ABSTRACT

Title of Thesis:	**PRODUCTION RECOMMENDATIONS FOR INDUSTRIAL HEMP (CANNABIS SATIVA) FOR FIBER PRODUCTION IN MARYLAND: OPTIMIZING PLANTING DATE FOR FIBER YIELD, QUALITY, AND WEED MANAGEMENT**
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Management recommendations, namely timing of planting and harvest, are well established for a wide range of agronomic crops, but this data is lacking for industrial fiber hemp (*Cannabis sativa* L.), especially in the Mid-Atlantic region. With the re-introduction of legal hemp production in the US in 2014, farmers faced many challenges to growing this crop, both policy and production challenges alike. As hemp production was illegal since World War II, there was virtually no applied agronomic research performed on hemp in that time. Moreover, there are no pre-emergence herbicides approved for weed management in industrial hemp production, and research is needed to determine which cultural practices can be utilized to manage weeds in this crop. This void of applied research performed on fiber hemp has left many Land-Grant universities and Extension personnel unable to provide basic production recommendations to farmers interested in growing this novel crop. To begin providing such recommendations to Maryland farmers interested in incorporating fiber hemp into their crop rotation, the objectives of this research were to 1) determine the effect of planting and harvest date on fiber hemp yield, plant characteristics, and fiber quality and 2) observe weed populations

under a competition or germination prevention scenario in fiber hemp across the planting date spectrum. Based on this research, we believe fiber hemp can be successfully incorporated into Maryland crop rotations, as early planting and harvest of fiber hemp will result in quality fiber hemp, management of weeds through available cultural practices, and minimal disruption to other agronomic crops.

PRODUCTION RECOMMENDATIONS FOR INDUSTRIAL HEMP (CANNABIS SATIVA) FOR FIBER PRODUCTION IN MARYLAND: OPTIMIZING PLANTING DATE FOR FIBER YIELD, QUALITY, AND WEED MANAGEMENT

by

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Chapter 1: Literature Review

1.1 US Industrial Hemp Production

Industrial hemp (*Cannabis sativa* L.) was first introduced into the United States in the 18th century and was grown primarily for production of textiles and rope (Fike, 2016). Production continued, with slight decrease, until 1937 when hemp production was made illegal, due to its relation to marijuana, which was classified as a Schedule 1 drug by the US Drug Enforcement Administration (Sunoj, 2023). As a result, hemp was not grown in the US for approximately 100 years, only to be reintroduced by the 2014 Farm Bill, and later reinforced by additional legislation in the 2018 Farm Bill (Agricultural Act of 2014, Pub. L. No. 113-79 2014, Agriculture Improvement Act of 2018, Pub. L. No. 115-334 2018). It is important to understand that both marijuana and hemp are the *Cannabis sativa* plant but differ in their concentration of tetrahydrocannabinol (THC), the phytochemical responsible for a psychoactive response. Legally, the Farm Bill operationally defines hemp as "the plant *Cannabis sativa* L. and any part of such plant, whether growing or not, with a delta-9-THC concentration of not more than 0.3 percent on a dry weight basis" (Agricultural Act of 2014, Pub. L. No. 113-79 2014).

While hemp was banned from production, agricultural advancements (including but not limited to fertilizer usage and agricultural equipment) and research benefited the production of other commodity crops such as corn (*Zea mays* L.) and soybeans (*Glycine max* L.) (Egli, 2008). Public and private breeding programs have optimized desirable traits for these crops and decades of applied research has helped farmers optimize production systems to maximize crop yields. For industrial hemp, even basic agricultural production practices, such as variety selection, planting dates, and harvesting processes are unknown.

In addition to challenges with general agricultural practices, farmers may avoid industrial hemp production due to current legislative hurdles associated with its production. Unlike other agricultural crops, hemp production is entrenched with policy-based legal ramifications that create additional consequences for farmers. While legislation is constantly changing in attempts to make hemp production less limiting, these adjustments are slow and have a steep learning curve (Jelliffe, 2020). Issues include, but are not limited to, the possibility of a 'hot' crop (those with THC levels above the 0.3% federal limit) to be destroyed, the lack of standardized sampling and testing procedures, as well as lack of education on how management methods can impact THC levels (Skorbiansky, 2021). Tools such as crop insurance, which are used to manage risk in commodity crop production, are complicated for a "new" crop like hemp, lacking options for farmers if their crop exceeds the federal THC limits. The overlapping jurisdiction of multiple government agencies, including USDA, FDA, and state-based entities, can complicate even applying for a license to grow hemp.

Policies, therefore, vary from state to state, with Maryland having its own specific challenges. While voters legalized marijuana production and possession on a limited scale in July of 2023, this did not impact industrial hemp production in the state. It is currently more difficult for a farmer to produce or possess industrial hemp than marijuana in Maryland; with potential farmers required to submit an application to the State of Maryland, complete a federal background check, and pay a $550 registration fee per production location per year (*Hemp Production Application*, 2023). This process is a major deterrent to industrial hemp production in Maryland.

Despite the lack of production and management guidance and the regulatory barriers to industrial hemp production, the promise of extreme profitability, mainly for products such as medicinal supplements, encouraged farmers and non-farmers alike to adopt hemp production. After early successes, market saturation of these products created a decrease in final product value (Sterns, 2019). The uncertainty of the market for industrial hemp products, with the additional misconceptions of the legality of the crop, has decreased initial interest in floral hemp production since 2018, despite continued lessening of legislations on production (Dhoubhadel, 2021).

The initial popularity of floral hemp increased public perception due to a renewed interest in other products made from fiber hemp. While nationwide total fiber hemp production decreased 37% from 2021 to 2022, yields showed an increase on less acres planted, supporting that fiber hemp production may be viable with increased production knowledge (Honig, 2023). Despite being the same plant, production systems for floral and fiber hemp are distinctly different, as discussed below. The shift in popularity from floral hemp to fiber hemp production domestically indicates future hemp production for fiber may be successful, if applied research can fill production knowledge gaps and develop recommendations for production of fiber hemp like an agricultural crop.

1.2 Hemp Production Systems

Hemp varieties can be classified into one of three main categories: floral, fiber, or dual purpose. These are not only genetic differences but also differences in the production systems associated with the various end-products of the plant. Utilizing the correct variety within the correct production system is paramount not only to yield, but overall quality of the desired end product.

1.2.a Floral Hemp

Floral hemp production is similar to tomatoes, tobacco, or other high-value, management intensive horticulture crops and is characterized by individual, bushy hemp plants, grown approximately two meters apart in rows. Floral hemp is grown for phytochemical extraction, namely CBD (cannabidiol), produced from colas (flowering portion) and additional biomass. These varieties are more closely related to marijuana strains, with the production goal of maximizing the floral component of the plant and phytochemical concentrations. Floral hemp production is focused on the female flowers. As a result, production originates with clones that start in greenhouses and can either be transplanted outside or continue to grow in greenhouse conditions (Adesina, 2020). Products derived from floral hemp include CBD oils and supplements, balms, lotions, in addition to other health and cosmetic products. Management of floral hemp tends to be labor intensive, requiring intensive weed management practices to ensure a clean seedbed. These include tillage, plastic mulch, cultivation, and hand-weeding. Harvest is a laborious task requiring hand labor to carefully remove the desired plant material. This system is a stark contrast to fiber hemp production systems.

1.2.b Fiber Hemp

Production of fiber hemp is more agronomic in nature, often using similar equipment to corn (*Zea mays)* and soybean (*Glycine max*) production, allowing for an easier transition to production than floral hemp. The goal of a fiber hemp production system to is maximize fibers extracted from the stalk of the plant, through optimizing plant height and minimizing the biomass produced (Adesina, 2020). Fiber hemp can be planted with a drill or planter, generally into soil that has been tilled to prepare the seedbed. Minimal in-season management is required for fiber hemp, with cultural practices for weed management described below. While large-scale equipment specifically for fiber hemp harvest is not commercially available, equipment used to harvest forages, such as a discbine or sickle bar mower, can be repurposed to harvest fiber hemp, virtually eliminating the need for hand labor. Fiber hemp varieties often exhibit late season flowering, allowing for as much vegetative growth as possible before harvest. Harvest takes place during the transition from vegetative to reproductive growth, prior to the onset of female flowers (Cosentino, 2012). The end product can vary greatly for fiber hemp but is predominantly focused on the outer fiber (bast) portion of the stalks of the plant. Fiber removed from the inner portion of the stalk (hurd) is processed for use in clothing or can be ground with the hurd to create building supplies, flooring substitutions, and animal bedding.

1.2.c Dual Purpose Hemp

Some hemp varieties are dual purpose, and can be grown for both fiber and grain, when the grain is harvested first, followed by the fiber of the plants. These varieties are similar to fiber hemp, but may have less dense spacing to allow for the development of branching for some flower production. In these systems, seeds harvested can be used as grain for both animal and human consumption. The productivity of these dual-purpose varieties widely varies, as they show more plasticity in their genetics and are more influenced by environmental factors such as temperature and growing degree days (GDD) (Sikora, 2011). As such, dual purpose varieties are less common in hemp production systems than their floral and fiber counterparts.

While fiber hemp has the potential to be managed like an agricultural crop, challenges to its incorporation into current crop rotations exist, mostly due to a lack of production and management recommendations. Current knowledge of fiber hemp production from domestic and international research and existing knowledge gaps are presented herein. Reintroduction of industrial hemp production is hindered by additional difficulties, such as changes in agricultural practices, climate, and machinery in addition to the development of production recommendations.

1.3 Timing of Planting

1.3.a Mid-Atlantic Planting Practices for Agronomic Crops

Current Mid-Atlantic agronomic crop rotations include field corn or soybeans produced during the summer growing season. In the winter, small grains (such as wheat [Triticum aestivum L.] or barley [*Hordeum vulgare* L.]) or cover crops (often rye [*Secale cereale*]) are established to capture water quality benefits, including scavenging for remaining nutrients or prevention of soil erosion (Farmaha, 2022). Corn planting typically occurs in late April or early May with planting of full-season soybeans overlapping with corn planting, starting in May or into early June. Following small grain harvest soybeans can be planted, delaying it into late June (Vann, 2021).

Corn and soybeans differ in their length of growing season related to their general growth habit. Corn is growing degree unit (GDU) dependent, referring to the sum of effective temperature (heat) accumulated during the growth of a crop. For corn, physiological maturity is reached around 2700 GDU, or approximately 150 days after planting, depending on the weather that year (Qian et al., 2019). Soybeans, however, are photosensitive crops, whose maturation is dependent on the duration of night hours, where maturity groups are paired to different latitudes to optimize production across different day and night lengths. Extensive research in soybeans has resulted in latitude-specific production recommendations to maximize soybean grain yield under that region's photoperiod cycle (Salmeron, 2014). Such research provides guidance on timing soybean maturity group with planting date to the transition to reproductive growth once ample vegetative growth has occurred. Fiber hemp is also a photosensitive crop, in which a short-day length is required to induce reproduction or flowering. Management strategies need to be implemented to prolong vegetative growth and delay flowering until the end of the growing season.

1.3.b Gaps in Hemp Planting Date Knowledge

Planting date studies have been conducted internationally, and several sources support the selection of climate- or environmental-specific varieties in order to combat premature flowering in fiber hemp. While adjusting planting dates can help mitigate some climate adjustments (i.e. planting fiber hemp varieties for cooler climates earlier in the season, and ones adapted to warmer climates later), the photoperiod sensitivity of fiber hemp can cause early flowering to occur before desired, representing the need for not only using the correct variety in the proper environment, but also using the correct management (Sikora, 2011). This is supported by Campbell et. al (2019), who investigated the effects of genetic environmental interactions (GxE) on fiber hemp production, finding that the different varieties of fiber hemp (genetics) play a role in the success of the crop, even without the additional factors of planting dates (environment).

Planting date modifications in the literature to increase fiber yield prior to flowering ranged in number of planting dates used, but consistently found that using proper varieties within the correct climate range allowed planting dates to benefit yields, as it adjusted for the correct photoperiod length and the length of the desired growing season (Adamovics, 2017; Cosentino, 2012). Early planting for several varieties in Italy and southern Spain showed an increase in biomass yield (Ferfuia et al., 2021; Garcia-Tejero et al., 2019). These studies were done in Europe, and research continues to grow in other locations where hemp production is increasing. Current trials are attempting to understand the impacts of planting dates and varieties. Hall et al (2013), demonstrated that Canadian hemp varieties pose early flowering issues due to daylength and planting shifts creating decreased yields in Australia. This supports the concept that both region-specific (photoperiod appropriate) cultivars and planting date management are required to increase fiber hemp yields.

The production of photoperiod sensitive crops in MD represents a unique challenge, as the climate straddles both warm and cool characteristics. Additionally, many industrial hemp varieties are developed for cooler temperatures, due to photoperiod sensitivity and current areas of production (Wolfe, 2018; Cosentino, 2012). Therefore, selecting region specific varieties is crucial in fiber hemp production, and is mainly latitude-based due to photoperiod sensitivity (Hall, 2014; Johnson, 2021). This specificity has also been demonstrated in US studies where certain cultivars that performed well in some latitudes did not perform as well in others (Fiorellino & Ristvey, 2020). Planting dates are important as they aid in understanding how yield is impacted and can determine how or if industrial fiber hemp can be added into current rotations.

1.4 Weed Management Practices

Multiple tactics are available for weed management in traditional agriculture production systems. The general goal is to limit or prevent weed growth prior to cash crop planting and to create a weed-free period to allow for proper establishment and canopy cover of the main crop. Tools for this include tillage with or without pre-plant or pre-emergence herbicide with residual activity to last through crop canopy. Herbicides can be applied to herbicide tolerant crops to kill weeds without impacting growth. These tools can be used independently or combined and are supported by decades of research performed to optimize the use of these tools in combination with management practices such as row spacing on traditional agronomic crops.

1.4.a Current Mid-Atlantic Weed Management for Agronomic Crops

In addition to planting and harvesting data being well known for corn and soybean production, in season management of weeds is also well documented and for many farmers is second nature to apply. Common tools include herbicide sprays, herbicide-resistant crops, as well as cultural methods such as row density and spacing, and cover crops.

Cover crops, such as rye, are frequently incorporated into Mid-Atlantic crop rotations. It is common practice to plant corn and soybeans into terminated rye, in spring plantings. The cover crop is usually terminated herbicides weeks prior to planting, allowing farmers to use traditional seeders or no till drills for either corn or soybean planting. Rye cover acts as a weed suppressant within these systems, as well as being herbicide tolerant, allowing for rye cover crop planting in the fall, as soon as the main crop is removed (Essman, 2023; Wallace, 2017). Additionally, in no-till cover crop systems, yields for corn and soybean were not impacted, while cover crops were able to provide ecological benefits. (Qin, 2021).

For corn, in addition to field preparation techniques such as tillage or planting into residue, post-emergence chemical applications of glyphosate are used in GMO (Genetically Modified Organism) corn to terminate weeds that survived initial field preparation (Dalley, 2004). These practices are used in soybean production as well, however the use of other cultural practices, namely row spacing adjustments, can also be incorporated into production systems to manage weeds (Vann, 2021).

1.4.b Weed Management in Hemp

While corn and soybeans have a variety of established weed management practices, and often rely on herbicide applications, weed is a more complicated issue in fiber hemp production, as farmers cannot apply post-emergence herbicides to hemp crop (Flessner, 2020). Lack of post-emergence development on the part of herbicide manufacturers as well as legislative hurdles have slowed chemical management in hemp. Previous gaps in research have been addressed by multiple authors (Sandler, 2019; Bhattarai, 2014) noting that in order to push fiber hemp into a more widespread commodity crop, weed management, among other issues, would have to be resolved.

Research on the impacts of hemp in a no-till system is lacking, as production focus tends to be on more conventional planting and harvest methods. Hemp has lower germination in no-till systems and best controls weeds when given proper seed to soil contact (Rühlemann, 2016). In this instance, it is important to recognize that this research needs to be applied regionally, and locally, as weed populations differ greatly from field to field. Ideally, hemp would be able to compete with the existing weed population, via the use of cultural practices and no additional inputs.

Management practices, such as seeding rate and row spacing, allow for weed control without the need for additional inputs (Pudelko, 2014). This is further supported by research from Bhattarai et al. (2014) finding that increased fiber hemp density decreased weed populations, however too dense of a population could cause self-thinning or stunted growth of the crop. Some studies suggest that management practices are not the only ways that fiber hemp could be suppressing weeds, and that additional chemical interactions could be at play; namely allelopathic compounds found in fiber hemp extracts that decreased germination rates in other monocots and dicots (Vera, 2006). Currently, there is limited research on these allelochemicals so the focus of fiber hemp-based weed suppression should be on management practices.

Available literature does support that fiber hemp is generally sufficient at suppressing weeds on its own, however more support is needed for the impact of planting dates and environment, as well as the physical and cultural mechanisms that fiber hemp crops use to suppress weeds. As herbicide approvals are still uncertain, focus on management-based weed control in hemp is paramount. Studies on planting density frequently demonstrate hemp's ability to suppress weed germination via rapid canopy development, but studies of the impacts on planting date are non-existent. It is hypothesized that if hemp is able to germinate prior to or at the same time as weeds, given proper field cultivation, it will be able to compete with weed establishment and quickly create a dense canopy that further limits weed germination.

1.5 Harvest

1.5.a Mid-Atlantic Agronomic Crop Harvest

Agronomic crops, such as corn, soybeans, small grains, and forages, are mechanically harvested, due to the amount of acreage under production of these crops. Combines are the most common way that corn and soybean are harvested, and with different attachments, one combine can be used to harvest most grain crops produced in the US (Paulsen et. al, 2013). Timing of harvest for these agronomic crops is based both on physical maturity as well as moisture content, which has been found to have impact on crop loss during and after harvest, as well as complicating storage procedures (Paulsen et. al, 2013). Moisture content of agronomic crops can be measured in the field, prior to harvest, using handheld moisture meters (Nelson, 2012).

In the Mid-Atlantic, corn is harvested between late September to early November, with soybean harvest occurring from October through November (Vann, 2021). While harvests may be slightly staggered depending on the variety of each crop used, there is usually overlap between the two harvests, especially as most Mid-Atlantic farmers will be growing both crops simultaneously.

1.5.b Fiber Hemp Harvest

The mechanical advancements in place for corn and soybeans are lacking in fiber hemp systems and represent a major hurdle for production. Currently, few machines are well adapted for large-scale fiber hemp harvest. While some farmers employ sickle-bar mowers or attachments commonly utilized in hay operations, others use forage harvesters, or even make custom adjustments to pre-existing machines (Assirelli, 2020; Paun, 2022). Harvesting via sickle bar mower is the current industry standard when growing acres of fiber hemp, where the stalks are left to ret in the field post-harvest (Adesina, 2020). The retting process is further defined and discussed in section 1.6.b. In small research plots, fiber hemp is often harvested by hand, something not feasible for acres of fiber hemp production. The lack of a supported harvest standard represents a major barrier to farmers, who may not have the time or resources to customize a machine or designate one solely for hemp harvest.

The timing of the hemp harvest may be equally as important as planting date. Fiber hemp is usually harvested prior to or at the onset of flowering, and before seed formation, to ensure fiber quality (Adesina, 2020). Primary fiber forms during the plants' vegetative growth stages and is made up of cellulose, hemicellulose, and low levels of pectin and lignin. As the plant matures and reaches the flowering stage, the secondary fiber begins to form, identified by higher levels of lignin and pectin (Mediavilla, 2001). Harvesting prior to flowering is a key factor in fiber hemp production, as flowering decreases fiber quality and is associated with increases with secondary fiber formation (Mediavilla, 2001). Secondary fibers increase the time needed for retting and processing and are also lower in quality than primary fibers. Generally, desirable bast fibers are mainly 'primary fiber' and not 'secondary fiber'. Additional literature supports that harvest should occur roughly 90 days after planting, as timing is reliant on the flowering period of the variety.

Other sources support that the use of growing degree days (GDD) in future studies could help define the harvest period, based on variety and location of production (Tsaliki, 2021; Sikora, 2011). GDD and the flowering associated with plant maturity are important as fiber hemp needs to be compliant with THC regulations, falling under the 0.3% limit. Ideally, fiber hemp is harvested at the onset of flowering when the end of the vegetative growth is reached. The caveat to this is different varieties and management strategies for hemp can increase THC levels, and so consistent testing is not only important for farmers but complicates the harvest timing in ways not seen in other agronomic crops (Campbell, 2019).

1.6 Post Harvest Processes

Most agronomic crops have little to no post-harvest processing, and once harvested are either immediately stored or transported to the first point-of-sale. This can vary for specialty crops, such as tobacco, or forages, where multiple post-harvest operations are required either to ensure proper quality standards are met or to complete the end product. Farmers who are not producing specialty or forage crops are generally not concerned with post-harvest operations.

1.6.a Mid-Atlantic Crop Post Harvest Processes

Corn and soybeans require little to no post-harvest processing, except for ensuring grain that will be stored has low enough moisture to prevent spontaneous combustion. In terms of post-harvest, forages or hay often undergoes curing and drying in the field. However, most grain farmers are not growing hay, and so may not understand the importance and time required to process a crop after it has been harvested.

1.6.b Fiber Hemp Post Harvest Processes

Post-harvest processing of fiber hemp often begins immediately, and in the same field as it was grown. When the crop is grown only for the bast fiber, or outer fiber portions, it first has to go through a process called retting. Retting is when microorganisms, occurring naturally in the soil, will infect the harvested hemp plants and begin the breakdown of lignin and pectin, which connect the bast fibers to the inner, hurd portion of plants (Thomsen, 2005). This process can be viewed similarly to inoculating and ensiling forages that will be fed to ruminant animals, a process that begins the fermentation process before the ruminant ingests the feed.

The most common type of retting is field or dew retting, which is low input and low maintenance. Other types of retting have the benefits of being able to remove the hemp from the field but require more maintenance and take up space in other areas. These include water, enzymatic (biological), chemical, and mechanical. Each of these have their own advantages and disadvantages, including duration of retting, impacts on fiber quality, monetary and environmental costs, as well as input costs. For example, chemical and enzymatic retting processing take mere hours to produce retted fiber, but are high in costs, creating low strength and poor color fiber (Tahir, 2011). While each retting process has costs and benefits, for farmers starting to grow hemp, field retting is still the best option, despite its limitations on field space and timing.

Field retting allows the stalks to break down in the field where they were grown, whereas other processing methods (water tank, chemical) require more equipment and inputs. While field retting requires the continued use of the field, this process is low input, making it the most accessible retting technique available to farmers. Field retting is highly dependent on field and other weather conditions and is ideal in areas with late season rainfall (Schluttenhofer, 2017). The moisture encourages microbial activity and subsequent breakdown of organic material, needed to separate the outer fiber. This process requires soil contact, meaning that even once hemp is harvested, it still takes up space in the field it was planted in. To be able to incorporate hemp into current rotations, a combination of a short growing season with a high yield is ideal. The short growing season is a must, as an additional month is needed for the retting process, taking up vital field space that could instead be used to plant cover crops or small grains later in the season.

Retting time can vary greatly depending on the climate but also the fiber hemp variety. Sources have noted retting times from weeks to months; this disagreement is furthered by lack of standardization of the retting process (Assirelli, 2020). One main issue in this process is not knowing when retting is complete, and the crop is ready to be collected and be sent off for processing. Changes in stalk color (from green to darker brown), ease of removal of bast by hand, or additional moisture tests have been used in attempts to justify an end time for field retting (Bennet, 2006). Lengths in retting time have also been focused on, especially on how it can impact fiber quality. Additional research from Bennett et al. (2006) supports that crops can ret for longer periods of time than originally thought, but they nonetheless observed varying impacts on fiber quality in extreme cases.

Once stalks are retted, some farmers have been able to square or round bale the crop (Private communication), however, sharing of designated hay equipment has been faced with unwillingness from farmers who see hemp as a supplemental crop. Additional issues with already retted material include transportation, storage of bales, locations for additional processing facilities (decortication and degumming), as well as overall quality measures.

1.7 End-Product Quality Measures

1.7.a Mid-Atlantic Crop Quality Parameters

For grain farmers in the Mid-Atlantic, quality parameters are less of a concern than overall yield of the crops. Some soybean farmers are concerned with oil content in the harvested grain and generally, corn and soybean farmers aim to harvest grain when moisture levels are low enough for safe storage (Hammond, 2016). Generally, agronomic production systems are designed to maximize grain yield independent of other quality measures.

Mentioned previously, some aspects of hay and forage production more closely align with the production focuses and needs of fiber hemp. For both silage and forages, the amount of dry matter at the time of harvest can impact the overall end quality of the product, as well as how well it maintains its quality during silage (Borreani, 2018). Especially for forages, or crops grown for grazing animals, there are many influences of forage quality. These include things such as percent dry matter, amount of protein and minerals, as well as fiber content, with the purpose of these factors being defined by how much energy the crop can provide to the animal (Bayhan, 2022). For both grain/silage and forage end products, the parameters determine how much the farmer is able to make off of their crop, which in turn is often controlled by their particular management strategies for that given year.

1.7.b Fiber Hemp Quality Parameters

In both literature and industrial applications, there are no defined quality parameters for fiber hemp, and so management strategies may be the key to understanding how environmental factors can change the physical and chemical characteristics of the final product.

There are many uses for fiber hemp, ranging from nutritional, textile, biofuel, and construction-based materials; the end product of the fiber seems to depend on the needs of the industry that intends to use it (Rehman, 2021). Organic fibers have existed for thousands of years, and recent industry standards provide metrics for quality in crops such as cotton and flax. While proponents of hemp fiber in textile often tout it being able to replace cotton, hemp and cotton fibers are very different. Hemp fiber is more similar to jute and flax, as it is multicellular, unlike cotton which produces a unicellular fiber (Tahir, 2011). These differences in textile uses increase the variety of products that can be made from hemp, while still being able to produce high quality textile when blended with cotton or linen.

Specific quality parameters currently exist for flax, but not for hemp. Physical attributes such as color, tensile strength, and flexibility are metrics commonly used in flax fiber operations, and some fiber hemp research has been done in that area (Tsaliki, 2021). Additional chemical elements, such as percentage of cellulose, hemicellulose, and lignin have also been used to determine what makes a 'better' fiber (Thomsen, 2005; Jankauskienė, 2015). Despite this, there are still no industry standards for fiber hemp, such as a range of secondary fibers that is acceptable or unacceptable, a requirement for tensile testing, or desired percentages for lignin concentrations, as large ranges have been used depending on the end product (Promhuad, 2022).

As the end product may go through a variety of steps before reaching the manufacturer, the main goal of fiber hemp production is to grow a plant that is easy to process. At these early stages of fiber hemp production, especially in the US, processability is favored over initial plant quality. Processing of this crop is one of the major hurdles to industrial fiber hemp, as facilities are few and far between, in addition to requiring large amounts of space and having high costs associated with their development (Quaicoe, 2023). Additional preparation steps may include decortication and degumming, which further prepares the fiber for processing. Decortication involves removing the bast from the hurd of the plant, separating the two sections. This step is followed by degumming, to further clean the fiber, removing additional impurities and preparing material for textile-based uses, such as rope or clothing (Zimniewska, 2022). These steps may not be necessary if the fiber hemp is intended for use as animal bedding or in paper production, as both the hurd and bast are used for these products. An attainable end goal is still somewhat vague, as buyers of this product are still unsure of what specifications they require from farmers, and needs can vary from product to product.

Current resources support that even if there are no set metrics for fiber quality, a good starting point would be to grow hemp whose fiber is easier to process than that which is higher in quality, with thinner stalks (smaller diameters) being a common source of interest (Personal communications). The less processing that fiber requires, the quicker it can become its end product, with lower inputs required to do so. Given the lack of supported knowledge, future research will need to define quality standards for hemp fiber, in addition to understanding how the establishment, in-season management, harvest, and post-harvest measures can impact the end product.

1.8 Addressing Knowledge Gaps for Mid-Atlantic Fiber Hemp Production

While there are many knowledge gaps present in terms of optimizing fiber hemp production similar to agronomic crops, the present research focuses on understanding the impact of planting and harvest timing of fiber hemp on both yield and quality parameters and weed pressure within these treatments. Chapter 2 summarizes results of the effect of planting and harvest timing on fiber hemp yield and quality.

Chapter 3 provides information on weed suppression research within the planting date study. Understanding the use of planting date as a weed management method provides guidance to farmers who are unable to use herbicides for weed management. This research provides an understanding of hemp competition against weed populations through the use of two microplots, one where weeds and hemp were allowed to germinate simultaneously, and the other where weeds were removed after hemp canopy cover was established.

1.9 Generating Guidelines for Hemp Production in Maryland

These available data highlight an important issue; current fiber hemp research tends to focus on a single topic, so while studies on fiber hemp planting dates have been conducted, none of those had the added element of weed suppression and the possible interactions between the two. For farmers in MD to be able to grow fiber hemp, reliable and yield based recommendations must be developed with the use of planting and harvest dates for this region. The retting process that prepares the crop to transition into a usable product needs to be adjusted for timing, based on the climate of the region, and keeping in mind methods for harvesting and baling. New infrastructure needs to be supported so that, once removed from the field, the crop can be processed into a usable end product for a diversity of companies. Impacts from pressures from common weeds need to be addressed, so that farmers can adjust cultural and management practices to counter any possible yield detriments, as current herbicide labels and standards have not yet caught up to the reintroduction of this crop.

The comparison of fiber hemp to other known agronomic crops, namely corn and soybean, aid in identifying the lack of knowledge for fiber hemp. Lack of information for planting and harvest dates, as well as end product fiber quality measures are the priority for this study. The goal of focusing on these knowledge gaps is to be able to support farmers in adding fiber hemp into existing crop rotations, specifically in optimizing production parameters for Mid-Atlantic growing conditions.

Chapter 2: Early Establishment and Harvest Increases Yield and Fiber Quality of Industrial Hemp (*Cannabis sativa* L.)

Abstract

Planting dates are well established for a wide range of agronomic crops, but this data is lacking for industrial fiber hemp (*Cannabis sativa* L.), especially in the Mid-Atlantic region. The objective of this research was to establish planting and harvest date recommendations for fiber hemp based on yield, plant height, stalk diameter, stand counts, and fiber quality. We hypothesized that earlier planting and harvest would increase fiber hemp yield and quality. The two-year study was performed in two locations in Maryland (three total site-years) and utilized a split plot, randomized complete block design with planting date as main plots. In 2022, variety was used as split plots and in 2023 harvest date was used, with five planting dates, staggered three weeks apart, and four replicates both years. In 2022, the two varieties (Bialobrezkie and Yuma) were harvested approximately one week after the onset of reproductive growth in the Yuma variety, due to premature flowering in Bialobrezkie. In 2023, Yuma was utilized, with one harvest 90 days after planting for each planting date and one final harvest for all plots on 25 September. At harvest, fresh hemp weight, plant height, and stalk diameter were measured, and plant samples were left ret in the field for approximately a month, at which time bast fiber was collected for quality analysis. Hemp yield was generally greatest where hemp was established between mid-April and mid-June. Retted fiber lignin content, a proxy for fiber quality, decreased with later establishment in year one. Early establishment and harvest resulted in higher yield and fiber quality which implies that fiber hemp could

be included into current agronomic rotations in the Mid-Atlantic region to further diversify crop rotations and increase farmer resilience.

2.1 Introduction

Industrial hemp (*Cannabis sativa* L.) was not grown in the US for approximately 100 years, when hemp production was made illegal after World War II due to its relation to marijuana (Sunoj, 2023). Agricultural research was not performed on industrial hemp during this time and, consequently, limited production and management guidance existed when the production of industrial hemp was reintroduced by the 2014 Farm Bill, and later reinforced by additional legislation in the 2018 Farm Bill (Agricultural Act of 2014, Pub. L. No. 113-79 2014, Agriculture Improvement Act of 2018, Pub. L. No. 115-334 2018). Generally, industrial hemp is produced in two different production systems, either for extraction of phytochemicals from plant biomass and flowers (herein referred to as floral hemp) or for harvest of seeds or fibers from plant stalks (herein referred to as fiber hemp). These different production systems require different production recommendations, as floral hemp is produced more like a horticultural, specialty-type crop, and fiber hemp is produced more like an agronomic, field crop.

While many legal barriers currently limit widescale production of industrial hemp in the US, there exist many research questions regarding production management practices and their effect on not only yield of desirable plant material (either biomass or seed or stalk, production system dependent) but plant material quality measures and concentration of Federally-regulated phytochemicals in the plant, namely tetrahydrocannabinol (THC), which must remain below 0.3% of plant material on a dry weight basis (Agricultural Act of 2014, Pub. L. No. 113-79 2014). Moreover, crop rotations in the US have changed since the 1950s. The successful production of fiber hemp as an agricultural crop will be dependent on its ability to incorporate into current crop rotations across the country.

Industrial hemp is a photoperiod-sensitive crop, meaning its maturation is dependent on the quantity of daylight hours, and timing of both planting and harvest would impact production. Fiber hemp planting date studies have been conducted internationally, and several sources support climate or environmental specific varieties in order to combat premature flowering in fiber hemp (Cosentino, 2012; Dimitriev, 2021). While adjusting planting dates can help mitigate some climate adjustments (i.e. planting fiber hemp varieties for cooler climates earlier in the season, and ones adapted to warmer climates later), the photoperiod sensitivity of fiber hemp can cause early flowering to occur before desired, representing the need for not only using the correct variety in the proper environment, but also using the correct management (Sikora, 2011). This is supported by Campbell et. al (2019), who investigated the effects of genetic and environmental interactions (GxE) on fiber hemp production, finding that the different varieties of fiber hemp (genetics) play a role in the success of the crop, even without the additional factors of planting dates.

Research applications of planting dates to increase yield prior to flowering ranged in number of planting dates used, but consistently found that using proper varieties within the correct climate range allowed planting dates to benefit yields (Adamovics, 2017; Cosentino, 2012). Early sowing times for several varieties was shown to increase biomass yield (Ferfuia et al., 2021; Garcia-Tejero et al., 2019).

While these studies were mainly done in Europe, other locations where hemp production is increasing have begun to perform trials to understand the impacts of planting dates and varieties, such as Australia, where Canadian hemp varieties pose early flowering issues due to daylength and planting shifts creating decreased yields (Hall, 2013). This supports the concept that both region-specific (photoperiod appropriate) cultivars and planting date management are required to increase fiber hemp yields.

The timing of the fiber hemp harvest may be equally as important as planting date. Fiber hemp is usually harvested prior to or at the onset of flowering, and before seed formation, to ensure fiber quality (Adesina, 2020). Harvesting prior to flowering is a key factor in fiber hemp production, as flowering decreases fiber quality and is associated with increases with secondary fiber formation (Mediavilla, 2001). Secondary fibers increase the time needed for retting and processing and are also lower in quality than primary fibers. Additional literature supports that harvest should occur roughly 90 days after planting, as timing is reliant on the flowering period of the variety (Bhattarai, 2014; Mediavilla, 2001). After cutting, fiber hemp plants must ret in the field, to allow microorganisms present in the environment begin the process of lignin and pectin breakdown that connect the bast fibers to the inner hurd portion of plants, to make the decortication and final processing of hemp fibers easier (Thomsen, 2005). This necessary process requires additional time in the field dedicated to fiber hemp production and potentially impacting planting of the next crop of the rotation.

The objective of this research was to determine the effect of planting and harvest timing on fiber hemp yield, plant height, stalk diameter, and fiber quality in the Mid-Atlantic region. We hypothesized that earlier planting and harvest would increase fiber hemp yield and quality. The goal of focusing on these knowledge gaps is to be able to support farmers in adding fiber hemp into existing crop rotations, specifically in optimizing production parameters for Mid-Atlantic growing conditions.

2.2 Materials and Methods

2.2.1 Plot Establishment and Data Collection

Field trials were conducted at Wye Research and Education Center (Wye) in Queenstown, MD in 2022 and at Wye and Central Maryland Research and Education Center - Upper Marlboro (UM) in 2023 (Table 2.1). Agronomic soil samples collected for each field indicated the fertility level prior to plot establishment (Table 2.2). All soil samples were analyzed at Waypoint Analytical Lab (Richmond, VA), which used 1:10 soil to water ratio for determination of pH (Large, 2023), Mehlich-3 extraction of soil nutrients (Mehlich et al., 1983) and concentrations determined using inductively coupled plasma-atomic emission spectroscopy (ICE-AES), and organic matter was determined via loss on ignition (Large, 2023).

2.2.1.a 2022

In 2022, prior to plot establishment, tillage was performed on the intended study area at Wye on 31 March (chisel plow), 22 April (disked with packer), and 26 April (450 Vibra Shank field cultivator with rolling basket) to prepare the seedbed and manage weeds. Fertilizer was also applied prior to planting (Table 2.3). Small plots (2 m x 6 m) were established in a split plot, randomized complete block design with planting date as main plots and variety as split plots, utilizing two varieties (Bialobrezkie, a dual purpose variety [King's AgriSeed, Inc., Lancaster, PA] and Yuma, a fiber variety [Kanda Industries, Cambridge, MA]), five planting dates (PD, Table 2.4), and four replicates, using a 1.6 m wide cone planter (Hege Equipment Inc., Colwich, KS). The germination rate of each variety was evaluated upon receipt of seed to adjust seeding rate to target 33 kg live seed ha^{-1}. The pre-plant tillage controlled weeds in PD 2 and 3 plots prior to planting, but to manage weeds in PD 4-6, 224 l ha^{-1} glyphosate (Bullzeye, Growmark Inc., to deliver 1892 g ae ha^{-1}) was applied pre-plant (04 June for PD 4, 20 June for PD 5, and 13 July for PD 6) with additional tillage performed prior to planting in PD 5 and 6 plots (disking and packing on 13 June).

Harvest data was collected by plot for the Yuma variety only on 20 September (approximately one week after all five PDs had reached the reproductive growth stage). Whole plants were harvested from a 6 m^2 area of each plot using a Carter Harvester (Carter, Brookston, Indiana) to chop plants and collect plant material, which was weighed in the field using an Ohaus SD 75 Series portable scale (Ohaus Corporation, Parisippany, NJ). Individual whole plants were removed from an additional 0.4 m^2 area from each plot with hand loppers and counted to determine stand count. Average plant height and stem diameter were determined using a tape measure and Lyman Digital Caliper (Lyman Products Corp., Middletown, CT), respectively, on the harvested whole plants. The stalks from the sub-sample were left to dew (field) ret for approximately three weeks, until the outer bast fiber could be removed from the hurd fiber by hand and a color change was observed. Bast fibers were collected by hand on 11 October, air dried in lab conditions, ground, and evaluated for quality. In lieu of standardized fiber hemp quality measures, a forage quality analysis was performed using near-infrared reflectance spectroscopy to determine moisture, dry matter (DM), crude protein, acid detergent fiber (ADF, as percent neutral detergent fiber (NDF) and percent DM), aNDF (amylase NDF), and lignin (as percent NDF and percent DM) at Cumberland Valley Analytical Services in Waynesboro, PA.

2.2.1.b 2023

Changes to the study design in 2023 included the addition of a second location, the use of Yuma variety only, and the addition of a second harvest. At both Wye and UM, Yuma seed purchased in 2022 and stored until 2023 was used to establish PD 1 and 2. Germination rate was re-evaluated on the seed in 2023 to adjust target seeding rate. Upon receipt of additional Yuma seed (South Bend Industrial Hemp, Great Bend, KS), PD 3-6 were established, with seeding rate adjusted based on germination to target 33 kg live seed ha^{-1}. All plots in PD 1 at Wye were terminated on 12 July due to poor germination, likely due to use of carryover seed. Planting date 6 was added in place of PD 1 at Wye only (Table 2.4). Seeding rate in PD 3 at UM was not adjusted with receipt of new seed, with new seed planted at 95 kg ha^{-1} when seeding rate should have been 44 kg ha^{-1}, based on percent germination. The seeding rate was decreased for PD 4 and 5 at UM. All plots in 2023 were established with a 1.67 m width Great Plains Drill (Great Plains, Salina, KS).

Study design followed a similar pattern to 2022, where small plots (1.6 m x 7 m) were established in a split plot, randomized complete block design with planting date as main plots and harvest date as split plots, utilizing five PDs, two harvests, and four replicates at each location. The first harvest was approximately 90 d after planting for respective planting dates and the second harvest represented a full growing season where all plots, regardless of planted date, were harvested on the same date (25 September, Table 2.4).

At UM, prior to plot establishment, fertilizer was applied (Table 2.3) and tillage was performed to prepare the seedbed and manage weeds. Conventional tillage (to depth of 11.5 cm) was performed on 18 March, and again on 24 March and 3 April, to a depth of 7.6 cm. Minimum tillage (Turbo Till to 5 cm) was performed on 4 April followed by pre-emergent herbicide application (1.55 l ha^{-1} s-metolachlor [Dual II Magnum, Syngenta] to deliver 1424 g ae ha^{-1} and 1.17 l ha^{-1} paraquat [Gramoxone SL 2.0, Syngenta] to deliver 420 g ae ha^{-1}) on 5 April. To manage weeds in PD 3-5, conventional tillage (to a depth of 5 cm) was performed on 15 May then again on 7 June to PD 4 and 5 plots. Another pre-emergent herbicide application (1.55 l ha^{-1} s-metolachlor [Dual II Magnum, Syngenta] to deliver 1424 g ae ha^{-1} and 1.17 l ha^{-1} paraquat [Gramoxone SL 2.0, Syngenta] to deliver 420 g ae ha^{-1}) was made on 8 June to PD 4 and 5 plots.

Prior to plot establishment at Wye in 2023, fertilizer was applied (Table 2.3) and conventional tillage was performed on 10 March (to depth of 28 cm then 46 cm with ripper) and 15 March (to depth of 13 cm with disk and rolling basket), then soil preparation and residue removal performed on 31 March (to depth of 13 cm with disk and packer) and 3 April (to depth of 10 cm with Vibra Shank Field Cultivator). Weeds were managed in PD 2-6 plots with a pre-emergent herbicide application (224 l ha^{-1} glyphosate [Sunphosate 5 Max, Wynca Internat. Holdings Co., to deliver 2031 g ae ha^{-1}) one day after plots were planted (Table 2.4).

In 2023, due to the smaller plot size, harvest was performed by hand loppers at both harvest dates. Harvest area varied by plot due to differences in stand densities across planting dates, but whole plants within a known harvest area were cut at soil level in each plot and counted to determine stand count. Average plant height and stalk diameter (using tape measure and Lyman Digital Caliper [Lyman Products Corp, Middletown CT], respectively) were measured and plants were weighed in the field (Heeta Waterproof Fish Scale). Height and stem diameter were recorded on 10 representative stalks per plot. After harvest measurements were collected, subsamples of each plot were left to field (dew) ret for approximately a month after each respective harvest date, then collection of bast samples was done again by hand, as in 2022. Fiber sample analysis was repeated, with representative samples from both locations sent to Cumberland Valley Analytical Services for quality analysis.

2.2.2 Statistical Analysis

Prior to performance of statistical analysis, data were removed from 2023 in treatments where carryover seed from 2022 was planted and seeding rate was not adjusted for the use of new seed (PD 2 at Wye 2023 and PD 1-3 at UM 2023). Some data with all PD are presented herein to discuss environmental conditions, however statistical analysis was only performed on dataset with these erroneous plantings removed. Fresh plant yield, plant height, plant diameter, and fiber quality characteristics were analyzed by harvest date using a mixed model ANOVA in R (R Core Team, 2022) where replication was the random effect and planting date and site-year were the fixed effects. Mean separations were performed using Tukey's HSD at P = 0.05. Normality assumptions were checked through observation of residual plots. Harvest and quality measures were correlated to one another using the "corrplot" package (Wei, T. & Simko, V., 2021) in R (R Core Team, 2022).

2.3 Results and Discussion

All measures were analyzed by harvest date, and it is important to acknowledge the unbalanced nature of the datasets that comprise each harvest date. Harvest 1 was included at the two locations in 2023 only, while Harvest 2 includes final harvest for all three site-years. Statistical relationships that shift between Harvest 1 and Harvest 2 do not necessarily indicate the difference between early and later harvest, but the inclusion of the 2022 site data within analysis of Harvest 2 data can be responsible for differences in statistical relationship in the present study.

2.3.1 Field Differences Considerations

Precipitation varied across years (2022 and 2023) and locations (Wye and UM) of the study (Fig. 2.1). There were fewer precipitation events and decreased quantity of precipitation throughout the growing season at Wye in 2023 compared to UM in 2023 and Wye in 2022. In 2022, rain events were well dispersed over the course of the growing season, with rainfall occurring before and after all planting dates, with a total growing season (April through September) accumulation of 63 cm. In 2023, the UM location had similar accumulation (62 cm) during the same time period, however rain events were more spaced out and had higher individual accumulation. This difference is especially true during May and June, when over half of the planting dates took place. While precipitation totals at Wye 2022 and UM 2023 were similar, Wye 2023 had approximately 15 cm less precipitation than those locations (50 cm accumulation between April and September).

Due to the proximity of the Wye location to the Chesapeake Bay, it is common for storms moving west to east across the Bay to attenuate before reaching Wye, where the more western UM location was often in the path of summer storms in 2023. However, compared to long-term precipitation data these locations in MD, precipitation totals in the years of the study are not dissimilar to the 20-year average, with the 20-year average (2000-2020) growing season precipitation total was approximately 70cm at both Wye and UM. It is important to recognize that while there were not any major differences in the amount of rainfall across all three site-years during the growing season, there were differences in daily accumulations (Fig. 2.1), as well as differences as to when the rain events occurred in relation to the planting dates.

Variations in soil type and nutrient availability were present across all site years within the study (Table 2.1 and 2.3). Both locations have soil types recognized within the coastal plain region; at Wye, the soil type is a silt loam, whereas the UM location has a fine sandy loam. Water retention at Wye was slightly greater than that at UM, but both are classified as having well-drained soils.

In addition to variations in crop rotations, nutrient availability differed between all site years, most notably between the concentrations of potassium and phosphorus (Table A.1). At Wye and UM in 2023, the potassium concentration was nearly twice that at Wye in 2022. Previous research has identified that there is no significant correlation between fiber hemp yield and soil potassium levels, hemp requires low levels of potassium, and that additional uptake of potassium is luxury (Deng et al., 2019; Finnan, 2013). Therefore, these differences in potassium concentrations between site years were unlikely to impact yields.

Phosphorus concentrations were similar for both years at Wye but were nearly doubled at UM (medium versus high concentration levels, Table 2.2). For hemp production, phosphorus is nearly as important as nitrogen concentrations, as both increase yield (Deng et al., 2019). Within this study, similar concentrations of NPK were applied at field preparation between site years (Table 2.3), and so the initially high concentration of phosphorus at the UM location could have had a positive impact on yields.

2.3.2 Yield

All results from Harvest 1 and Harvest 2 are presented independently herein, as statistical analysis revealed harvest date impacted variables measured. Harvest 1 represents a 90-d growing season regardless of PD and was established in 2023 only. Harvest 2 represents a typical harvest timing based on plant transition to reproductive growth and was established in both 2022 and 2023. The first planting at Wye (PD 2) and the first two plantings at UM (PD 1 and 2), were planted with seed leftover from 2022, whereas the other later plantings were planted with new seed purchased in 2023. Seeding rates were adjusted with the use of fresh seed, except for PD 3 at UM, where the fresh seed was planted at the higher seeding rate (determined for the carryover seed). Data from these plots were removed for subsequent statistical analysis.

2.3.2.a Harvest 1

Yields from all treatments for Harvest 1 are presented in Figure 2.2, but statistical analysis was performed on the dataset with PD 1-3 at UM 2023 and PD 2 at Wye 2023 removed. For the full data, there was no pattern in yield across planting dates for the Wye location; PD 3 and PD5 had the highest yields. At UM, the full data showed more of a pattern, with an increase in yield until PD 4, as the plateau, and then a decrease into PD 5. For Harvest 1, the full data sets support that mid to late season planting dates generate higher yields than the earlier planting dates.

There was an interaction effect of site-year and planting date on hemp fresh weight at Harvest 1 (Table 2.5). While the UM site outyielded the Wye 2023 site, the earliest plantings (PD 3 at Wye and PD 4 at UM) yielded highest at both locations, with yield decrease observed with later plantings. At Wye, the yields observed for PD 4 and PD 5 are significantly lower than PD 3, however, yield at PD 5 is numerically greater than yield at PD 4. The increased yields in the later plantings, established between 1 June and 22 June, are likely due to the increase in daylength which in turn increased photosynthetic potential and vegetative growth. The highest yielding short-season hemp plots were harvested between mid-August and mid-September, which in the Mid-Atlantic region is approximately two months prior to corn and soybean harvest. The production of 'short season' hemp (established early and harvested early) would allow for earlier fall planting of small grains or cover crops following hemp harvest, even with the time needed for field retting considered. The timing of planting and harvesting of short season hemp in PD 3 and PD 4 had the benefits of not overlapping with other crop plantings or harvests in the Mid-Atlantic, while still having yields similar to other research in the region (D. Suchoff, personal communication).

2.3.2.b Harvest 2

For Harvest 2, in which fresh yields were collected at the end of the growing season for all PDs, both PD and site-year significantly affected fresh yield (Table 2.7). Across all PDs, UM in 2023 and Wye in 2022 yielded similarly (38133 ± 4102 kg ha^{-1} and 33278 ± 2801 kg ha^{-1}, respectively), with significantly lower mean yield observed at Wye in 2023 (16464 ± 2955 kg ha^{-1}). Generally, greater yield was observed with earlier PDs (Table 2.8). Although not significant, yields decreased numerically with later PDs, with a significant decrease in yield not observed until the latest PD (mid- to late-July).

Growing fiber hemp in a shortened, 90 d season is not recommended to maximize fresh yield, as numerically greater yields were obtained when fiber hemp grew through the entire summer season, maximizing light interception. Early planting of fiber hemp allows the plants to maximizing vegetative growth, which translates to yield, and while yield decreased with later plantings, the yields were statistically similar, indicating there is flexibility in planting date without significantly impacting yield.

2.3.3 Height and Diameter

Recent research has indicated that fiber hemp plant height is generally controlled by genetics, with environment minimally impacting plant height (Campbell, 2019). Data collected within this study suggests that environmental factors, namely length of growing season, may have more of an impact on height potential than previously thought. Stalk diameter, however, has been found to be inversely related to seeding rate or plant population, which is supported by this research in it being controlled by primarily environmental factors (Dimitriev, 2021).

2.3.3.a Harvest 1

For measurements of height and diameter in 2023 at Harvest 1, no significant effects (treatment effects of PD and site-year) or interaction effects observed (Table 2.9). The shortened growing season may not have allowed enough time for potential differences in plant height or diameter to be observed. Data collected on diameter size at the 90-day mark can be found in the appendix (Table A.2). The values suggest that a shortened growing season generates thinner, more desirable diameters (private communications). Upon removal of data from plots where carryover seed and incorrect seeding rate were used, we eliminated possible human-induced factors that could change plant population within plots, as previous research has indicated hemp stalk diameter is inversely related to plants area-1 (Amaducci et. al, 2008; Dimitriev, 2021).

2.3.3.b Harvest 2

When hemp plants experienced a longer growing season and were harvested near the onset of flowering, significant treatment effects of PD and site-year on plant height and significant effect of PD only on hemp stalk diameter were observed (Table 2.10). The tallest plants were observed at Wye in 2022 (284 ± 16 cm), then UM in 2023 (239 ± 11 cm), then Wye in 2023 (206 ± 8 cm), with only Wye in both years differing significantly from one another. Taller plants were observed in earlier PDs (Table 2.11), which resulted in a longer growing season to allow plants longer time in the vegetative growth phase, supporting the impacts of environmental differences on height potential.

Stalk diameter decreased across PDs for Harvest 2, likely due to the increase in germination visually observed in the later PDs (Table 2.11). Precipitation became more consistent later in the season, allowing for increased germination (Fig. 2.1). Increased germination increased the density of the later plantings, inversely impacting the stalk diameter, as supported by previous literature (Bhattarai, 2014; Dimitriev, 2021; Struik, 2000).

The lack of differences in plant height and diameter by PD or site-year at Harvest 1 may be a result of shortened growing season minimizing height potential of the hemp. However, the significant effect of both PD and site-year on height at Harvest 2 may be a factor of the inclusion of the Wye 2022 data. A similar trend was observed at both harvests, with shortened plants and smaller stalk diameter observed when growing season is shortened – either by early harvest or later planting.

2.3.4 Plant Population

For the short season hemp (Harvest 1), an interaction between planting date and site-year was observed for plant population (Table 2.12). More favorable weather conditions at UM in 2023 likely resulted in greater germination and the numerically greater population at this site, with a significantly greater population observed in PD 5 at this location (Table 2.13). At Harvest 2, only an effect of site-year was observed (Table 2.12), with mean plant population at Wye in 2023 (28 ± 2) significantly less than Wye 2022 (52 ± 3) and UM 2023 (59 ± 6), which were similar to one another. While equipment seeding rate, and seed were the same within site-year, it is likely that weather conditions negatively impacted germination at Wye in 2023, leading to a significantly lower population.

2.3.5 Fiber Quality

There is a lack of standardized definition of hemp fiber quality and these measures are generally dependent on the end product for which the fiber is produced. Moreover, there is minimal understanding of the management factors that impact fiber quality. To characterize some measure of plant quality, fiber hemp samples collected at Wye in 2022 were analyzed for measures of forage quality, as this testing is readily available and not prohibitively expensive. Forage quality measures evaluate the digestibility of plant material, or the proportion of less digestible and structural components of plants. Of the forage quality measures, planting date only significantly affected lignin content (Table 2.14), with lignin content decreasing across planting dates (Table 2.15). Lignin is a double bonded phenyl that is located between cellulose, providing strength and protection to the plant (Thomsen, 2005). It serves as an important metric across all fiber industries and can often demonstrate the overall quality of the fiber, especially in post-harvest processing. In the case of fiber hemp, textile uses require lower lignin content for ease of processing, whereas other uses, such as paper, construction materials, or animal bedding may require higher lignin context for product stability (Petit, 2020). These results follow previous research in forages, indicating increased proportions of less-digestible components (namely lignin) with more mature plants and provides guidance to hemp farmers regarding management of hemp for lignin content (Atis, 2012; Xu, 2023).

2.3.6 Correlation of Measured Variables

All measured variables, including significant quality measures (i.e. lignin content) were correlated to one another by harvest timing (Tables 2.16 and 2.17). At Harvest 1, plant population was significantly correlated to stalk diameter and fresh yield (Table 2.16). Diameter and plant population were strongly inversely related, as it is well supported that as population increases, hemp stalk diameter decreases (Bennett et al., 2006; Struik et al. 2000). Yield and population were also strongly correlated, as the increase in population predictably leads to an increase in overall yield.

For the 2022 season, lignin content was positively and significantly correlated to fresh yield and height (Table 2.17). Plant height was strongly positively correlated to plant population and fresh yield and plant population was also strongly and positively correlated to fresh hemp yield (Table 2.17). Generally, these data indicate that population and germination should be optimized to maximize fiber hemp yield if a limited growing season is planned. However, with a longer growing season, a focus on maximizing plant height may impact fiber hemp yield. The use of height in forages to predict yield is not a new concept, especially in other forages or hay production (Mut, 2014), and many studies have demonstrated that the two are commonly positively correlated (Aydin, 2010; Gill, 2016). Height measurements over the course of the season could be used to predict yields, and when height measurements begin to plateau, that could help establish better harvest timing, without a loss in yield.

2.4 Conclusions

Through the comparison of Harvest 1, representing a 90-d growing season, to Harvest 2, representing hemp harvest near transition to reproductive growth, the present study indicated that to maximize fiber hemp yield and associated desirable plant traits, hemp must maximize light interception throughout the entire summer growing season, therefore, shortened-season fiber hemp is not likely to maximize productivity. Numerically, early planting of fiber hemp produced the highest yields, although no significant difference in fresh fiber hemp yield was observed across planting dates ranging from late April to late June in the Mid-Atlantic. Fiber hemp plant height and stalk diameter decreased with later plantings, likely due to a shortened growing season which prevented fiber hemp plants from reaching their full vegetative growth potential. Only lignin, a structural component of plants, was significantly impacted by planting date; early planted fiber hemp which was more mature at harvest contained greater proportion of lignin, which follows research performed on other forage crops. Fiber hemp plant height, population, and fresh yield were correlated to one another, which indicates hemp farmers should focus on establishing a good stand at an earlier time to maximize plant height and optimize yield of fiber hemp.

These results are promising for the incorporation of fiber hemp into current crop rotations in Maryland. The flexibility around optimal planting of fiber hemp allows farmers to prioritize planting of summer cash crops such as corn and soybean ahead of fiber hemp while minimizing concerns of negatively impacting fiber hemp yield in this scenario. While a shortened fiber hemp growing season may negatively impact fiber hemp yield and quality and may not be advised, future research should focus on an intermediate harvest timing, that is, > 90 d growing season but slightly before reproductive growth and prior to corn or soybean harvest, to provide guidance to farmers interested in growing fiber hemp as part of their crop rotation.

2.5 Tables

Table 2.1. Site locations and soil types for the trial.

Site	Location	Soil Type	Soil Classification
Wye	38° 55’ N, 76° 08’ W	Nassawango silt loam	Fine-silty, mixed, semi active, mesic Typic Hapludults
UM	38° 51’ N, 76° 46’ W	Annapolis fine sandy loam	Fine-loamy, glauconitic, mesic Typic Hapludults

Table 2.2. Agronomic soil test results (variable and sufficiency category) for two locations for the study (Wye in 2022 and 2023, and UM in 2023). Wye soil samples were collected in 2021 and 2022 (for 2022 and 2023 analysis, respectively).

	Wye 2022		Wye 2023		UM 2023	
Variable	**Concentration**	**Category**	**Concentration**	**Category**	**Concentration**	**Category**
pH	6.5		6.9		5.7	
Phosphorus, ppm	37	Medium	48	Medium	80	High
Potassium, ppm	51	Very Low	95	Medium	134	High
Calcium, ppm	747	High	1038	High	1004	Medium
Magnesium, ppm	108	High	135	High	106	Medium

Sulfur, ppm	11	Low	6	Very Low	7	Very Low
Boron, ppm	0.3	Very Low	0.3	Very Low	0.3	Very Low
Zinc, ppm	1.5	Low	1.5	Low	1.9	Low
Organic matter	2.3%	Low	2.6%	Medium	2.6 %	Medium

Table 2.3. Fertilizer application to study area prior to plot establishment.

Date	Location	Amendment Applied
15 April 2022	Wye	12-17-17-10 S at 224 kg ha^{-1}
18 April 2022	Wye	6-28-22-3 S at 90 kg ha^{-1}
20 April 2022	Wye	0-0-60 MOP at 140 kg ha^{-1}
11 Feb 2023	UM	Hi-mag wet lime at 3363 kg ha^{-1}
21 March 2023	UM	0-0-60 MOP at 93 kg ha^{-1}
16 March 2023	Wye	5-26-30 at 111 kg ha^{-1}
31 March 2023	Wye	0-0-60 MOP at 36 kg ha^{-1}
13 April 2023	UM	46-0-0- at 67 kg ha^{-1}

Table 2.4. Planting dates for Wye 2022 and 2023 and UM 2023 with Julian date in parenthesis. In 2022, all plots were harvested on 20 September (263). In 2023, Harvest 2 was 25 September (268) for all plots at both locations. †90 d growing season for PD 6 at Wye in 2023 coincided with harvest during Harvest 2, therefore no Harvest 1 data was collected for this treatment.
‡ Data collected from these treatments were removed from statistical analysis due to use of carryover seed with poor germination or incorrect seeding rate.

Planting Date (PD)	Wye 2022		Wye 2023		UM 2023	
	Planting	Harvest	Planting	Harvest 1	Planting	Harvest 1
1	-	-	-	-	03 April (93) ‡	02 July (183) ‡
2	26 April (116)	20 Sept (263)	24 April (114)‡	23 July (204) ‡	24 April (114) ‡	23 July (204) ‡
3	17 May (137)		15 May (135)	13 August (225)	15 May (135) ‡	13 August (225) ‡
4	07 June (158)		01 June (152)	30 August (242)	01 June (152)	30 August (242)
5	28 June (179)		22 June (173)	20 Sept (263)	22 June (173)	20 Sept (263)
6	20 July (201)		10 July (191)	-†	-	-

Table 2.5. Results of ANOVA of the effect of planting date, site-year, and their interaction on fresh yield at Harvest 1.

Measure	Variable	P-Value
Yield	Plant Date	<0.0001
	Site-year	<0.0001
	Interaction	0.0293

Table 2.6 Mean fresh hemp yield and standard error for each planting date by location for Harvest 1. Different letters denote a significant difference at P < 0.05 (Tukey's HSD).

	Wye 2023	UM 2023
Plant Date	Yield (kg ha^{-1})	
1	-	-

2	-	-
3	26641 ± 1647 b	-
4	7656 ± 576 c	37276 ± 3492 a
5	12540 ± 1607 c	32287 ± 1445 ab
6	-	-

Table 2.7. Results of ANOVA of the effect of planting date, site-year, and their interaction on fresh yield at Harvest 2.

Measure	**Variable**	**P-Value**
Yield	Plant Date	<0.0001
	Site-year	<0.0001
	Interaction	0.1496

Table 2.8. Mean fresh hemp yield and standard error by planting date for Harvest 2. Different letters denote a significant difference at $P < 0.05$ (Tukey's HSD).

Plant Date	**Fresh Yield (kg ha^{-1})**
2	42613 ± 5577 a
3	38057 ± 2402 a
4	30247 ± 4626 a
5	25739 ± 3463 ab
6	10914 ± 2326 b

Table 2.9. Results of ANOVA of the effect of planting date, site-year, and their interaction on height and diameter at Harvest 1.

Measure	**Variable**	**P-Value**
Height	Plant Date	0.1203
	Site-year	0.5195
	Interaction	0.0542
Diameter	Plant Date	0.3097
	Site-year	0.1145
	Interaction	0.0529

Table 2.10. Results of ANOVA of the effect of planting date, site-year, and their interaction on height and diameter at Harvest 2.

Measure	**Variable**	**P-Value**
Height	Plant Date	<0.0001
	Site-year	0.0005
	Interaction	0.1760
Diameter	Plant Date	0.0020
	Site-year	0.2607
	Interaction	0.1073

Table 2.11. Mean plant height and diameter and standard error by planting date at Harvest 2. Different letters within variable denote a significant difference at $P < 0.05$ (Tukey's HSD).

Plant Date	Height (cm)	Diameter (mm)
2	361 ± 30 a	16.7 ± 2.1 a
3	273 ± 23 b	16.4 ± 2.0 a
4	252 ± 14 b	11.1 ± 0.7 b
5	230 ± 6 bc	10.3 ± 0.5 b
6	183 ± 15 c	10.8 ± 1.2 b

Table 2.12. Results of ANOVA of the effect of planting date, site-year, and their interaction on plant population for both harvest timings.

Measure	Variable	P-Value
Harvest 1	Plant Date	0.0121
	Site-year	<0.0001
	Interaction	0.0005
Harvest 2	Plant Date	0.0842
	Site-year	<0.0001
	Interaction	0.1167

Table 2.13. Mean population and standard error by site-year and planting date at Harvest 1. Different letters denote a significant difference at $P < 0.05$ (Tukey's HSD).

	Wye 2023	UM 2023
Plant Date	Population (plants m^{-2})	
1	-	-
2	-	-
3	26 ± 2 b	-
4	35 ± 2 b	46 ± 4 b
5	28 ± 7 b	88 ± 8 a

Table 2.14. Results of ANOVA of the effect of planting date on fiber quality measures at Wye 2022 (Harvest 2 only).

Variable	**P Value**
Dry Matter	0.562
Crude Protein	0.412
ADF (% of NDF)	0.696
ADF (% Dry Matter)	0.695
aNDF (% Dry Matter)	0.163
Lignin (% of NDF)	0.002
Lignin (% Dry Matter)	0.002

Table 2.15. Mean plus standard error for fiber quality measures by planting date at Wye 2022 (Harvest 2 only). Different letters within measure denote a significant difference at $P < 0.05$ (Tukey's HSD).

Plant Date	Dry Matter (%)	Crude Protein (grams)	ADF (% of NDF)	ADF (% Dry Matter)	aNDF (% Dry Matter)	Lignin (% of NDF)	Lignin (% Dry Matter)
2	93.60 ± 0.06	7.18 ± 0.50	89.38 ± 1.12	65.10 ± 1.65	72.88 ± 2.37	9.49 ± 0.96 a	6.87 ± 0.58 a
3	93.90 ± 0.04	6.50 ± 0.24	87.48 ± 2.14	66.68 ± 1.29	76.25 ± 0.67	7.97 ± 0.85 ab	6.07 ± 0.65 ab
4	93.80 ± 0.09	7.10 ± 0.45	87.05 ± 1.23	67.35 ± 1.00	77.40 ± 1.31	6.71 ± 0.15 abc	5.19± 0.13 abc
5	93.95 ± 0.13	6.58 ± 1.38	85.85 ± 1.57	68.93 ± 3.11	80.25 ± 3.26	5.30 ± 0.71 bc	4.22 ± 0.48 bc
6	92.43 ± 1.61	8.60 ± 0.98	86.70 ± 2.34	65.68 ± 2.23	75.70 ± 0.69	4.73 ± 0.61 c	3.58 ± 0.46 c

Table 2.16. Pearson's correlation coefficient (r) and P values for variables measured at Harvest 1, both locations combined.

	Diameter (mm)	Height (cm)	Population (plant m^{-2})	Fresh Yield (kg ha^{-1})
Diameter (mm)	r = 1.0	-	-	-
Height (cm)	r = 0.4163 *P = 0.0679*	r = 1.0	-	-
Population (plant m^{-2})	r = -0.5958 *P = 0.0056*	r = -0.0727 *P = 0.7608*	r = 1.0	-
Fresh Yield (kg ha^{-1})	r = -0.2553 *P = 0.2773*	r = 0.3326 *P = 0.1519*	r = 0.5062 *P = 0.0228*	r = 1.0

Table 2.17. Pearson's correlation coefficient (r) and P values for variables measured at Harvest 2, both locations combined. Quality results (†) from Wye 2022 at Harvest 2 only.

	Lignin† (% dry matter)	Diameter (mm)	Height (cm)	Population (plant m^{-2})	Fresh Yield (kg ha^{-1})
Diameter (mm)	r = 0.3338 *P = 0.1503*	r = 1.0	-	-	-
Height (cm)	r = 0.5667 *P = 0.0092*	r = 0.3378 *P = 0.1064*	r = 1.0	-	-
Population (plant m^{-2})	r = 0.3468 *P = 0.1341*	r = -0.1194 *P = 0.5785*	r = 0.4353 *P = 0.0335*	r = 1.0	-
Fresh Yield (kg ha^{-1})	r = 0.4802 *P = 0.0321*	r = 0.3753 *P = 0.0707*	r = 0.8090 *P < 0.0001*	r = 0.6001 *P = 0.0019*	r = 1.0

2.6 Figures

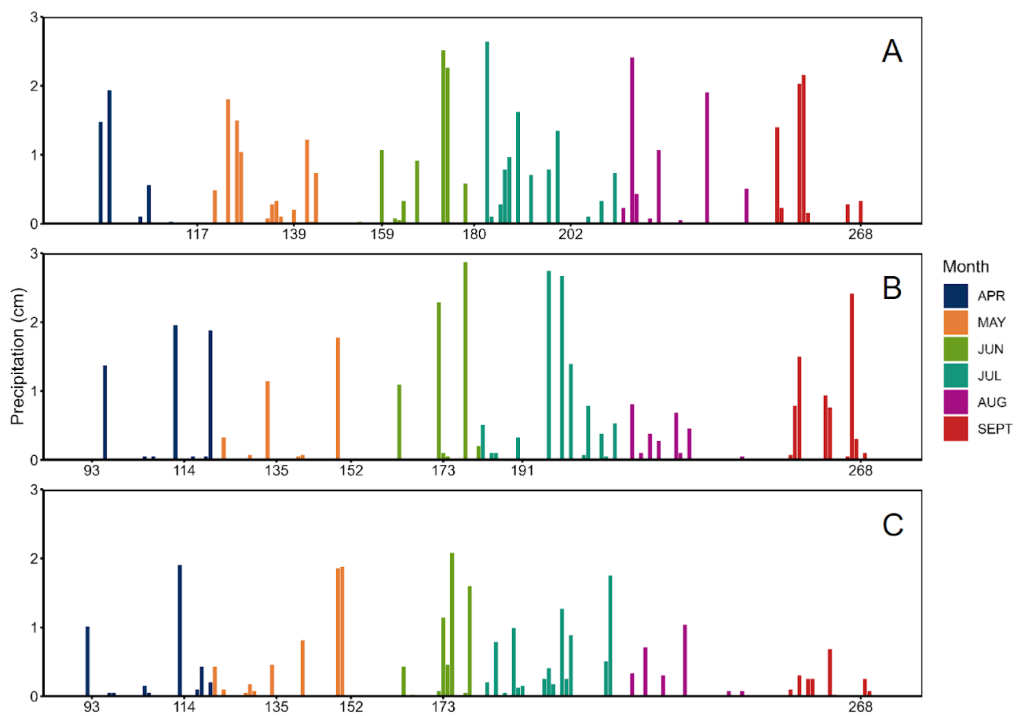

Figure 2.1. Daily precipitation values for 2022 (A – Wye) and 2023 (B – Wye and C – UM) by month. Julian dates correspond to the planting dates, with the final value corresponding to the end of season harvest (Harvest 2).

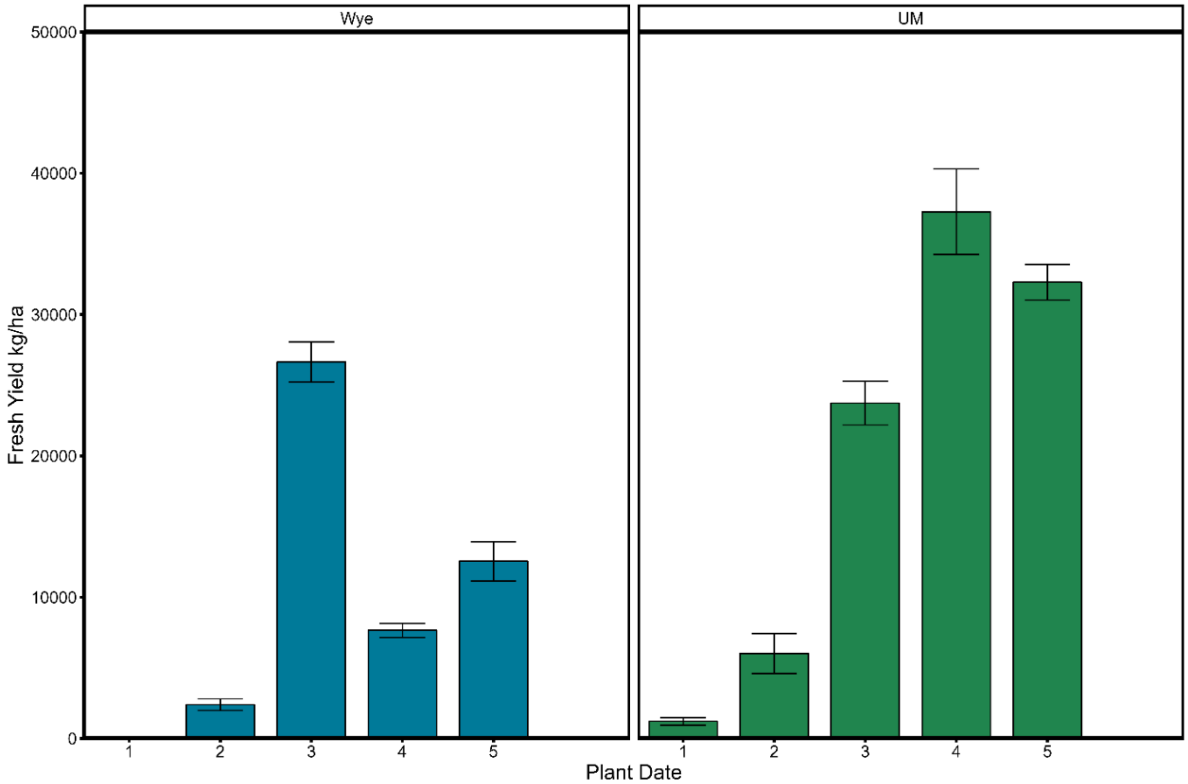

Figure 2.2. Mean fresh hemp yield and standard error by planting date and location in 2023 for Harvest 1. No statistical analysis presented here, as erroneous PDs were removed prior to data analysis.

Chapter 3: Weed Pressure across Sequential Plantings of Industrial Fiber Hemp (*Cannabis sativa* L.)

Abstract

With the lack of herbicides approved for use in industrial hemp (Cannabis sativa L.) production, it is important to determine which cultural practices can be utilized to manage weeds. The objectives of this research were to determine how hemp planting date impacts weed pressure. Treatments were evaluated under a competition or germination prevention scenario. At the Wye location, weed density remained relatively consistent across planting dates in both years, with weed density for winter annuals decreasing by 75% between initial and final harvests, and summer annuals decreasing by 50% or remaining constant. At the Upper Marlboro (UM) location, weed density decreased to no weeds present where hemp was planted after mid-May. Weed density for winter annuals and summer annuals was only found under germination prevention scenarios. Winter annual density decreased by 100% across all planting dates, while summer annual density was found to increase by 100%. Our results support that weed biomass is best controlled by planting hemp in May or later, but is also dependent on hemp density, germination, and field location.

3.1 Introduction

Industrial hemp (*Cannabis sativa* L.) was not produced in the US since World War II due to its association with marijuana, however its production was reintroduced by the 2014 Farm Bill, and later reinforced by additional legislation in the 2018 Farm Bill (Agricultural Act of 2014, Pub. L. No. 113-79 2014, Agriculture Improvement Act of 2018, Pub. L. No. 115-334 2018). While industrial hemp was banned from production, decades of applied research was performed on other agronomic crops (i.e. corn [*Zea mays*], soybeans [*Glycine max*], and wheat [*Triticum aestivum*]) to optimize their production, including fertility and weed management. Significant breeding efforts have resulted in genetically modified crops, allowing for the application of herbicides to manage weeds that have germinated after crop emergence without damage to the crop. Information is lacking on industrial hemp production as an agronomic crop due to the lack of research performed while it was banned from domestic production (Adesina, 2020).

While fiber hemp, herein referring to industrial hemp, is grown for extraction of fiber components from the plant stalk, has the potential to be managed like an agricultural, as opposed to horticultural, crop. Challenges to its adoption into current crop rotations exist, namely, the limited understanding of and options available for managing undesirable weed species. In other agricultural crops, there is a wide range of weed management options. These include chemical management, such as pre- and post-emergence herbicides, as well as cultural management, often in the form of tillage. These can be used independently or combined and are supported by decades of research performed to optimize the use of these tools in combination with management practices such as row spacing on traditional agronomic crops. While corn and soybeans have a variety of established management practices, and often rely on herbicide applications, weed suppression is an increasing issue in fiber hemp production, as producers cannot apply post-emergence herbicide to hemp crops (Flessner, 2020). Previous gaps in research have been addressed by multiple authors (Sandler, 2019; Bhattarai, 2014) noting that in order to push fiber hemp into a more widespread commodity crop, weed management, among other issues, would have to be resolved. The objective of this research was to observe the ability of fiber hemp to compete with weed species under two germination scenarios (simultaneous germination of hemp and weeds or hemp establishment prior to weed germination) across a planting date continuum. We hypothesize the combination of early fiber hemp planting and hemp germination prior to weeds will minimize weed populations and subsequent impacts to fiber hemp yield.

3.2 Materials and Methods

3.2.1 Plot Establishment

The study was conducted at three locations over two years. Detailed description of study establishment across three site years (Wye 2022, Wye 2023, UM 2023) is provided in Chapter 2. Pertinent details relating to the current chapter are presented herein. The study was a split plot arranged in a randomized complete block design with four replications. Whole plots consisted of planting date (03 April through 20 July, planted every three weeks), subplots consisted of variety (2022) or harvest date (2023).

In 2022, prior to plot establishment, tillage was performed on the intended study area on 31 March (chisel plow), 22 April (disked with packer), and 26 April (450 Vibra Shank field cultivator with rolling basket) to prepare the seedbed and manage weeds. The pre-plant tillage controlled weeds at planting date (PD) 1 and 2 plots prior to planting, but to manage weeds in PD 3-5 plots, a pre-plant application of glyphosate (Bullzeye, Growmark Inc) was applied at 1,892 g ae ha-1 via backpack sprayer using flat fan 8006VS (Tee-Jet, Tee-Jet Technologies, Springfield, PA) to deliver 224 L ha-1 (04 June for PD 3, 20 June for PD 4, and 13 July for PD 5) with tillage performed prior to planting in PD 4 and 5 plots (disking and packing on 13 June).

At UM, prior to plot establishment, tillage was performed to prepare the seedbed and manage weeds. Conventional tillage (to depth of 11.5 cm) was performed on 18 March, and again on 24 March and 3 April, to a depth of 7.6 cm, minimum tillage (Turbo Till to 5 cm) was then performed on 4 April. All pre-emergent herbicide applications were made with a tractor-mounted 3-point sprayer. Spray volume was 187 L ha-1 and nozzles were AIC11003 (Tee-Jet, Tee-Jet Technologies, Springfield, PA) with a pressure of 345 kPa. On 5 April, *S*-metolachlor [Dual II Magnum, Syngenta] was applied at a rate of 1,424 g ha-1 and paraquat [Gramoxone SL 2.0, Syngenta] at a rate of 420 g ha-1. To manage weeds in PD 3-5, conventional tillage (to a depth of 5 cm) was performed on 15 May then again on 7 June to PD 4 and 5 plots. Another pre-emergent herbicide application of S-metolachlor (Dual II Magnum, Syngenta) was applied at a rate of 1424 g ha-1 and paraquat, at a rate of 420 g ha-1(Gramoxone SL 2.0, Syngenta), was made on 8 June to PD 4 and 5 plots, following the same spray application procedure as the 4 April application.

Prior to plot establishment at Wye in 2023, conventional tillage was performed on 10 March (to depth of 28 cm then 46 cm with ripper) and 15 March (to depth of 13 cm with disk and rolling basket), then soil preparation and residue removal performed on 31 March (to depth of 13 cm with disk and packer) and 3 April (to depth of 10 cm with Vibra Shank Field Cultivator). Weeds were managed in PD 2-6 plots with a pre-emergent herbicide application via backpack sprayer, using flat fan 8006VS (Tee-Jet, Tee-Jet Technologies, Springfield, PA) (2031 g ae ha-1 glyphosate [Sunphosate 5 Max, Wynca Internat. Holdings Co.] set to deliver 224 l ha-1) one day after plots were planted.

Two distinct sampling areas, herein referred to as micro-plots (MPs), were established within each plot at each site year to evaluate hemp canopy cover effects on weed populations. Micro-plot A (MPA) was utilized to assess the effect of season-long weed competition on fiber hemp, and micro-plot B (MPB) was used to assess the effects of fiber hemp canopy on weed emergence. In both years, two 0.25 m^2 MPs were placed 1.5 m from the front and back of each plot and centered at 1 m within the plot.

3.2.2 Data Collection

Weed biomass, weed species identification, and weed counts were performed on all microplots in all Yuma variety plots in 2022 and in both harvest timing plots in 2023. Data was collected when weed species reached approximately 7.5 cm in height and within one week prior to a plot's scheduled hemp harvest.

At the initial data collection, weeds were counted and characterized by species (broadleaf or grass species) and life cycle (summer annual, winter annual, or perennial) in all microplots (Table 3.1 and 3.2). In MPB, all weeds were removed after being characterized.

The final data collection timing occurred at the same time as the planned hemp harvest date. In 2022, all plots were harvested on the same date, while in 2023, harvest date treatment plots were split to create plots harvested on two different dates. Therefore, in 2023, final data collection occurred twice, with half of the plots evaluated on each date (Table 3.2). At the final data collection, in each microplot, weeds were counted and characterized similarly to the initial data collection timing. All weed aboveground biomass was removed from a 0.25 m^2 area within each microplot using hand pruners.

3.2.3 Data Cleaning and Statistical Analysis

Weed biomass was analyzed by harvest date and micro-plot using a mixed model ANOVA in R (R Core Team, 2022) where replication was the random effect and planting date, and micro-plot were the fixed effects. Weeds were absent from many treatments throughout the study. As a result, minimal replication remained to perform statistical analysis of the data. Therefore, raw data is presented and discussed in the subsequent section of this chapter.

3.3 Results and Discussion

3.3.1 Weather Considerations

For weather considerations, reference chapter 2, section 2.3.1. For temperature and its relationship to growing degree information, reference tables 3.5 through 3.7.

3.3.2 Weed Characterization

Common species found within these plots included both winter and summer annuals, as well as perennials species. Winter annuals included but were not limited to chickweed (*Stellaria media*) and henbit (*Lamium amplexicaule*). Summer annuals included but were not limited to common lambsquarters (*Chenopodium album*), redroot pigweed (*Amaranthus retroflexus* L.), spurred anoda (*Anoda cristata*), morning-glory spp. (*Ipomoea spp),* and jimsonweed (*Datura stramonium*). Perennial species included but were not limited to yellow wood sorrel (*Oxalis pes-caprae*), common pokeweed (*Phytolacca americana*).

3.3.3 Effects of Weed Competition on Hemp

3.3.3.a Weed Density

Under the effects of hemp competition, winter annual broadleaf species were only found at both Wye locations in 2022 and 2023, but not at UM in 2023. Additionally, the counts of these species decreased by 70% on average from the initial sampling to the final sampling done at the end of the growing season (data not presented). Such species were only found in the mid spring through early summer plantings (plantings 2-4; late April through early June). All counts decreased by 75-100% within a square meter, ranging from 16 plants m^{-2} initially to 4 plants m^{-2} at the end of the season, to 4 plants m^{-2} initially to none present at the end of the season (data not shown). The early presence of winter annual broadleaf species is not surprising within the initial sampling, and both the lack of them at the final sampling as well as the low growth patterns of these species (chickweed, henbit) support that they are not a threat to hemp production.

Under the effects of hemp competition, summer annual broadleaf species were only found at both Wye locations in 2022 and 2023, but not at UM in 2023. The counts of these species found that weed density increased from the initial sampling to the final sampling done at the end of the growing season (data not presented). Such species were only found in the mid spring through early summer plantings (plantings 2-4; late April through early June). All counts increased by 50-100% within a square meter, ranging from 4 plants m^{-2} initially to 8 plants m^{-2} at the end of the season, to no weeds present initially to 4 plants m^{-2} observed at the end of the season (data not shown). The increased density of summer annual broadleaf species is not surprising, as their germination and development coincided with the planting dates in which they were found. With the summer annual broadleaf species, the increased weed density is only a concern to hemp production if such species exhibit difficult growth patterns (morning-glory) or (pigweed, jimsonweed, lambsquarters).

Hemp competition resulted in lower densities of perennial and grass species compared to winter and summer annual broadleaf species. At initial and final sampling, perennial weeds were only observed at Wye 2022 in planting date 2 (mid spring). Perennial weed density was initially found to be 12 plants m^{-2} and decreased to 8 plants m^{-2} by the end of the growing season (data not shown). Perennial weeds can be difficult to manage, but it is important to recognize that they were only present in one of the planting dates across all three site years (6% of observations). Similarly, summer grasses were only found in planting 2 at Wye in 2022 and in planting 3 at Wye in 2023 (mid and late spring, respectively). Initial and final grass counts remained consistent at Wye in 2022 (4 plants m^{-2}) but increased at Wye in 2023 with no grasses found at the initial sampling, and 4 weeds per square meter at the final sampling (data not shown).

3.3.3.b Weed Biomass

Weed biomass data were analyzed by MP across PDs after removal of plots with no weed biomass or unrealistic outliers. As such, minimal data remained to be analyzed (Table 3.3 and 3.4) as there was limited weed biomass present in many of the plots.

Not all PDs had weeds present and no weeds were found in any of the plots at Harvest 1 at either location in 2023 or in Harvest 2 at UM. Weed biomass was present only at the Harvest 2 sampling date in select planting dates at Wye 2022 and Wye 2023 (Table 3.3). Planting date did not significantly impact broadleaf weed biomass at Wye in 2022 ($P = 0.593$). Observationally, the later plantings reduced weed density and biomass across site-years. The biomass that was present varied widely, as over 100 g of broadleaf biomass was collected at Wye in 2023, but only from one PD. There was less variability in the weed biomass across PDs at Wye in 2022, where the majority of the biomass fell below 40 g m^{-2}. It is important to note that all plots with grass biomass had additional broadleaf biomass, whereas not all broadleaf biomass plots had grass biomass.

3.3.4 Effects of Hemp Canopy on Weed Emergence

3.3.4.a Weed Density

Under the effects of hemp canopy cover development, winter annual broadleaf species were only found within the late spring planting date. All locations had the initial sampling performed once hemp canopy cover had been established but weeds were only present at the Wye locations at the full season harvest, with average density decreasing by 100% for both years (data not presented). At UM, weeds were only present at the final sampling for the short season harvest (90 days after the planting), with weed density decreasing by 100%. At both Wye locations, weed density decreased from either 12 plants m^{-2} to none, or from 4 plants m^{-2} to none (2022, 2023 respectively). At UM, 12 plants m^{-2} were observed at the initial sampling, and none were found at the time of the final harvest (data not shown). The early presence of winter annual broadleaf species is not surprising within the initial sampling, and both the lack of them at the final sampling as well as the low growth patterns of these species (chickweed, henbit) support that they are not a threat to hemp production. The increase of winter annual broadleaf density at the UM location could be in part to poor germination rates of the hemp at that planting date but is not a source of concern as the overall increase is marginal.

Summer annual broadleaf species were only found within the late spring planting date (planting date 2, done April 26 in 2022 and April 24 in 2023) under the effects of hemp canopy cover development. All locations had the initial sampling performed once hemp canopy cover had been established (Table 3.1 and 3.2), but weeds were only present at the locations in 2023. At the Wye location, weeds were present only in the long season harvest of the second planting date, with weed density increasing by 100%. At UM, weeds were only present at the final sampling for the short season harvest of the second planting date (90 days after the planting), with average weed density also increasing by 100%. At the Wye location, weed density increased from 4 plants m^{-2} to 12 plants m^{-2} (data not shown). Similarly, at UM, no weeds were observed at the initial sampling and density increased to 16 plants m^{-2} at the time of the final harvest. The increased density of summer annual broadleaf species is not surprising, as their germination and development coincided with the planting dates in which they were found. With summer annual broadleaf species, the increased weed density is only a concern to hemp production if such species exhibit difficult growth patterns (morning-glory) or (pigweed spp., jimsonweed, lambsquarters).

Perennial and grass species were found at much lower densities than winter and summer annual broadleaf species under the effects of hemp canopy development. Perennials were only found at Wye in 2022, and only at the initial sampling for planting date 2 (mid spring). Weeds decreased from 8 plants m^{-2} to no weeds present at the final sampling. Under hemp canopy development, grasses decreased or remained consistent between initial and final sampling. Grasses were present at all both sites in 2023, but not at Wye in 2022. At Wye in 2023, grasses were only found in the full season data, in the mid spring planting, and had the same pressure at both initial and final sampling (4 plants m^{-2}). At UM in 2023, weeds were only found in the short season (Harvest 1) data, again in planting date 2 (mid spring). Grasses at UM decreased from initial to final sampling, from 4 plants m^{-2} to 2 plants m^{-2} (data not shown).

3.3.4.b Weed Biomass

Weed biomass data were analyzed by MP across PDs after removal of plots with no weed biomass or unrealistic outliers. As such, minimal data remained to be analyzed (Table 3.3 and 3.4) as there was limited weed biomass present in many of the plots.

In 2022, the initial data collection time, and removal of weeds, occurred at varying times respective to PD, and anywhere from 10 to 56 DAP, whereas in 2023, the removal was more consistently performed at 21 DAP, despite the consistent GDD per month across site years (Tables 3.5-3.7). The spacing of these events was determined by the appearance of the hemp canopy cover, which did not establish at a consistent rate in 2022 due to the lower seeding rate of the hemp (Table 3.1). These data support previous findings, despite not suppressing all weed growth, the majority of the plots remained weed free or contained very low weed biomass (Bhattarai, 2014). Weed biomass across planting dates and site-years varied, as biomass that was present was either in large (several hundred grams) or small (less than 10 grams) quantities, with few intermediate data points. This suggested that either individual, large weeds or larger quantities of small weeds are able to germinate after fiber hemp canopy is established, but an intermediate quantity of weeds are suppressed by the hemp canopy.

3.4 Conclusion

The most problematic species in the present study were morning-glory, jimsonweed, and pokeweed, to a lesser extent. Due to their size, jimsonweed and common pokeweed were observed primarily on the perimeters of plots, and, while they could be detrimental during harvest, the perimeters could be avoided if they are found to be especially weedy. Additionally, the vining growth pattern of morning glory may pose additional challenges to hemp harvest. The authors recommend that farmers with fields with high morning glory pressure consider shifting hemp production to fields with lower morning-glory pressure.

Weed biomass was generally higher in earlier planting dates, supported by a greater number of weed species observed in those treatment plots. Planting date was not a significant factor in weed suppression in the present study, suggesting that field history and weed species present within a field may play more of a role in weed pressure within fiber hemp plantings. Even in plots with high weed biomass, it is important to note the magnitude of the units of weed biomass, grams m^{-2}, likely had no effect on fiber hemp yield, which was measured in kg ha^{-1}. The pattern of increased hemp yields as the planting dates progressed into the season matches the pattern of decreased weed biomass (Chapter 2), suggesting that high hemp yields mitigate weed germination.

The data supports that when hemp must compete with pre-existing weeds, canopy cover resulting from earlier planting dates was unable to offer levels of control and that later planting dates were more ideal for weed suppression (Sandler, 2019). However, if weeds were not initially present, they then did not germinate, supporting that hemp is a strong competitor with weeds. Proponents of weed research within hemp production have highlighted the unknowns within possible yield losses due to weed competition (Sandler, 2019), and while these data demonstrate that summer broadleaf weeds were present in higher numbers than grasses, it is unlikely that these weeds cause yield losses within this study. Within these plots, some grasses were present, but in low numbers, and unless individual fields have high numbers of grasses, it is less of a concern for hemp production. These data aligned with previous research that found that earlier planting dates for hemp were worse at suppressing weeds, and recommended planting hemp once soil temperatures were warm enough to do so, otherwise spring weeds would be able to outcompete the hemp (Ehrensing, 1998).

Field management and pre-emergence herbicide applications were not standardized across all site years due to existing management practices at the respective locations, which is representative of the varying management practices between farmers. The use of a pre-emergence herbicide with up to six weeks of residual activity (*S*-metolachlor) at the UM location likely affected weed emergence in the later PD treatments, thus impacting the results of the observation of weed emergence at this location. Upon observation of the timing of herbicide application and precipitation events (Fig. 3.1), *S*-metolachlor was generally applied after, and not before, significant rain events. The lack of precipitation following the herbicide application may not have fully activated the active ingredient in the herbicide.

Seeding density varied in treatments where carryover seed from 2022 was planted and seeding rate was not adjusted for the use of new seed in the early and mid-spring treatments (PD 2 at Wye 2023 and PD 1-3 at UM 2023). These adjustments affected plant population for the hemp and may have had an additional effect on the present weed populations. For more information see Chapter 2, section 2.2.

As noted by Sandler and Gibson (2019), many industrial hemp studies lack any mention of weed control or the impacts of weeds on hemp yield, supporting the need for more research in this area. Within the present study, more broadleaf species were found across all site-years than grass species, and while this may be location dependent, it supports that within the location of this study, weed management in hemp production should focus on broadleaf control compared to grasses. Our results agree with previous studies showing both grasses and broadleaf weeds were found at similar densities and were controlled by a higher seeding rate (Bhattarai, 2014; Vera et. al., 2006). These results support that hemp is able to control weeds under varying conditions, and that proper germination as well as canopy cover are important factors in weed suppression. Prior studies and data from this study support that cultural or management practices, such as increased hemp seeding rate, could be a viable weed control option for fiber hemp production where few chemical options exist.

Future research should consider the implications of planting density on weed control, in addition to planting date. As planting density increases have been found to be beneficial to hemp production, understanding the impacts of planting density on weed control is necessary to understand how cultural management can control weeds over chemical applications. Additionally, in-depth studies on weed germination could be helpful in determining if hemp canopy cover is sufficient at preventing germination in certain species better than others to identify problem species that hemp does not control as well, in order to provide more specific local recommendations to farmers based on their field histories.

3.5 Tables

Table 3.1. Study schedule for 2022 at Wye location.

<table>
<tr><th>Treatment</th><th>Planting Date</th><th>Planting Date (Season)</th><th>Initial Data Collection</th><th>Final Data Collection</th><th>Hemp Harvest</th></tr>
<tr><td>PD 1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>PD 2</td><td>26 April</td><td>Mid Spring</td><td>21 June (56 DAP)</td><td rowspan="2">14 September (73 DAP)</td><td rowspan="2">20 September</td></tr>
<tr><td>PD 3</td><td>18 May</td><td>Late Spring</td><td>21 June (34 DAP)</td></tr>
</table>

PD 4	07 June	Early Summer	17 July (10 DAP)		
PD 5	28 June	Mid Summer	03 August (36 DAP)		
PD 6	20 July	Late Summer	25 August (36 DAP)		

Table 3.2. Study schedule for 2023 at Wye and UM locations. †PD1 was terminated shortly after initial data collection and PD6 was established at Wye location only. The shortened growing season of PD6 resulted in final data collection during Harvest 2 only. ‡PD1 through PD5 were established at UM.

Treatment	**Planting Date**	**Planting Date (Season)**	**Initial Data Collection**	**Final Data Collection – Harvest 1**	**Final Data Collection – Harvest 2**	**Hemp Harvest 2**
PD 1†	3 April	Early Spring	24 April (21 DAP)	02 July	20 September	25 September
PD 2	24 April	Mid Spring	15 May (21 DAP)	23 July		
PD 3	15 May	Late Spring	01 June (17 DAP)	13 August		
PD 4	01 June	Early Summer	22 June (21 DAP)	30 August		
PD 5	22 June	Mid Summer	12 July (21 DAP)	20 September		
PD 6	12 July	Late Summer	12 August (31DAP)	n/a‡		

Table 3.3. Mean plus standard error broadleaf and grass weed biomass under the effects of hemp competition on late season weed biomass, by planting date and site year. Plots with zero values were removed from the dataset. † Values without standard error represent data from one replicate only.

	g/m²					
	Wye 2022[a]			Wye 2023[b]		
Plant Date	Broadleaf	Grass	Total[c]	Broadleaf	Grass	Total[c]
1	-	-	-	-	-	-
2	22 ± 11.2	27.2 ± 22.8	49.2 ± 34	-	-	-
3	10.4†	-	10.4†	-	-	-
4	-	-	-	442.4†	19.2†	461.6†
5	6.4 ± 3.6	14.8 ± 1.2	21.2 ± 4.8	-	-	-
6	-	-	-	-	-	-

a. Planting dates in 2022 are as follows, with no planting date 1; 26 April, 18 May, 07 June, 28 June, 20 July.
b. Planting dates in 2023 are as follows, with no planting date 1; 24 April, 15 May, 01 June, 22 June, 12 July.
c. All biomass represented in this table was collected at Harvest 2, done on September 20 in 2022 and September 25 in 2023. No weed biomass was present at the Harvest 1 collection.

Table 3.4. Mean plus standard error broadleaf and grass weed biomass under the effects of hemp canopy development on late season weed biomass, by planting date and site year. Plots with zero values were removed from the dataset. † Values without standard error represent data from one replicate only.

	g/m²								
	Wye 2022[a]			Wye 2023[b]			UM 2023[b]		
Plant Date	Broadleaf	Grass	Total[c]	Broadleaf	Grass	Total[c]	Broadleaf	Grass	Total[c]
1	-	-	-	-	-	-	-	-	-
2	301.6†	33.2†	334.8†	718.4†	400.8†	1,119.2†	108.8 ± 90.8	154.4 ± 118	263 ± 208.8
3	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-
5	30.8†	12.8†	43.6†	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-

a. Planting dates in 2022 are as follows, with no planting date 1; 26 April, 18 May, 07 June, 28 June, 20 July.
b. Planting dates in 2023 are as follows, with no planting date 1; 24 April, 15 May, 01 June, 22 June, 12 July.
c. Harvest for biomass at both Wye locations is shown for Harvest 2 (full season, September 20 in 2022 and September 25 in 2023). Harvest for biomass at UM is shown for Harvest 1 (short season, collected 90 days after each respective planting). Harvest 1 and Harvest 2 were collected at all three site years, but values not shown were zeros and removed from this data set.

Table 3.5. Monthly precipitation total, mean high and low temperatures for Wye 2022 during the growing season (April through September).

Month	Precipitation Total (cm)	Max Daily Low Temperature (C°)	Average Temperature (C°)	Max Daily High Temperature (C°)	Growing Degree Days (C°)
April	5.97	-2.06	10.89	28.78	331.90
May	0.23	1.22	18.00	33.00	538.88
June	0.00	9.61	21.94	32.94	634.94
July	1.42	14.83	24.17	33.83	761.45
August	0.30	11.94	22.17	31.89	745.02
September	0.10	5.11	18.83	31.06	589.90

Table 3.6. Monthly precipitation total, mean high and low temperatures for Wye 2023 during the growing season (April through September).

Month	Precipitation Total (cm)	Max Daily Low Temperature (C°)	Average Temperature (C°)	Max Daily High Temperature (C°)	Growing Degree Days (C°)
April	1.14	-1.06	13.06	29.89	421.79
May	0.30	2.78	15.72	29.17	477.83
June	3.98	6.72	19.89	33.83	602.10
July	4.42	15.17	24.67	35.44	769.18
August	0.36	11.11	23.06	33.11	718.39
September	6.35	7.72	19.28	35.89	606.02

Table 3.7. Monthly precipitation total, mean high and low temperatures for UM 2023 during the growing season (April through September). Weather data collected varies slightly from that at the Wye locations in both years.

Month	Precipitation Total (cm)	Average Low Temperature (C°)	Average High Temperature (C°)	Growing Degree Days (C°)
April	6.99	8.33	22.22	407.78
May	5.84	10.56	22.78	462.22
June	5.88	15.00	27.22	585.83
July	18.31	21.11	31.11	758.06
August	12.80	18.89	30.00	701.67
September	10.08	15.56	27.22	593.06

3.6 Figures

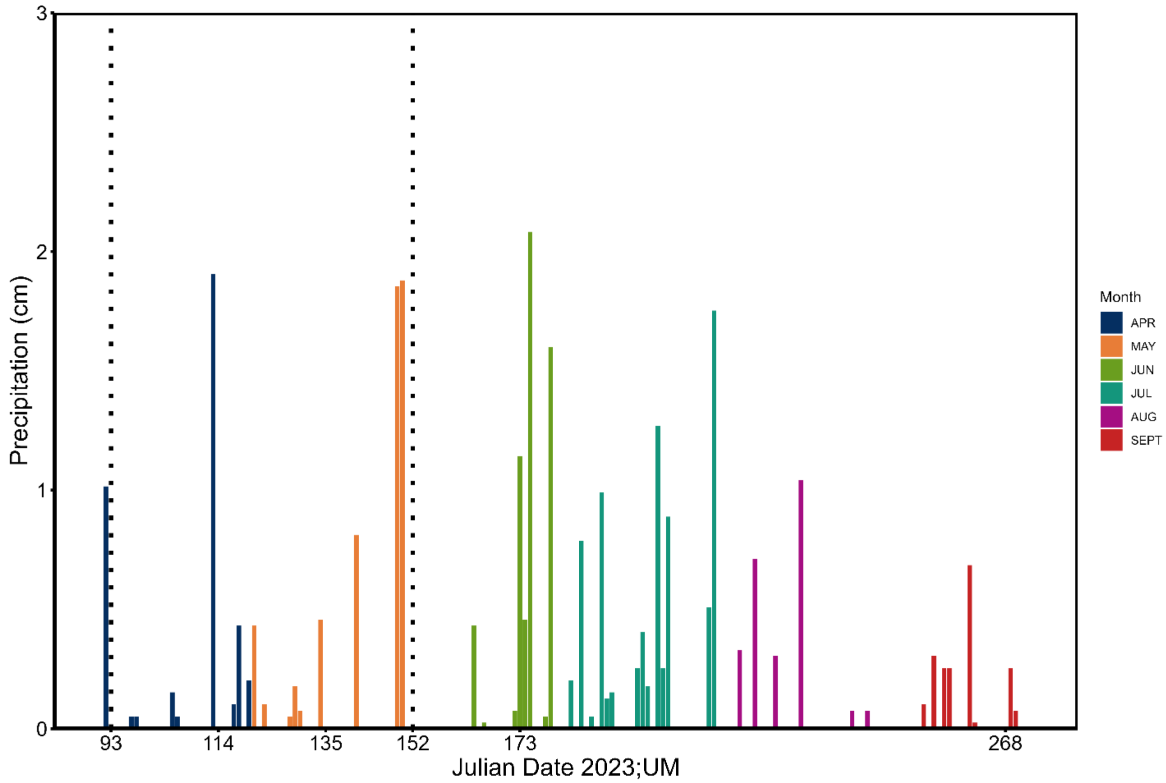

Figure 3.1. Depiction of precipitation events by month, with dotted black lines representing the two applications of s-metolachlor at UM in 2023.

Chapter 4: Conclusions

While industrial hemp was banned from production in the US, since World War II, there have been huge advancements in the productivity of other agronomic crops due to decades of applied research aimed at optimizing agronomic production systems. With the reintroduction of industrial hemp as a potential agronomic crop in the US, there exists huge knowledge gaps around industrial hemp production, especially fiber hemp produced within current agronomic crop rotations and especially in the Mid-Atlantic region. Generally, regional research has not been performed to determine the timing of fiber hemp planting and harvest to maximize fiber hemp yield. As hemp is a photoperiod sensitive crop, there is minimal understanding of the timing of fiber hemp establishment hemp about the summer solstice to maximize vegetative growth. Moreover, there is no standardized measure of fiber quality, with "quality" loosely defined based on the end-product or industry to which the fiber will be utilized. Without a clear definition of "quality", there is a further lack of understanding of how production management can affect these arbitrary quality measures. Finally, there are many claims about fiber hemp interaction with weed species but minimal research on the use of cultural practices (i.e. early planting of fiber hemp) to manage weed populations without the use of approved herbicides for use in hemp. Therefore, present research was executed to not only fill these specific knowledge gaps but to determine the feasibility of incorporating fiber hemp to current Mid-Atlantic crop rotations, by selecting planting and harvest dates to bookend recommended dates for other crops and to evaluate the impact of these treatments on weed management.

The present study evaluated planting fiber hemp from late-April through late-July under a shortened, 90-day, growing season or a full growing season with harvest around flowering, in Maryland. Generally, harvesting fiber hemp after a 90-day growing season, regardless of planting date, resulted in decreased yield, plant height, and stalk diameter. Fiber hemp yield can be maximized with a long growing season and earlier planting can increase yield. Crop height is also maximized with a longer growing season. Fiber quality was operationally determined in the present study through forage analysis at a commercial testing laboratory and lignin, a structural component of plant cells, was significantly affected by planting date, with earlier planted hemp containing greater proportion of lignin. While quality measures may differ depending on the specific industry standard, the results from the present study provide guidance on how quality measures may be manipulated by production management decisions.

Within the planting date evaluation, weed pressures were evaluated to understand hemp competition with weeds and the impacts of hemp canopy on weed germination. Little to no weeds germinated and did not negatively affect hemp yield. As weed populations and species vary from region to region, it is important to note that some weed species, namely jimsonweed, pokeweed, and morning-glory, were found to be problematic in some plots due to their size and growth patterns. For Mid-Atlantic farmers, the lack of approved herbicides for use in hemp would not be a barrier for fiber hemp production. The results of this study support that proper management of hemp, including early germination and establishment of optimal plant density, may be enough to suppress weeds without the need for herbicides.

The use of sequential planting dates within the study allowed for an understanding of how changes in yield occurred over the course of the growing season. For fresh yield, data supports that mid-season planting dates (ones planted in May and June), yield higher than the earlier (April) or later (July) plantings, due to photoperiod within that period. This was supported by both Harvest 1 and Harvest 2 (short and long seasons, respectively), but was more crucial for the short season crops, as there was less time for those to reach ideal heights, a direct variable that influenced overall yields. As height was impacted by genetic factors related to photoperiod sensitivity, diameter was instead related to environmental and management factors. An increase in seeding density in 2023 decreased the diameter, as well as having higher germination rates. This decrease is a desired trait in fiber hemp production, as it facilitates end-product harvesting. Fiber data, collected in 2022 only, supported that lignin decreased across planting dates, a beneficial pattern to understand as farmers producing fiber would want to plant later, whereas those looking to process hemp for animal bedding or paper would be able to plant earlier.

The results of the present study indicate fiber hemp can be incorporated into crop rotations in the Mid-Atlantic. The flexibility of either a short or long season hemp can provide farmers different options for production depending on their current rotations, with an understanding that a shorter fiber hemp growing season could impact yield. Short season fiber hemp should be planted early (mid-May to early June) and harvested within 90 days would provide greatest yield. This season would fit in best for farmers currently growing hay, as hemp would be planted after spring planting of hay and forages, and then harvested earlier than the hay. The retting timing for short season fiber hemp would occur during hay harvest, limiting the overlap of the use of balers. For farmers currently growing corn and soybeans, full season fiber hemp should planted prior to both crops (late April) with harvest occurring in early fall (early to mid-September), at least two weeks to one month prior to corn and soybean harvest. Hemp retting would then occur during corn and soybean harvests and would be able to be removed from the field in time to plant winter wheat, or other cover crops, if desired. As hemp weed suppression did not differ between the short and long season harvests within this study, both options are viable from a weed management standpoint. The additional ability of hemp to suppress weeds could make it an ideal candidate for especially weedy fields that are usually left fallow or would instead be cover cropped for that season.

While fiber hemp is a feasible crop in Maryland, there are many infrastructure hurdles currently preventing its widespread adoption. Post-harvest issues such as baling, transport, and processing facilities need to be the primary focus of region-specific research in the future. Specific hemp harvesters, especially ones for large scale production, are hard to find and expensive; once the hemp is harvested, the gap between the harvest, retting, and baling needs to be closed. Currently, there are no decortication or degumming facilities in the Mid-Atlantic, with the closest ones being in the Midwest and in North Carolina. Additionally, there are no set quality metrics for farmers, and an overall lack of communication between producers and sellers. As such, fiber hemp for textiles is not an attractive option for Maryland farmers, but other hemp products may be a viable alternative. Animal bedding, as well as paper production, use the entire fiber plant, removing the need for retting and additional fiber processing. These products allow for the hemp to be ground up, making it easier and faster to remove from fields, and then transport. However, producer-seller relationships are still lacking for these end products. A recent issue, such as the increase costs associated with pine bedding for chicken production on the eastern shore, fiber hemp could serve not only as a cost effective, but local solution (Roach, 2019). For fiber hemp production to increase to the extent where it can be considered a reliable cash crop, it must be treated as a specialty crop and fill specific niches in Maryland's agronomic systems.

Appendix

Table A.1
Previous crop rotations at each site year, three years prior to the hemp planting. All Soybeans were Yellow Soybeans, and all Wheat was Soft Red Winter Wheat. Abbreviation BVC refers to Barley, Vetch, and Crimson Clover; RRV refers to Rye, Rapeseed, and Vetch.

Site Year	2019	2020	2021	2022	2023
Wye 2022	Soybean followed by Wheat	Soybean double crop followed by Wheat	Soybean double crop followed by Wheat	Fiber Hemp (Bialobrzkie, Yuma)	NA
Wye 2023	NA	Soybean followed by Rye	Soybean followed by Wheat	Soybean followed by Wheat	Fiber Hemp (Yuma)
UM 2023	NA	Field Corn followed by RVV Cover	Soybean followed by BVC Cover	Field Corn followed by BVC Cover	Fiber Hemp (Yuma)

Table A.2
Diameter measurements from H1 (short season) harvest, including values removed from formal statistical analysis. Measurements were taken 90 days after planting.

	Average Diameter (mm)		
Planting Date	Wye 2022	Wye 2023	UM 2023
1	-	-	15.87 ± 1.28
2	16.70 ± 2.15	16.03 ± 0.67	12.92 ± 0.75
3	14.84 ± 1.42	14.19 ± 2.23	6.49 ± 0.76
4	13.26 ± 1.32	8.70 ± 0.29	9.87 ± 0.72
5	11.55 ± 0.88	10.59 ± 0.38	8.29 ± 0.40
6	12.94 ± 1.53	8.70 ± 0.66	-

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