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Industrial Hemp: Renewed Opportunities for an Ancient Crop

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ABSTRACT

Hemp (*Cannabis sativa* L.) has been a species of value to humans for much of our history given its broad adaptation and multiple uses. The plant is thought to have originated in Eurasia but has been carried to much of the rest of the world, largely for use as a fiber crop. Declining needs for fiber and competition from other plant fiber sources began to reduce demands for hemp. In turn, concern over psychotropically potent forms of hemp (i.e., marijuana) would lead to the crop's effective prohibition during much of the 20th century. Growing recognition of the many uses for hemp beyond the traditional rope, cordage, and canvas has helped revive interest in the crop, and a majority of US states have reduced restrictions to allow research with the plant. Although hemp now appears on the verge of returning to favor in the United States, there will be much to learn to make it a viable crop competitive with other commodities. Variety and photoperiodicity, site suitability, end use (grain, fiber, or dual purposes) and management, and the interactions of these factors will have a strong impact on crop productivity and suitability for post-harvest use. In addition, the harvest and processing technologies (particularly for fibers and essential oils) that are needed to optimize the plant's value are limited or lacking in the United States. Disease and pest issues are often considered of little concern for hemp, but these likely will grow as the plant's range expands. Opportunities for hemp have increased with the recognition that the crop offers growing and diverse uses for not only its fibers, but for its seed grain and essential oils as well. Several studies indicate that hemp grains are nutritious as feed and food additives and its essential oils are of interest given a number of pharmacologically beneficial properties. Although full of promise given its numerous potential benefits and uses, building markets for these products will be a critical (and likely slow) part of hemp's development into a useful agronomic species for US growers.

KEYWORDS
adaptation; additives; economics; history; processing; production

Among agronomic crops, perhaps no other has sparked as much passion as industrial hemp. Long a pariah given its association with illicit forms of *Cannabis*, industrial hemp now appears to be gearing up for a new day in the sun. The tremendous enthusiasm for hemp has been building across the political spectrum. In some sense, this may be built into humanity's DNA given our long and fruitful interactions with the species as food, medicine, clothing, and engineering material. This article gives a brief review of hemp, outlining its origins, adaptation as well as past and possible future uses, particularly in a US context.

I. A short history of hemp's use for industrial purposes

Humanity's long history of hemp (*Cannabis sativa* L.) use is estimated to have begun with a first harvest around 8500 years ago (Schultes, 1970), and active cultivation has occurred for over four to six millennia (Small, 2015; Vavilov, 1992). From its origins in temperate Asia, hemp would migrate around the globe, reflecting both its broad adaptability and its importance to people on the move. The species found its way to Europe around 1500 BC (Simmonds, 1976), and over time, it was widely cultivated for fiber and seeds, although historically, its greatest value was as an industrial crop used for fiber production. For example, it was especially important in England and other maritime countries in the 1700s given its use for the canvas (the word being derived from *Cannabis*) and the cordage needed for naval vessels (Fortenberry and Bennet, 2001; Roulac, 1997).

Hemp arrived in the New World with the Spanish, who brought the plant to Chile in 1545 (Husbands, 1909). The plant was grown for fiber in New England from about 1645 and became an important crop for rope production in Colonial America. Presidents Washington and Jefferson both grew hemp and were strong

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proponents of its production, although neither man profited from growing the crop (Small and Marcus, 2002). As the United States expanded, settlers carried hemp further into North America, and a commercial cordage industry developed and flourished in Kentucky after 1775. This industry would spread west to Missouri and Illinois during the mid-1880s (Fortenberry and Bennet, 2001; Roulac, 1997).

US hemp production eventually declined due to competition from other fiber sources and reduced demand. Introduction of the cotton gin lowered cotton processing costs, and production of that fiber expanded accordingly. Cheaper, imported jute and abaca fibers also put pressure on hemp's market, which was further eroded by the loss of demand as sailing ships were replaced by steam- and fossil-fuel-powered vessels (Fortenberry and Bennet, 2001; USDA, 2000).

Hemp's fall from grace was hastened by concerns over its use for hallucinogenic purposes. This led to Congress' passage of the Marihuana Tax Act in 1937, which placed cultivation of all *Cannabis* under control of the US Treasury Department (USDA, 2000). The act required growers to be registered and licensed with the federal government in order to restrict production of psychoactive varieties (Ehrensing, 1998). This constraint effectively ended hemp production in the United States until fiber supplies to this country were interrupted by events during World War II. Several thousand farmers were thus recruited to grow "hemp for victory" (Johnson, 1999), and the USDA's Commodity Credit Corporation contracted War Hemp Industries, Inc. to construct several processing mills in the Midwestern United States. Production peaked in 1943–1944 (USDA, 2000), only to decline after the war in the face of competition from cheaper imported fibers and renewed legal restrictions on the crop.

Interest in hemp in the United States resurfaced largely from the mid-1990s following European and Canadian decisions to allow hemp production. Given the many potential uses of the plant (Figure 1), several states began authorizing feasibility studies to determine its potential value as a crop. By 1999, 19 states had introduced legislation with 9 states passing laws related to hemp study, research, and production (USDA, 2000). However, progress with research efforts was slowed by restrictions imposed by the US Drug Enforcement Agency (DEA), which carries out regulatory authority of the crop. DEA's treatment of hemp as a Schedule I controlled substance, regardless of its drug content, made work with the crop all but impossible—particularly at a commodity scale—given the strict fencing and surveillance required at the time.

The political environment for hemp production changed markedly in the following decade, and many states began to explore ways to create opportunities for hemp research and production. Passage of the US Farm Bill (signed into law as the Agriculture Act of 2014) created room for hemp study through section 7606, on "The Legitimacy of Industrial Hemp Research." Although answers to questions of "when" (rather than "if") hemp's outright legalization will occur remain unknown, these changes to the law bode well for hemp to legally return to US production fields with federal government blessing.

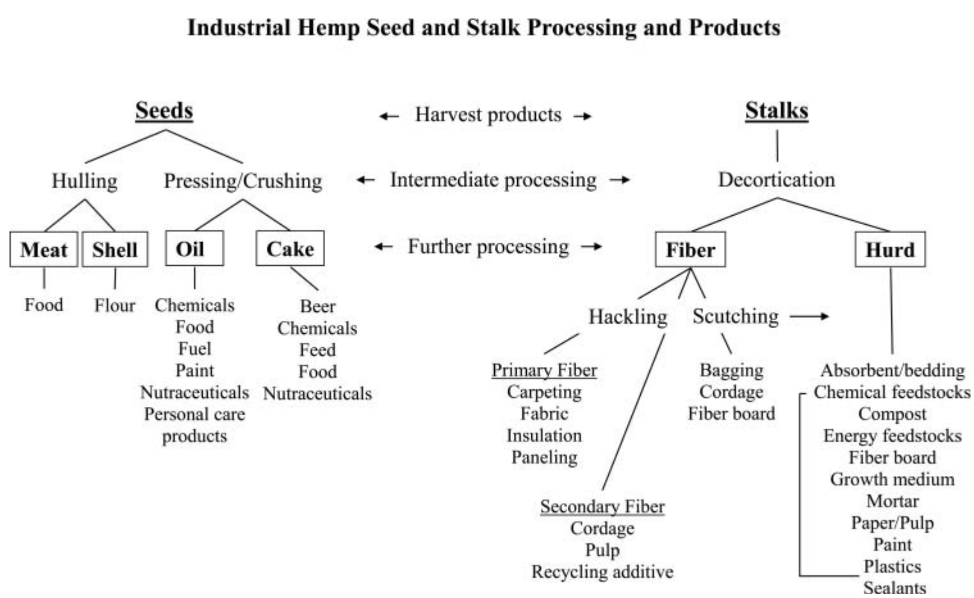

Figure 1. Industrial hemp products and processing routes. Modified and adapted from Kraenzel et al. (1998). Hackling is a process in which the fibers are "brushed" with steel combs to separate the fibers, whereas scutching removes smaller bits of woody tissues that are adhering to the phloem fiber (Small, 2015).

As of this writing, 27 states have changed the restrictions on hemp research (see http://www.votehemp.com/state.html), making it possible to conduct pilot programs on the growth, production, and marketing of the crop, and this number is expected to grow. Past restrictions on hemp have been tied to US drug policy and political and law enforcement concerns over the inability to distinguish between industrial hemp and marijuana. In the next section, the relationships between lines of industrial hemp and their psychotropic cousins are explored briefly.

II. Center of origin and species designation

Eurasia is considered the center of origin for *Cannabis* with fiber lines migrating both east to China and west to Europe. In contrast, selection pressure was for drug strains in the *Cannabis* that moved to Southern and Southeast Asia (Small, 2015). Although there have been attempts to classify the two as separate species (e.g., Hillig, 2005), both hemp and marijuana have historically been considered members of the species *C. sativa* L. Hemp often has been classified as *C. sativa* subsp. *sativa* and marijuana as *C. sativa* subsp. *indica*, but these designations have not been without contention and are not accepted (Rahn, Clarke, Gray, & Trigiano, 2016). Indeed, Small's (2015) opinion was that "no other species has generated so much misunderstanding, argument and contradictory literature"—and the debate is likely to continue until the genetics of these plants are more fully worked out as discussed within Clark and Merlin, 2016; Bailey *et al.*, 2016; Lynch *et al.*, 2016; and Vergara *et al.*, 2016.

Interestingly, in spite (or because) of its notoriety, rather limited genetic research has been conducted on *Cannabis* to date. Making matters murkier, the nomenclature used for hemp is often confounded by the mixed and varied use of "*indica*" and "*sativa*," particularly within *Cannabis* producer/user communities (Sawler *et al.*, 2015).

Recent genetic analysis is beginning to peel away the layers of misunderstanding about these two forms of *Cannabis*, however. For example, Sawler *et al.* (2015) investigated single-nucleotide polymorphisms to test the relationships of several hemp and marijuana lines. Interestingly, many of the supposed hemp varieties considered to be *C. sativa ssp. sativa* were mainly composed of *C. sativa ssp. indica*, whereas different drug varieties that previously were considered to be composed of *C. sativa ssp. indica* did "not reflect a meaningful genetic identity" (Sawler *et al.*, 2015).

III. Distinguishing hemp from marijuana

In general, hemp is more robust, as might be expected for a fiber crop, whereas marijuana, whose desired output are inflorescences, is often more bushy in appearance (Small and Cronquist, 1976; Small and Marcus, 2002). These differences can be further amplified by the agronomic practices required for a given end use (Figure 2). However, Small and Marcus (2002) note that hemp and marijuana strains *can* be quite similar, and this has been cited by some lawmakers as the primary basis for preventing the development of hemp production systems in the United States (*e.g.*, Sturgeon, 2011).

Hemp and marijuana have been differentiated in more recent history based on chemistry because of the

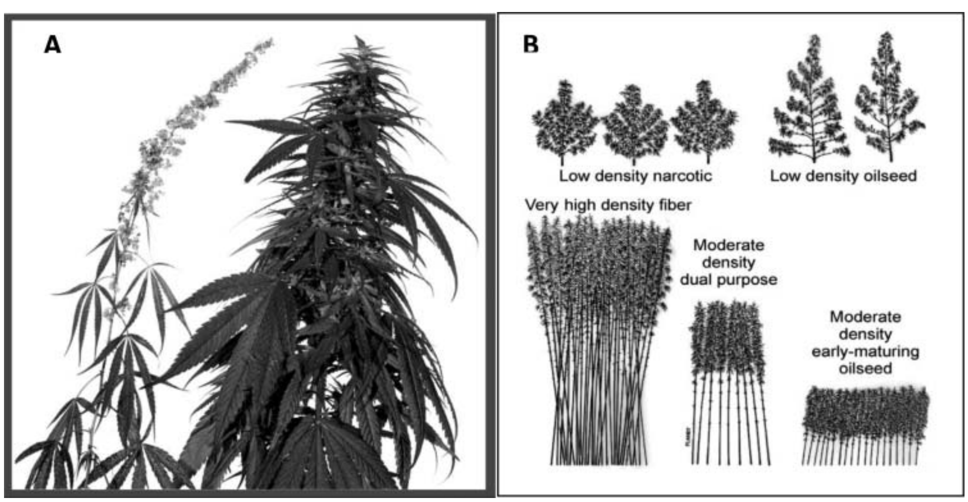

Figure 2. Staminate ("male") and pistillate ("female") *Cannabis* plants (A) (left and right) and the typical architecture of hemp grown for narcotics, oil seeds, and fibers under different densities (B). Adapted from (Small and Marcus, 2002). Reprinted with permission from Agriculture and Agri-Food Canada.

challenges in distinguishing the plants based on morphology. Although this method of segregating the *Cannabis* types has limitations (Staginnus *et al*., 2014), hemp generally contains little Δ^9-tetrahydrocannabinol (THC). THC is the psychoactive compound found in marijuana, and plants that contain less than 0.3% THC (dry weight) in their inflorescences are considered hemp (Small and Cronquist, 1976). While THC level currently is used as the measure of what makes hemp "hemp," this too can be misleading or subject to interpretive error because THC levels can vary by plant part, developmental stage, and growing conditions (Staginnus *et al*., 2014). Instead, the ratio of cannabidiol (CBD) to THC may be a better marker, as this remains constant over the life cycle of the plant (Staginnus *et al*., 2014).

In Europe, hemp cultivars legally allowed for production may not exceed 0.2% THC on a dry weight basis (EFSA, 2011), whereas THC in marijuana varieties can range from 1% to 20% or more (Grotenhermen and Karus, 1998; Small and Marcus, 2002; Staginnus *et al*., 2014). Several countries have ongoing breeding programs to develop high-yielding, low-THC varieties, and more recent research suggests that THC concentrations are declining in European hemp varieties (Holler *et al*., 2008). Along with low THC, traits of interest include: high primary fiber yield for use as pulp, extra-fine fibers for textiles, increased cellulose content for biofuel, larger seeds to facilitate hulling, specific amino acid and fatty acid (oil) profiles, and the production of cannabidiols and other compounds of nutritional or medicinal interest (Aizpurua-Olaizola *et al*., 2016; Bertoli *et al*., 2010; USDA, 2000). More extensive discussion of plant products is presented later in this review and in Clarke & Merlin, 2016.

IV. The hemp plant

Hemp is an herbaceous plant that can grow from about 1 to 6 m tall, depending on factors such as cultivar and environmental and agronomic conditions. Over the course of the growing season, the plant produces rigid, woody stalks that can be 2.5–5 cm in diameter. Plant morphology varies with planting density. At high seeding rates (i.e., in thick stands), hemp plants develop thinner stalks with fewer lateral branches. Low planting densities, typical for oil-seed production, result in highly branched plants with much larger stem diameters.

Hemp plants are diploid ($2N = 2X = 20$) and typically dioecious (having male and female) flowers on separate plants. Among dioecious varieties, male (staminate) plants are taller and thinner, have few leaves around the flowers, and die soon after shedding pollen. The shorter female (pistillate) plants produce many more leaves at the terminal inflorescences and survive through seed maturity. Along with the differences in morphology, the asynchronous maturity can create challenges for harvest, and the dioecious types may have lower seed yield (Amaducci *et al*., 1998; Faux *et al*., 2013; Razumova *et al*., 2016).

Because sex is an important trait for production, much effort has been given to understanding its control and in developing lines that are more suitable for agronomic systems (Hall *et al*., 2012; Moliterni *et al*., 2004). In turn, breeders have developed monoecious (having both male and female flowers on the same plant) and hybrid plants that are more uniform. Much of the early breeding and hybridization research occurred from the 1930s through the 1960s in the former Soviet Union and Communist Bloc countries (ArynŠtejn and Hrennikova, 1967; Bócsa, 1958; Breslavec and Zaurov, 1937; Davidjan, 1963; Grecuhin and Belovickaja, 1940; Nevinnyh, 1962; Nikiforov, 1958; Rjazanskaja, 1963; Sizov, 1934). More recent efforts to understand the genetic control of monoecy have provided evidence that monoecious plants have XX chromosomes (Faux *et al*., 2014; Razumova *et al*., 2016). Although sexual expression is affected by environment and can be altered with growth regulators (Faux *et al*., 2014; Razumova *et al*., 2016), reproductive commitment may occur fairly early in plant development, perhaps at the time of leaf emergence from the fourth node (Moliterni *et al*., 2004).

Along with the effects of reproductive features, hemp production is significantly affected by photoperiodicity (Cosentino *et al*., 2012; Faux *et al*., 2013). Plant maturity is delayed under a long-day regime, and the plant sets seeds as photoperiods grow shorter over time (Hall *et al*., 2014; USDA, 2000). This characteristic increases the importance of matching variety with site and planting date. For example, if plants adapted to higher latitudes are grown closer to the equator, they may enter the reproductive phase of development sooner than would occur in their place of origin. This results in shorter plants with lower fiber and potentially lower grain yields. Understanding the interactions of cultivar photoperiodicity with planting date and environmental conditions, such as temperature and fertility, has been an important part of hemp research (Amaducci *et al*., 2008a, b, c; Cosentino *et al*., 2012; Hall *et al*., 2012, 2013) and likely will be particularly important for study in the United States, given the country's broad latitudinal range, diversity of climate, and complexity of cropping systems.

V. Adaptation

Hemp is broadly adapted, having essentially global distribution (Johnson, 1999), but production for industrial purposes historically has been concentrated in northern temperate regions of the globe. The plant grows best at temperatures between about 15°C and 27°C, but tolerance to quite low temperatures allows for its planting before corn (*Zea mays* L.) (Ehrensing, 1998). This, in turn, allows early plantings to reach a closed canopy, supporting rapid growth and minimizing weed competition (Werf *et al*., 1996).

Edaphically, hemp is best suited to well-drained soils with high fertility. Such conditions likely were common along trails and at the dung heaps of campsites, which were frequently located along streams and lakes. Collection and use of preferred plants and the deposition of their seed to such enriched and protected sites likely were common during hemp's early days as a "camp follower" (Schultes, 1970; Small, 2015), and these early stages of selection would be the first step on the road to active cultivation.

Although capable of growing across a range of soils, hemp cultivation typically is more successful on well-drained loams that are high in organic matter and low in acidity (Johnson, 1999; USDA, 2000). Soil pH is considered optimum in the 5.8–6.0 range by some growers (Bócsa and Karus, 1998), although others indicate that a higher range (6.0–7.5) is more appropriate (Amaducci *et al*., 2015). Development of the hemp industry in Kentucky, US, likely grew out of its generally high fertility and good soil conditions for the crop (Dewey, 1913).

Soil moisture is an important determinant of hemp production. Moisture during establishment is essential, although the plant is tolerant of drought after it is well rooted (Dewey, 1913). Optimum yields typically require 50–70 cm of available moisture, particularly during the vegetative growth phase in June and July in the Northern Hemisphere (Bócsa and Karus, 1998). However, too much available moisture can limit production or cause failure, particularly in low lying and poorly drained fields (Ehrensing, 1998).

VI. Hemp production—Establishment and fertility management

General recommendations are to plant hemp on well-prepared, tilled seedbeds using conventional planting equipment. The typical planting depth is about 3 cm (Amaducci *et al*., 2015) although deeper plantings are more successful in drier years (Borisens and Vasilenko, 1970). Row spacings of 8 to 18 cm are typical (Amaducci *et al*., 2015; Ehrensing, 1998). No reports on zero or "no till" establishment methods currently are available, but these planting techniques were developed well after the decline of hemp production in the United States. Our initial work suggests that these methods will work in some environments (Fike and Wilkinson, 2016), and such methods would be warranted, given their benefits for reducing run-off and erosion.

Plant density recommendations for successful fiber production typically are about 100–200 plants/m^2; attendant seeding rates will vary based on seed size and weight. Although stem yield may be maximized at lower plant densities, stem quality can improve with greater densities (Werf *et al*., 1995b). Higher density plantings result in plants with smaller fiber diameter and increased fiber tensile strength (Khan *et al*., 2011). Greater seeding rates also can have beneficial effects in terms of reduced weed density and size (Vera *et al*., 2006). The value of the greater quality of the crop must be balanced with the added cost of higher seeding rates, particularly with limited seed availability.

Many popular press articles assert that hemp requires little or no fertilizer, but this is a mischaracterization of the plant, perhaps due to a misreading of older research. Response to fertilizer inputs is dependent on the native soil fertility, and past studies suggesting that hemp is unresponsive to fertility inputs typically were conducted on high fertility soils of the US Corn Belt (Ehrensing, 1998). The concept of limited response to fertility may also reflect a sense of relative requirement given that commercial grain crops, especially maize, receive much higher rates of fertility than hemp.

Recent studies with fiber crops suggest that typical optimum nitrogen recommendations for hemp will be between 100 and 150 kg N ha^{-1} (Ngobeni *et al*., 2016; Sausserde and Adamovičs, 2013; Werf *et al*., 1995a), although this may be affected by the seeding rate and row spacing. The crop's end use also is an important consideration for fertility management. For example, excessive levels of nitrogen can negatively affect fiber quality (Ehrensing, 1998), whereas high N rates may be needed to maximize grain yield (e.g., Vera *et al*., 2010).

Interactions of N rate and seeding density have received some consideration. High rates of N typically promote stand self-thinning (i.e., plant mortality), especially at high seeding rates (Augustinović *et al*., 2012b; Werf *et al*., 1995a). Nitrogen rate affected plant morphology before self-thinning began to occur and had a greater effect than row width (12.5, 25, and 50 cm) in this regard (Werf *et al*., 1995a). Although there was a greater mortality with higher rates of N, total plant yield was greater with the high N rate (200 kg ha^{-1}). In apparent contrast, lower fertility inputs (about 60 kg N ha^{-1}) in combination with high seeding rates (200–300 germinated seeds m^2) were considered suitable for fiber production, providing satisfactory stem thickness, plant height, and technical and internode lengths of the hemp crop. A greater percentage of female plants under higher density and N treatments was also reported (Augustinović *et al.*, 2012b).

The potential does exist to produce hemp with moderate fertility inputs, and such management would be warranted to limit nutrient losses to the environment (e.g., Izsáki, 2010). Traditional harvest methods, particularly those relying on field retting (described in a following section), returned much of the plant's nutrients to the soil via leaves and roots. One would anticipate that newer harvest practices that remove the whole plant will require greater nutrient inputs or some method of returning the nutrients in the waste products (if such exist). Even if these plant nutrients are recycled back to the soil, concerns remain regarding potential nitrogen leaching losses and erosion during the fallow phase of the production cycle.

There is little (but conflicting) information in the literature to provide guidance on fertility timing. Ritz (1972) reported that a split application of N (100 kg N ha^{-1} at planting and 20 kg N ha^{-1} about 3 week after emergence) produced the greatest stem yields in the former Yugoslavia. In contrast, workers in Ireland who were trying to reduce the N required for biomass production found no benefit to biomass yield when N was applied at points in time after emergence or in split applications, and net greenhouse gas emissions were estimated lowest at 120 kg N ha^{-1} (Finnan and Burke, 2013).

Hemp can respond to phosphorus and potassium fertility (Johnson, 1999), but requirements generally are lower than for other crops (Finnan and Burke, 2012). Luxury consumption (uptake greater than crop demand) was observed by Finnan and Burke (2012), who found highest levels of potassium in the stem. The authors suggested that a strategy of replacement following harvest would be a suitable management practice.

VII. Hemp production—Weeds, pests, pathogens, and diversity issues

Hemp generally has few weed issues, although this is a function of management and environmental conditions. Hemp fields had higher levels of weeds in a year with high air temperatures in late spring (Jankauskien□ *et al.*, 2014), but its ability to outcompete most weed species under favorable growing conditions, such as early planting and sufficient moisture, would typically mean that fewer herbicides would be required in hemp cropping systems. Such generalizations also should be considered in the context of end use, however, as the wider-spaced plantings typical for seed production often do not produce canopies of sufficient density to suppress weed growth (Baxter and Scheifele, 2008).

Hemp production can be affected by parasitic and climbing weeds. Parasitic plants, such as broomrape and dodder, can reduce productivity, and broomrape can cause hemp plants to die before maturity. This is not likely to be a large issue, as varieties with resistance to these pests are available (Ehrensing, 1998). Climbing weeds such as morning glory, bindweed, and vetch (*Ipomoea, Convolvulus*, and *Vicia* spp.) may also present problems, particularly for seed production, given the difficulties in screening and separating similar-sized seeds (Ehrensing, 1998).

Hemp is consumed by many insect species. Although some do not consider this a problem of economic consequence (Ehrensing, 1998), our initial observations suggest that some form of control may be needed to prevent economic losses in grain production systems (Fike and Kuhar, personal observations). Stem quality also could be an issue because feeding by boring insects can produce cankers that weaken the stem. There are concerns that hemp production could be constrained, in particular, by European corn borer (*Ostrinia nubilalis*) (Parisi and Ranalli, 2000), although this will be a function of severity of predation.

Insect predation in some cases may even be beneficial. In a study in Canada, increased stem weight and grain yield were reported in plants penetrated by *Ostrinia* larvae because branches proliferated in response to the attack (Small *et al.*, 2007). A similar idea has intentionally been applied to hemp stands in Europe, where multiple cuts made during the growth phase stimulated tillering. This management may dramatically reduce seeding rate requirements because of increased lateral shooting. Grain yields were reportedly increased, and although fiber yield was decreased, it was considered as a much better quality (Leonte *et al.*, 2015; Popa *et al.*, 2015).

Several species of nematode infest hemp, but this too is generally considered a minor problem. A wide range in hemp resistance to nematodes has been reported and could allow for breeding resistance should this become an issue (Ehrensing, 1998). However, recent data suggest that hemp may actually be useful for combating nematodes, as compounds from the plant may have nematicidal effects (Tariq *et al.*, 2012), and reduced nematode pressure in soybean (*Glycine max* L. Merr.) grown following a hemp crop was associated with a >10% yield increase (Zhang *et al.*, 2013).

Fungal diseases are most likely to occur with cool-to-moderate temperatures and high humidity and may also occur via the bore holes created by boring insects. Such pathogens are not considered a large issue for industrial hemp production systems, despite the fact that the plant is susceptible to many minor diseases (McPartland, 1996). However, if selected hemp cultivars chosen for high productivity enter cropping systems on a large scale, it is certainly possible that pathogen or pest issues will begin to arise as has been seen with other "new crop" introductions such as switchgrass (*Panicum virgatum* L.).

Although monocultural production systems often present a number of challenges in terms of sustainability, some have suggested that in this regard, hemp production would be better than most other crop monocultures. Montford and Small (1999a) suggest that hemp is more "environmentally friendly" than many other crops based on a number of production and environmental criteria (Figure 3), and hemp has been used in crop rotations to break weed and pest cycles (Johnson, 1999; Zegada-Lizarazu and Monti, 2011). Hemp's limited pest problems should translate to input costs lower than for other crops. While this may be appealing to crop growers, ultimately hemp's value must be compared with existing agricultural enterprises in terms of dollar return (Montford and Small, 1999b), and little information exists on this subject.

VIII. Hemp production—Yield potentials

Hemp production potential plays a key role in the crop's economic value to a producer. Thus, yield trials have been conducted in a number of studies in quite diverse sites. Most available yield data come from Europe, and production responses among locations and managements have varied considerably. Ehrensing (1998) noted that some of the excitement surrounding very high purported yields may in fact represent a misinterpretation of yields presented in kilograms or megagrams/hectare by US audiences used to English (tons/acre) units. In addition, the maximum yield of whole standing crops (which are often tested) does not translate to actual fiber or seed yields.

Some of the highest reported yields (>22 Mg ha^{-1}) come from sites as diverse as Italy and the Netherlands (Struik *et al*., 2000), and yields >34 Mg ha^{-1} were reported in Croatia (Augustinović *et al*., 2012a), although the methods presented for these studies were somewhat limited. More typical yields are in the broad range of about 7–13 Mg ha^{-1}. Alaru *et al*. (2009) reported yields of about 7 Mg ha^{-1} in Estonia when applying nitrogen at 100 kg ha^{-1}. In contrast, Burczyk *et al*. (2008) reported yields in Poland between 10 and 15 Mg ha^{-1}; similar dry matter yields (~14.5 Mg ha^{-1}) have been reported for several cultivars grown in Denmark (Deleuran and Flengmark, 2005). For high-fiber hemp cultivars, fiber yields were about 3 Mg ha^{-1}. Yields were increased with

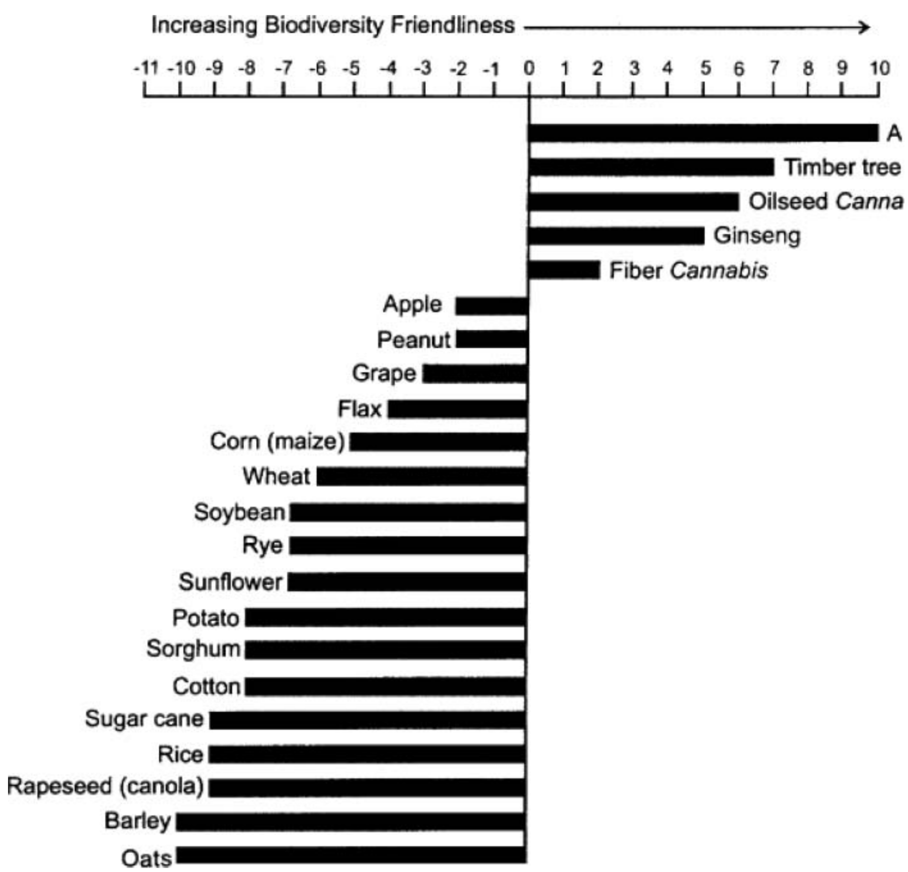

Figure 3. Biodiversity "friendliness" of hemp for oilseeds or fiber as compared with other major crops. From Figure 1 of Montford and Small (1999a). Reprinted with permission from Agriculture and Agri-Food Canada.

greater seeding rates, which increased stand density (Deleuran and Flengmark, 2005).

Research yield data from the US are quite scarce. Although a report from Florida suggests that hemp has great yield potential (~15 Mg ha^{-1}; Figure 4), biomass yields at more northern latitudes are likely to be substantially lower, e.g., Canadian research biomass yields were 4–7 Mg ha^{-1} with grain yields of about 1100 and 850 kg ha^{-1} for a grain and a dual-purpose cultivar, respectively (Vera *et al.*, 2010). Although speculating on potential yields in other parts of North America would be imprudent, it is not unreasonable to expect that yields would land somewhere within the range of yields reported previously and could be higher given newer, more productive genetic material expected to be available over time. Appropriate cultivar selection would be an important factor in optimizing yields, as one would want to match the variety and its end use to the growing conditions of the region where planted.

The ability to capture the value of more than one product (as with Vera *et al.*, 2010) would add economic appeal to hemp production and perhaps reduce the pressure to maximize single-component yields. However, although hemp can be grown both for fibers and seeds, trade-offs exist between the production and quality of the desired outputs. When grown for fiber, hemp often is harvested 70–90 days after seeding when plants are tall but have few leaves. The longer growing season required for seed production reduces the plant's quality for fiber

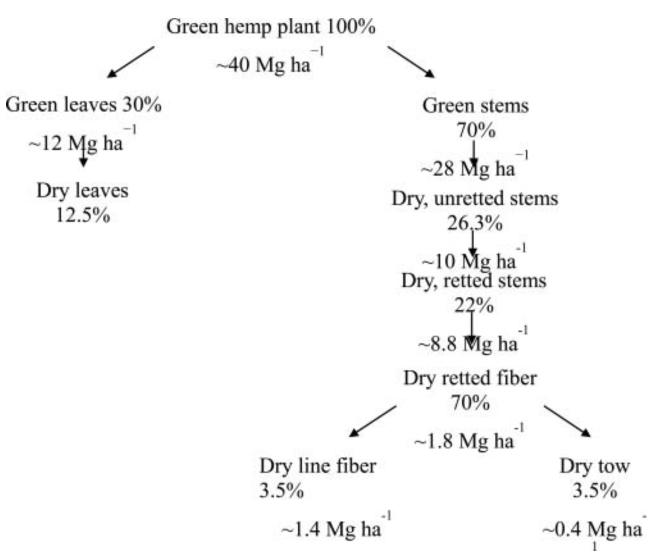

Figure 4. Hemp for fiber's wet ("green") vs. dry leaf, stem and fiber constituents (adapted from USDA, 2000). Note: Although these stem and fiber yields are from 1970, they illustrate how bast fibers are only a small portion of total crop yields. Source: Dempsey, J. M. Hemp. In *Fiber Crops*, p. 82. University of Florida, 1975, pp. 46–89.

applications as the materials become too course for use in textile production (Fortenberry and Bennet, 2001). Of course, the combined value of all the products (and their fixed and variable input costs), along with hemp's "fit" with the rest of the cropping system must be considered. This will be discussed later in the section on economics.

IX. Hemp production—Harvest and decortication

In conventional harvest systems, dioecious hemp crops produced for fiber typically are harvested when the male plants have finished flowering. In southern latitudes of the northern hemisphere, this is in late July/early August, and harvest occurs in late August/early September further north. Crops grown for grain or bioenergy would be harvested later, once seeds are mature or when the biomass is best suited for the needs of whatever conversion process to which it is headed. A number of new approaches to collecting hemp are being explored, and while this review will not be exhaustive, several of these systems under consideration will be touched on briefly because the evolution of harvest and processing operations likely will be an essential part of making hemp a scalable and economically viable industry.

When new cropping systems develop, the initial efforts for their advancement often are focused on the end links of the chain: agronomic production and post-harvest processing (Fike *et al.*, 2007). It is perhaps not surprising, then, that several years after the "re-start" of hemp agriculture in Europe, harvest systems were identified as a bottleneck in hemp for fiber production (Venturi and Bentini, 2001). Older harvest systems used equipment designed to keep hemp stems aligned in parallel and maximize the recovery of long fibers, but such systems are slow. Traditional hay-making equipment has been used for hemp fiber harvest and can speed up the harvest process, but this method prevents the processing of long fibers with traditional separation machinery (Ehrensing, 1998). In some cases, rotary mowers may be challenged by the wrapping of long fibers on rotating parts and quality losses during harvest due to raking/turning, and delayed baling can be disadvantageous (Ivanovs *et al.*, 2014; Ivanovs and Rucins, 2014). Bale-based systems are also challenged by the need to handle bales at several points during the collection and gathering process.

The opportunity to defer harvest over the winter or into spring has been explored more recently. Grain or fiber harvests or the combination of the two can be challenging, particularly at greater latitudes given typical wintertime weather and field conditions (Budde *et al.*, 2013). Spring harvest thus might expand the window of harvest opportunity and perhaps allow the material to dry in the field, reducing the need for expensive, specialized equipment that would be needed to gather in the crop (Hoffmann *et al.*, 2013; Ivanovs *et al.*, 2015a). Work from Germany indicated that hemp would be suitably dry (90% dry matter) for collection in February or March (Hoffmann *et al.*, 2013), but significant mass losses (25–52%) and reductions in straw quality were reported in Latvia (Ivanovs *et al.*, 2015a). If seed were harvested in fall, spring fiber yields would be reduced by previous field traffic during grain harvest, whereas a single spring harvest would have to come with complete grain loss given shattering and predation by wildlife. Thus, considerations of crop volume and quality and grain and fiber prices would be central to determining the value of these different strategies (Ivanovs *et al.*, 2015a).

Fiber production in conventional systems typically relies on field drying and straw retting, a process by which microbes break the bonds between the plant's bast fibers and woody core (Figure 5). Retting removes lignin, pectin, waxes, and minor compounds and disaggregates "the pectin-lignin matrix that bounds the elementary hemp fibers and created fiber bundles" (Sisti *et al.*, 2016). Sufficient moisture assures that the microbially driven degradation processes occur; however, extended retting time can reduce fiber quality due to microbial action against cellulose (Liu *et al.*, 2015), which was perhaps the source of quality decline observed by Ivanovs (2015). Harvest following the retting process requires a period of dry weather conditions to ensure that the hemp stalks can be baled, and weather conditions during the harvest interval can affect fiber quality (USDA, 2000). To address the challenges of moisture at harvest, some recent efforts have been made to dry bales from inside out using solar

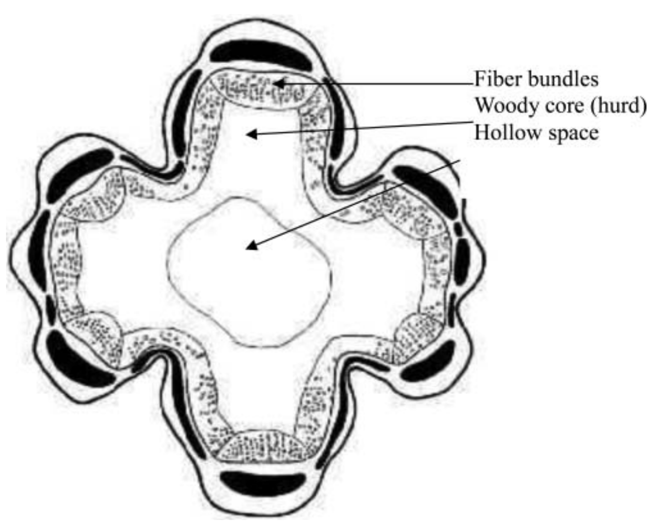

Figure 5. Hemp stem cross section (adapted from McPartland, 1996).

electric energy (Zagorska *et al.*, 2015). Practical, economical, and large-scale application of this type of technology would seem far-off, however. As an alternative to field retting, hemp may be processed by water retting. In this case, the plant is submersed in water for a period of time. Fibers extracted following water retting have greater uniformity and quality, but such retting systems are expensive, laborious, require greater skilled labor, and have higher environmental effect (USDA, 2000). In light of the weather risks and costs associated with traditional harvest systems, newer systems based on chopping and anaerobic storage have proved suitable (Idler *et al.*, 2011), and a pilot facility has been built in Europe that can process hemp fibers into insulation, boards, and granules for injection molding (Pecenka *et al.*, 2009).

Historically, whole stem harvesting, in which stems are cut near the base of the plant and laid in parallel in rows or stacked in piles for subsequent collection, drying, and processing, was the typical method of fiber collection. Some field equipment has been developed to perform these tasks, but utility is limited, largely because today's processing industries typically cannot work with stems longer than 1 m (Pari *et al.*, 2015). Today, cut stem harvesting systems are more commonly deployed. In many cases, plants simply are mown and strewn on the ground as they flow out of the harvester in no particular arrangement. Such methodology is deployed because the forage harvesting equipment used is widely available, whereas equipment specific to hemp is not. However, this has negative impacts on the quality of fibers collected and limits usability in the textile industry (Pari *et al.*, 2015). Headers for combines have thus been developed that feed stalks through the header in a longitudinal fashion, and pieces are cut at about 0.6–0.7 m lengths before being put in a swath. An alternative, tractor-pulled mower with horizontal cutter bars at different heights from the ground can cut stems into section lengths that satisfy the needs of processing facilities, but the system faces other challenges, which have limited adoption (Gusovius *et al.*, 2016; Pari *et al.*, 2015).

Two-pass harvest systems in which seeds were first combined with a high header and the residual straw was cut and baled have been common in lower latitudes in Europe, but effort has been given to equipment to do both simultaneously, reducing passes over the field (Gusovius *et al.*, 2016). Recent innovations have seen the development of equipment systems that can simultaneously harvest and separate both panicles and straw; depending on time of harvest, panicles may be collected for essential oil extraction (at flowering) or threshed for grain (at seed maturity) (Gusovius *et al.*, 2016). Other systems are in various stages of development, all with the purpose of maximizing the harvest of valuable products and improving the competitive value of the fiber crop (Gusovius *et al*., 2016). At current costs, specialized harvesters and collection systems may not be economical, and ultimately, however, they must be assessed on the value of the fibers produced as they are limited to the short fiber market.

Following harvest and prior to processing, the hemp fibers must be decorticated (i.e., separated from the stalk—see Figure 6), and typically, this happens following field collection. To eliminate this step, research has been conducted on improved harvesters that can separate dry fibers from stalks in the field (Gratton and Chen, 2004), and reports from Europe (Munder *et al*., 2004) suggest that this may be possible without the need for retting. Such systems rely on field chopping and wet material storage (ensiling) (Pecenka *et al*., 2009) or processing of green stems (LüJiangNan *et al*., 2014; Riddlestone *et al*., 2006). The systems have promise for reduced in-field biomass loss, in-field particle size reduction, and reduced weather-related harvest risks (Idler *et al*., 2011; Pecenka *et al*., 2009). However, haulage costs will be increased by the additional water weight, and the process is not well suited for producing dry process composite boards (Ehrensing, 1998). Whether these harvest systems can return sufficient value through the production chain to warrant their added equipment and haulage costs remains a question.

X. Hemp fibers in industrial applications

Once at a biorefinery, hemp fibers can be used in any number of applications depending on their quality. Opportunities for hemp to advance as a viable crop will depend on new markets developing around different hemp-based products that return value throughout the supply chain. While the following list of uses (and references) is not meant to be exhaustive, it is both broadly categorical and informative. Indeed, Small (2015) quoted a Popular Mechanics (1938) article claiming that hemp "can be used for produce more than 25,000 products, ranging from dynamite to Cellophane." Pulp and paper (Barberà *et al*., 2011; Correia *et al*., 2001; Gorchs and Lloveras, 2003; Lloveras *et al*., 2006; Marques *et al*., 2010), ethanol (Kuglarz *et al*., 2014, 2016), fabrics (Chen and Liu, 2010), fibers and carpet (Bhavani, 2015; Zhang *et al*., 2014), acoustical and heat insulation (Chabriac *et al*., 2016; Ivanovs *et al*., 2015b), nanocrystals and nanofibers (Luzi *et al*., 2014; Mondragon *et al*., 2014), reinforced foam packing materials (He *et al*., 2011), biocomposites and particle board (Li *et al*., 2014; Lühr *et al*., 2013, 2015; Sam-Brew and Smith, 2015; Xiao *et al*., 2014), and reinforced plastic and concrete (Arizzi *et al*., 2016; Idler *et al*., 2011; Le Troëdec *et al*., 2011; Merta and Tschegg, 2013; Pecenka *et al*., 2009; Snoeck *et al*., 2015) are among the multitude of uses.

The value and desirable features of hemp fibers are found in their length, strength, and durability. The plant's primary bast fibers typically are 5–40 mm long individually and 1–5 m when bundled (Small and Marcus, 2002). Interest in these has risen owing to their good mechanical and insulative properties and perceived lower environmental effects compared with glass- and petroleum-based fibers (Bourmaud *et al*., 2011). Breeding can substantially increase the amount of fiber in hemp's bark (e.g., Grabowska *et al*., 2009), and concentrations may range from 15% to 45% (Fortenbery and Mick, 2014). Breeders can also greatly reduce the amount of woody core typical for nonfiber strains (Figure 7), although new research suggests that these core fibers can be developed for a variety of uses, which will increase the crop's value (Barberà *et al*., 2011).

Although hemp fibers may have certain advantages over petroleum- and glass-based fibers, cost has placed

Figure 6. A hemp stem showing the bast fibers, which grow under the "bark" layer. Photo in the public domain.

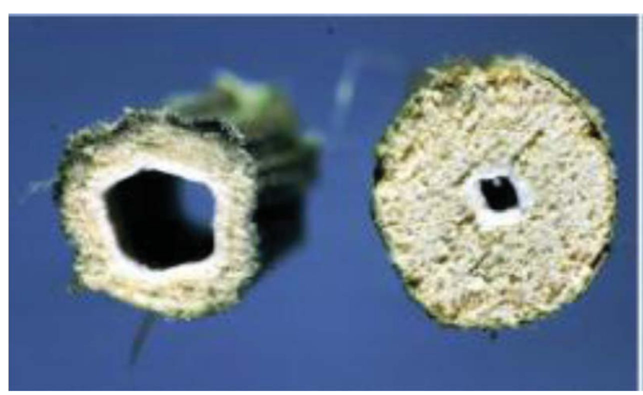

Figure 7. Stem cross sections of hemp fiber (right) and narcotic (left) plants. From Figure 12 of Small and Marcus (2002). Reprinted with permission from Agriculture and Agri-Food Canada.

some constraints on their use, particularly in the long-fiber market. Long fibers harvested using traditional retting practices are especially expensive, and following retting, specialized equipment is needed to process, spin, and weave the fibers. Because of their expense, these materials largely have been limited to markets for fine textiles and specialty cloth manufacturing (Small and Marcus, 2002). While new equipment and systems could create opportunities for growers in Europe and North America, any emerging hemp textiles industry likely also will be challenged to compete with China's existing processing infrastructure, much lower costs of labor, and long tradition of hemp production (Small and Marcus, 2002). These factors, coupled with China's intentions to increase hemp acreage (see http://www.naturalfibres2009.org/en/stories/hemp.html) suggest that this will be the case for some time to come.

Hemp has found some use in the pulp and paper industry, although the price of hemp-based paper currently is not cost competitive with wood pulp for commodity papers (Johnson, 1999; Small and Marcus, 2002). The ability to make and recycle paper depends on fiber length, and using hemp's long fibers for paper would double the number of cycles that the paper could be recycled compared with a wood-based product (Small and Marcus, 2002); the energy values for pulping hemp also are less than those for wood (Correia *et al*., 2001). Despite this, the greater cost associated with existing production and processing methods currently make hemp papers economically infeasible except in high-end niche markets. The exceptions include specialty applications such as paper currency, cigarette papers, tea bags, art supplies, filters, and hygiene products that require greater tear resistance and wet strength capacity; however, North America has essentially no such industry (Small and Marcus, 2002).

Some argue that hemp production systems could yield more biomass than forestry and that using hemp for paper could reduce pressure on both primary forests and the biodiversity the forests support. Although yields may be about double that of pine plantations, several factors present challenges to developing a hemp-based paper industry. The type of processing requires different facilities than wood papers, and current process systems only use the bast fibers, although this may change with the development of new process technologies. One recent study suggests that changes in processing methods may allow greater use of hemp core fibers, or "hurd." Utilizing the hurds, traditionally a process by-product, would thus support increased hemp paper yield (Barberà *et al*., 2011) and might provide better system economics. However, unlike trees, the harvest window for hemp is quite restricted because the material is only harvested at the end of the growing season. Because hemp is less dense than wood, it will have greater hauling costs, and using hemp for pulp would entail more storage and handling costs as the material would need to be stored and moved to the mill throughout the year (Small and Marcus, 2002).

Although these market issues may limit hemp's being a challenger crop relative to traditional fiber industries, production in Europe (and perhaps North America) appears to be getting new "life" with the advent of new uses and technologies. Much of the recent research with hemp has focused on the potential to use its fibers to reinforce plastics and other polymeric materials. A publication from the early days of such research described results from the German Research Centre for Air and Space Travel in which hemp-reinforced polymers were better than other those based on other fiber sources and had the same performance characteristics as glass-fiber-reinforced polymers (Anonymous, 1995). Growth of fiber composite use by the automotive industry has continued from that time. Hemp composites are a superior product, and the fibers are used in door panels, linings, decks, and pillars (Small and Marcus, 2002). Demand for these products has increased (Karus and Vogt, 2004) perhaps in part driven by the European Union's directive for all new vehicles to be 95% recyclable by 2015 (Europa, 2000). While much of this fiber supply has been met with flax, reduced flax production subsidies coupled with greater understanding of hemp production and increased infrastructure are expected to support hemp's growth into the future (Karus and Vogt, 2004).

In addition to the growing market for use in automobile parts, hemp fibers have also been used to make insulation, lightweight fiber boards, as well as plasters and insulative concrete mixtures for home construction (Figures 8 and 9). Current hemp-lime concretes lack sufficient strength to be load-bearing blocks, but the material works well as a breathable, structural component around or within the building skeleton (Figure 9). Pretreating hemp may further improve this functionality as it can increase the strength of the binding matrix (Le Troëdec *et al*., 2011).

Along with these many structural and construction uses, hemp (hurds and litter) is valued for animal bedding given its high absorbency (Bouloc, 2013; Lühr *et al*., 2015). This quality also may make it useful for cleaning up industrial spills, although cost is an issue. Hemp fibers also have been explored for use in geotextile ground covers and erosion control barriers. Its value for this purpose may depend on the desirability of biodegradability, however (Small and Marcus, 2002).

XI. Hemp seed as a source of feed additives

The utility of hemp as a feedstuff for animal diets has been explored by several researchers. Early studies

Figure 8. House insulated with hemp constructed in Asheville, North Carolina, USA. Photo courtesy of Clarke Snell.

suggested both positive and negative effects of feeding full-fat hemp seed to cattle. While animal performance metrics were unaffected when hemp seed were included at up to 14% of dietary dry matter, the impact on meat fatty acid profiles was both negative in terms of increased trans and saturated fats and positive by increased conjugated linoleic acid, an important dietary anticarcinogen (Gibb *et al*., 2005). Other reports of altered milk chemistry and meat fatty acids (Cozma *et al*., 2015; Mourot and Guillevic, 2015) suggest that feeding hemp oil and seeds to livestock may have positive consequence for the human end consumer due to improvements in nutritional profiles.

Whether the improvements in meat quality are sufficient to warrant hemp seed production and feeding is an open, if not moot, question. To our knowledge, no human health trials have been conducted utilizing muscle tissues derived from animals fed hemp products. However, the changes in fatty acid profiles measured in meat tissues suggest that these products would be healthful. Despite this, the increased value in the animal product may not be readily captured from the market, and questions remain as to whether or not these are great enough to offset hemp seed production costs relative to other feedstuffs.

Given the value of the oils (see next section), future use of products in animal feeds may be limited to the by-products cakes produced after the oils have been extruded. Still, adding hemp to animal diets has potentially positive human nutrition implications. In one study of calves fed hempseed cake, animal performance measured as weight gain was not different between hemp and standard soybean + barley (*Hordeum vulgare* L.) diets (Hessle *et al*., 2008), but both greater concentrations of monosaturated and polyunsaturated fatty acids and a better n-6:n-3 ratio were reported for the hemp-seed-fed steers (Turner *et al*., 2008). However, the high level of polyunsaturates (Woods and Forbes, 2007) may represent a storage and handling issue due to their greater potential for oxidation. Hempseed cake also has been fed in dairy diets with variable effects on milk yield, and quality responses in terms of fatty acid profiles were not reported (Karlsson *et al*., 2010).

Along with potential benefits, European scientists have had concerns over possible entry of THC into meat and milk, and on this basis, set standards on the use of hemp products in animal diets (EFSA, 2011). Because THC is largely present in plant tissues, consumption of animal products derived from hemp (plant)-based products could result in exposure at levels above safe standards. Thus, EFSA (2011) recommended restricted or prohibited feeding of the plants in animal diets and introduced a maximum THC level of 10 mg/kg in seed-based feed products. A follow-up study suggested that THC levels in milk are unlikely to be of concern, although accurate risk assessment was not feasible (EFSA, 2015).

Figure 9. Cured hempcrete installed around framing timbers. Forms are set to pour the next layer of lime-hemp mixture. Photo courtesy of Carol Brighton.

XII. Hemp seed and essential oils as a source of human food additives

The potential of hemp as an animal feed is dwarfed by its value to the foods, supplements, and cosmetics industries that create products for human use or consumption (Leson, 2013). Demands for “natural foods” in US markets have been a major driver of Canadian hemp production (Leson, 2013). Growth in this market is not surprising given that hemp seeds are considered a functional food, have excellent fatty acid profiles and protein qualities, and have been used for centuries to treat various disorders (Callaway, 2004). Although much work is needed to verify various claims about hemp’s efficacy for addressing any number of ailments, compounds derived from various parts of the plant are being used in treatments as diverse as hypertension and oxidative stress (Girgih *et al.*, 2014a, Girgih *et al.*, 2014b) to inflammatory bowel disease (Parian and Limketkai, 2016), to cancer (Pathak *et al.*, 2016).

Hemp seeds (Figure 10) contain roughly 27–38% oils, which are rich in essential fatty acids such as α-linolenic acid (Iványi and Izsáki, 2010; Kriese *et al.*, 2004; Woods and Forbes, 2007). The n-3:n-6 ratio in the oil is about 3:1, which is the preferred ratio for human nutrition (Woods and Forbes, 2007). Hemp currently is also the only known natural source of gamma-linolenic acid, a widely consumed supplement with numerous health benefits. These factors should give hemp seed oils strong market value and make it likely that the primary end use would be in human food and nutritional supplements.

Excitement over this potential needs to be cautious, however, because data in the literature regarding hemp's nutritional benefits are somewhat limited and variable, and much of the work has been conducted with animal models. A study comparing fish oil, flaxseed oil, and hempseed oil found that hempseed oil had no impacts on plasma fatty acids in healthy adults over a 12-week period (Kaul *et al.*, 2008), and none of the treatments affected platelet aggregation or inflammatory markers. Research with rabbits, however, has indicated that feeding hempseed meal resulted in normal platelet aggregation when the animals were fed elevated levels of cholesterol (Prociuk *et al.*, 2008). A small study with human subjects found that those consuming hemp oils had better serum high-density lipoprotein (HDL)-to-total cholesterol ratios relative to those consuming flaxseed oil (Schwab *et al.*, 2006).

Although most research has focused on hemp seeds as a source of oils and proteins, research suggests that hemp inflorescences from fiber plants also could be a good source of essential oils for flavorings and fragrance additives (Bertoli *et al.*, 2010) and medicinal compounds (Fernández-Ruiz *et al.*, 2013). These essential oils also have moderate antimicrobial and insecticidal activities (Górski *et al.*, 2009; Novak *et al.*, 2001; Thomas *et al.*, 2000). While the economic potential of these oils remains undefined, it is noteworthy that the hemp inflorescence heretofore largely has been considered a crop residue. If these uses can be developed, hemp could prove a dual-purpose crop even without need for grain harvest.

Figure 10. Hemp seeds with a match for scale. Taken from Figure 33 in Small and Marcus (2002). Reprinted with permission from Agriculture and Agri-Food Canada.

XIII. Beyond fibers, feeds, and foods— New uses for hemp in energy production

In one of the first reports evaluating hemp as a potential energy crop, Hanegraaf *et al.* (1998) used life cycle analysis to compare the crop with other potential energy sources. The authors used a number of criteria, including energy balance, greenhouse gas emissions, resource use, biodiversity effects, and economic returns. Compared with other feedstocks for use in electricity production schemes, hemp was one of the best crops when evaluated across all categories. Hemp also had the highest energy gain (158 GJ/ha yr^{-1}) among species (including poplar and willow) that were tested in a German study (Scholz and Ellerbrock, 2002). While such results may be true at more northern latitudes (Hanegraaf *et al.*, 1998), they may not hold in more southern climes (Venturi and Bentini, 2001). In addition, parameters such as biomass fuels cost and greenhouse gas abatement are highly dependent on end use(s) of the materials (Dornburg *et al.*, 2005).

Although humans have a long history of using hemp seed oil (Gibson, 2006), it has only more recently been considered for use in biodiesel production. Rates of conversion from oils to fatty acid methyl esters are typically 90% or more, and product yield in some studies has approached 97% (Ahmad *et al.*, 2011; Li *et al.*, 2010; Yang *et al.*, 2010). However, as noted previously, the current value of these oils for human uses likely will preclude their use for industrial bioenergy systems unless and until large-scale production provides economies of scale that lower their costs.

More promising, perhaps, are efforts in biomass-based combustion and biogas synthesis, although combustion systems likely would have the most utility in the United States given existing infrastructure. In Europe, rapid expansion of the biogas industry from 600 plants in 1999 to >4000 in 2007 (Lamp, 2007) has led the push for research comparing various feedstocks. Corn has been one of the most productive feedstocks to date, but hemp has performed comparably or better depending on the fertility management scenario (Alaru *et al.*, 2009). Tests in Sweden indicate that hemp's optimum harvest time for biogas production is in September or October (Kreuger *et al.*, 2011; Prade *et al.*, 2011) with biomass yields approaching 14.5 Mg/ha. Gas yields were similar to other annual crops, such as sugar beets (*Beta vulgaris* L.) and corn, with an energy yield of about 296 GJ/ha (Prade *et al.*, 2011). Hemp production was more variable with weather than with fertility (nitrogen) inputs; thus, the value of hemp is largely from its lower input needs and its high productivity at greater latitudes. However, hemp may work well both at northern and southern latitudes in (energy) cropping system rotations (Rice, 2008; Zegada-Lizarazu and Monti, 2011), both in terms of breaking pest cycles and improving soil quality.

XIV. Economic prospects

Clearly, there is great interest in the agricultural community and beyond given hemp's multiple uses for value-added products in existing and potential future industries, and the current economic prospects for hemp in the United States are uncertain, but getting brighter. Growing enthusiasm for the legalization of hemp production has come from wide ranging segments of society, and legislation to free hemp as an industrial purpose crop has been supported by politicians across the political spectrum. The excitement over hemp may reflect the plant's potential as a source of multiple products, particularly for high-value industrial, nutritional, and personal care uses, but there also is perhaps, a twinge of "forbidden fruit" syndrome motivating the push for hemp to become the next big thing.

Some perspective must be given to counterbalance the idea that hemp will be a miracle crop to save the earth and rural economies. Legalizing hemp production certainly would provide the agricultural sector with new opportunities, but developing a profitable industry will take time and an ability to capture value-added income. Small and Marcus (2002) noted that industries using new agricultural crops often require 10–15 years to reach maturity, and as yet, no such industry has been allowed to develop in the United States.

Beyond simple legalization and allowing new start-ups, a hemp industry in the United States will need rigorous crop testing. Efforts to better understand yield potentials, production costs, best methods of harvest, handling, storage, and processing, and determining the ability to compete within existing and new markets will be needed to understand hemp's viability as a commodity crop. While the USDA's assessment (2000) downplayed hemp's potential, Small and Marcus (2002) noted that (at the time) there could be little in the way of objective analysis of hemp's merits in that climate, and despite restrictive policies, hemp product development and market use have continued to grow.

A large concern for the growth of hemp production systems involves the "chicken-or-the-egg" conundrum. While many industries could and would use hemp products, doing so may be challenged by lack of supply. Producers, on the other hand, are not going to invest in growing crops to supply a market that does not exist. Such issues are likely to take time to work themselves out, and it may be informative to look at the hemp market's development in other countries. For example, the land devoted hemp seed production in Canada varied greatly between 1998 and 2010 (Figure 11). Many farmers may have jumped in without truly knowing the crop's suitability for their farming operation, and the collapse of a commercial buyer left many farmers holding unsalable seed and fiber (Small and Marcus, 2002). In addition, boom-season production and the resultant drop in prices created unprofitable conditions for many growers. This may have been avoidable had the growers had a strong marketing board to bridle the early competitive forces

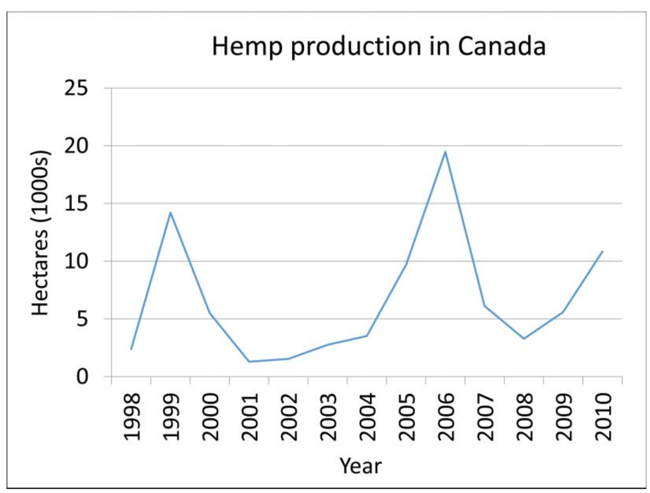

Figure 11. Industrial hemp production in Canada following legalization of planting in 1998. Source: Government of Alberta (Laate, 2015).

and to dampen the large price fluctuations. Without a similar mechanism in the United States, similar overproduction risks and fluctuations are likely given the large amount of hype and propaganda surrounding the crop (Small and Marcus, 2002).

XV. Conclusions

The growing list of hemp's potential uses suggests that the crop has much promise for agronomic production systems in the United States. However, many of the claims surrounding hemp's productivity and utility must be taken with caution because in many cases, the production systems and markets for these products must be developed. Agronomic research will be needed to match cultivars to different soils and climates and determine resource input requirements (as fertilizer, herbicides, and pesticides) that optimize the volume and value of outputs. In addition, new harvest and processing systems are likely to be needed to capture these products. Development of industrial hemp as an important fiber resource is, in part, dependent upon the growth and maturation of natural fiber technologies. Use in mixed composites for automotive parts has been growing since its introduction in the mid-1990s. These new fiber products are desired for their lighter weight and excellent structural properties relative to typical glass- and resin-based fibers, and the fibers are finding use in home construction materials. These fiber-based end-use technologies in turn still may need agricultural innovations that can both reap high-quality fibers and reduce harvest costs. Seed and seed products have perhaps the greatest potential for developing markets. Hemp seed and essential oil products have use as nutritional and nutraceutical supplements and functional foods with good fatty acid and amino acid profiles. These products also are being used in cosmetics and increasingly being explored for medicinal applications and therapies. New applications in energy and environmental quality may further expand the potential of this ancient crop.

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