Iowa. Iowa Agriculutral Experiment Station Bulletin P49, Iowa State College, Ames, Iowa, 587-600.

Wood, I.M., D.J. Quick, R.A. Stiff, and N.H. Adams. 1978. Harvesting kenaf with sugar cane harvesters. World Crops September/October, 200-205.

Wood, I.M. 1981. The utilization of field crops and crop residues for paper pulp production. Field Crop Abstracts 34 (7): 557-568.

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

Zimmer, H. and F.H.K.D. Kloss. 1995. Ultrasonic Breakdown of Hemp. Proc. Bioreource Hemp Symposium, Frankfurt, Germany.

Zomers, F.H.A., R.J.A. Gosselink, J.E.G. van Dam, and B.F. Tjeerdsma. 1996. Organosolv pulping and test paper charcterization of fiber hemp. Tappi Journal 78(5): 149-155.