AN AGRONOMIC AND SOCIAL PERSPECTIVE OF INDUSTRIAL HEMP ADOPTION BY ORGANIC FARMERS IN THE MIDWEST

by

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ABSTRACT

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Hemp (*Cannabis sativa* L.) is an annual crop used to produce a wide range of products including foods, beverages, nutritional supplements, fabrics, and textiles. Hemp has long been conflated with marijuana and has not been grown in the United States for decades. Due to recent legislation, the legal restrictions on growing hemp seem likely to be lifted. However, although interest is high, industrial hemp has not been grown in the U.S. for nearly 80 years and research on virtually all aspects of hemp production in the U.S. is in its infancy. We lack fundamental knowledge regarding cultivar performance, interactions with pests, particularly weeds, and nutrient requirements. Research is needed to address this knowledge gap and potential production issues as well as to determine the attitudes, perceptions and concerns of farmers regarding the potential adoption of this "new" crop. Importantly, research should be conducted before the crop becomes widely available so that farmers can make informed decisions and avoid costly mistakes. My dissertation consists of four chapters. In Chapter 1, I examine the literature for weed management in hemp production and identify research gaps. In Chapter 2, I investigate the complex legal framework that surrounds *Cannabis* and the resulting complications for hemp production. In Chapter 3, I present research conducted to determine the attitudes, perceptions, interests and concerns of organic farmers regarding the reintroduction and potential adoption of hemp was completed through survey research. Finally, in the fourth chapter, I present research conducted to characterize the growth and phenology of industrial hemp cultivars and identify cultivars suitable for growing conditions in the Midwest, and to determine the effect of delayed planting on the phenology and growth of seed and fiber hemp varieties in the Midwest.

Weed control and weed management in industrial hemp production is a surprisingly understudied field. Few peer-reviewed field studies on hemp exist on any subject and in particular, weed control and weed management is understudied. Specifically, only three studies designed to address a weed management issues exist in the literature dating back to 1900. Most

commodity crops have extensive literature discussing weed management, and such an extensive gap in the hemp literature suggests that research needs to be conducted to determine the impacts of weeds on hemp production. Discrepancies among state laws and current federal drug legislation have created a convoluted, confusing, and impractical framework currently surrounds hemp production in the U.S. The building of pesticide regulation and product safety systems that are specific to the many end uses of Cannabis have yet to occur in the U.S. Interactions between producers, state and federal government, and third-party testing laboratories need to be facilitated to build regulation systems along with educational programs to train growers appropriate best management. Organic farmers are generally considered less risk adverse than the general farming population and often considered early adopters of technology. I surveyed organic farmers in seven Midwestern states and found that 98.5% of the respondents were generally open to new technologies, but that demographics variables explained little of the variation for respondents' level of innovativeness as well as their openness to hemp. The respondents were generally open to hemp production (88.2% agreed with the statement that they were open to trying hemp production on their farm) and found that attributes of hemp production that conferred relative advantage and were compatible with existing systems were important. Delayed planting of hemp generally reduced the onset and duration of female flowering and the time to seed formation but the magnitude of these effects varied among cultivars. Seed, stalk, and total above ground dry weight yields varied across cultivar and planting date which may have been impacted by inconsistent stand densities stemming from heavy rainfall and wet soils. Results from this dissertation suggest that hemp is an understudied crop in the U.S., but that interest in its production among organic farmers exists. Field results support the importance of both planting date and cultivar for hemp phenology discussed in previous literature and so research needs to be conducted to explore best hemp production practices in the U.S.

CHAPTER 1. A CALL FOR WEED RESEARCH IN INDUSTRIAL HEMP (*CANNABIS SATIVA* L)

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1.1 Abstract

Industrial hemp (*Cannabis sativa* L.) is grown in over 30 countries for fiber, seed, flowers, and acreage is increasing globally. Hemp has long been promoted as a crop that competes well with weeds and requires little intervention to prevent yield losses. We conducted a literature review and found little peer-reviewed research to support this claim. We identified only three articles that specifically addressed weed management under field conditions and none provided information on hemp yield losses from weeds. These findings highlight a clear need for research-based information on interactions between weeds and hemp that address potential yield losses under various production conditions and that provides a research-based framework for weed management in industrial hemp.

1.2 Introduction

Industrial hemp (*Cannabis sativa* L.) is an herbaceous, wind-pollinated annual originally cultivated in Asia but now grown in over 30 countries for fiber, seed, flowers, and leaves (Small and Marcus, 2002; Johnson, 2017). Hemp is a minor global crop with approximately 91,055 hectares planted annually in 2016 (Johnson, 2017). Hemp was legalized in most European countries by 1996 and the amount of land in production has remained relatively stable at around 20,000 hectares (Carus, 2017). Canada has grown hemp, primarily for oilseed, since 1994 (Johnson, 2017) with 55,853 hectares registered in 2017 (Health Canada 2018). In 1970, the U.S. Congress passed the Controlled Substance Act declaring all *Cannabis* varieties, including hemp, as Schedule I controlled substances (drugs with no accepted medical use) which effectively criminalized hemp production (Kolosov, 2009). The 2014 Farm Bill modified the federal definition, distinguishing hemp from marijuana based on THC (tetrahydrocannabinol) concentrations (hemp has $< 0.3\%$ THC) (Young, 2005; Williams & Mundell, 2015). Production in the U.S. remains relatively small with 10,405 hectares planted across 19 states in 2017 (U.S.

Hemp Crop Report). However, industry estimates of the current U.S. market for hemp-based products (food, beverages, nutritional supplements, fabrics, textiles, and construction materials) (Small & Marcus, 2002; Anum Laate, 2012) were more than $580 million annually (Johnson, 2017), and the Hemp Industries Association (HIA) claimed that U.S. hemp retail sales grew more than 15% annually from 2010 to 2015 (Johnson, 2017).

Hemp has long been promoted as a crop that, due to its rapid growth and canopy closure, has a competitive advantage over weeds (Dewey, 1901; Ehrensing, 1998; Kraenzel et al., 1998; Ranalli, 1999). Amaducci et al. (2015) reviewed agronomic practices for fiber production in Europe and noted that weed control was usually unnecessary. The Canadian Hemp Trade Alliance (CHTA) as well as extension services from Ontario, Manitoba, Saskatchewan and Alberta also suggest that hemp is able to suppress weed growth through early vegetative growth (CHTA, 2018). If weeds have little effect on hemp yields, then hemp would compare favorably to many other crops. However, even if true, it is possible that varieties developed for seed or fiber at higher latitudes in Europe and Canada may be less vigorous and less competitive with weeds at lower latitudes in the U.S. and elsewhere. This may be particularly true for seed varieties which are typically shorter and sown at lower densities than fiber varieties, and which may be less competitive with weeds (McPartland et al., 2004). It is also possible that, even in hemp-growing countries, sufficient research has not been conducted to adequately characterize relationships between weeds and hemp. Since there are no herbicides registered for use in the U.S. to prevent or respond to weed outbreaks in hemp, an overly optimistic view of the ability of hemp to compete with or suppress weeds could be costly for farmers.

1.3 Methods

We conducted a literature review to assess weed issues and management in industrial hemp. We used Web of Science, a scientific citation indexing service, as the search engine to map the available literature and depth of scientific research on weed management in hemp across a range of databases and scientific disciplines. This search engine contains articles dating back to 1900. The keyword "*Cannabis sativa*" was used with the Boolean operators AND "hemp" and NOT "marijuana". Using 'AND' fetched articles that mention both the words, while using 'NOT' fetched articles containing the first word but not the second, thus narrowing the search (Grewal et al., 2016). No time, language or document type restrictions were applied.

We used a three step screening strategy to determine the relevance of articles returned from our initial search. First, titles and abstracts were reviewed to ensure that the articles reported information from field studies. We excluded literature reviews, model outputs, or meta-analyses, and studies that took place exclusively under greenhouse or growth chamber conditions. We focused on field studies since crop performance under field conditions is particularly relevant for understanding the potential effects of weeds on hemp growth and yields. Second, full texts for articles meeting the initial inclusion criteria were downloaded and reviewed for 1) their description of weed management and 2) any statements of how weed biology influenced hemp production. This screening process followed protocols described by Rosenstock et al. (2016). Data extracted from studies included year, location and any mention of weed control. A third and final step was included to ensure all field papers on hemp production were recovered. Reference sections from all articles whose full text were reviewed were systematically checked to identify any field research not located in the original Web of Science search. Articles identified by this approach were downloaded and reviewed.

1.4 Results

The screening strategy identified 661 articles (633 from the first two steps with an additional 28 from the third step). Of these, only 84 articles met all criteria. Eight of the 84 articles were not available in full text (three were published in non-English languages, while the others were not available in any form) and were discarded. Weeds were not mentioned in any context in 42 of the remaining articles. Weeds were mentioned in eighteen articles (Meijer et al., 1995; Van der Werf & Van der Berg, 1995; Van der Werf et al., 1995a; Cromack, 1998; Sankari & Mela, 1998; Schumann et al., 1999; Cappelletto et al., 2001; Keller et al., 2001; Mediavilla et al., 2001; Svennerstedt & Svensson, 2006; Höppner & Menge-Hartmann, 2007; Westerhuis et al., 2009a; Westerhuis et al., 2009b; Faux et al., 2013; Finnan & Burke, 2013; Sausserde & Adamovičs, 2013; Sausserde et al., 2013; Gorchs et al., 2017) but only to note that no weed management was performed. The authors of six of the eighteen articles specifically indicated that weeds were suppressed well enough by the crop that weed management was unnecessary (Meijer et al., 1995; Van der Werf & Van den Berg, 1995; Van der Werf et al., 1995a; Lisson & Mendham, 1998; Deleuran & Flengmark, 2006; Gorchs et al., 2017). The use of mechanical and/or manual weed control was mentioned in nine articles although the effect of weeds on hemp yields was not described (Van der Werf et al., 1995b; Lisson & Mendham, 1998; Bertoli et al., 2010; Aubin et al., 2015; Aubin et al., 2016; Angelini et al., 2016; Campiglia et al., 2017; Rijavec et al., 2017; Papastylianou et al., 2018). Jankauskienė & Gruzdevienė, (2010) did not control weeds in their study although they reported on weed densities. Yield losses to hemp were not described. Finally, Mankowski (2003) and Tang et al., (2016) used the herbicide linuron in their study of hemp cultivars, but weed management was not a treatment in their studies and potential hemp yield differences from herbicide application were not provided.

Only three articles were found that specifically addressed weed management (Vera et al., 2006; Hall et al., 2014; Jankauskiené et al., 2014). Jankauskiené et al., (2014) evaluated the potential suppression of weeds by eight monoecious hemp cultivars in Lithuania. Weed densities were relatively high (133–202 plants m^{-2} depending on year) which the authors hypothesized stemmed in part from environmental conditions. At hemp harvest, the highest weed densities existed in plots with cultivars USO 31, the variety with the shortest growth period and plant height, and Beniko, a variety also considered to mature early. The authors suggested that early flowering could potentially limit canopy development and thus the ability of the crop to suppress weeds. Yields were not reported. Vera et al. (2006) investigated the impact of seeding rate and row spacing on the ability of hemp to compete with weeds in Saskatchewan. Increasing the seeding rate from 20 to 80 kg ha^{-1} decreased weed density in all years by an average of 33% and reduced weed biomass by 34% (Vera et al., 2006). The wider row spacing (36 cm) resulted in higher weed density in one year but lower densities in the following year. Over all, weed density was affected by cultivar and seeding rate in all years, and by row spacing in two of the years (Vera et al., 2006). Hall et al. (2014) also focused on the effect of hemp density on weed, crop growth and yield in Australia. They determined that weed suppression increased with increasing plant population. Low yields were reported due to unsuitable short photoperiods that caused early flowering and relatively short plants. None of the three articles discussed potential yield loss from weed competition.

1.5 Discussion

Three key findings are evident from the literature review. First, the majority (78%) of the field studies on hemp were conducted in Europe. Information on Canadian hemp can be found on several governmental websites and hemp has been grown in Canada since 1998. However, only seven peer-reviewed field studies have been published on Canadian hemp. Although China is the single largest supplier of U.S. imports of raw and processed hemp fiber (Johnson, 2017), there are surprisingly few papers (only one from our search). This, however, may reflect that research from that region is not available in English language journals (Amaducci et al., 2015). It is unclear how well studies conducted in Europe, primarily on fiber varieties, will predict hemp behavior at lower latitudes in the USA.

Second, a majority of articles that provided information on weed management noted that weeds were not actively controlled. The lack of any weed management in a majority of the articles and the reliance on cultivation in a few supports the idea that weed management may not be necessary in hemp. It is worth noting that the absence of herbicides in these papers also supports the idea that weed control may not be important for hemp production. Of the 84 articles, only Tang et al., (2016) and Mankowski, (2003) used an herbicide (linuron) to control dicotyledonous weeds after sowings in Czech Republic and Poland, respectively. Ehrensing (1998) and Kraenzel et al., (1998) suggested that hemp might be well-suited for organic production and the absences of herbicides from the studies support this assertion. There are currently no labeled pesticides for hemp in the U.S. Lack of labeling means that any pesticide applications to industrial hemp crops are off-label and therefore illegal. Additionally, hemp has shown high levels of sensitivity to herbicide applications. Maxwell (2016) found three post-emergent herbicides (rifloxysulfuron, bispyribac-sodium, and rimsulfuron) caused 90% injury or more and reduced hemp biomass in Kentucky studies. Additionally, while hemp appeared tolerant to early post applications of bromoxynil and bispyribac-sodium, pre-applied products significantly reduced hemp yields (Woosley et al., 2015). Unpublished research conducted in Indiana testing 15 different post-emergent herbicides in hemp, found that all herbicides caused 53-99% injury in hemp with the exception of clethodim (Young, personal communication).

Finally, and perhaps most importantly, we found no peer-reviewed papers that describe relationships between weeds and hemp yields. Research describing relationships between weed densities and crop yields as well as on the optimal timing of weed control to limit yield losses is common for many crops, including corn (*Zea mays*) (Vangessel et al., 1995), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*) (Appleby et al., 1975; O'Donovan et al., 1985), soybean (*Glycine max*) (Klingman & Oliver, 1994), chickpea (*Cicer arietinum*) (Whish et al., 2002) and cowpea (*Vigna unguiculata*) (Aggarwal & Ouedraogo, 1989) but completely absent for hemp.

Yield losses in corn and soybean in the U.S. from weeds have been estimated up to 34% and 38%, respectively, even under the best management practices (Chandler, 1984; Knezevic et al., 1994; Bensch et al., 2003; Liphadzi & Dille, 2006).

Weed management issues have also been explored for other minor oilseed crops such as safflower (Anderson, 1987; Blackshaw et al., 1990; Blackshaw, 1993; Jalali et al., 2012; Naghavi et al., 2012; Sadeghi & Sasanfar, 2012) and sunflower (Aly et al., 2001; Fried et al., 2009; Jurado-Expósito et al., 2017; Sans et al., 2011; Sauerborn et al., 2002) as well for minor fiber crops such as kenaf (Burnside & Wiliams, 1967; Kuchinda et al., 2001; Kurtz & Neill, 1992; Mahapatra et al., 2014; Malan, 2011). Yield reductions due to weeds can be substantial with safflower yields reduced by nearly a third to over 70% (Naghavi et al., 2012; Jalali et al., 2012; Blackshaw et al., 1990; Uslu et al., 1998). Sunflower production has seen 58 - 99% weed infestation in some areas (Jurado-Expósito et al., 2017; Sauerborn et al., 2002) and yield reductions of 37% by broomrape (Orobanche cumana) (Mijatovic & Stojanovic, 1973). Weeds reduced kenaf yields by 40% in the Sudan (Fageiry, 1985) and by 32% - 53% in Nigeria (Kuchinda et al., 2001). Cultivation significantly increased kenaf yield and stem diameter when compared with weedy plots in the U.S. (Burnside & Wiliams, 1967) with losses of 907 kg ha^{-1} from weed competition (Williams, 1966). Flax, another minor crop produced for fiber and oilseed, has a relatively poor competitive ability with weeds (Kurtenback, 2017) and has seen reductions of dry matter yield up to 19% (Gruenhagen & Nalewaja, 1969) and 82% for oilseed yield (Bell & Nalewaja, 1968) while yields can improve five times over uncontrolled weedy plots (Chow, 1983). In the absence of any peer-reviewed research, we cannot even estimate potential yield losses in hemp.

Additional research on hemp is needed if hemp production is to expand, particularly in the United States. Globally, potential yield losses are greater from weeds than other pests in major crops (Oerke, 2006) with estimates of economic losses in the U.S. of $27 billion per year in corn alone (if weeds were left uncontrolled) (Soltani et al., 2016). Minor crops, such as hemp, may be particular affected by weeds due to a lack of registered herbicides. Biotic stressors, such as weeds, are among the major factors that cause yield instability and even total crop failures for minor crops (Peltonen-Sainio et al., 2016). Most minor crops have major weed problems and control is generally a complex and expensive process (Macleod, 1996). Fenimore & Doohan (2008) argued that research is particularly needed for minor crops in the U.S. because of the limited options for weed management and because they receive only a small fraction of the funding made available for weed research in major crops. Similarly, Santín-Montanyá et al. (2017) argued there is an urgent need in the European Union for research and investigation into weed management, particularly in ‘minor use’ crops due to the significant reduction of approved active substances.

1.6 Summary

Weed control and weed management in industrial hemp production is a surprisingly understudied field. There are few peer-reviewed field studies on hemp on any subject and only three specifically designed to address weed management. Hemp has long been promoted as a crop that competes well with weeds and requires little intervention to prevent yield losses. However, there is very little research to support this position and hemp’s reputation may be based on fiber varieties. Hemp grown for seed and CBD are relatively high value crops where even small yield reductions due to weeds could be costly. Additionally, as hemp appears to be sensitive to herbicides, it is critical that research be conducted to better understand the effect of pre and post emergence herbicides on hemp growth and yields. We note that is not uncommon for crops that were introduced with great fanfare to fail to meet expectations, particularly when research efforts were insufficient (Cherney & Small, 2016). We suggest that weed science studies, particularly those that examine potential yield losses due to weeds, should be part of a larger effort to establish a research-based framework for industrial hemp as its acreage increases globally.

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CHAPTER 2. *CANNABIS* AS CONUNDRUM

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2.1 Abstract

Cannabis (*Cannabis sativa* L.) is the genus name for plants that include numerous species, but can be separated broadly into two classes of plants: industrial hemp and marijuana. Despite clear differences in desirable traits, hemp and marijuana appear to readily interbreed making it difficult to legally separate the two species. The current regulatory and legal system in the U.S. is convoluted, confusing, and impractical with the federal government considering all *Cannabis* a Schedule 1 drug and thus handcuffing itself from all further necessary policy in terms of end use differentiating, pesticide regulation, and product safety development. Additionally, state governments have moved forward with *Cannabis* legislation and without federal oversight have many different interpretations of the law. Current discrepancies among state laws and between federal drug legislation pose a dilemma in how pesticide use in *Cannabis* production can be addressed. A working regulatory system for agricultural pesticides requires interactions between producers, state and federal government, and third-party testing laboratories, along with educational programs to train growers appropriate best management and pest management practices for their business model.

2.2 What is *Cannabis*?

Cannabis (*Cannabis sativa* L.) is the genus name for plants that include numerous species, cultivated varieties and hybrids used in hemp and marijuana production (Clarke and Merlin, 2013). A biochemically dynamic plant that produces over 400 chemicals and has over 60 different cannabinoids, *Cannabis* contains many terpene phenolic structures that have not been isolated from any other plant or animal species (Clarke and Merlin, 2013). Although the exact taxonomy and nomenclature of the *Cannabis* genus continues to be debated (McPartland & Guy, 2017). *Cannabis* can be separated broadly and practically into two classes of plants based on their use. Marijuana is primarily bred for the psychoactive compound THC (delta 9-

tetrahydrocannabinol) which causes the 'high' marijuana is known for. Industrial hemp is valued for its fiber, seed, and medicinal compounds (e.g. cannabidiol [CBD]) (Schluttenhofer & Yuan, 2017) (Fig. 2.1). Traditionally hemp serves more as an agricultural commodity and is produced in the field, while marijuana is almost exclusively grown in greenhouses or other controlled environment facilities. Breeding programs exist and varieties have been developed for both hemp and marijuana (Ranalli, 2004; Salentijn et al., 2015). Despite clear differences in desirable traits, hemp, marijuana, and their feral counterparts all appear to readily interbreed. This has made it difficult to legally separate marijuana and hemp. The current regulatory and legal system in the U.S. is convoluted, confusing, and impractical. However, even if the laws change there will be a serious need for research and regulation of the various components of *Cannabis* whether that be hemp or marijuana.

2.3 Pests and Pesticides

There is a limited amount of knowledge about *Cannabis* pests. Hemp has only been legally grown in U.S. for several years, and there is virtually no peer-reviewed literature on pests and their impact on hemp yields in Europe and Canada (Sandler, unpublished). However, there is some literature that has identified pests present in both hemp and marijuana. In hemp, damping off diseases caused by water molds (*Chromista*), *Pythium* species (*P. aphanidermatum* and *P. ultimum*), and several other fungal species are ubiquitous problems that attack all cultivars grown under field conditions (Beckerman et al., 2017; McPartland, 1996b; McPartland & McKernan, 2017) (Table 1.1). Additionally, arthropod pests include lepidopterous stem borers, predominately European corn borers (*Ostrinia nubilalis*) and hemp borers (*Grapholita delineana*), lepidopterous caterpillars, coleopteran beetles, and leafminers (*Agromyzidae*) (McPartland, 1996a; McPartland, 1996b). Aphid (*Aphis* spp.) pressure has also been observed in field-grown hemp (Couture & Beckerman, unpub.; Darby, 2016). Plant propagation of marijuana often occurs in an enclosed greenhouse or warehouse via vegetative propagation (also called clonal reproduction) that creates genetically identical plants that produce consistent levels of THC when grown under controlled environmental conditions. Arthropod insect pests attacking greenhouse grown marijuana plants are insects with piercing-sucking mouthparts, such as aphids, whiteflies (*Trialeurodes vaporariorum*), and mealybugs (*Psuedococcidae*), in addition to western flower thrip (*Frankliniella occidentalis*) (McPartland, 1996a). Greenhouse pathogens of marijuana include gray mold (*Botrytis cinerea*) which infects flowering tops of large moisture-retaining female buds during flowering along with cuttings and seedlings, powdery mildew (McPartland, 1996b), and root rots like *Pythium* (Beckerman et al., 2017) and *Fusarium* species (Beckerman et al., unpub.).

However, there are virtually no published papers showing yield loss from any pests. Even books such as "*Hemp diseased and pests: management and biological control"*, do not discuss yield losses from pests. McPartland (1996b) mentions yields to state that pests reduce yields, however, he does not cite literature to support this claim. There are no papers that discuss yield loss in hemp from weeds (Sandler, unpub.). Amaducci et al. (2015) reviewed agronomic practices for fiber production in Europe and noted that weed control after planting was usually unnecessary. However, varieties developed for seed or fiber at higher latitudes in Europe and Canada may have decreased vigor at lower latitudes in the U.S. and elsewhere. Additionally, seed varieties, which are phenotypically different than fiber varieties, may not close canopy as quickly and may be less competitive with weeds (McPartland et al., 2004).

To date, there are no pesticides labeled for industrial hemp production in the U.S. While hemp production has been legal for decades in Europe and Canada, there are few registered pesticides used in its production in Europe and information available from Europe does not mention pesticide use in hemp production (Gorchs & Lloveras, 2008; Lloveras et al., 2006). The sole exception was research conducted in Poland, where grass herbicides proved to be useful for fighting monocot weeds in hemp (Heller & Pracyzk, 2009). Among herbicides controlling dicot weeds applied after emergence, only metamitron showed relative selectivity towards hemp and still caused a reduction in yield (Heller & Pracyzk, 2009). In Italy, using multi-screening methods, hemp products were tested for 71 different pesticides residues (Fusari et al., 2013). Results found that amitraz, chlorpyrifos-methyl, and trifluralin had unacceptable levels of residue (using 0.010 mg kg^{-1} as the acceptable residue limit) (Fusari et al., 2013). Circumstantial evidence suggests that pesticides are being used in Italy and elsewhere demonstrating that growers will turn to products on the market to protect their crops even if the products are not registered for their crops. However, finding information on pesticide usage is difficult. The only pesticides recommended for hemp use in Canada are quizalofop-P-ethyl (0.036-0.07 kg ha^{-1}), a post emergent grass herbicide or non-selective products such as paraquat (0.55-1.1 L ha^{-1}) and glyphosate (0.75-4.68 L ha^{-1}). The latter two can only be used only as pre-plant applications (OMAFRA, 2016; Maxwell, 2016; Scheifele, 1998).

Finally, limited research has been conducted on pesticide use in hemp in the U.S. In Kentucky, a series of 11 herbicides (five pre-emergent and six post-emergent) were tested for weed control in hemp. Pre-emergent herbicides resulted in comparable yields to the weed-free check with the exception of mesotrione and were less damaging than post-emergent herbicides (Maxwell, 2016). Trifloxysulfuron, bispyribac-sodium, and rimsulfuron, all post emergent herbicides, caused > 90% injury of hemp plants and reduced hemp biomass (kg m^2) more than other herbicide treatments (Maxwell, 2016). Unpublished research conducted in Indiana in 2015 found 15 different post-emergent herbicides caused 53-99% injury to hemp plants with the exception of clethodim (Young B, 2015, pers. comm.). However, testing for efficacy is not the same as getting the products registered and it is important to note that these trials were strictly for demonstration purposes.

In the absence of clear relationships between pests and reduction in *Cannabis* yields, there is currently no incentive for pesticide companies to invest in developing new or registering existing pesticides for *Cannabis*. Additionally, if pesticides are going to be used they will have to be registered and regulated and this leads to the many conundrums facing *Cannabis* production and use.

2.4 Conundrums facing Cannabis

2.4.1 Conundrum 1. *Cannabis* is a Schedule 1 drug under federal laws

In 1970, Congress passed the Controlled Substance Act declaring all *Cannabis* varieties, including hemp, as Schedule I controlled substances (along with heroin, LSD, peyote, and ecstasy). The United States Attorney General is responsible for promulgating regulations related to the registration of Schedule 1 drugs, the control of the manufacture and distribution of controlled substances, and enforcement of the law and regulations (Kolosov, 2009). The U.S. Drug Enforcement Agency (DEA) serves as the regulatory authority over Schedule 1 controlled substances (Title 21 US Code Controlled Substance Act). Thus, interpretation and enforcement of laws affecting both hemp and marijuana at the federal level currently fall under the Department of Justice (DOJ) and the DEA.

2.4.2 Conundrum 2. Dichotomy within the federal government and between state legislation

The 2014 Farm Bill modified the federal definition of *Cannabis* as a way of separating the agronomic and pharmaceutical use of *Cannabis* from psychoactive uses. This federal legislation focused on the concentration of THC by weight, defining a *Cannabis* plant as either marijuana (>0.3% THC) or industrial hemp (<0.3% THC) (Williams & Mundell, 2015; Young, 2005). The red line of 0.3% THC content is a value used in existing state laws as well, although some argue that this value was not based on science but instead arbitrarily assigned (NCSL, 2017; Small et al. 2003).

While the farm bill divided *Cannabis* into hemp and distinguishes it from marijuana, the Controlled Substance Act remains in place categorizing all *Cannabis* as a Schedule 1 drug. As such, the Schedule 1 designation takes precedence over the farm bills separation of *Cannabis*, and regardless of THC level, *Cannabis* is treated as a Schedule 1 drug. Thus, the DOJ regulates hemp seed as a Schedule 1 narcotic, requiring researchers that participate in hemp research programs to possess a Schedule 1 license. By regulating hemp seed as a controlled substance, the DOJ impedes those states that seek to plant and do research on *Cannabis* as a viable crop.

The continued status as a Schedule 1 compound directly impacts whether or not conventional pesticides can be legally used to manage those pests attacking *Cannabis*. The federal government, through the Environmental Protection Agency (EPA) does not allow the registration of pesticides on *Cannabis*, because federal laws categorizes the plants as illegal. Without a federal registration (known as EPA Reg. No.), conventional pesticides cannot be used legally in the United States. Therefore, while a state can legalize the production of *Cannabis* setting up the conflict between the states and federal government, growers will not have conventional pesticides that could be labelled for controlling the multitude of pests as long as all forms of *Cannabis* remains as a Schedule 1 drug. It also prevents the manufacturers from investing their research efforts in finding pesticide solutions for *Cannabis* due to conflicting policies, regulations, and legislation.

2.4.3 Conundrum 3. EPA statutes superseded by federal drug laws

The EPA has oversight of pesticide registration, safe use, and enforcement. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) administered by the EPA, and the Federal Food, Drug, and Cosmetic Act (FFDCA), administered by the Federal Drug Administration

(FDA), requires that data from EPA scientists indicate a product can be used with minimum risk to people or environment before that pesticides can be federally registered (Ollinger & Fernandez-Cornejo, 1995; Osteen, 1994).

Prior to EPA pesticide registration, a crop must have a tolerance established (i.e., the maximum amount of a pesticide allowed to remain in or on a food). Under FIFRA, the EPA sets a pesticide tolerance for each crop, which are maximum residue levels acceptable for a specific crop (see Table 2.2 for examples). Setting tolerance limits is complex, time-consuming, and data-driven. There are at present no currently established tolerances for *Cannabis* whether in the form of hemp or marijuana meaning there are no pesticide products that can be legally used. As long as *Cannabis* remains a Schedule 1 drug under federal law, the EPA cannot recognize it as a legal crop thereby preventing the establishment of pesticide tolerances.

It is important to clarify that pesticides require multiple registrations for different crops based upon cropping practices, human exposure to pesticides, and the site of application (e.g., field, nursery, greenhouse, etc.). These registrations are listed on the pesticide label and permit their sale and use in accordance with the EPA requirements to protect human health and the environment.

2.4.4 Conundrum 4. States attempt to work around federal statutes

This inability of the EPA to federally register pesticides has had downstream consequences for state agricultural agencies that regulate pesticide use and enforcement. Several of the states that allow the production of *Cannabis* have tried to circumvent the lack of federal progress on pesticide registrations by using available alternative EPA policies and programs. These programs include using pseudo-registration and registration exemptions that state departments of agriculture can implement under federal law, and include FIFRA Section 24C (Special Local Needs), FIFRA Section 18, FIFRA 25B, and United States Department of Agriculture (USDA) Minor Use Program.

2.4.4.1 Section 24C—Special Local Needs

States have been granted the authority to issue a special local needs (SLN) registration under certain conditions that EPA must approve [FIFRA, §24(c)]. California, Washington and Colorado were earlier adopters of 24c when they petitioned the EPA to allow the use of federally registered pesticides on *Cannabis*. The EPA initially agreed, stating that those pesticides could be legally used on *Cannabis* production, similar to other crops with an exemption from tolerance requirements (Voelker & Holmes, 2015). However, by 2017, the EPA changed course, informing the California Department of Pesticide Regulation that products the state had registered for use on *Cannabis* through the 24C were no longer approved. Scott Pruitt, then EPA Administrator wrote, "Under federal law, cultivation (along with sale and use) of *Cannabis* is generally unlawful as a Schedule 1 controlled substance under the Controlled Substance Act….. the general illegality of *Cannabis* cultivation makes pesticide use on *Cannabis* a fundamentally different use pattern" (Pruitt, 2017).

2.4.4.2 Section 18—Emergency Exemptions

Emergency exemptions are a temporary pesticide registration that, under certain circumstances, Section 18 of FIFRA authorizes the EPA to permit the use of a pesticide *for a limited time* on a crop that is not on the pesticide label (Table 2.3). Section 18 registration is the only avenue that can permit legal pesticide usage when no residue tolerance has been federally established. This is an important tool in protecting currently produced crops, but an emergency exemption is not the same as the full Section 3 registration—it is a short-term end around. It is important to note that the state must agree to submit a Section 18 to the EPA, who must approve the emergency use request. Finally, the manufacturer of the products being requested must also agree to support the Section 18 by producing a product label for that special use.

2.4.4.3 Section 25B—Reduced Risk

There are active ingredients exempt from all FIFRA registration requirements (Stone, 2014; William & Mundell, 2015). The federal list of these exempt active ingredients is limited to a small set of naturally-occurring active ingredients encompassing microbial agents, biochemical agents of natural origin, plant-incorporated protectants, and certain minerals that are *assumed* safe and efficacious for their intended use (Stone, 2014). This is only assumed, as toxicological and environmental data are not required by the EPA (Stone, 2014). Their efficacy with respect to pest control is not established and seldom supported by scientifically-based field trials.[30] Regardless, the active ingredients that fall under the Section 25B exemptions can legally be used on *Cannabis.* With the potential for *Cannabis* to be grown on large acreage, producers would expect products to have proven high efficacy rates to deem the application worthwhile. Thus far, for the control of plant pathogens and weeds by 25B active ingredients research suggests otherwise (Hallett, 2005; Ojiambo & Scherm, 2006).

2.4.4.4 USDA Minor Use Program

One final avenue for obtaining residue tolerances for *Cannabis* is through the USDA Minor Use Program. To be considered for inclusion in the minor use program, an applicant must show that: 1). Adding a new crop to a pesticide label does not provide sufficient economic incentive for a federal registration and 2). That an efficacious, federally-registered pesticide is not already available.

To facilitate this process, the Interregional Research Project No. 4 (IR-4) was created through a cooperative effort of the USDA, EPA, land grant universities, and the pesticide industry. The IR-4 program develops residue data that is required for EPA tolerance setting and federal registration, thereby expanding the number of sites that a pesticide can be used. The USDA minor use program attempts to develop tolerances for crops that then allows the manufacturer to add these crops to their pesticide product labels with minimal cost. While tagged as minor use, these crops represent one-half of US agricultural sales.

Tolerance setting for minor use crops is more an issue of economics: To register an active ingredient and bring it to market represents an investment of approximately $260 million dollars and it takes about 9.5 years to conduct the EPA-required research and to go through the registration process (McDougal, 2016) (Fig. 2.2). The largest acreage crops in the United States justify the investment in terms of time and money. However, there are currently no incentives for pesticide manufacturers to expand, let alone develop, products for minor crop uses in light of the economic, regulatory and market challenges. This creates an economic issue that crops with limited acreage do not provide enough revenue for the manufacturers to justify spending limited resources developing tolerances for these minor use crops. *Cannabis*, as a potential minor crop with significant production acreage, may serve as an exception.

An overriding charge of IR-4 is to obtain residue tolerances for food and feed crops, but this task requires a pre-existing tolerance for the pesticide in question. *Cannabis* is still held hostage to the creation of this first tolerance, but IR-4 may provide a solution to this conundrum by including incentives for chemical pesticide producers to pursue minor crop use registrations.

Overall, even with some exemptions, the current system of registering pesticides at the federal and state level as currently conducted is nothing more than a stop-gap measure. Current regulations are not long-term solutions and cannot replace an overarching pesticide labeling system for *Cannabis*.

2.4.5 Conundrum 5. Legal conflicts create an atmosphere for illegal use of pesticides

Cultural and biological controls provide an important foundation for successful *Cannabis* production. However, unlike producers of many other crops, without registered pesticides, growers face a daunting task in saving or salvaging hemp or marijuana from damage when these tactics fail to control a pest.

Not having federally registered pesticides for *Cannabis* ignores an important reality. Growers have an economic incentive to improve the quantity and quality of *Cannabis* through the use of registered pesticides available for other agricultural crops to deal with similar pest problems. While *Cannabis* crops have similar pests to other agronomic and greenhouse crops, those pesticides used on other crops cannot be legally used on *Cannabis* in the U.S. Under federal and state laws, using a pesticide on a crop that is not listed on a product's label is considered an illegal act subject to crop confiscation, fines, and imprisonment. Unlike pharmaceuticals which can be prescribed for off label use, (U.S. FDA, 2018) amendments to FIFRA (7 U.S.C. §136 et seq.) banned the application of any registered pesticide for uses not specified on its label. This meant that there are no 'blanket labels,' and that each crop (known as the site) must appear on the label being used.

For some *Cannabis* growers, going "off-label" seems to be the only option. Early studies on indoor C*annabis* production revealed limited pesticide use (McLaren et al., 2008). However, two years later, a survey of 40 indoor marijuana operations in the U.S. found a number of pesticides (the insecticides dicofol, chlordane, malathion, chlorpyrifos, fenvalerate, cypermethrin, tetramethrin, permethrin, and the fungicide chlorothalonil to name a few) in 12% of the operations (Koch et al., 2010). In 2015, marijuana growers were suspected of using federally registered pesticides for *Cannabis* (Voelker & Holmes, 2015). A list of 65 pesticides was compiled from survey data, extensive conversations with growers, and sales data from suppliers providing pesticide products to *Cannabis* growers. Twenty-four of the 65 pesticides were detected on marijuana flowers or extracts (Voelker & Holmes, 2015).

Oregon requires marijuana to be tested for four classes of pesticides, including chlorinated hydrocarbons, organophosphates, carbamates, and pyrethroids. A detection threshold at or above 0.1 ppm requires destruction of the *Cannabis* product. However, those four classes of pesticides represent hundreds of compounds. Pesticide screening involves identifying individual compounds not classes. Thus, in order to actually meet the Oregon rule, each sample would have to be screened for hundreds of individual compounds, a task that is too time consuming and cost prohibitive (Voelker & Holmes, 2015). Additionally, there are fungicides and herbicides used on *Cannabis* which do not fall into these four classes of the Oregon. The Oregon-specified categories carry the dangerous implication for growers that other types of compounds, by not being included in the list to be sampled, are by default, acceptable for use on marijuana (Voelker & Holmes, 2015). This ruling in Oregon, along with other competing laws in California, Washington, and other states, illuminate issues that arise from states attempting to create pesticide regulation independently.

An important question arises of whether or not allowing legal residues promotes the use of illegal pesticides on those crops. It should be noted that by allowing some fraction of a residue based on a set of criteria, whatever they may be, is not the same as setting a tolerance though it creates that illusion that it is appropriate to use illegal pesticides.

2.4.6 Conundrum 6. Does illegal use of pesticides pose a risk to users of *Cannabis* products?

The EPA also fails to examine the potential health effects of pesticide compounds on *Cannabis* by not offering a comprehensive risk assessment at the federal level. Since the EPA has not established risk assessments for pesticides used on *Cannabis,* it is difficult to determine how serious the exposure might be to people consuming these products. To answer the question would require toxicological evaluations, consumption amounts, and frequency of exposure to calculate whether or not the level of exposure is of concern to human health. Some states like Colorado and Washington allowed marijuana to contain residues of federally registered pesticide up to a level less than the lowest legal residue of the pesticide on food (Voelker & Holmes, 2015). In short, it would be assumed that this lower level of residue would not be health-threatening if calculated in the EPA risk assessment process. However, this remains an untested proposal.

While there are grounds to be concerned about potential pesticide contaminants in products derived from *Cannabis,* there has been no systematic monitoring to identify risk (McLaren et al., 2008). Research is only beginning and the majority of references used in the literature that discuss the contamination of marijuana with unregistered pesticides are anecdotal, often lacking critical peer review (Pérez-Parada et al., 2016; Subritzky et al., 2017). The potential threat of pesticides residue exposure to *Cannabis* users is substantial and poses a significant toxicological risk to the user, with 69.5% of tested pesticides including bifenthrin, diazinon, and permethrin remaining in *Cannabis* smoke condensate (Sullivan et al., 2013).

The results from testing 390 samples, found marijuana products contained levels of pesticides residues in 55% of plant extracts, contaminated with levels that exceeded 50,000 ppb, tolerances set for other crops (Voelker & Holmes, 2015). Additionally, some concentrates contained insecticides piperonyl butoxide, carbaryl, chlorfenapyr, and the fungicide myclobutanil at concentrations greater than 100,000 ppb which are levels that exceed tolerances many times over those used on other commodities. A survey in Uruguay using seized and legally produced marijuana samples found high levels of residues of the insecticides diazinon, teflubenzuron, and the fungicide tebuconazole from *Cannabis*' inflorescence (Pérez-Parada et al., 2016). Additionally, some synthetic chemicals are systemic which can be particularly dangerous on plants destined for human consumption as the active ingredient remains in plant tissues with little to no breakdown. Contamination from pesticides may be of particular concern for medicinal marijuana users, with weakened constitutions and immune systems (Pérez-Parada et al., 2016; Voelker & Holmes, 2015).

Marijuana is the second most widely smoked substance after tobacco, primarily inhaled from a cigarette or water pipe (Tashkin, 2013). If marijuana was not typically consumed by smoking, it would fall more clearly under existing guidelines covering pharmaceuticals or agricultural products; however, inhalation presents a different set of health concerns than oral ingestion (Holmes et al., 2015). Using surrogate data to represent marijuana, 1.5 to 15.5% of pyrethroid insecticides on treated tobacco were transferred to cigarette smoke that was inhaled (Cai et al., 2002). Direct inhalation of pesticides is only one potential risk; burning of leaves can cause decomposition of the pesticide and form toxic mixtures or other toxic pesticide contaminants (Lorenz et al., 1987). The complexity of marijuana use, which includes edibles and vaping, require significantly more oversight than hemp because of the many ways it can be consumed.

A distinction should be made between recreational and medical uses of marijuana. The population using marijuana for medical reasons as previously stated may have compromised immune systems or other health issues that could make potential contaminates from unregulated pesticide applications even more dangerous (Sullivan et al., 2013). For example, diseases of the liver may intensify the toxicological effects of pesticide exposure (Sullivan et al., 2013). In 2013, a medical marijuana dispensary with several locations throughout Maine was fined $18,000 by the Maine Department of Health and Human Services for illegal pesticide applications (Noi-Noi, 2013). At the time, Maine's law prohibited the use of any pesticides in *Cannabis* production (Noi-Noi, 2013). The dispensary and other medical *Cannabis* providers in the state successfully lobbied for a bill, LD 1531, which now allows for the application of 25(b) pesticides in *Cannabis* production and exempt from federal registration.

The different uses of *Cannabis* will require distinct risk assessments when it comes to the evaluation of pesticides used in its production (Table 2.4). In California, there has been no clear determination as to whether marijuana is an agricultural commodity or a medical drug. This complicates the state's Compassionate Use Act which guarantees ill Californians access to medical marijuana. Even if marijuana is deemed a medicine, it nevertheless is derived from a crop, and the cultivation of the crop is subject to production input use restrictions (Lindsey, 2012). In 2016, the state of Washington declared that all medical-grade *Cannabis* in the state will be regulated under I-502 and must pass mandatory residue tests for pesticides (Stat. Auth. RCW 69.50.342 § 314-55-102).

With so many different end uses—fiber, oil, food, or THC and/or CBD— consumed by ingestion or inhalation will require more than one tolerance for the use of a pesticide. This means the industries represented by *Cannabis* production will need separate policies and regulations dependent on the products fabricated and their end uses, and strict enforcement of these uses to ensure consumer safety.

2.5 The Way Forward: Pesticide Registration and Use

2.5.1 Congress must decide if *Cannabis* is truly a Schedule 1 Drug

While the number of states allowing *Cannabis* to be legally grown, harvested, and processed continues to grow, the federal government continues to hold *Cannabis* as a Schedule 1 drug. The current system that says *Cannabis* is both an illegal drug and a potentially valuable crop is not sustainable. Currently, no Section 3 pesticides are labeled for usage on C*annabis*, and as such, any application of a registered pesticide on this crop would be a violation of federal and state statutes (Stone, 2014; William & Mundell, 2015; Voelker & Holmes, 2015). Four years after the recreational marijuana market was legalized by the Colorado General Assembly, state leaders continue to grapple with how to provide properly registered and labeled pesticides to growers of *Cannabis* (Subritzky et al. 2017). Other states face similar problems. Without the federal government removing *Cannabis* from the list of Schedule 1 drugs, the EPA will not be able to register potential pesticide products. The 2018 Farm Bill contains language that would legalize production and sales of hemp separate from marijuana.

2.5.2 Finding compromise among federal agencies and state governments

The current system of registering and enforcing pesticides at the federal and state level has come to a loggerhead. Current regulations are not long-term solutions and cannot replace an overarching pesticide labeling system for *Cannabis*. A final product for pesticide regulation in *Cannabis* production would be one that provides a framework and systems approach to regulation of production, gives growers clear rules, guidelines and best management practices, and implements a system for effective enforcement to assure consumer safety. In some ways, many of the western states like California have put in place an extensive network of regulations to deal with the production of *Cannabis.*

It is essential to define clearly which *Cannabis* products are being discussed when developing pesticide use regulations due to the multiple pathways humans will interact with these products. Products containing THC and/or CBD extracts are inhaled via smoking or vaping, ingested as food products, and can be introduced by dermal exposure via lotions and creams. Hemp, on the other hand, can be manufactured into fiber, food (hemp oil and seed), cosmetics, and animal feed, with user interfaces such as ingestion, inhalation, and as topical lotions and ointments.

2.5.3 Support research and outreach to *Cannabis* growers

To date, engagement between *Cannabis* growers and experts in pest management, pesticide science and regulation has been limited, if not outright prevented (Colorado State University legal counsel, 2014). Cooperative activity among land grant universities, farmers, and local and federal governments, via the Morrill, Hatch, and Smith-Lever Act was critical in making agricultural commodities successful. These partnerships are still needed today if *Cannabis* is to be successful. Historically, land-grant universities and industries have developed production guidelines and recommendations for which pesticides to use on corn, soybean, cotton, flax and even tobacco. These approaches could be applied to *Cannabis* as well. However, this would require research by land grant universities, which at the time of writing is largely not done due to legal concerns.

Although regulation and enforcement may be the initial priority, long-term solutions will need to include a great deal of education. Engagement of stakeholders will be important and outreach to the *Cannabis* industry from credible sources like land-grant universities, crop consultants, and growers can facilitate cooperation. Extension and educational programs will provide opportunities for *Cannabis* producers to interface with specialists and pesticide regulatory authorities.

2.5.4 Determine HACCP procedures and policies

Many growers in other agricultural settings use a system called HACCP— Hazard Analysis Critical Control Points. HACCP provides a framework for monitoring the total food system from planting, harvesting, shipping and storage as a way of reducing the risk of foodborne illnesses. The tool assesses hazards and establishes control systems that focus on prevention rather than relying mainly on end-product testing. Food safety is addressed through the analysis and control of biological, chemical, and physical hazards through the entire food processing system: raw material production, procurement and handling, manufacturing, distribution and consumption of the finished product (Cargill, 2012). Few plants have the diversity of uses and human interactions as *Cannabis*. The different products derived from *Cannabis* production means that different agricultural production systems will be required. Thus, a HACCP system-like approach will need to be created for specific end uses and products of *Cannabis* (Biros, 2017; US FDA, 2006); with the recognition that regulations need to be implemented to support a diversity of business sizes and models (Taylor, 2001). In 2017, a technical committee comprised of industry, scientific, provincial and Canadian Grain Commission experts developed a generic HACCP Plan for milling of grains, oilseeds, and pulses (Canadian Grain Commission, 2017). Additionally, industry and government experts created a group of generic prerequisite programs made up of 15 Good Operating Practices (Canadian Grain Commission, 2017). This generic HACCP Plan as well as the determined 15 Good Operating Practices are a good basis to begin regulation of hemp grain and other *Cannabis* products destined for consumption.

2.6 Conclusion

The current situation between federal government law and state government work-arounds is convoluted and opaque. A working regulatory system for agricultural pesticides requires interactions between producers, state and federal government, and third-party testing labs, along with educational programs to train growers appropriate best management and pest management practices for their business model. The federal government plays a central role in this system as it must establish the overall rules regarding pesticide legislation and implement a program for inspection and enforcement, which it currently does for registered pesticides.

There is a certain irony in that a Schedule I drug has been legalized in some states prior to the pesticides potentially needed to produce and protect it. This gives the appearance that pesticides are more strictly regulated in the United States than a Schedule 1 drug. Conversations between growers, policymakers and elected officials needs to focus on how to resolve issues between state and federal law. A lack of clarity regarding how *Cannabi*s should be classified for production purposes or intended end uses still persists, but differentiating between end use, and agronomic hemp (fiber, oilseed) and pharmaceutical *Cannabis* (for CBD or THC, as edibles and inhaling agents) will be a critical first step in resolving this conundrum.

Current discrepancies among state laws and between federal drug legislation pose a dilemma in how pesticide use in *Cannabis* production can be addressed. Pesticide use policy needs to be congruent with the intended products of the crop and fit into existing federal guidelines of agencies like the EPA, USDA, and FDA. Different industries that emerge from *Cannabis* production should have specific policies that are accompanied by specific pesticide use regulations, and HACCP assessments to aid growers and industries in production (Biros, 2017). A governing body must establish licensing requirements, provide a list of allowed pesticides, and develop a system for on-site inspections of *Cannabi*s production facilities (Voelker and Holmes, 2015).

The development of regulations and the registration of pesticides for *Cannabis* will require extensive research to address tolerances for health and environmental issues, identify critical control points and extend best practices to a nascent industry. Like all new products, this will require significant investment by commercial entrepreneurs. Historically, land grant universities assisted in the development of these trials and practices, but current federal law prevents universities from using federal funds in doing such research. A significant amount of work will need to be undertaken by a variety of stakeholders before the conundrum that is *Cannabis* will be solved. It is the hope of the authors that providing a comprehensive look at the issues facing *Cannabis* production in the United States will point a way forward and keep the conversation progressing.

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Table 2.1 Common Cannabis diseases and pests

Seedling diseases	**Flower & leaf diseases, outdoors**	**Flower & leaf, diseases, indoors**	**Stem & branch diseases**	**Root diseases**
Damping-off fungi Pythium Phytophthora Rhizoctonia Fusarium Storage fungi Genetic sterility	Gray mold Multiple leaf spots Downy mildew Nutritional disorders Brown blight Bacterial leaf diseases	Nutritional disorders Pink rot Gray mold Powdery mildew Multiple leaf spots Brown blight Virus diseases	Gray mold White mold Hemp canker Fusarium canker Fusarium wilt Stem nema Charcoal rot Anthracnose Bacterial spot and blight Dodder	Fusarium Pythium Phytophtora Rhizoctonia Root rot Root knot nema Broomrape Sclerotium rot Cyst nematode
Cutworms Birds Hemp beetles Crickets Slugs Rodents	Hemp flea beetles Hemp borers Budworms Leafminers Green stink bugs	Spider mites Aphids Whiteflies Thrips Leafhoppers	European corn – borers Hemp borers Weevils Mordellid grubs Longhorn grubs	Hemp flea beetles White root grubs Root maggots Termites Ants Fungus Gnats Wireworms

Table 2.2 An example of established tolerances for the fungicide, azoxystrobin, and the insecticide imidacloprid on various commodities. There are no registered pesticides for C*annabis* production, thus, agricultural commodities in the table were selected for their similarity to potential C*annabis* products.

Commodity	Azoxystrobin (ppm)	Commodity	Imidacloprid (ppm)
Barley, bran	6.0	Canola, seed	0.05
Citrus, oil	40.0	Cotton, gin byproducts	4.0
Corn, field, refined oil	0.3	Cotton, undelinted seed	6.0
Cotton, gin byproducts	45	Flax, seed	0.05
Cottonseed subgroup 20C	0.7	Herbs subgroup 19A, dried herbs	48
Ginseng[1]	0.5	Hop, dried cones	6.0
Herb Subgroup 19A, dried leaves	260	Rapeseed, seed	0.05
Hop, dried cones	20.0	Soybean, meal	4.0
Spearmint, tops	30		
Quinoa, grain	3.0		
Rapeseed subgroup 20A	1.0		
Tea, dried[1]	20.0		

Table 2.3 Differences between Section 18 and Section 24(c) Special Local Needs registrations. Both exemptions require scientific evaluation, a letter of authorization from the registrant, and approval by EPA (modified from Bishop, 2016).[50]

	Section 18	**Section 24(c) Special Local Needs (SLN)**
Tolerances	No current tolerance established EPA will establish a time-limited tolerance.	Tolerance or exemption already established.
Reasons for use	For limited use To treat sudden and limited emergency pest infestations	Used to meet a special local need (may be a region or whole state)
Documentation	Emergency situation must be well documented and not a historical pest problem Economics and lack of alternatives must be verified	Justification and lack of alternatives must be documented
Public comment period	Can be used during the 30-day public comment period	Must be posted for a 30-day public comment period before use is allowed
Requests	Made through state department of agriculture and issued after EPA approval Includes the use, limitations on acreage and location, and the time-limited tolerance	State department of agriculture may issue without EPA review - EPA has 90 days to comment
Expiration dates	Not to exceed one year, except quarantine exemptions (up to three years) Renewable if emergency recurs or persists	Usually issued without expiration date May be inactivated by applicant, DPR[†], or EPA
Applicators	Must be third-party (someone other than the registrant)	May be first-party (the registrant) or third-party (someone other than the registrant)
Fees	Not subject to EPA maintenance fee No DPR fee	Subject to EPA maintenance fee. No state department of agriculture fee
Permits	Requires a restricted materials permit even if product is not a restricted material	Requires a restricted materials permit only if product is a restricted material

[†] Department of Pesticide Regulation California

Table 2.4 Abbreviated list of permissible exposure levels for marijuana production dependent on end use, either edible or inhaled in California.

Residual pesticide	Edible Cannabis Products (ppm)	Dried Cannabis Flowers (ppm)	All Other Processed Cannabis (ppm)
Azoxystrobin	0.01	0.01	0.01
Dimethomorph	0.01	0.01	0.01
Fludioxonil	0.02	0.02	0.02
Metalaxyl	0.01	0.01	0.01
Myclobutanil	0.02	0.02	0.02
Paclobutrazol	0.01	0.01	0.01
Propiconazole	0.02	0.02	0.02
Tebuconazole	0.01	0.01	0.01
Trifloxystrobin	25	0.1	0.02

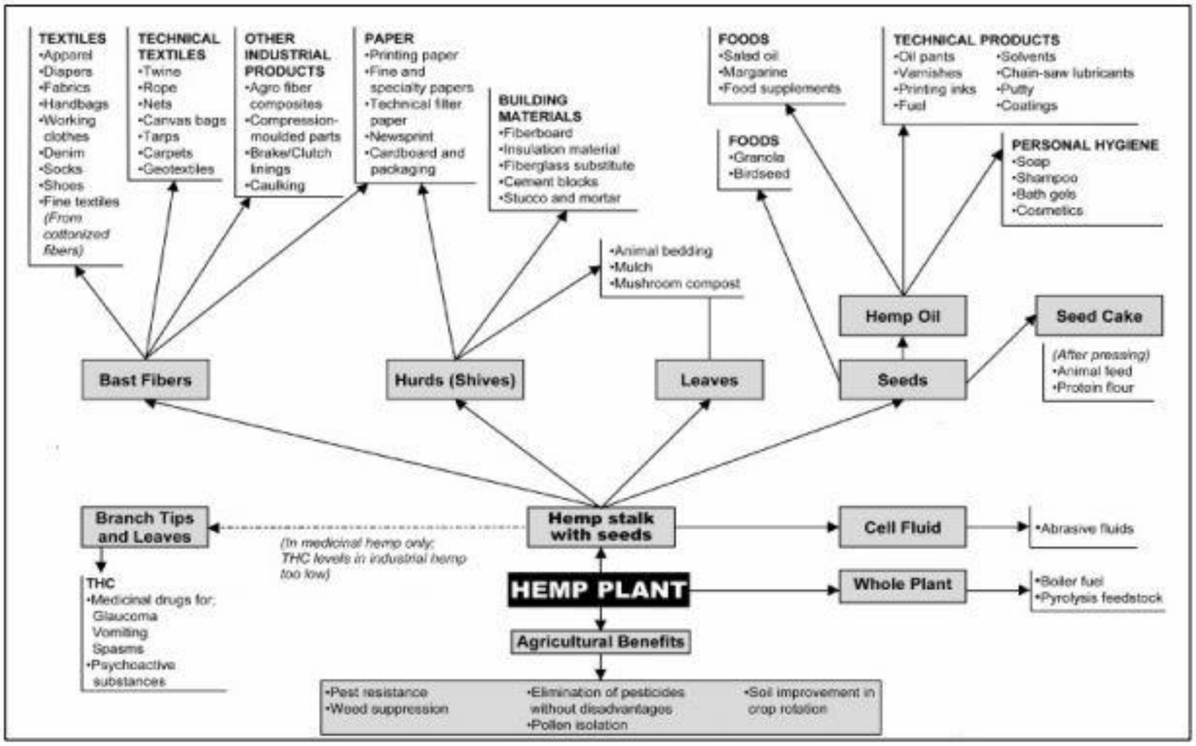

Figure 2.1 Products derived from industrial hemp. Adapted from Johnson, 2017.

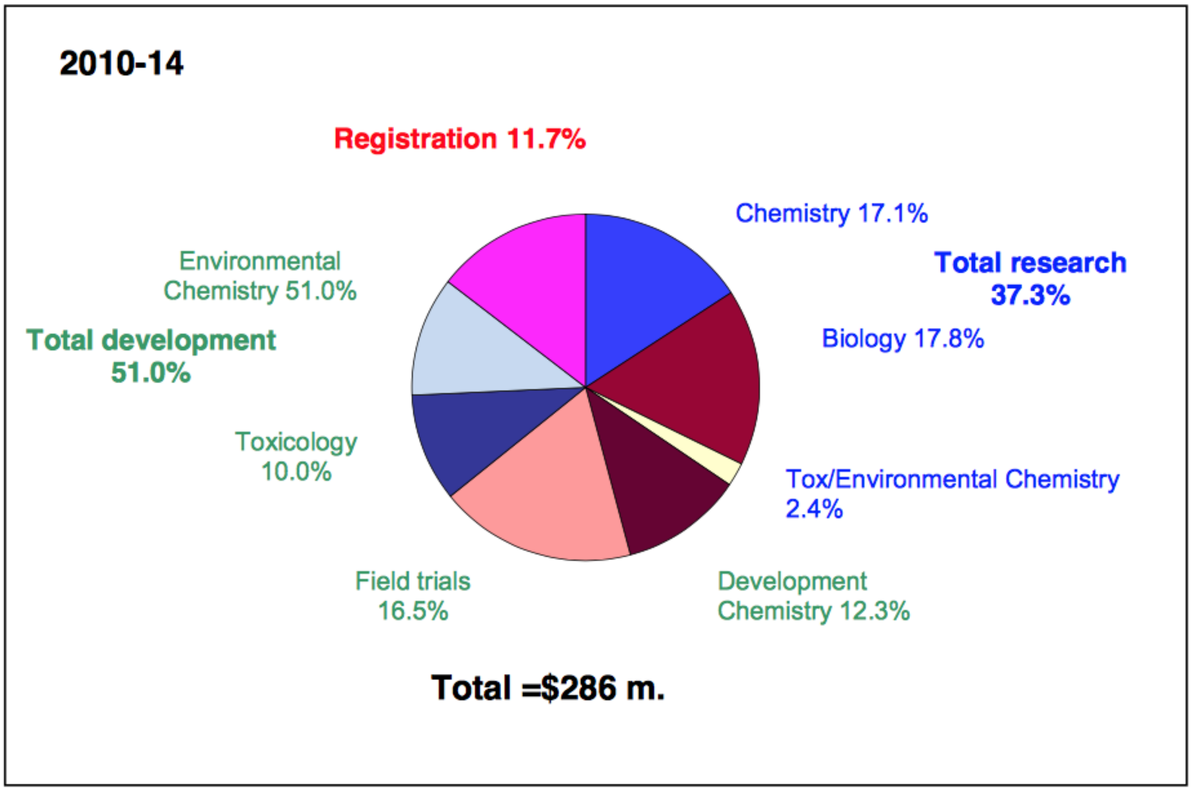

Figure 2.2 A breakdown of the components (by percentage) needed to bring a new crop protection product to market (McDougall, 2016).

CHAPTER 3. THE ADOPTION OF INDUSTRIAL HEMP BY ORGANIC FARMERS IN SEVEN MIDWEST STATES

3.1 Abstract

Industrial hemp (*Cannabis sativa* L.) is an annual crop currently grown in over 30 countries for fiber, seed, flowers, and leaves. Production in the U.S. remains small but there appears to be potential for increases in hemp acreage, including certified organic acres. However, to the best of our knowledge, research identifying the perceptions, knowledge, and interest of organic farmers regarding industrial hemp adoption has never been studied. Using a diffusion of innovation framework, this paper seeks to understand the potential adoption, as well as perceived barriers and opportunities, of hemp production by organic farmers. Certified organic farmers in seven Midwest states were contacted by email, postcard, and organic association newsletters and invited to complete an online survey focused on farm and farmer characteristics, adoption of new technology, knowledge of hemp, interest in adopting hemp, and attributes of hemp that might affect adoption. Farm and farmer characteristics of the respondents (261 surveys were completed) were similar to values reported for organic farmers in other studies. Based on their responses to a series of statements about their behavior, a majority of the respondents might be considered innovators or early adopters and were open to trying hemp on their farm. Their willingness to try hemp was affected by their estimated level of innovativeness as well as their income and farm enterprises. Principal components analysis was used to generate synthetic variables (principal components) for innovativeness that were used in regression analyses. The synthetic variables explained 43% of the variation in responses but were not strongly correlated with farmer or farm characteristics. The farmers indicated a greater willingness to adopt hemp for attributes associated with compatibility (consistency of an innovation with existing systems) and relative advantage (perception of an innovation being better than previous ones) than for complexity (difficulty of an innovation to understand) suggesting that farmers may particularly benefit from research focused on how hemp can fit into existing farming practices and systems.

3.2 Introduction

Industrial hemp (*Cannabis sativa* L.) is an annual crop currently grown in over 30 countries for fiber, seed, flowers, and leaves (Johnson, 2017; Small & Marcus, 2002). Production in the U.S. remains relatively small (10,405 hectares across 19 states in 2017) (U.S. Hemp Crop Report, 2018) because all *Cannabis* varieties, including hemp, were designated as Schedule I controlled substances (the most strictly regulated controlled substances that have no accepted medical use and a high potential for abuse). The 2014 Farm Bill modified the federal definition by distinguishing hemp from marijuana based on THC (tetrahydrocannabinol) concentrations (hemp has < 0.3% THC), and allowed industrial hemp to be grown for research purposes (Williams & Mundell, 2015; Young, 2005). A majority of states authorized programs that allowed farmers to grow industrial hemp under the guidelines established by the 2014 Farm Bill (NCSL, 2018). More recently, the passage of the 2018 Farm Bill legalized hemp production nationally, making it likely that farmers will soon be able to grown hemp commercially throughout the U.S. Although in its infancy, there is strong support for hemp production from a variety of groups including the American Farm Bureau Federation, the National Association of State Departments of Agriculture and the National Conference of State Legislatures (American Farm Bureau, 2018; Holte, 2018; Patton, 2014). This support suggests that hemp has the potential to become a widespread crop in the U.S.

New crops have the potential to increase farm income, diversify products, expand or create new markets, decrease imports, improve human and livestock diets, and create new industries (Blade & Slinkard, 2002; Fletcher, 2002; Janick et al., 1996; Theron, 2002). Soybean, an example of successful crop introduction, contributed more than $500 billion to the U.S. economy in the first 60 years of production, and is now grown on 89.6 million acres (NASS, 2018). Other successful crop introductions include avocado and pistachio in California and pearl millet in the southeastern states (Andrews et al., 1993). However, crop introductions have not always been successful and it is not uncommon for crops that were introduced with high expectations to underperform, particularly when the crops receive little attention from researchers (Cherney & Small, 2016; Small & Marcus, 2002). New crops may have agronomic, processing, economic, and/or social issues that can prevent them from achieving their potential (Cherney & Small, 2016). Hemp faces all of these issues to some extent. Recently, interest in new crops has intensified due to low prices for major commodities, interest in a more sustainable and diversified agriculture, and consumer demand for new foods and products (Borras et al., 2016).

The successful introduction and resulting adoption of a new crop by farmers derives from the transfer of skills, knowledge, and germplasm from one person to another (Fletcher, 2002). Rogers (2003) defined the diffusion of innovation as “the process in which an innovation is communicated through certain channels over time among the members of a social system.” Rogers (1962) proposed a theory to explain the diffusion of innovations in which the adoption of a new technology or innovation followed an “S-shaped curve” where only a few individuals initially adopt the new technology followed by increasing number of individuals before adoption eventually levels off. The diffusion of innovation theory assumes that people go through four stages (awareness, evaluation, trial, and adoption) in order to adopt innovations (Sarcheshmeh et al., 2018). Rogers (1963) identified five adopter groups based on the speed with which members of a group adopted a new technology: innovators, early adopters, early majority, late majority and laggards. Innovators and early adopters account for 2.5% and 13.5% of the adopter population, respectively, suggesting that they are relatively rare (Aoki, 2014). The theory has been applied to the adoption of agricultural innovations (Adjei et al., 2017; Altobelli et al., 2017; Cirani et al., 2010; Lin, 1991; Pulschen et al., 2007; Sarcheshmeh et al., 2018) and structural characteristics such as farm size, market position, solvency, and the age of the farmer have been used to explain differences in adoption behavior among farmers (Diederen et al., 2003; Läpple & Van Rensburg, 2011). In addition to demographic characteristics, risk-taking, social norms and attitudes, and perceived economic benefits or constraints can influence adoption rates (Abdulai & Huffman, 2014; Cullen et al., 2012; Greiner & Gregg, 2011; Long et al., 2016; Pannell et al., 2006).

In addition to characteristics of the adopter, the attributes of the innovation itself can help to explain adoption behavior. Five attributes of innovation that are thought to influence adoption (Rogers 2003; Sarcheshmeh et al., 2018): relative advantage (the degree to which an innovation is perceived as better than previous ones); compatibility (the way an innovation is consistent with existing systems and values); complexity (the perceived difficulty of an innovation to understand or use); trialability (the potential to experiment with an innovation); and observability (visibility of results of an innovation). Beissinger et al., (2018) examined the non-adoption of potato virus management practices by seed Washington potato growers. They attributed the non-adoption in part to the lack of relative advantage and compatibility of the proposed potato virus management practices. Relative advantage was the most significant factor affecting adoption of rhizobium inoculation of legumes in North-West Cambodia (Farquharson, 2013). Reimer et al., (2012) explored factors that impacted farmers' adoption of conservation practices and found that perceived high levels of relative advantage and compatibility were most important in increasing adoption of conservation practices. Tornatzky & Klein (1982) conducted a meta-analysis of the literature and identified compatibility, relative advantage, and complexity as the three most important attributes for innovation adoption. This agrees with research regarding consumer behavior that identified relative advantage and compatibility as the two most important attributes of innovation for predictors of innovativeness (Ostlund, 1974).

Industrial hemp has been suggested as an ideal crop for organic agriculture because it is believed to compete well with weeds, has relatively low disease and insect damage, and improves soil structure (Dewey, 1901; Ehrensing, 1998; Kraenzel et al., 1998). There are currently no synthetic pesticides registered for hemp production in the U.S. and it seems unlikely that there will be any in the near future (Sandler et al., 2018). While hemp production has been legal for decades in Europe and Canada, there are few registered pesticides used in its production in Europe (Gorchs & Lloveras, 2008; Lloveras et al., 2006). In Canada, the only herbicides recommended for hemp are quizalofop-P-ethyl, a post emergent grass herbicide, and non-selective products such as paraquat and glyphosate (OMAFRA, 2016). The latter two can only be used only as pre-plant applications (OMAFRA, 2016; Maxwell, 2016; Scheifele, 1998). Pest management in hemp may therefore rely on organic practices for both organic and conventional growers in the short-term. In addition to potentially serving as a new cash crop, hemp may be useful as a summer cover crop in organic rotations as it is harvested early enough to allow for fall cover or cash crops to be planted (Pasanen, 2017). Finally, there appears to be a market for certified organic hemp (Pasanen, 2017; Technavio 2018). The hemp-based food market is projected to grow at a compound annual rate of more than 24% by 2022, and, importantly, the increased demand for organic hemp is one of the key trends that will contribute to the market growth (Technavio, 2018).

Organic farmers appear to have adoption behaviors that distinguish them from conventional farmers. Several studies have shown that organic farmers are less risk adverse, a characteristic of earlier adopters, than conventional farmers (Berensten & Van Asseldonk, 2016;

Gardebroek, 2006; Läpple, 2012; Lien et al., 2003). Early adopters of organic farming in Spain's olive-groves were less risk adverse than farmers that adopted organic production methods later (Parra-Lopez et al., 2007). Dutch organic farmers had significantly lower absolute Arrow–Pratt coefficients, a measurement of absolute and relative risk-aversion, than non-organic farmers (Gardebroek, 2006). Differences in risk attitudes between organic farmers and non-organic farmers may reflect the position of the former as 'innovators', implying a greater willingness to accept risk than non-organic farmers (Gardebroek, 2006). In a review of 100 studies focused on organic farmers over a period of approximately 20 years, Padel (2001) concluded that organic farmers shared characteristics typical of innovators and suggested that because organic farming is a complex system change from conventional farming, those that adopt its practices are more likely to assume higher risk and place less emphasis on profit maximization.

Research on the diffusion of innovations typically examines the adoption or non-adoption of an innovation in retrospect. Assessing the perceived importance of key attributes of hemp before it is widely available might help guide future research, extension and outreach programming for this new crop. Organic farmers may be positioned to adopt hemp production as it could fit into their farming rotations well and their adoption behavior may differ from conventional farmers. However, the historical conflation of hemp and marijuana and the general lack of knowledge regarding hemp in the U.S. may pose adoption challenges even for organic farmers who do not fit the traditional adoption curve (Burton et al., 1999, Fisher, 1989). This research was completed to 1) identify characteristics of organic farmers that may impact hemp production adoption, 2) understand organic farmers' organic farmer pre-existing knowledge and perceptions of hemp, 3) determine their openness to hemp adoption, and 4) identify potential barriers and opportunities to adoption.

3.3 Methods

3.3.1 Survey construction

A five part survey investigating organic farmer adoption rates and hemp knowledge was constructed (Appendix 1). The first section included 11 questions that addressed farmer characteristics (education, income, age, and gender) and farm characteristics (size, enterprise, ownership, etc.). The questions were developed so that most answers were categorical and discreet. However, respondents were provided with a list of potential farm enterprises (vegetable, grain, poultry, etc.,) and asked to indicate all enterprises that applied to their farm. In the second section, respondents were asked to indicate their level of agreement, on a five point Likert scale ranging from “strongly agree” to “strongly disagree”, with 11 statements designed to determine where they might fall along the innovation continuum from innovators to laggards. Following survey protocol (Dillman, 2007), ideas were presented in both positive and negative ways in order to gather as accurate data as possible. The third section contained six true or false statements that were used to determine farmer knowledge of hemp. Responses were summed and a single score was calculated for each farmer (higher scores represented more knowledge). Prior to this section, respondents were provided no information about hemp production so that responses would be based solely on the respondents pre-existing knowledge of hemp. A short paragraph describing industrial hemp and its current production in the U.S. was provided after this section to standardize hemp knowledge among respondents. The fourth section of the survey contained six statements designed to determine the interest of the respondents in hemp production and their willingness to adopt it. A four-point Likert scale from “strongly agree” to “strongly disagree was used. Respondents were asked to report their level of interest in trying hemp production, learning more about farming practices, and obtaining a certificate to grow hemp. In the final section of the survey, we asked farmers to respond to twenty statements designed to determine how attributes of industrial hemp might influence their willingness to adopt its production. A five-point Likert scale ranging from “very positive” to “very negative” was used. Each statement was assigned to one of three attributes: relative advantage, compatibility, and complexity. Answers for all questions that corresponded with each attribute were averaged, thus assigning each respondent a score for each attribute. A cumulative score was calculated for each of the attributes to determine how the surveyed population valued each attribute of innovation. Only these three attributes of innovation were used as research showed that these three were the most influential in adoption behavior (Beissinger et al., 2018; Tornatzky & Klein, 1982).

3.3.2 Survey distribution and data collection

A list of 4,983 certified organic farms in Indiana, Illinois, Ohio, Minnesota, Wisconsin, Iowa, and Michigan was obtained using the USDA’s Organic Integrity Database. The database provided information on all farmers certified at the time of survey distribution, including certifier, certification status, date of last certification, operation ID, crops certified, name, address, and, if available, an email address. An online survey was developed using Qualtrics software and multiple approaches were used to encourage farmers to participate. First, a short email describing the project goals and containing a link to the questionnaire was sent on March 24, 2017 to 908 email addresses, which was the number of usable email addresses obtained from the database. Reminder emails were sent on March 29, April 5, and April 15, 2017. Second, postcards were mailed on March 31, 2017 to 4,061 addresses, which was the number of usable street addresses. The postcards contained an explanation of the project and instructions on how to access the online survey. Finally, in an attempt to increase the number of respondents, an alert letter was created for organic associations within the seven targeted states. These associations were the Midwest Organic & Sustainable Education Service, the Illinois Organic Growers, the Minnesota Crop Improvement Association, the Ohio Ecological Food and Farm Association, the Iowa Organic Association, and the Michigan Organic Food and Farm Alliance. The organizations were asked to include an alert or blurb in their respective newsletters or monthly emails and include a link to the online survey. All organizations confirmed that they would include the alert and survey. These alerts or emails were broadcast and sent throughout the months of April and May 2017. All three approaches contained links to an identical survey; however, links were different for the three approaches allowing for respondents to be separated into groups by how they received the survey. Responses were anonymous but respondents could be tracked through the survey software. All survey material was approved by the Institutional Review Board (IRB). Surveys were attempted by 318 respondents (124 email, 106 postcard, and 88 association alerts, respectively) and 261 completed surveys were used in our analyses. Relying solely on an online questionnaire may have contributed to the relatively low response rate observed in this study. Several farmers called a phone number included in the postcards and email to request a paper copy of the survey or to respond to the survey by phone.

3.3.3 Statistical analysis

All statistical analyses were completed using SAS 9.3 (SAS Institute, Cary, NC). A combination of single and multiple regression analyses were used to examine key relationships among farmer and farm characteristics, innovativeness, and willingness to adopt hemp. For multiple regressions, optimal subsets of independent variables were obtained by using the SELECTION=STEPWISE (stepwise regression) option in PROC REG in SAS (Freund & Littell, 2000). The stepwise regression option includes algorithms that operate by successive addition or removal of significant or non-significant terms (forward selection and backward elimination, respectively). Mallow's C Selection (C_p) was used to assess the fit and to select among models (models with the smallest values were chosen). Standardized regression coefficients were calculated in PROC REG to determine the relative importance of independent variables in multiple regression models for farm income and farm size. Multicollinearity among variables was assessed using variation inflation factors (VIF); variables with high values were removed from the model. Farm enterprise was represented on a binary scale, and respondents could select more than one farm enterprise, creating a non-discreet variable. PROC ANOVA was used to determine if respondents differed in their assessments of the importance of the three attributes: relative advantage, complexity, compatibility. Means were separated by least significant difference at the 0.05% level when ANOVA revealed significant ($P<0.05$) differences among attributes.

Principal component analysis (PCA) is a statistical technique that can be used to reduce a number of redundant variables to smaller set of summary variables, i.e., principal components, that can be used in univariate analyses (Peck, 2016). We used PCA with varimax rotation and a cut-off value of 0.4 (Manly, 1986) to examine responses to the eleven statements in the second section of the survey, all of which addressed where a respondent might fall along the innovation continuum from innovators to laggards. Two principal components, referred to as factor 1 and factor 2 below, explained 43% of the variance in the data. Including additional principal components did not improve the fit of the model and only the first two principal components were used in regression analyses as synthetic variables for innovativeness. The level of innovativeness was only calculated within the population of respondents and does not correlate specifically with general adoption curve categories. However, it allows for comparison within the population of respondents and level of innovation. PROC CORR, which computes Pearson correlation coefficients, was used to evaluate correlations among farm enterprises and principal components identified in principal component analyses. Pearson correlation was used as it allows comparison among continuous variables with a scatter plot to make sure the relationship between variables is linear.

3.4 Results and Discussion

3.4.1 Farmer and farm characteristics

Surveys were completed by certified organic farmers in all seven states (Fig. 3.1). The mean age of respondents was 51.7 years +/- 0.9 SE (values ranged from 22 to 84 years) which is lower than the national average of 58 years for all farm operators (Prager & Williamson, 2018). The average age of organic farm operators was 53 years, according to a national survey of all certified organic farmers in 2012 (NASC, 2014). Women comprised 20.9% +/- 0.7 SE of the respondents, which is similar to percentages reported by NASC (2014) for organic farmers but more than the national average of 12.9% (Prager & Williamson, 2018). A majority (>57 %) of the respondents operated farms smaller than 180 acres and reported gross incomes under $100,000 (Fig. 3.1). The USDA-ERS (2010, 2012) statistics show that the average organic farm was 285 acres, smaller than the general national average farm size of 418 acres. Fewer than 13% of the respondents operated farms larger than 1,000 acres or grossed more than $500,000 in income per year (Fig. 3.1). A majority of the respondents had at least an undergraduate degree (Fig. 3.1). In contrast, Prager & Williamson (2018) reported that the median education for a national survey of farmers was a high school diploma. A majority of the respondents (64%) indicated that they grew grain crops (Fig. 3.2). Forty-five percent of respondents who grew grain crops indicated that they also grew other crops or raised livestock. Of the 93 farmers who indicated that they did not grow a grain crop, 60% grew vegetables, 30% grew fruit, and 28% operated pastures. Farm and farmer characteristics of the respondents were comparable to values reported for organic farmers in other studies (Flaten et al., 2005; Läpple, 2012; Läpple & Van Rensburg, 2011; Lockeretz, 1995, 1997; Padel, 2001). Organic farmers tend to be younger, have higher levels of education, include more women, and in some cases have a higher proportion of people from urban backgrounds (Flaten et al., 2005; Läpple, 2012; Läpple & Van Rensburg, 2011; Lockeretz, 1995; Lockeretz, 1997; Padel, 2001).

Farm size alone explained 45% of the variation in farm income ($y = 1.3 + .75x$, $R^2 = 0.45$, $p < 0.01$ where y is farm income and x is farm size). However, including additional variables in the regression the model helped explain 51% of the variation in farm income (Table 3.1). Two farm enterprises (vegetable, dairy) were positively related to farm income but operating a pasture farm was negatively related (Table 3.1). A review of standardized regression coefficients suggests that operating a vegetable, dairy, or pasture farm contributed nearly equally to the regression model. Grain, livestock and dairy farms were positively related to farm size, while vegetable and poultry farms were negatively correlated (Table 3.1). A review of standardized regression coefficients suggested that most of the explanatory power for the model is derived from farm income and grain farming operations (Table 3.1). Interestingly, vegetable operations were positively correlated with income but negatively correlated with farm size. Organic vegetable farms are often smaller than other operations such as grain or livestock (Scott, 2017).

3.4.2 Likelihood to adopt new technology in general

Our analyses suggest that a majority of the respondents could be categorized as innovators or early adopters. Nearly all respondents (98.5%) agreed or strongly agreed with the statement that they were open to trying new or alternative crops, practices, or technologies on their farm (Table 3.2). Additionally, 70% agreed or strongly agreed that they were usually the first person in their area to try a new crop, cultivar or farming practice. Half of the population indicated that they did not require information from experts to make production decisions and 74% did not wait to observe success from a new technology on other farms before trying it on their own. Almost all respondents agreed that they are always looking for ways to improve their farm, although 25% were reluctant to change farming practices from year to year (Table 3.2). A slight majority agreed that they would only try a new technology if there were sufficient evidence that it worked. Our findings support research suggesting that organic farmers may be innovators and early adopters of innovations. Organic farmers are generally considered less risk averse than the general farming population and are often considered early adopters of technology (Berensten & Van Asseldonk, 2016; Gardebroek, 2006; Läpple, 2012; Lien et al., 2003; Padel, 2001; Pennings & Wansink, 2004).

A biplot with the two factors identified from PCA and an overlay of the eleven statements was created (Fig. 3.3). Factor 1 and factor 2 explained 30% and 13%, respectively, of the variation in the respondent data regarding their place on the innovation continuum. Factor 1 appears to reflect variability among respondents in their need to see evidence showing the success of a new technology before adoption and Factor 2 appears to reflect variability in the interest of respondents in finding new ways to improve their farm or try new products to please customers. High scores for factor 1 clustered variables that all related to behavior characteristics commonly identified with later adopters. Conversely, larger scores for factor 2, also clustered, correlated with characteristics of innovators or early adopters (Fig. 3.3). This clustering validates the strength of the questions by demonstrating an inverse relationship between factor scores that relate to opposite ends of adoption behavior. Farm and farmer characteristics were not significantly correlated with either factor (Table 3.3). Although farm and farmer characteristics have been correlated with adoption behavior, Diederen et al., (2003) noted that the correlations may require a population that includes early and late adopters. Since a majority of the respondents in our study could be characterized as innovators or early adopters, it may not be surprising that farm and farmer characteristics were not significantly correlated with either factor.

3.4.3 Willingness to adopt hemp

A majority of the population was interested in growing hemp on their farms and learning more about hemp production (Table 3.4). A large majority (>90%) of respondents were also interested in learning about hemp markets. Research has shown that farmers, even early adopters and early majority adopters (Aoki, 2014), ordinarily are not interested in new crops without an assured market (Diederen et al., 2003; Janick et al., 1996). Thus, the respondents, while open to hemp production, also showed a clear desire to gain information on hemp markets. Only 22% of the population were primarily interested in growing hemp for cannabadiol (CBD) oil, and a majority (63%) had no opinion about CBD production (Table 3.4).

Both PCA factors, type of farm enterprise (grain), and age were negatively associated but income was positively associated with willingness to adopt hemp (Table 3.5). Low scores for the dependent variable indicate that a respondent was more likely to adopt hemp. Negative correlations therefore suggest that as values for the dependent variables increase, respondents were more likely to adopt hemp. Factor 2 explained the most variability of any single variable which suggests that farmers who routinely try new products might be more willing to adopt hemp. Industrial hemp can be produced for edible grain or pressed for oil and may therefore be attractive to farmers who currently grow similar oil crops such as canola or sunflower. Potentially, hemp represents a diversification tool for grain farmers, rather than an entirely different commodity altogether as it might to non-grain farmers. Our research suggests that younger farmers may be more willing to adopt hemp. This supports several other studies which have concluded that older farmers are less likely to be early innovation adopters than younger farmers (Diederen et al., 2003; Gould et al., 1989; Knowler & Bradshaw, 2007; Läpple & Van

Rensburg, 2011; Rubas, 2004; Somda et al., 2002; Vanclay & Lawerence, 2007). However, no single variable explained more than 10% of the variability and all five variables only explained 21% of the variability in willingness to adopt hemp. Of the 261 respondents, 50.2% (132) strongly agreed and 38% (100) agreed with the statement that they were open to trying hemp production on their farm. Thus, the survey may have selected for those that were already interested and open to hemp.

3.4.4 Knowledge of hemp

Seventy-nine percent of the respondents answered at least five of the six true and false questions about hemp production correctly (Table 3.6), suggesting that this population was relatively knowledgeable about the crop. However, when asked if hemp was a perennial crop, 31% of the population were unsure and only 47.6 % answered correctly. Respondents may be better informed about the legality of hemp than about the biology and production of the crop. For example, only 18.4% of the population was unsure if hemp could be grown for research purposes in some states, but 31% were unsure if it was a perennial crop. Higher levels of knowledge and training have been associated with higher adoption rates (Diederen et al., 2003; Fletcher, 2002; Kaltoft, 1999). New crop adoption derives from the transfer of skills and knowledge (Fletcher, 2002), with adoption of an innovation influenced by the availability of information (Jamal & Pomp, 1993). However, 54% of respondents in our study reported that a lack of knowledge regarding hemp would not affect their willingness to try hemp.

3.4.5 Attributes of innovation as perceived to apply to hemp

A majority (>75%) of the respondents indicated that their willingness to adopt hemp would be positively impacted if hemp fit into their current rotation, allowed them to diversify and reach markets for certified products, competed well with weeds, had low insect pressure, and could be certified as an organic product (Table 3.7). In contrast, more than half of the respondents indicated that unclear legal regulations, a small number of markets, having to invest in new equipment, and a lack of local infrastructure would negatively affect their willingness to adopt hemp (Table 3.7). The ability to sell CBD oil had no effect on the willingness of 52.3% of the respondents to grow hemp. Respondents indicated a greater willingness to adopt hemp for attributes associated with compatibility and relative advantage than with complexity (Table 3.7).

The average score for components associated with complexity was 3.4 which, on a 5 point Likert scale, suggests that the attribute might have little effect on the willingness of the respondents to adopt hemp (Fig. 3.4). Our findings align with several studies regarding the attributes of innovation. Rogers and Stanfield (1962) examined hundreds of empirical studies and noted that compatibility and relative advantage were positively related to the rate of adoption. A meta-analysis of 75 articles concerned with attributes of an innovation, suggested that compatibility and relative advantage were positively related to adoption, while the complexity of an innovation was negatively related to adoption (Tornatzky & Klein, 1982). More recent research regarding producers' adoption of best management practices in watersheds found that relative advantage and compatibility were most important for increasing adoption (Reimer et al., 2012). Non adoption of production practices to limit potato virus in Washington were attributed to the lack of perceived relative advantage and compatibility and overall complexity of the practices (Beissinger et al., 2018). The lack of importance that respondents attributed to complexity may be due to their overall low risk adversity and larger comfort level with complex systems as organic farmers.

3.5 Conclusion

Industrial hemp has not been grown on significant acreage in the U.S. for decades. There appears to be great potential for hemp to emerge as a new crop, particularly one that is managed organically. However, little is known about the interests and perceptions of certified organic farmers regarding hemp. To the best of our knowledge, research that aims to identify the perceptions, knowledge, and interest of organic farmers regarding industrial hemp and the potential for adoption has never been studied. This study is therefore the first attempt to understand how organic farmers might view the adoption of industrial hemp. Our research suggests that there is considerable interest among certified organic growers in adopting hemp. The respondents in our study share characteristics associated with organic farmers in other studies (Flaten et al., 2005; Läpple, 2012; Läpple & Van Rensburg, 2011; Lockeretz, 1995; Lockeretz, 1997; Padel, 2001). Their responses suggest that a majority might be considered innovators or early adopters. However, the low response rate of our survey prevents us from extrapolating to the entire organic farming community in the Midwest and the interest in most respondents in adopting hemp suggests that our sample pool might be skewed towards people already interested in the crop. Nonetheless, the respondents appear to prize hemp attributes associated with compatibility and relative advantage over attributes associated with complexity. Thus, research focused on ways that hemp production may fit into existing farming practices and systems may be particularly useful.

3.6 References

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Table 3.1 Relationships between various factors and their influence on farm income and size. Parentheses enclose standard errors for the intercept and regression coefficients.

	Regression coefficient										
Y^b	Intercept	Size	Vegetable	Dairy	Pasture	Livestock	Income	Grain	Poultry	Adj. R^2	P value
Farm Income	1.18 (0.24)	0.78 (0.06)	0.5 (0.19)	0.79 (0.25)	-0.59 (0.17)					.51	<0.001
Farm Size	0.95 (0.17)		-0.47 (0.15)	0.48 (0.2)		0.41 (0.14)	0.46 (0.04)	1.06 (0.14)	-0.42 (0.19)	.64	0.001
	Standardized regression coefficient										
Y^b	Intercept	Size	Vegetable	Dairy	Pasture	Livestock	Income	Grain	Poultry	Adj R^2	P value
Farm income	1.7 (0.56)	0.70 (0.07)	0.12 (0.20)	0.14 (0.28)	-0.16 (0.19)					.52	<0.001
Farm size	1.3 (0.42)		-0.12 (0.15)	0.1 (0.21)		0.1 (0.15)	0.51 (0.04)	0.31 (0.15)	-0.1 (0.19)	.64	<0.001

Table 3.2 Response of certified organic farmers to statements about the technology adoption and farming practices. Values indicate the percentage of farmers who agreed or disagreed with each statement.

	Strongly Agree	Agree	Disagree	Strongly disagree
	---------------------	%	----------------------	
I am always looking for ways to improve my farm	71.8	27.5	0.4	0.4
I am open to trying new or alternative crops, practices, or technologies on my farm	47.2	51.3	1.5	0.0
My farm size and income allows me to experiment with new crops and farming practices	27.9	55.4	14.9	1.9
I respond quickly to customer interest in new products	21.9	59.3	17.8	1.1
I am usually the first person in my area to try a new crop, cultivar or farming practice	19.0	51.5	29.5	0.0
Other farmers frequently ask me questions about my farming practices	17.9	57.5	23.1	1.5
I will only try a new crop, farming practice, or technology if I see sufficient evidence that is works	9.0	42.0	44.2	4.9
I rarely change my farming practices from year to year	3.4	21.3	62.3	13.1
I am usually not the first person in my area to try a new crop, tool, or practice	2.6	29.1	55.1	13.2
I like to wait and see if something works on other farms before adopting it on my farm	1.5	24.9	62.3	11.3
I am usually reluctant to try new crops or farming practices	1.1	6.0	63.1	29.9

Table 3.3 Pearson correlation coefficients for all demographic variables and factors identified from the PCA. Values are correlation coefficients, parentheses enclose p-values.

	Factor 1	Factor 2
Farmer age	-0.03 (0.59)	-0.08 (0.21)
Farm size	0.11 (0.07)	0.09 (0.15)
Farm income	0.10 (0.11)	0.08 (0.20)
Level of education	0.03 (0.67)	0.06 (0.32)
Gender	-0.01 (0.92)	-0.05 (0.42)
State	-0.08 (0.19)	-0.06 (0.35)
Vegetable†	0.05 (0.45)	0.06 (0.38)
Grain†	0.06 (0.35)	0.05 (0.45)
Poultry†	-0.01 (0.89)	0.05 (0.39)
Livestock†	0.10 (0.10)	0.01 (0.92)
Dairy†	0.02 (0.78)	-0.08 (0.21)
Pasture†	0.04 (0.51)	-0.08 (0.22)
Fruit†	-0.03 (0.66)	0.10 (0.12)
Flower†	0.04 (0.54)	-0.04 (0.49)

† Farm type

Table 3.4 Response of certified organic farmers to statements about industrial hemp. Values indicate the percentage of farmers who agreed or disagreed with each statement.

	Strongly Agree	Agree	Neither disagree nor agree	Disagree	Strongly disagree
	----------------------------	%	--------------------------		
I am open to trying hemp production on my farm	50.2	38.0	8.0	2.7	1.1
I am interested in learning more about hemp production practices and adapted cultivars	56.9	35.5	4.2	1.9	1.5
I am interested in learning more about hemp markets	56.7	37.3	3.0	1.9	1.1
I am interested in learning more about the legality of growing hemp in my county/state	52.5	38.8	4.6	3.0	1.1
I am interested in obtaining a certificate to begin growing hemp	43.3	33.0	18.0	3.5	2.3
I am primarily interested in growing hemp for cannadiol (CBD) oil	7.3	14.6	63.1	9.2	5.8

Table 3.5 Relationships between various factors and the willingness of respondents to adopt hemp. Values are coefficients calculated from regression models built using stepwise selection. Adjusted R^2 values for each model ($p \leq 0.05$) are presented.

Model	Intercept	Factor 2	Factor 1	Grain	Income	Age	Adj. R2	C(p)†
1	1.64	-0.29					0.09	25.3
2	1.65	-0.29	-0.16				0.12	16.6
3	1.8	-0.28	-0.15	-0.24			0.14	12.5
4	1.53	-0.29	-0.16	-0.33	0.09		0.19	5.7
5	1.11	-0.28	-0.16	-0.35	0.09	-0.008	0.21	2.5

†C(p) = Mallows' C selection

Table 3.6 Response of certified organic farmers to statements about their knowledge regarding hemp production. Values indicate the percentage of farmers who answered true, false or unsure.

	True	False	Unsure
	------------	%	-------------
Hemp was previously grown in several states in the Midwest	84.3.	2.4	13.4
Hemp is grown in Canada and Europe	78.0	0.8	21.3
Hemp is a perennial crop	21.4	47.6	31.0
Hemp contains large amounts of THC, the psychoactive chemical in marijuana	4.7	86.7	8.6
Hemp can be grown for research purposes in some states	79.2	2.4	18.4
Hemp can be grown for fiber and/or grain	79.2	4.7	16.1

Table 3.7 Effect of potential hemp attributes on the willingness of respondents to grow hemp. Values indicate the percentage of farmers who viewed each statement as positive or negative. An attribute of innovation was associated with each question.

	Attribute[†]	Very positive	Positive	No effect	Negative	Very negative
		----------	----------	%	----------	----------
Competes well with weeds	COM	71.7	23.6	4.7	0.0	0.0
Has low insect pressure	COM	66.0	29.7	4.3	0.0	0.0
Knowing there are markets for certified organic hemp seed and hemp fiber	RA	59.5	38.2	1.9	0.4	0.0
Knowing that my certifier would approve hemp as an organic crop	COM	54.4	37.1	8.1	0.4	0.0
Allows me to diversify my farm	RA	50.2	44.0	5.0	0.8	0.0
Would allow me to reach new clients or markets	RA	44.2	38.8	15.5	1.2	4.0
Fits into current rotation	COM	40.1	39.3	17.1	3.5	0.0
Able to sell at restaurants, farmers markets, and wholesale	RA	37.0	35.1	23.9	1.5	1.5
Ability to plant and/or harvest hemp using existing equipment	COM	33.0	39.2	14.7	10.1	3.1
Being one of the first farmers in my area to grow and sell it	RA	30.1	30.5	35.9	3.1	0.4
Ability to sell cannabidiol (CBD) oil	RA	10.6	28.9	52.3	5.9	2.3
Having to send tissue samples to the state chemist each year to be tested for THC	LEX	9.7	15.5	46.5	22.1	6.20
Lack of infrastructure in my area for processing fiber	LEX	5.1	7.0	24.2	49.2	14.5
Need to invest in new equipment for planting and harvesting	LEX	4.0	6.2	23.4	54.9	11.7
Seed only available from international seed companies	LEX	3.9	7.0	54.7	27.1	7.4
Small number of markets to sell product	RA	3.1	9.0	27.3	50.0	10.6
Potential negative social attitudes of community toward crop	RA	3.1	6.6	64.8	20.7	4.7
Unclear legal regulations	LEX	3.1	6.6	34.8	46.0	9.7
Could negatively impact my reputation	RA	2.3	5.5	67.2	19.5	5.5
Personal lack of knowledge and information about hemp	RA	1.5	10.0	54.1	30.1	4.3

[†] COM = Compatibility, RA = Relative advantage, LEX = Complexity

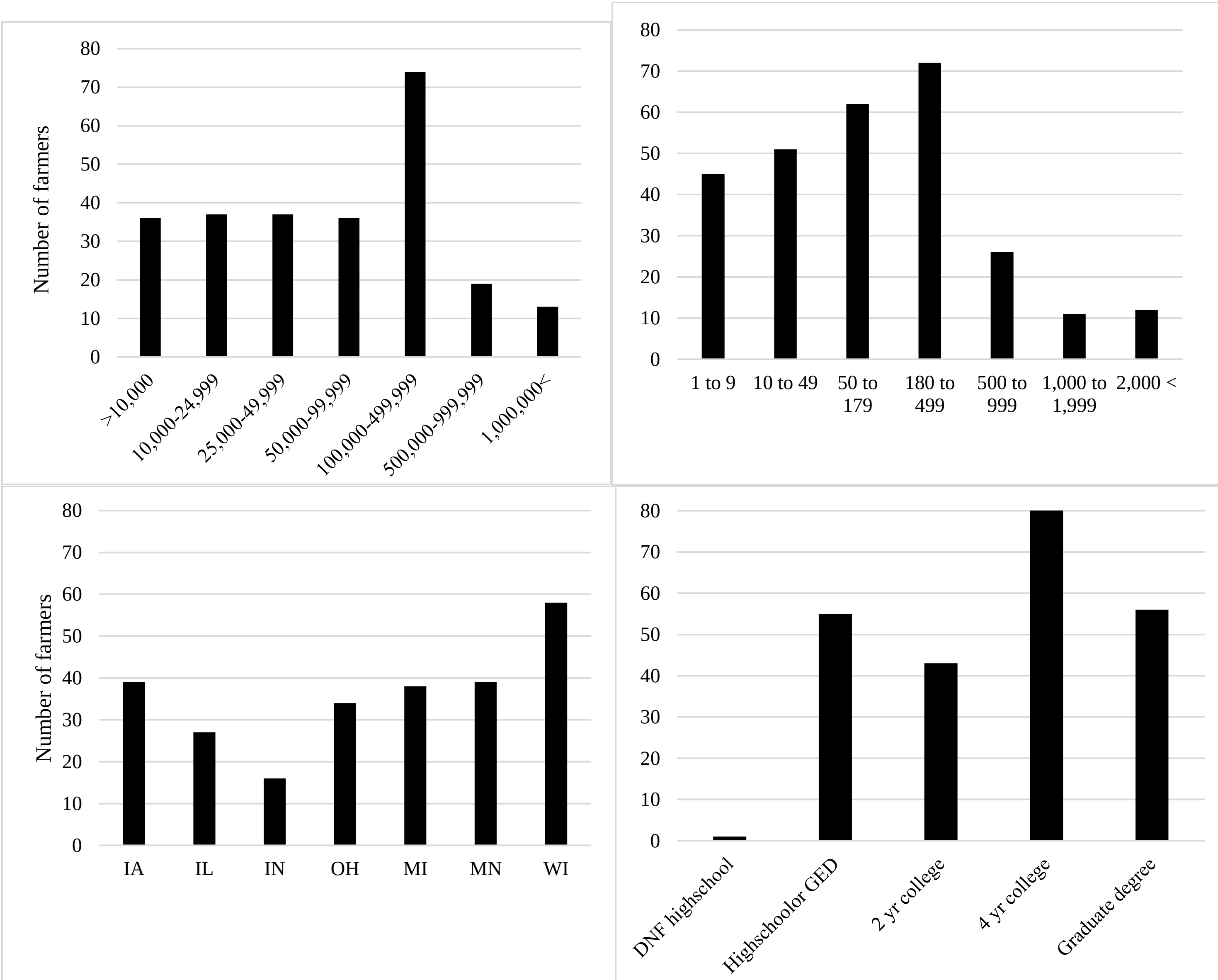

Figure 3.1 Respondents' gross income (in dollars), farm size (in acres), resident state, and level of education.

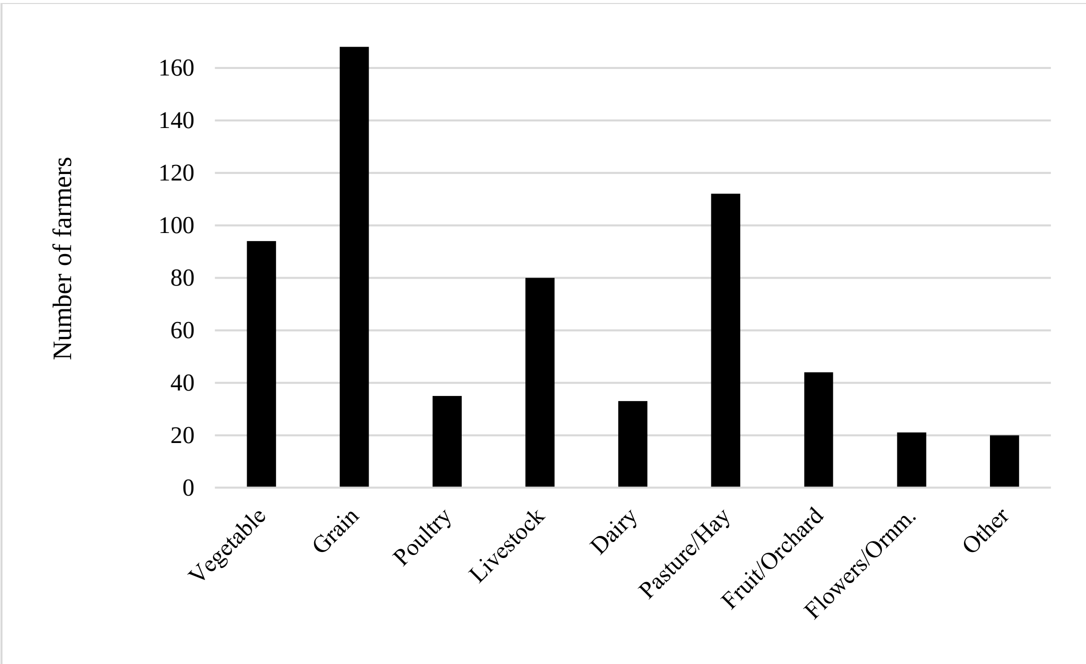

Figure 3.2 Type of farm enterprise for survey respondents. Respondents could select more than one farm enterprise to fully describe their farming operations thus variables are non-discreet and total number of responses is greater than number of respondents, which indicates that many farmers produce a variety of product.

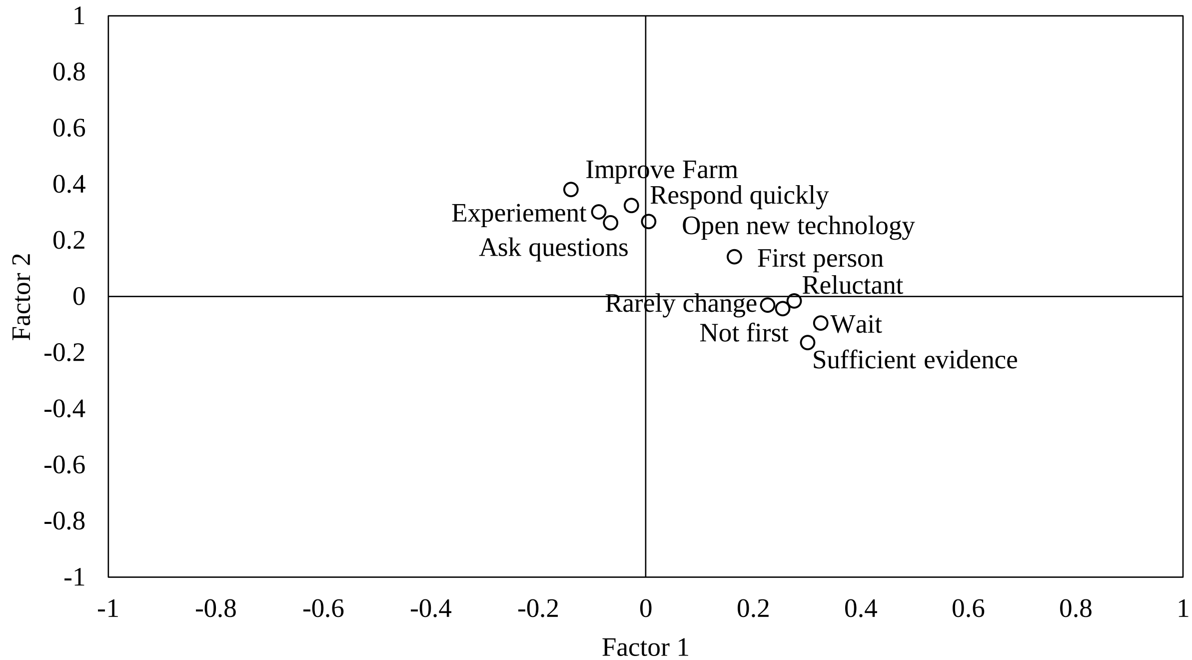

Figure 3.3 Biplot for calculated standardized scoring weights for two factors identified from PCA with an overlay of the eleven statements. Statements related to respondents' adoption behaviors and larger weights signify a stronger correlation with that axes or principal component.

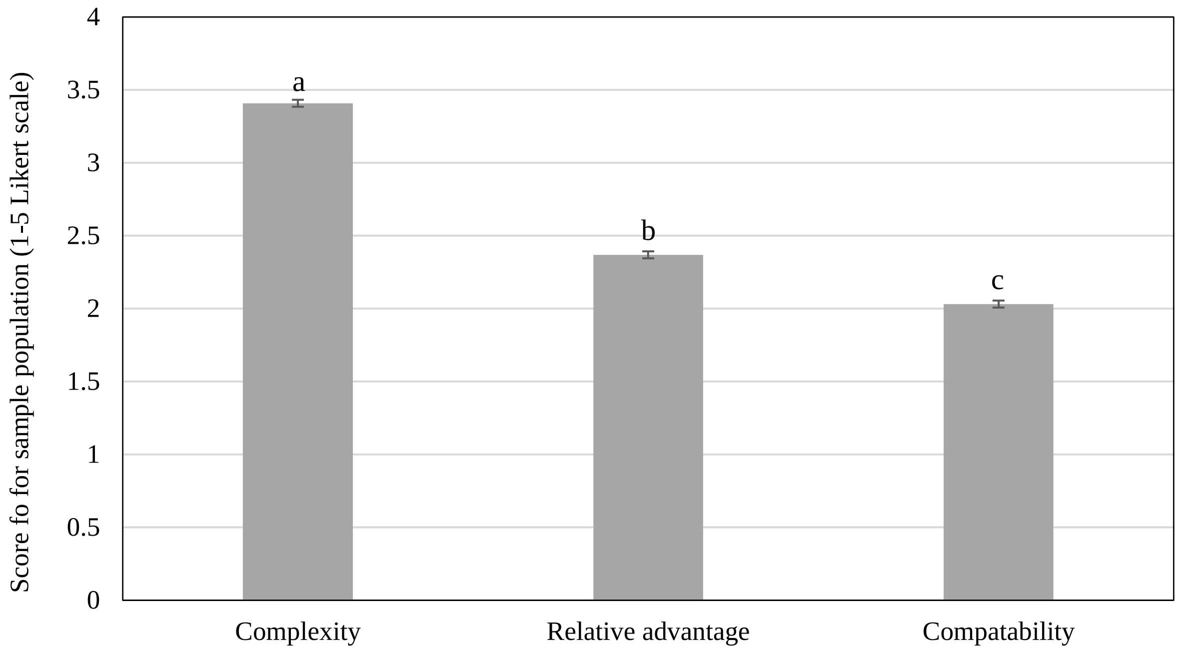

Figure 3.4 Average scores for the responses of certified organic farmers to influence of attributes of hemp production on their willingness to adopt hemp. Answers for all questions that corresponded with each attribute were averaged, assigning a score for each attribute. A cumulative score was calculated for each of the five attributes to determine how the surveyed population valued each attribute of innovation. Values indicate a composite score from a 5-point Likert scale that ranged from strongly agree (1) to strongly disagree (5). Standard error bars and letters indicate significance between attributes (p=0.05).

CHAPTER 4. IMPACT OF PLANTING DATE AND CULTIVAR ON HEMP PRODUCTION IN INDIANA

4.1 Abstract

Industrial hemp (*Cannabis sativa* L.) is an annual crop grown for fiber, seed, and flowers in over 30 countries. Production was outlawed in 1970 in the U.S., but recent legislation makes it likely that farmers will soon be able to grow hemp commercially in this country. However, U.S. farmers will rely, at least in the short-term, on varieties developed for northern Europe and Canada that may grow poorly at lower latitudes. The objectives of this research were 1) to characterize the growth and phenology of industrial hemp cultivars and identify cultivars suitable for growing conditions in the Midwest, and 2) determine the effect of delayed planting on the phenology and growth of seed and fiber hemp varieties in the Midwest. Cultivars were planted on 3 dates in 2016 (June 2, June 20, and June 30), 4 dates in 2017 (May 17, June 1, June 14, and June 28) and 4 dates in 2018 (May 14, May 30, June 18, and July 2). Cultivar selection was affected by seed availability, but at least two fiber and two seed varieties were planted each year. Delayed planting generally reduced the onset and duration of female flowering and the time to seed formation, but the magnitude of these effects varied among cultivars. Seed varieties flowered within 30 days of the first plantings in all years measured, well before the summer solstice. This suggests that flowering for seed cultivars was initiated at day-lengths slightly under 15 h. Fiber varieties in the first planting flowered between 31 and 57 days after planting, which suggests that they may be less sensitive to day-length than the seed varieties. The response of seed, stalk, and total aboveground dry weight to planting date was inconsistent across years and cultivars. Stand densities were generally low and emergence was affected by heavy rainfall and wet soils. Our ability to assess the effect of delayed planting was limited by poor stand establishment which was affected by heavy rainfall and wet soils. Our research suggests that farmers in the Midwest should expect currently available hemp cultivars to flower early in the growing season but hemp densities, growth, and yields may be strongly affected by stand establishment issues.

4.2 Introduction

Industrial hemp (*Cannabis sativa* L.) is an annual crop originally cultivated in Asia but now grown for fiber, seed, and flowers in over 30 countries (Johnson, 2017). Hemp seeds are rich in oil, protein, and key fatty acids and are produced for a wide array of products including food for humans (toasted hemp seed, hemp seed oil, and hemp flour), livestock and bird feed, and vegetable oil used in cosmetics, soaps, and nutraceuticals (Ehrensing, 1998; House et al., 2010; Small & Marcus, 2002; Williams & Mundell, 2015). Hemp fiber is used in textiles, paper, building materials, and animal bedding (Angelini et al., 2016; Kraenzel et al., 1998; McPartland et al., 2004; Striuk et al., 2000; Van der Werf et al., 1994). Hemp was brought to North America in 1606 and cultivated in several states, primarily as a source of fiber for textiles (Johnson, 2017; Small & Marcus, 2002). In 1970, the U.S. Congress passed the Controlled Substance Act listing all *Cannabis* varieties, including hemp, as Schedule I controlled substances (those without medical use and highly addictive) essentially outlawing further production of hemp (Kolosov, 2009). The 2014 Farm Bill distinguished hemp from marijuana based on THC (tetrahydrocannabinol) concentrations and made it possible for states to establish programs in which hemp could be grown for research purposes (Williams & Mundell, 2015; Young, 2005). A majority of states (38 at the time of submission) have passed favorable legislation and a variety of groups including the American Farm Bureau Federation, the National Association of State Departments of Agriculture, and the National Conference of State Legislatures have expressed strong support for the crop (American Farm Bureau, 2018; Holte, 2018; Patton, 2014). Recent legislation makes it likely that farmers will soon be able to grown hemp commercially in the U.S (U.S. 2018 Farm Bill). Current production in the U.S. is relatively small with 10,405 hectares planted across 19 states in 2017 (U.S. Hemp Crop Report, 2017). However, U.S. hemp retail sales grew more than 15% annually from 2010 to 2015 and hemp based products were valued at more than $700 million annually in 2017 (Johnson, 2017). With such significant backing and high interest in the crop, production may expand rapidly if current restrictions are lifted. Hemp was legalized in many European countries by 1996 but has remained a minor acreage crop grown primarily for fiber (Carus, 2017). Hemp has been grown in Canada, primarily for seed, since 1994 (Johnson, 2017) with 55,853 acres registered in 2017 (Health Canada, 2018).

Farmers interested in producing hemp in the United States are largely reliant on varieties developed at higher latitudes in Europe and Canada. Borthwick & Scully (1954) noted that hemp flowered promptly if subjected to photoperiods of 14 or fewer hours and conversely flowered with considerable delay or not at all, with photoperiods of 16 or more hours. More recent studies suggest flowering in hemp might be triggered at longer day-lengths with estimates from 14.5 to 15 hours (Amaducci et al., 2008a, 2008b; Consentino et al., 2012; Hall et al., 2014; Lisson et al., 2000). Early flowering has been recognized as a major factor limiting hemp yields because it generally stops vegetative growth (Meijer et al., 1995) and may affect fiber quantity (Struik et al., 2000; Van der Werf et al., 1994; Van der Werf et al., 1996) and quality (Amaducci et al., 2008b; Amaducci et al., 2012). The number of days to flowering appears to be substantially affected by genotype (G) and environment (E) (Amaducci et al., 2008a, Amaducci et al., 2012; Bócsa & Karus, 1998; Hall et al., 2014; Struik et al., 2000) suggesting that research examining GxE interactions will be necessary in areas where hemp has not been grown for decades.

The U.S. market for organically produced products has more than doubled in the last decade and sales of organic products totaled $49.4 billion in 2017, up 6.4% from the previous year (Organic Trade Association, 2018). Organically grown foods now account for 5.5% of the food sold in retail channels in the U.S. (Organic Trade Association, 2018). Although still only a fraction of total U.S. cropland, the number of farms certified by USDA for organic production practices increased from 2015 to 2016 by 11% and the number of acres certified for organic production practices increased by 15% to 5.0 million (NASS, 2017). A potentially unique opportunity exists for organic production of hemp in the U.S. Currently no synthetic pesticides are registered for hemp production in the U.S., and it seems unlikely that there will be any in the near future (Sandler et al., 2018). Therefore, pest management may rely on organic practices for both organic and conventional growers in the short-term. Additionally, there appears to be a market for certified organic hemp (Pasanen, 2017; Technavio 2018), with predictions from market research that the hemp-based food market will grow more than 24% by 2022 driven, in part, by demand for organically produced hemp (Technavio, 2018). Hemp may also fit well into organic rotations, with potential for use as a summer cover crop (harvested early enough to allow for fall cover or cash crops) (Pasanen, 2017). Additionally, hemp is believed to compete well with weeds, experience relatively low disease and insect damage, and improve soil structure (Dewey, 1901; Ehrensing, 1998; Kraenzel et al., 1998).

Research to address gaps in knowledge regarding hemp production should be conducted before the crop becomes widely available so that farmers can make informed decisions and avoid costly mistakes. The objectives of this research were 1) to characterize the growth and phenology of industrial hemp cultivars and identify cultivars suitable for growing conditions in the Midwest, and 2) determine the effect of delayed planting on the phenology and growth of seed and fiber hemp varieties in the Midwest.

4.3 Materials and Methods

4.3.1 Experimental conditions, design, and plant material

Experiments were conducted on certified organic land at the Meigs Horticulture Research Farm at Throckmorton Purdue Agriculture Center near Lafayette, IN from 2016 to 2018. The soil in each year was a Starks-Fincastle silt loam (Alfisol, mesic Aeric Endoaqualfs). Hemp cultivars were selected to include variability in reproductive biology (monoecious and dioecious) and use (seed and fiber) (Table 4.1). Seeds were sourced from Parkland Industrial Hemp Growers and Hemp Genetics International in Canada, Schiavi Seeds in Kentucky and Associazione Canapa SRL in Italy. Cultivar selection in each year was affected by both seed availability and delays in importing seed to the U.S. Thus, not all cultivars were planted in each year.

The experiment followed a split-plot design with planting date as the main plots and cultivar as subplots. Cultivars were seeded into a tilled seed bed at 16-cm row spacing with a plot drill on 3 dates in 2016 (June 2, June 20, and June 30), 4 dates in 2017 (May 17, June 1, June 14, and June 28) and 4 dates in 2018 (May 14, May 30, June 18, and July 2) (Fig. 4.1). Subplots were 1.5 m by 6.1 m in all years. Plots were seeded at 27.8 kg ha^{-1} in 2016 and 2017. In 2018, rates were increased to 55.6 kg ha^{-1} due to poor establishment in previous years. In 2017 and 2018, seed viability was assessed by the Indiana State Chemist and seeding rates were increased for cultivars with low germination rates. In 2016, seed arrived too late to conduct viability analyses before planting. In all years, 2.1 m buffers separated subplots and 4.6 m buffers separated blocks. At the beginning of the trial (in 2016), ten soil samples were taken at a depth of 0.025 m from across the field, mixed and sent to a commercial lab (A&L Great Lake Laboratories, Fort Wayne, IN) to be tested. Pelletized chicken litter (4-3-3, Cheep Cheep, North Country Organics, Bradford, VT) was applied on May 27, 2016 and May 15, 2017 at 111 kg N ha^{-1}, 83.3 kg P ha^{-1}, and 83.3 kg K ha^{-1} with a fertilizer cart and incorporated into the soil. Rates were chosen based on recommendations found in the literature (Cherney & Small, 2016; Meijer et al., 1995; Williams & Mundell, 2015). In 2018, pre-season soil tests showed low phosphorus, and fertilizer rates were adjusted to 133.3 kg N ha^{-1}, 100 kg P ha^{-1}, and 100 kg K ha-1 and chicken litter was applied on April 26, 2018.

Data were collected from two 1.8 m sections of row (0.64 m^2 quadrats) throughout the season. The Mediavilla staging system (Mediavilla et al., 2001) was used to determine phenological stages weekly for 20 plants until the onset of flowering when data were collected every two days until harvest. Because there is an irregular dynamic between the beginning and end of flowering (up to 60 days from the appearance of the first to the last flower) (Amaducci et al., 2008a), observations were increased during flowering to accurately record flowering patterns. As observed by Faux et al., (2013), the timing of male and female plant flowering largely coincided in our study. We therefore limit our data analyses and discussion to phenophases for female flowers. Plots were manually weeded as needed throughout the season to keep the plots weed-free.

Plants were harvested by hand clipping stalks approximately 2 cm from the soil surface (August 17, August 31, and September 8 in 2016; August 10, August 15, August 24, and September 5 in 2017; and August 8, August 13, August 27, and September 8 in 2018). Fiber plants are typically harvested at flowering. However, we were interested in understanding the phenological response of all cultivars and allowed fiber varieties to produce seed. This may have affected stalk dry weight for fiber cultivars. Heights of all plants were recorded at harvest. Leaves and inflorescence were separated from stalks in the field, and following harvest, all components were dried at 60°C for 72 h to determine yields on a dry weight (DW) basis. Dry weights were recorded for stalks. Seeds were separated from leaves using blowers and sieves and weighed. Leaf DW was calculated by subtracting seed dry weight from total inflorescence dry weight. Seed was sent to a commercial lab (Midwest Laboratories, Omaha, NE) where crude protein and seed fatty acid concentration were determined using AOAC methods (Latimer, 2016). Infloresences were collected and analyzed by the Indiana State Chemist Office (West Lafayette, IN) following protocol by the U.S. Drug Enforcement Agency to ensure that THC concentrations were below the authorized limit of 0.3% DW for all years (data not shown). Weather data were downloaded from a meteorological station at the research site.

4.3.2 Statistical analysis

Statistical analyses were completed using SAS 9.3 (SAS Institute, Cary, NC). The fit of residuals to normal distribution and homogeneity of residual variance were improved if necessary by log10 transformations for yield data (Box et al., 1978). Data were back-transformed for presentation as needed. A mixed model analysis of variance (PROC MIXED) was used to analyze the effect of cultivar and planting date on harvest data (seed, stalk, and total dry weight, height, density, and seed component analyses) and phenophases (time to flowering, time to first mature seed, and flowering duration). Blocks were treated as a random effect; cultivar, planting date and their interaction were treated as fixed effects. Data were analyzed separately by year since some varieties were not present in each year. LSMEANS estimates, adjusted with the Tukey method, were computed for all possible interactions first and then fixed discrete effects if interactions were not significant ($P = 0.05$).

Regression analyses were used to examine the impact of delayed planting and cultivar on phenophases. A continuous variable was calculated based on the number of days between 14 April (the earliest planting date in any year) and each planting date. Growing degree days (GDD) were also calculated as the time integral of $(T_{min} + T_{max}) \times 0.5 - T_b$, where T_{min} and T_{max} were the minimum and maximum daily temperatures and T_b was a base temperature (10.2 ˚C) (Faux et al., 2013). The regression analyses were conducted using PROC GLM because it allows the inclusion of categorical variables such as cultivar. Data were pooled across years. R^2 values for the regression models used and presented take into account delay of planting as well as all cultivars. Regression analyses were also used to examine the effect of cultivar, delayed planting, and precipitation on stand densities. For the regression analyses, precipitation was calculated as the sum of rainfall beginning one week after each planting date. Hemp typically emerges within 10 days after planting (Amaducci et al., 20008b). Stand densities were measured 10 day after planting and used in the regressions after each planting date.

4.4 Results and Discussion

4.4.1 Environmental conditions

Day-length at this location peaks at 15.0 h on June 20 or June 21 and declines to 14.5 h by July 15 and 14.0 h by August 9 (Fig. 4.1). Monthly precipitation was higher in 2016 and 2017 than monthly averages for 2006-2015 for all months during which hemp was planted (Table 4.2). Monthly precipitation was below 10-year averages in 2018; however, heavy rains occurred after several 2018 planting dates (Fig. 4.1). Monthly maximum and minimum temperatures were similar to 10-year averages for all years (Table 4.2). Initial soil fertility in 2016 was 7.3 pH, 22 No_3N ppm, 30 P_2O_5 ppm, 113 K_2O ppm, 2.2 % OM and 16.1 meq/100g CEC (AOAC, 1990).

4.4.2 Density

Cultivar and planting date interacted to affect stand densities in each year (Table 4.3). Planting date was therefore analyzed separately for each cultivar (Table 4.3). CFX-1, CFX-2, CRS-1, and Delores stand densities were not affected by planting date (Table 4.3). The remaining cultivars were affected by planting date in at least one year but the responses varied by years and cultivar. In 2016, stand densities were greater for Canda, X-59 and Felina planted on June 20 than on June 2 or June 30 (Table 4.3). Joey and Futura stand densities were not affected by planting date (Table 4.3). In 2017, stand densities were greater for Felina and Futura planted on June 1 than on May 17 (Table 4.3). Planting date did not affect stand densities for the remaining cultivars in 2017. In 2018, stand densities were greater for hemp planted on May 14 than on July 2 (Table 4.3). Stand densities were greater for May 14 than June 18 plantings for Joey, Tygra, and Eletta compana.

Optimal stand densities for fiber production are about 100 hemp plants m^{-2} (Amaducci et al., 2002; Meijer et al., 1995; Van der Werf et al., 1995) and 25 to 30 plants m^{-2} for seed production (Amaducci et al., 2002). Stand densities were highly variable but generally low for most cultivars and planting dates in this research. Researchers have associated poor stand establishment and low yields with wet soils (Aubin, 2014; Baxter & Scheifele, 2009). Hemp appears to grow poorly in saturated soil and may be susceptible to fungal diseases associated with wet soil conditions (Beckerman et al., 2017; McPartland, 1996; McPartland et al., 2000). In Vermont, Darby et al., (2018a) suggested that poor stands, due in part to cold and wet weather causing seed rot and weak seedling establishment, led to low yields. Monthly precipitation in 2016 and 2017 was unusually high relative to 10-year averages (Table 4.2) and wet soils made planting difficult in each year of our study. Regression analysis suggests a relationship between stand density and precipitation: $y = 26.3 - 0.05x - 0.05z + 0.001xz$, adj. $R^2 = 0.26$, $p < 0.01$ where y is stand density (plants m^{-2}) taken 10 days after planting, x is precipitation for one week following planting, *z* is delayed planting (days after May 14), and *xz* is the interaction. A negative relationship between precipitation and stand density confirms the detrimental impacts of precipitation on hemp emergence and density. Including cultivar as an additional independent variable did not increase the explanatory power of the regression model.

4.4.3 Height

Planting date and cultivar interacted to affect final plant height in 2016 but not in 2017 or 2018 (Fig. 4.2). CFX-1, CRS-1, Joey and X-59 heights were not affected by planting date. Felina, Futura and Delores individuals planted on June 30, 2016 were shorter than individuals planted on June 2, 2016. However, Canda planted on June 20, 2016 was taller than Canda planted on June 2 or June 30, 2016 (Fig. 4.2). Planting date did not affect height in 2017 but differences were detected among cultivars. Futura was taller than all of the seed varieties and X-59 was shorter than all of the cultivars except CFX-1 and CFX-2 (Fig. 4.2). In 2018, both planting date and cultivar affected plant height (Fig. 4.2). Eletta compana was taller than all other cultivars and Tygra was taller than Joey. Hemp plants were taller in the fourth planting date than in the first planting date (Fig. 4.2). Planting date effects were inconsistent across years, possibly due to variability in stand densities as plant density can impact height and growth (Burczyk et al., 2009).

4.4.4 Phenophases

Data on hemp flowering was not collected in 2016. In 2017 and 2018, planting date and cultivar interacted to affect time to flowering and duration of flowering. In 2017, hemp planted on May 17 took longer to flower than hemp planted on June 28 (Table 4.4). Differences in time to flowering were also detected among the June planting dates but this varied by cultivar (Table 4.4). Planting date did not affect time to flowering for Canda in 2018 and inconsistently affected flowering for Tygra and Joey. However, time to Eletta compana flowering was greater for the first planting date than for the other three planting dates (Table 4.4). The duration of flowering generally decreased for all cultivars in 2017 and 2018 (Table 4.5). The reductions in flowering duration were substantial; Canda planted in mid-May flowered for 11 and 17 days more than Canda planted in late June or early July, respectively (Table 4.5). Amaducci et al., (2008b) found that in most cases, postponing sowing time resulted in shorter flowering durations which were related to low yields. Once flowering starts, the efficiency with which intercepted radiation is converted to dry matter drops rapidly (Struik et al., 2000; Van der Werf, 1994). In Italy, shorter days caused an early floral induction that strongly reduced stem and fiber elongation, and thus aboveground dry biomass and consequently stalk yields (Cosentino, 2012). Planting date and cultivar interacted to affect time to presence of first mature seed in all three years (Table 4.6). Hemp planted in late June or early July in each year reached mature seed production in fewer days than hemp planted in early June or mid-May (Table 4.6).

Cultivar and planting date explained 85% of the variability in time to flowering and duration of flowering and 83% of the variability in time to first mature seed (Fig. 4.3). When phenophases were expressed in GDD, cultivar and planting date explained 86% of the variability in time to flowering, 80% duration of flowering and 83% of the variability in time to first seed (Fig. 4.3). Flower initiation has been linked to day-length, while the duration of flowering and time to initial seed formation have been linked to other environmental factors (Amaducci et al., 2008a, 2008b; Van der Werf et al., 1995). In our study, seed varieties flowered within 30 days of the first plantings in both years, well before the summer solstice. This suggests that the flowering was initiated for seed cultivars in the study at day-lengths less than 15 h. Fiber varieties in the first planting flowered between 31 and 57 days after planting which suggests that they may be less sensitive to day-length than the seed varieties. Additionally, flowering may have been impacted by other factors such as temperature (Amaducci et al., 2008a, 2008b).

4.4.5 Seed yield, stalk dry weight, and total aboveground biomass yield

Planting date and cultivar interacted to affect seed, stalk, and total aboveground dry weight in 2016. Felina and Futura seed, stalk, and total aboveground dry weights were not affected by planting date in 2016 (Fig. 4.4). Seed DW was lower for the third planting date than for the first planting date for all seed cultivars. However, planting date did not affect stalk DW for most seed varieties and had no effect on CRS-1 and Joey total DW (Fig. 4.4). Stalk and total DW were greater for the second planting date for Canda than for the first planting date (Fig. 4.4). In 2017, planting date did not affect seed, stalk, or total dry DW (data not shown). Differences among cultivars were not detected in 2017 for seed DW (Fig. 4.5). Futura produced more stalk DW in 2017 than all other cultivars except Felina (Fig. 4.5). No differences were detected in stalk DW among the remaining cultivars. Similarly, Futura produced more total DW than Canda, CFX-1, and CFX-2 but differences in total DW were not detected among the remaining cultivars. In 2018, an interaction between planting date and cultivar was detected for seed DW but not for stalk and total DW (Fig. 4.6). Seed DW was greatest for the second planting date for all varieties except Eletta compana where yields were greatest for the final planting date. Eletta compana produced more stalk and total DW than all other cultivars and both fiber varieties produced more stalk and total DW than the seed varieties (Fig. 4.6). Stalk and total DW were lower for the last planting date than for all other planting dates. No other differences in stalk or total DW were detected among planting dates.

Seed yields and stalk DW varied across years, cultivars, and planting dates but were generally lower than average yields reported in Canada and Europe (Anum Laate, 2012; Aubin, 2014; Karus & Vogt, 2004; Struik et al., 2000; Vera & Hanks, 2004). Poor stand establishment and early flowering likely explains the relatively low yields. However, we did not include fertility as a treatment and it is possible that higher fertilizer rates might have affected yield and phenology. Additionally, it can be difficult to determine hemp yields at the plot level because of the large heterogeneity in the crop (Van der Werf et al., 1995; Vogl et al., 2004). According to Amaducci et al. (2008b), heterogeneity is influenced by the presence of plants of different heights (short plants have short inflorescences with few seeds) and the duration of hemp seed ripening. In addition, bird predation can greatly affect seed yield by actively eating seed and causing shattering (Amaducci et al., 2008a; Jankauskienė & Gruzdevienė, 2015; Van der Werf et al., 1995). Uneven seed ripening and shattering as well as bird predation were observed in our study, although it was not possible to calculate yield losses.

Optimal planting dates have been reported between the end of April and the first three weeks of May in southern Italy (Cosentino et al., 2012), mid-March in the Netherlands (Van der Werf et al., 1995), late November in Australia (the equivalent of a later May planting in the Northern hemisphere (Hall et al., 2013), and late May in Vermont (Darby et al., 2018b). Planting dates in both Europe and North America were determined in part due to day length, however, temperature can be a significant factor for determining optimal planting date as well. Cosentino et al. (2012) found that across cultivar emergence was faster at higher temperatures and lower temperatures reduced plant development and in the Netherlands, early or late plantings (outside of the optimal planting window) limited crop growth in response to low temperatures (Van der Werf., 1995). However, delayed planting only reduced seed yields in 2016 and our research does not clearly identify optimal planting dates based on seed or vegetative DW.

4.4.6 Grain content analyses

Planting date did not affect fatty acid concentration in 2016 but did in 2017 (Fig. 4.7). Fatty acid concentration was larger for the fourth planting date than all other planting dates (Fig. 4.7). The third planting date was dropped from the analyses in 2017 due to loss of grain samples from mice contamination and destruction. Futura had lower percentages of fatty acid than all other cultivars (Fig. 4.7). In 2018, planting date and cultivar interacted to affect fatty acid content of the grain. With the exception of Eletta compana, the fourth planting date had lower amounts of fatty acid compared with all other planting dates and Eletta compana had lower fatty acid concentration than all cultivars at the first three planting dates (Fig. 4.7). Cultivar and planting date affected grain protein concentration with no interaction (Fig. 4.8). In two of the three years, protein concentration was higher for later planting dates. The third planting date had larger protein concentration compared to the prior two planting dates in 2016 (Fig. 4.8). However, in 2017, the pattern switched and the first planting date had the largest protein concentration. There were few differences among cultivars. In 2018, Eletta compana had lower protein concentration compared to all cultivars. Additionally, the third and fourth planting dates had larger protein concentration than the first two across cultivar (Fig. 4.8).

Hemp seeds do not mature evenly on the grain heads, thus harvest is traditionally done when 70% of all seeds on the grain head reach maturity. Harvesting grain past the optimal time generally results in lower quality seed and yield losses due to shattering (Kaiser et al., 2015; McPartland et al., 2004; Williams & Mundell, 2015). Heterogeneity of hemp yields influenced, in part, by the long duration of hemp seed ripening, may have resulted in variable grain composition data. The range of oil concentration results may be attributable to differences in seed maturity, since formation of polyunsaturated fatty acids is incomplete in immature seed (Deferne & Pate, 1996). High variability among oil and protein concentration in hemp seed has also been attributed to difference in cultivar genetics (Galasso et al., 2016). Oil concentration varied greatly for cultivars grown in China (Chen et al., 2010) and noticeable differences among cultivars were detected for essential fatty acid, oil, and protein concentration in Canada (Vonapartis et al., 2015). Of 51 genotypes studied in Germany, the oil concentration of seed ranged from 26.3% to 37.5% and analysis revealed significant effects of genotype (Kriese et al., 2004). Chen et al. (2010) hypothesized that differences among cultivars was, in part, due to variable environmental conditions (as well as cultivar differences), which supported prior research that found high variability in hemp seed oil concentration across environments in Pakistan (Anwar et al., 2006). Climatic conditions may influence seed maturity thus impacting oil and protein concentration (Mölleken et al., 2000).

Interaction between cultivar and planting limited our ability to directly compare varieties in most years, and in combination with low stand establishment, limited our ability to identify fiber or seed varieties that might be well-suited for the Midwestern U.S. Delayed planting generally reduced the onset and duration of female flowering and the time to first mature seed formation but the magnitude of these effects varied among cultivars. Delayed planting only reduced seed yields in 2016 and our research does not clearly identify optimal planting dates based on seed or vegetative DW. The gap in our study between phenology and growth suggest other factors, possibly stand establishment, were important. Phenology might have had a greater impact on yields if stand densities were consistently higher. Our research suggests that heavy rainfall after planting can reduce stand densities. This is consistent with research suggesting that wet soils can substantially reduce hemp establishment and yields. Bowling et al., (2018) noted spring precipitation has increased over the last 30 years in Indiana, as a result of climate change, and this has limited early access to fields and decreased the number of days suitable for spring fieldwork. The sensitivity of currently available hemp varieties to wet soils may impact its adoption in the Midwest. There is a clear need for additional research to evaluate strategies to improve germination and early season vigor (i.e. seed treatments, seeding rates, starter fertilizers) and to develop hemp cultivars that are well-adapted to environmental conditions in the Midwest.

4.5 References

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Table 4.1 Hemp cultivars planted at Meigs Horticulture Research Farm near Lafayette, IN in 2016, 2018, and 2018. Asterisks indicate the year during which cultivars were planted.

Cultivar	Country of origin	Purpose	Reproductive biology	2016	2017	2018
Canda	Canada	Grain	Monoecious	*	*	*
CFX-1	Canada	Dual	Dioecious	*	*	
CFX-2	Canada	Grain	Dioecious	*	*	
CRS-1	Canada	Grain	Dioecious	*	*	
Delores	Canada	Grain	Monoecious	*	*	
Eletta compana	Italy	Fiber	Dioecious			*
Felina	Italy	Fiber	Monoecious	*	*	*
Futura	Italy	Fiber	Monoecious	*	*	
Joey	Canada	Grain	Monoecious	*		*
Tygra	Italy	Fiber	Monoecious			*
X-59	Canada	Grain	Dioecious	*	*	

Table 4.2 Average monthly temperatures and precipitation during the growing season for hemp and ten-year average values (2006-2015). Data were collected from a weather station at Meigs Horticulture Research Farm near Lafayette, IN.

	May	June	July	August	September	Total
			Precipitation (mm)			
2016	42.4	101.1	87.9	109.5	62.2	402.2
2017	130.2	144.0	89.7	8.4	22.4	394.7
2018	46.2	58.4	47.5	66.8	57.4	276.3
2006-15	79.0	85.0	74.1	51.6	29.5	319.2

Temperature (°C)

	May		June		July		August		September	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
2016	22.6	10.9	29.6	17.2	29.0	18.3	30.1	19.1	28.4	15.4
2017	21.9	8.9	29.0	16.1	29.7	18.5	28.1	14.9	27.7	13.6
2018	29.0	14.6	29.9	15.1	29.7	17.9	28.7	18.1	27.9	18.0
2006-15	20.4	11.3	28.3	16.7	29.0	17.7	28.6	16.8	27.4	14.7

Table 4.3 Final stand density (plants m^{-2}) by planting date for hemp cultivars planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. Interaction was detected between cultivars and planting date in each year. Values are means, parentheses enclose the standard error. Letters denote statistical difference among planting dates for each cultivar (p=0.05).

	Canda	CFX-1	CFX-2	CRS-1	Delores	Joey	X-59	Felina	Futura	Tygra	EC†
	Plants/m^{-2}										
2016											
June 2	11.2(2.6)b	9.0(1.4)a	11.6(1.5)a	6.6(0.2)a	9.6(3.4)a	6.6(1.4)a	6.9(2.0)b	24.0(3.1)b	27.0(4.4)a		
June 20	22.0(3.5)a	12.8(3.3)a	11.0(1.0)a	12.0(1.3)a	12.0(2.9)a	10.8(1.2)a	25.8(0.6)a	36.4(8.6)a	27.6(5.2)a		
June 30	14.2(2.5)b	11.8(1.6)a	17.6(1.6)a	12.2(2.4)a	15.0(1.5)a	8.6(1.3)a	14.8(2.7)b	26.8(2.6)b	34.6(3.4)a		
2017											
May 17	16.0(6.0)a	11.7(1.7)a	16.3(3.7)a	13.0(2.4)a	17.0(2.0)a		13.5(2.1)a	22.0(5.4)b	24.8(7.4)b		
June 1	28.8(3.8)a	24.3(7.1)a	30.0(4.4)a	34.0(3.6)a	26.0(5.4)a		35.5(2.9)a	71.0(21.4)a	59.8(8.3)a		
June 14	10.8(1.9)a	10.0(3.7)a	14.3(3.8)a	12.3(3.7)a	21.3(6.6)a		13.8(3.9)a	44.3(17.0)ab	31.3(12.9)b		
June 28	14.3(1.7)a	15.0(2.1)a	21.0(4.2)a	19.7(4.3)a	11.0(2.6)a		24.5(1.5)a	45.3(14.2)ab	20.6(5.9)b		
2018											
May 14	47.0(11.6)a					55.0(10.8)a				112.3(17.2)a	102.5(10.6)a
May 30	34.3(7.3)ab					30.9(10.5)ab				31.5(10.8)b	22.5(4.6)b
June 18	20.7(2.8)ab					16.3(9.4)b				26.3(11.1)b	12.0(3.1)b
July 2	2.7(0.9)b					3.0(0.6)b				2.7(0.7)b	4.3(0.7)b

† Eletta compana

Table 4.4 Time to flowering by planting date for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN in 2017 and 2018. Interaction was detected between cultivars and planting date in each year. Values are means, parentheses enclose the standard error. Letters denote statistical difference among planting dates for each cultivar (*p*=0.05).

	Canda	CFX-1	CFX-2	CRS-1	Delores	Joey	X-59	Felina	Futura	Tygra	EC†
					Days after planting						
2017											
May 17	30 (1.0)a	30 (1.0)a	26 (1.9)a	30 (1.9)a	30 (1.7)a		30 (1.6)a	39 (1.2)a	42 (3.2)a		
June 1	24 (1.2)ab	22 (1.0)ab	22 (1.0)b	25 (1.0)b	22 (1.0)b		22 (1.0)b	32 (2.0)b	31 (2.0)b		
June 14	26 (1.0)ab	26 (0.0)b	23 (0.0)b	23 (0.0)b	26 (1.2)b		23 (1.0)b	26 (0.0)c	27 (0.8)bc		
June 28	22 (0.5)b	22 (0.5)b	22 (0.5)b	22 (0.5)b	22 (0.5)b		22 (0.5)b	26 (0.0)c	26 (0.0)c		
2018											
May 14	28 (0.0)a					28 (0.0)b				31 (1.9)b	57 (0.0)a
May 30	30 (0.0)a					31 (0.8)a				35 (0.8)a	52 (0.6)b
June 18	28 (0.0)a					28 (0.0)b				29 (0.6)b	51 (0.0)b
July 2	30 (0.0)a					30 (0.0)a				30 (0.0)b	51 (0.0)b

† Eletta compana

Table 4.5 Duration of flowering period (days) for each planting date for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN in 2017 and 2018. Interaction was detected between cultivars and planting date in each year. Values are means, parentheses enclose the standard error. Letters denote statistical difference among planting dates for each cultivar (*p*=0.05).

	Canda	CFX-1	CFX-2	CRS-1	Delores	Joey	X-59	Felina	Futura	Tygra	EC†
						Days					
2017											
May 17	35 (2.0)a	35 (2.0)a	34 (1.8)a	35 (2.5)a	34 (1.8)a		34 (1.8)a	37 (1.8)a	33 (3.2)ab		
June 1	27 (1.0)b	28 (1.2)b	31 (2.2)ab	28 (1.2)b	29 (1.1)ab		31 (2.2)a	33 (1.9)ab	35 (1.7)a		
June 14	26 (1.6)b	28 (1.2)b	28 (1.2)bc	29 (1.0)ab	25 (1.9)b		30 (0.3)ab	36 (1.0)a	34 (0.8)a		
June 28	25 (1.5)b	24 (1.8)b	24 (1.8)c	25 (2.0)b	25 (1.5)b		25 (2.0)b	28 (1.4)b	27 (2.2)b		
2018											
May 14	55 (0.0)a					55 (0.0)a				52 (1.9)a	26 (0.0)a
May 30	45 (0.0)b					44 (0.8)b				39 (0.8)bc	23 (0.6)b
June 18	42 (0.0)c					42 (0.0)c				41 (0.6)b	19 (0.0)cd
July 2	38 (0.0)d					38 (0.0)d				38 (0.0)c	17 (0.0)d

† Eletta compana

Table 4.6 Time to seed formation (days) by planting date for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. Interaction was detected between cultivars and planting date in each year. Values are means, parentheses enclose standard error. Letters denote statistical difference among planting dates for each cultivar (*p*=0.05).

	Canda	CFX-1	CFX-2	CRS-1	Delores	Joey	X-59	Felina	Futura	Tygra	EC†
	Days after planting										
2016											
June 2	54 (0.0)a	54 (0.0)a	54 (0.0)a	54 (0.0)a	54 (0.0)a	54 (0.0)a	54 (0.0)a	71 (0.0)a	71 (0.0)a		
June 20	43 (0.0)b	43 (0.0)b	43 (0.0)b	43 (0.0)b	43 (0.0)b	53 (0.0)a	43 (0.0)b	67 (0.0)b	60 (0.0)b		
June 30	39 (0.0)c	36 (0.0)c	36 (0.0)c	36 (0.0)c	36 (0.0)c	43 (0.0)b	43 (0.0)b	43 (0.0)c	43 (0.0)c		
2017											
May 17	68 (1.3)a	68 (1.3)a	68 (1.2)a	68 (1.7)a	68 (1.7)a		68 (1.7)a	76 (1.0)a	76 (0.0)a		
June 1	53 (1.0)b	53 (1.0)b	53 (1.4)b	53 (1.0)b	53 (1.8)b		53 (1.4)b	65 (0.8)b	66 (0.8)b		
June 14	51 (1.0)b	48 (1.2)bc	48 (1.2)bc	51 (1.0)b	48 (1.0)bc		51 (1.3)b	61 (1.0)b	61 (0.0)b		
June 28	47 (1.3)b	47 (1.4)c	47 (1.4)c	47 (2.2)b	47 (1.3)c		47 (2.2)c	54 (1.4)c	54 (2.2)c		
2018											
May 14	51 (0.0)a					53 (0.5)a				57 (0.0)a	90 (0.0)a
May 30	51 (0.0)a					53 (0.0)a				57 (0.0)a	80 (0.0)b
June 18	51 (0.0)a					51 (0.0)b				53 (0.0)b	70 (0.0)c
July 2	48 (0.0)b					50 (0.0)b				50 (0.0)b	63 (0.0)d

† Eletta compana

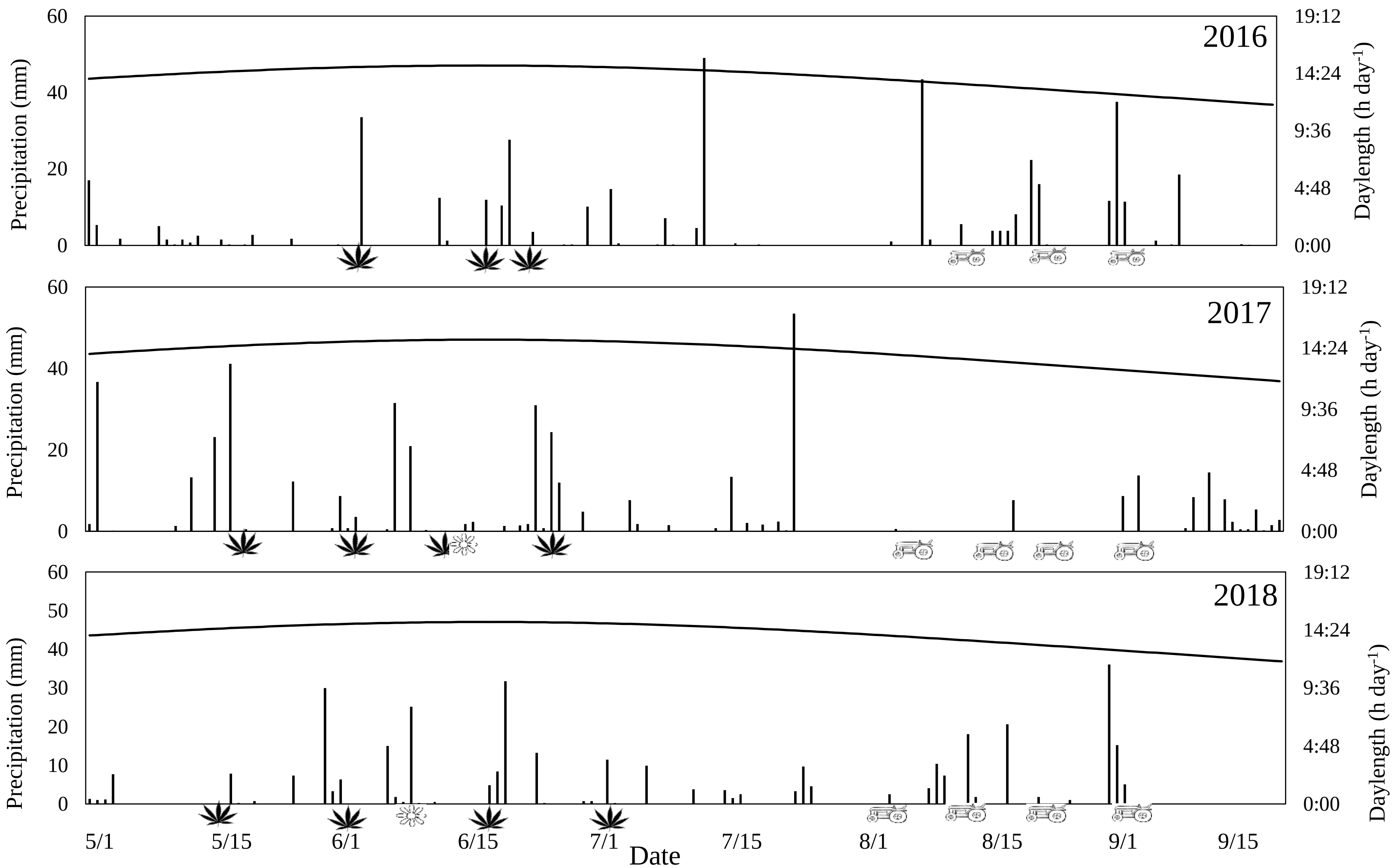

Figure 4.1 Precipitation and day length for the growing season in 2016, 2017, and 2018 at Meigs Horticulture Research Farm near Lafayette, IN. A hemp leaf represents the date of each hemp planting and a tractor the date of each hemp harvest. A flower image indicates the first appearance of female flowers in 2017 and 2018 at 15 h day length

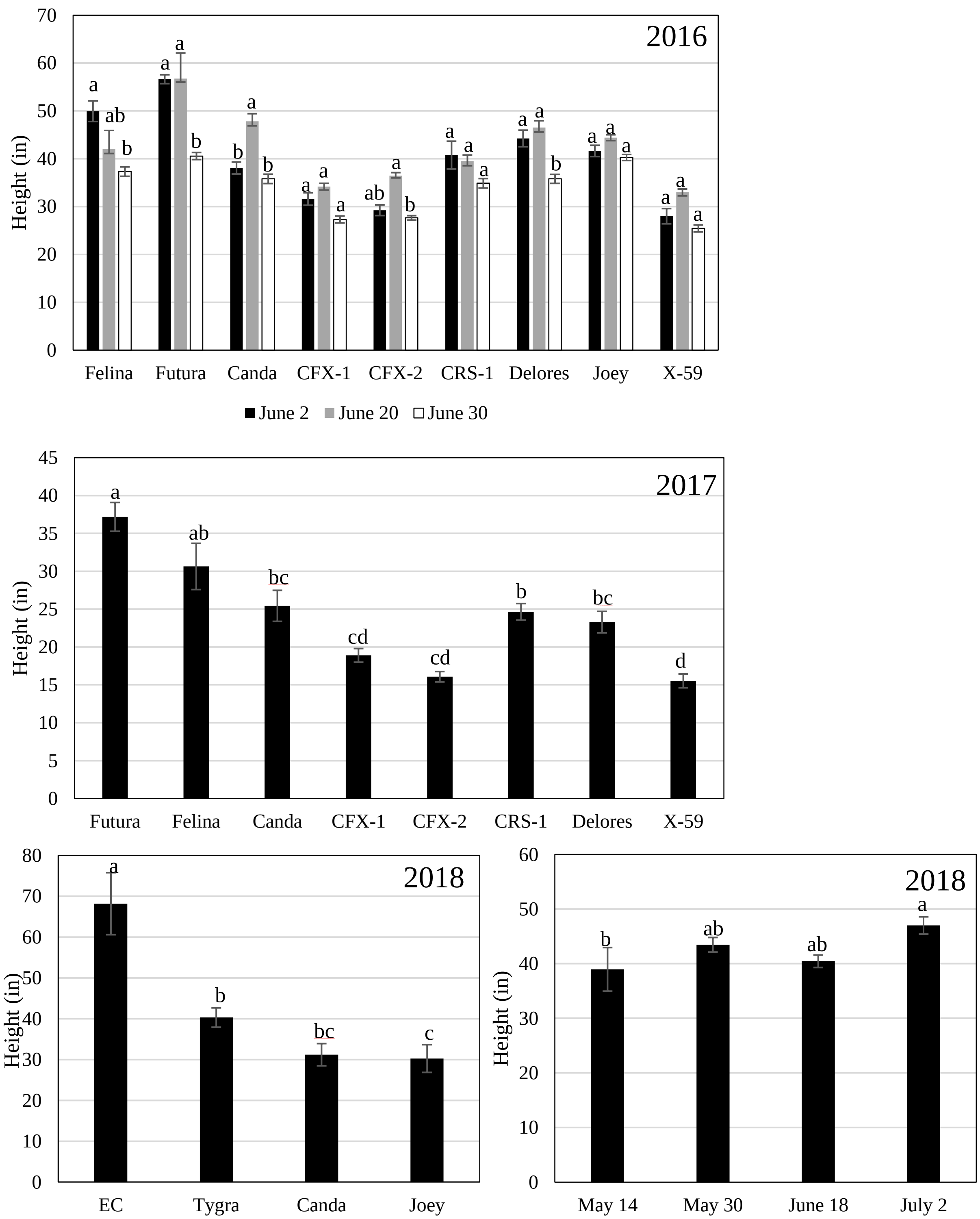

Figure 4.2 Final height at harvest for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. Interaction was detected between cultivars and planting date only in 2016. Cultivar affected height in 2017 and, in 2018, both cultivar and planting date main effects were significant. Values are means, standard error bars are presented, and letters denote significant differences among treatments (*p*=0.05).

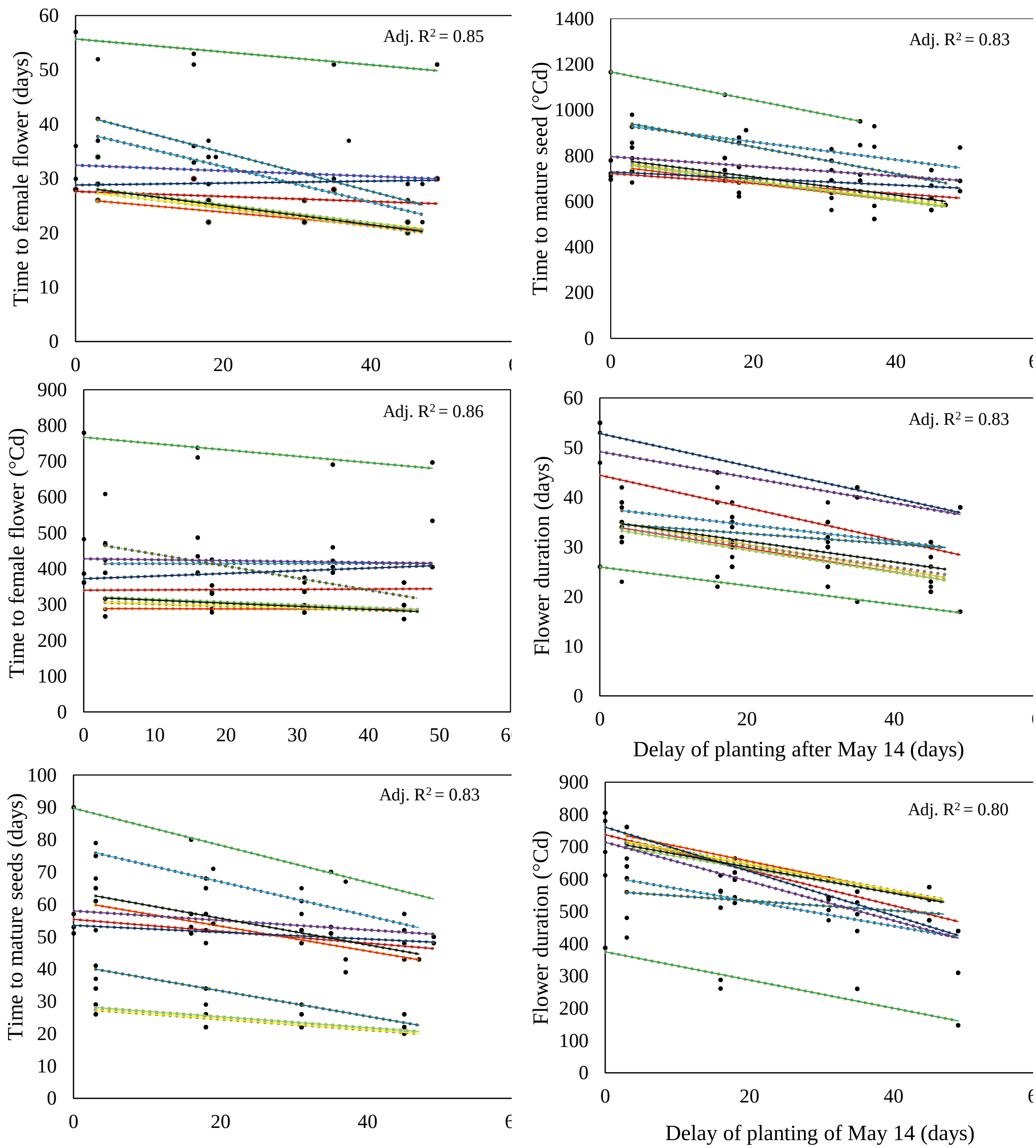

Figure 4.3 The effect of delaying planting date on the three phenophases (time to female flowering, time to first mature seeds, and flowering duration) in days and growing degree days (GDD) for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. Trend lines are separated by individual cultivar (red-Canda, light red-CFX-1, yellow-CFX-2, dashed black-CRS-1, dashed green-Delores, green-Eletta compana, light blue-Felina, blue-Futura, navy blue-Joey, purple-Tygra, balck-X-59). Adjusted R^2 values presented are for the entire regression model that includes all cultivars as well as delay of planting. Each point represents a single plot.

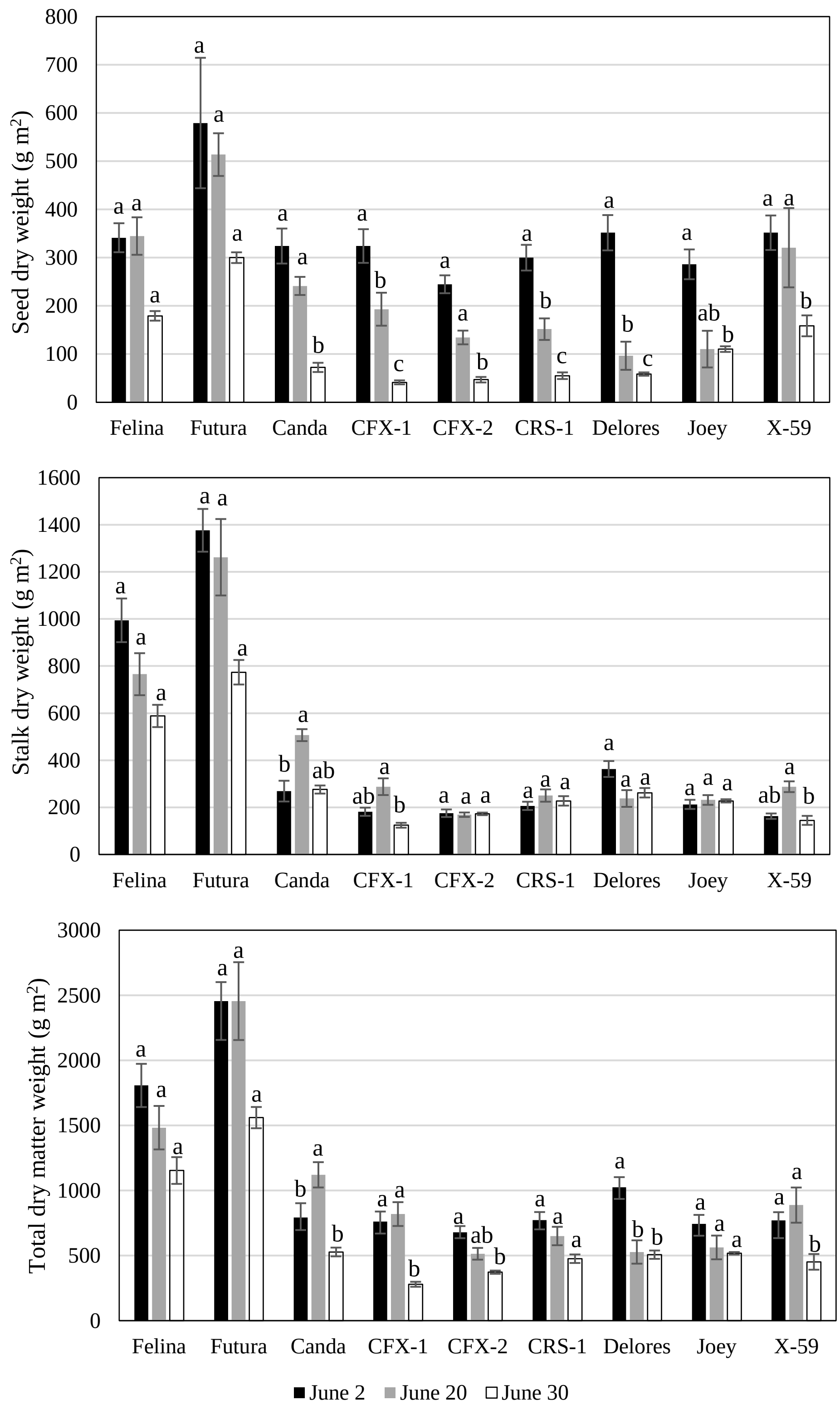

Figure 4.4 Seed, stalk, and total DW for all planting dates and cultivars planted at Meigs Horticulture Research Farm near Lafayette, IN in 2016. Standard error bars are presented and letters denote significant differences among treatments (p=0.05).

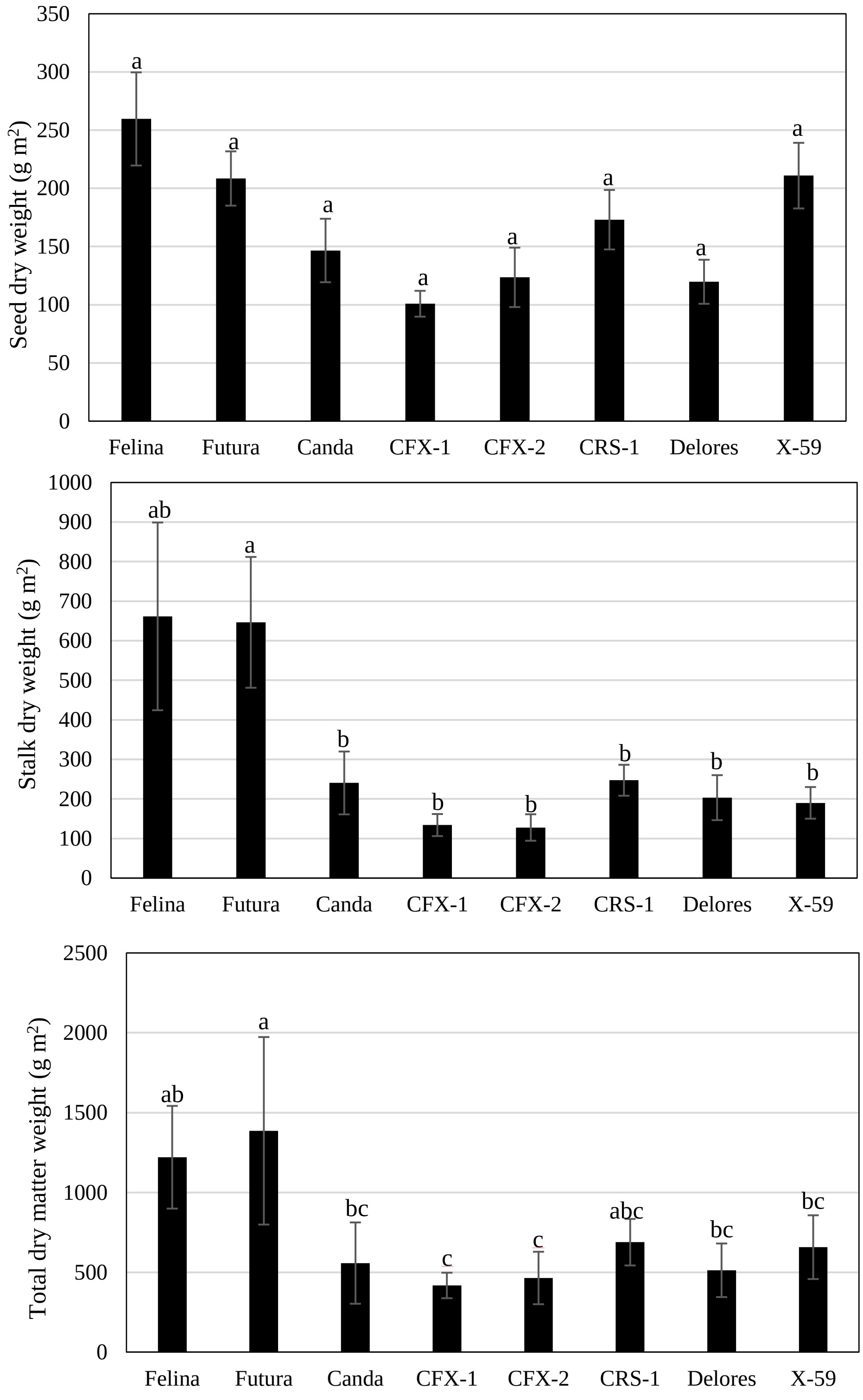

Figure 4.5 Seed, stalk, and total DW for all cultivars averaged across planting date planted at Meigs Horticulture Research Farm near Lafayette, IN in 2017. Standard error bars are presented and letters denote significant differences among treatments (*p*=0.05).

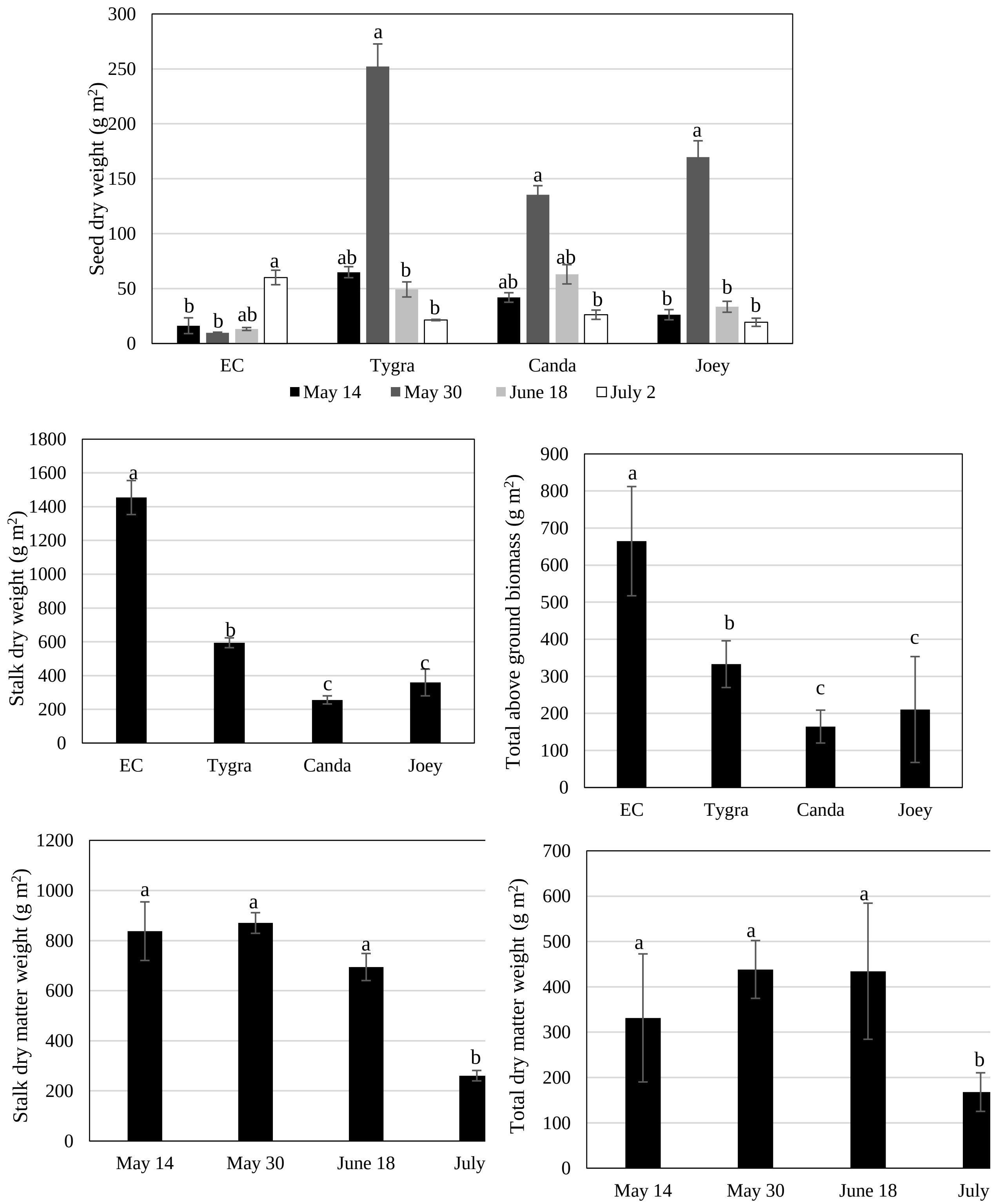

Figure 4.6 Seed, stalk, and total DW for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN in 2018. Interaction was detected between cultivars and planting date for seed DW, but not for stalk or total DW. Data are presented by main effect separately. Standard error bars are presented and letters denote significant differences among treatments (*p*=0.05).

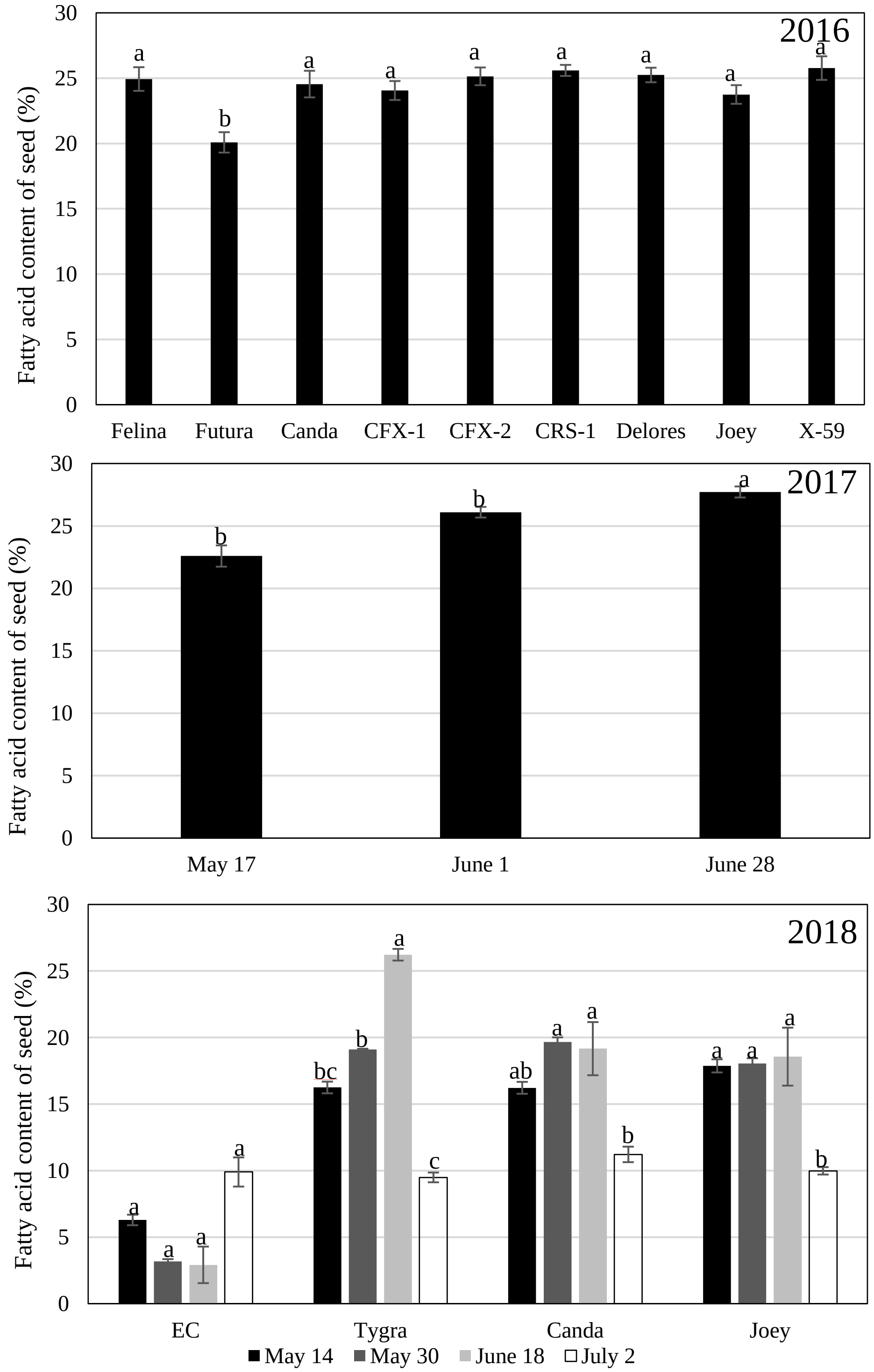

Figure 4.7 Fatty acid concentration as a percent of grain dry weight for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. No differences existed among planting date in 2016, nor cultivar in 2017. Interaction was detected between cultivars and planting date in 2018. Standard error bars are presented and letters denote significant differences among treatments (p=0.05).

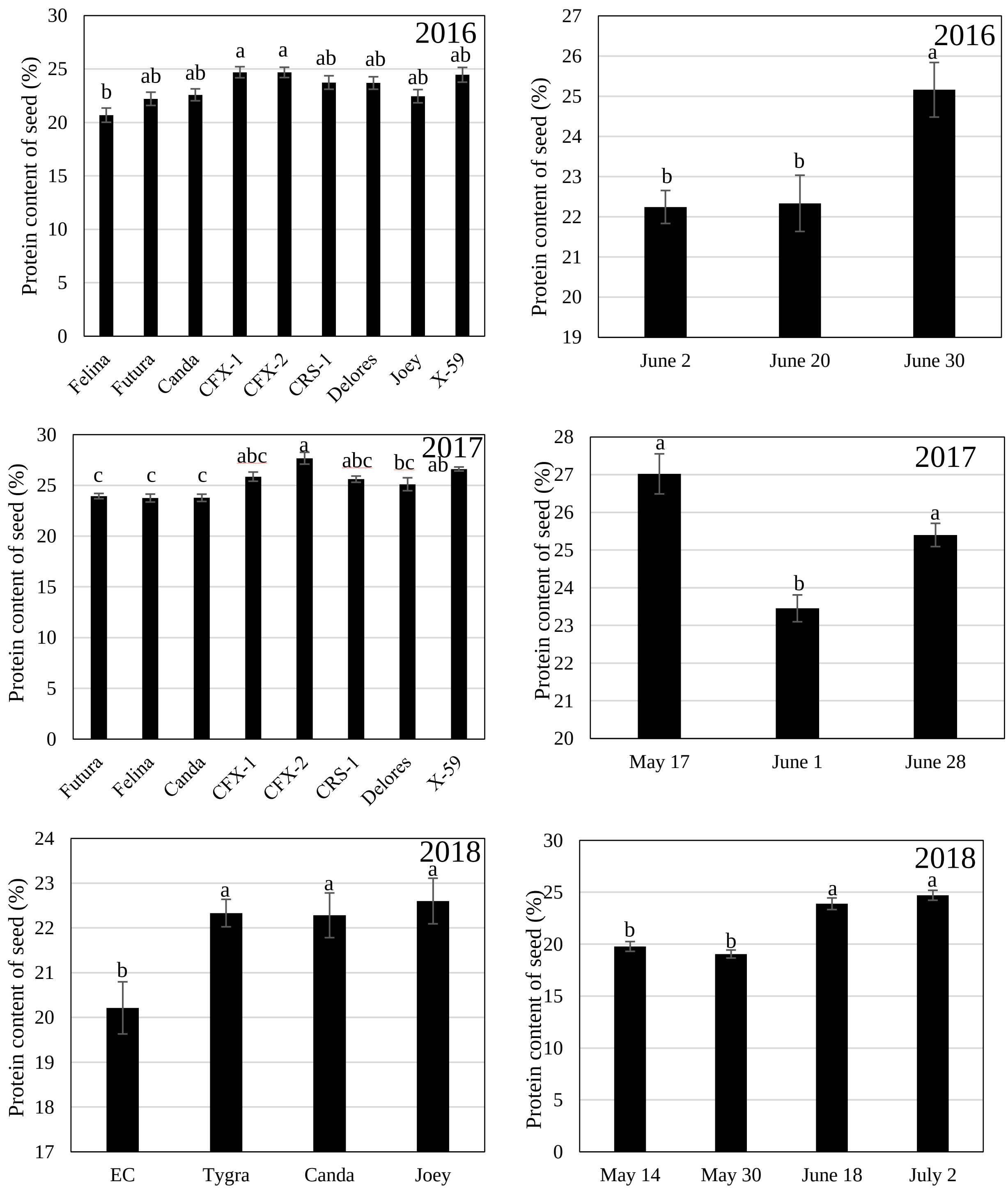

Figure 4.8 Protein concentration as a percent of grain dry weight for hemp planted at Meigs Horticulture Research Farm near Lafayette, IN from 2016 to 2018. Only main effects of cultivar and planting date were detected for all years. Standard error bars are presented and letters denote significant differences among treatments (*p*=0.05).