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Weed Science: Three Problem Plants That Call for More Research

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WEED SCIENCE: THREE PROBLEM PLANTS THAT CALL FOR MORE RESEARCH

by

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DEDICATION

I never got to sit with my grandpa and talk about farming. When he was young enough for me to ask about it, I was too young to know I would ever want to talk to him about it. Then by the time I started my path to agronomy, there were so many questions that I wanted to ask. The aching part is when I wanted to know, he could not answer. He just did not talk much for a really long time. As it was, that was the time that I had the passion to start on this path. He passed in April 2018, and if he had lived to October, he would have been 100.

I feel cheated out of something precious, but I have to know that it was never going to be possible. The time slots just did not match up for it.

He was a leader in the green revolution in Boone County, Nebraska. He was an early adopter of fertilizing with anhydrous ammonia and crop rotation. His efforts with terraces and waterways earned him the Boone County Soil and Water Conservation District conservation award in 1963. My grandfather was an amazing man, and I will always wish I knew earlier, I wish the impossible. The best I can do is write this and dedicate it to him.

In loving memory of

Carl Arthur Eucker

10/26/1918 - 4/21/2018

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ACKNOWLEDGMENTS

It has been quite a journey from barely getting out of undergrad, to my six months at Iams testing pet food and into my current position at Loveland Products. Then there was my academic redemption in this very program. So, as I reflect on all of it, there are many people I need to thank for getting here during my whole adventure.

Undergrad was a long time ago but there are three people key to me getting out of there in the end. First is my friend **Jessi Sanborn,** who even when it got really rough, was right there helping me through, from being there when I needed to sort out my head to when I finally graduated and helped me move. Second **Judy Schmitt**, lovingly labeled as Yoda, who did not give up on me when she was helping me do my special lab work credits. Third is **Monica Kinde**, probably the best mentor/teaching assistant in the world, who patiently pushed me through physical chemistry after struggling with the class for perhaps three semesters.

At Iams, I worked in the quality department for six months and had the honor of working with **Jeff Hargens** who was a wonderful co-worker and friend and also a very good reference; he had a lot of nice compliments in his letter getting into the program.

Dawn Miller is a superhero and especially a great friend. In 2012 I went about looking for any programs that might be out there for a distance learning solution. This turned into a series of emails between us which prompted in enrolling into prerequisites.

Jackie Papestein was my proctor for my first two classes that I had to take simultaneously because, procrastination. I then worked with **Karen Fox** and **Debbie Aden, and the rest of the staff at the Fairbury Library**, for my proctoring the rest of the way through.

Summer 2013, Dawn sends an email checking in on my prerequisites, at this point only having a biology class to go. She encouraged me to rope Yoda (Judy) into getting her recommendation letter done and sent

in. She did and so I entered the program as “Provisionally Accepted” based on my undergraduate grade point average. So then Spring 2014 I took my first graduate level class.

I owe my professors a lot right from the beginning. **Dr. Harbur** gave me an amazing introduction to the program in the statistics class. However, it was fall 2014 that took the cake. **Dan Dobill** is an awesome teacher (I still have my Soil Guru certificate), and to top that class off, I met **Anne Carlson**. We have been best friends in the program ever since and support for each other outside it. She might as well be my big sister.

So that brings us to my creative component. I originally had support from work to try different fertilizer blends with cobalt and molybdenum. I was planning on a series of treatments on soybeans to see how effective the cobalt itself was and its interactions with the molybdenum. **Mike Moritz** had the people to work with that had land to execute the study, but in the middle of getting trial details set up, he was no longer able to provide resources he had to help. A co-worker was willing to try the experiment with me, but it was rainy that summer (not as bad as this summer), but he was not able to get in the field in time. After that I could never find anyone that was willing to do it resulting in the Death of Creative Component number one.

Creative Component number two. A seed dealer that my in-laws knew, (**Marjean and Leroy Mostek**) had clients with soybean fields that had areas that were yellowing in certain spots in the fields. So I thought that we would try to see what was going on. Lots of miscommunication happened with this project, also the driving would not have been feasible. That was enough for Death of Creative Component number two to occur.

At this point I had nothing to show for it except a lot of research that got nowhere. **Dr. Lenssen** suggested going back to the CPS location and seeing if they would let me look at customer soil test reports and make fertilizer recommendations, evaluating cost between the two models. The CPS agronomist never got back to me even with multiple attempts. I am not sure who was the worst at communicating, the growers, the seed dealer, or CPS. So that was Death of Creative Component number three.

This paper stands for both Creative Components number four and five, a literature review. I say this because to get me going I ended up, after essentially two semesters of doing nothing because I had hard personal life problems going on elsewhere. So to get myself started I made what the writing coach put in as a "model of a class studying the weed seed bank by my Dungeons and Dragons character." There were funny one liners in there I wanted to use as a story surrounding the story this would entail. Things like "And that is how my Dungeons and Dragons character helped my grandpa win the 1963 Boone County Conservation award." It did not really fly. It did get me going on the project finally though. So this is Creative Component number five, the one that sticks.

Additionally, many people such as neighbors, co-workers, my Pokemon Go group, extended family (including my aunt **Viv Eucker**), my siblings, my dad, **Bob Dodendorf** and my late aunt and godmother, **Jackie McCabe**, were always there for support, prayers, well wishes and encouragement along the way. Finally, this whole journey would have never happened without my mom, **Chawna Dodendorf** and the love of my life, **Chris Mostek**.

Thank you all for your presence in my life.

INTRODUCTION

AN ABRIDGED HISTORY ON WEEDS AND WEED SCIENCE

Michael Pollan (1989) is an author and journalist who specializes in how the great outdoors and current culture meet each other (Pollan, 2019). “Weeds are Us” (Pollan, 1989) describes the adventures of his experiment with planting weeds that are very appealing visually. Pollan (1989) started out with this bit of poetry: “What is a weed? A plant whose virtues have never been discovered.” -Ralph Waldo Emerson

The lesson that Michael Pollan (1989) learned, was that cultivated plants take time and effort to grow where plants that are considered weeds easily populate the areas that have been disturbed such as roadsides, construction sites and agriculture fields. He planted wildflowers and let them alone for a beautiful and delicate atmosphere. Within a year, his garden with the wildflowers was a mess of weeds (Pollan, 1989).

The battle with weeds gives no home field advantages. Invasive species are that way because they are better adapted to niches where native are less competitive (Satin-Montanya et al., 2016). The weeds reduce resource availabilities for the desired plants, allowing the invasive plants to take the place of native species.

As the journey of this review there will be three weeds examined. There will be representation of plants that produce hundreds of seeds with the problem of the original patches beginning again if just a small amount of seed survive. There are weeds that spread clonally, keeping stolons and rhizomes in the soil just to come back the next season. Some of the weeds can travel, whether they are carried by wind or water, or even attaching themselves by attaching themselves to clothing, animals, and equipment to find places to start again. Yet perhaps the most insidious of weeds are the ones that were crops the year before, which puts them into competition with the crops the next year. All these characteristics can make weeds noxious (Baker, 1974).

Some species can have quite an impressive longevity, to the extent that there are seeds from archaeological digs that can still germinate. Pollan (1989) remarks on the weeds through the words of Sara Stein, wherein she reports Japanese knotweed can dig through four inches of asphalt. Scary does not even come close. Consider this: in the process of artificial selection for crops, those choices allowed for the artificial selection of the plants that are not wanted. As crops were diversified the weeds also diversified themselves. To that end as crops were developed, the weeds found the places that were disturbed while pursuing urban development (Baker, 1974). As time drifted choices made continued to shape the development of the desirable plants and our selections for weeds did the same; we made the weeds. The thought is profound in a way, it's just not something that comes to mind.

Another interesting thought exercise is this: it could be said that there were no weeds in North America before the Puritans (Pollan, 1989). They brought dandelions from the Old World, because as weedy as dandelions are now, they were a pretty good self-sustaining food source. Bringing the dandelion to the New World allowed for the introduction of the first invasive plants of the continent (Baker, 1974; Pollan, 1989). Likewise, Columbus took more plants home with him; the first invasive plants from the New World (Baker, 1974).

Zimdahl (2010) paints a picture of a world of three eras in agriculture. The first era is "Blood, Sweat, and Tears" where-in physical labor was the only means possible for the farmers. Throwing seed broadcast had been the way to plant at the time (Zimdahl, 2010). The second era is "Mechanical", this makes sense also as the advent of the machines that made the process of manufacturing easier to prepare seed beds and plant. The concept of a seed drill was invented in the 1600s, the idea just never caught on, even if this was the right idea, but wrong time (Zimdahl). The seed drill came back as a driver in the Mechanical era of better stands (Zimdahl, 2010). The present era is "Chemical". The transgenic abilities and bred resistances allowed for herbicides that could be sprayed on the target weed, while leaving the crop plant perfectly fine.

Starting with "Blood, Sweat and Tears", Timmons (2005) posits that the Egyptians were the first civilization to create steady agriculture that we know of from their records around 6500 BCE. As timed passed inventions that helped agriculture began to develop, slowly evolving into the "Mechanical" phase, where implements started to develop, such as such as the hoe, scythe, plows and into implements of equipment made for tillage that also helped with the weeds (Timmons, 2005).

The 1900s was a time for rapid development of equipment, one of the first developed explicitly for weeding was the rodweeder. In the 1930s animal powered farm implements were abandoned for tractors with implements for any task. Which took us from "blood sweat and tears" to "mechanical" (Timmons, 2005).

The discovery of 2,4-dichlorophenoxy (2,4-D), allowed for the abandonment of some herbicide practices that were probably not eco-friendly as well as horrible for soil fauna; such as salts and sulfates, gasoline and sulfuric acid (Timmons, 2005). 2,4-D transferred us from the era of "mechanical" phase of agriculture to the present as the "chemical" era of agriculture.

Weed science was a rather latecomer compared to entomology and plant pathology. There is evidence pointing to the conclusion that weed science may have been studied as early as the 1200s to 1500s (Zimdahl, 2010). Pathogens and insects just were found more urgent because the results were often very immediate, whereas the weeds seemed like no issue was ever actually raised. This makes some sense as at the time there was not the ability to even measure what weeds were taking away from the crop plants (Zimdahl, 2010). Entomology and pathology were already being heavily researched starting by the early 1900s. Weed science was not studied extensively until the early 1920s (Timmons).

Enter the founders of Weed Science. H.L. Bolley led the research of the first funded by the government which was granted to work on control of johnsongrass, in 1896 (Timmons). Dr. Alden S. Crafts was the first "weed scientist" in the United States when he started studying bindweed in 1931(Zimdahl, 2010). These and other notable figures helped shape weed science today, and there will always a new problem to solve.

Should funding appear for weed science, this review covers three weeds that could use some attention: *Cirsium arvense* the Canada thistle, *Cenchrus longispinus* the Field sandbur and *Zea mays,* volunteer corn.

CHAPTER ONE

CANADA THISTLE [*Cirsium arvense* (L.) Scop.]

The Canada thistle [*Cirsium arvense* (L.) Scop.] (also known as Creeping thistle and California thistle) is a tenacious weed that is considered noxious in forty-two states and six provinces in North America (Cowbrough, 2006). *Cirsium arvense* can be mistaken for other thistles, however, on closer inspection the thistle is distinct from other species with smaller flowerheads, leaf structure with a pappus with hairs, and rhizomes and extensive root networks (Stubbendieck, 2003; Wilson 2009). Canada thistle is most commonly present in disturbed environments such as roadsides, and construction sites. Thistle is shade intolerant and will be found on the edges of riparian zones and woods and in rich soil conditions occurring in grassland and prairie, and agricultural sites, especially those that contain rich black moist soils. (Stubbendieck, 2003; Wilson, 2009).

Worldwide, the Canada thistle is considered one of the most invasive plants ever (Guggisberg et al., 2012). The plant is insidious as its roots can extend up to 15 feet laterally and to a depth of 15 feet in a single season (Beck, 2013). Because of the way Canada thistle "creeps", it can turn up unexpectedly (Beck, 2013). Shoots from buds in the root system begin to grow at the same time as seeds, which causes competition that may help to weaken the plants when they start to emerge in mid to late spring (Gover et al. 2007; Bommarco et al. 2010; Beck, 2013). Root spread is an adaptive plant strategy that aids in taking over an area. Because Canada thistle is able to immobilize soil nutrients the weeds can reach it faster and more efficiently than crops once the thistle gets established. In as early as seven weeks of germinating, the root structure of the plant competes aggressively for nutrients, water and light (Beck, 2013).

The thistle can cause injury when they push into local soil system by occupying into niches meant for native plants. With the plant being dioecious, it is easy to have groupings of the weed with male only flowers or others with female only flowers (Nuzzo, 1997; Bommarco et al., 2010). However, with the distance that can exist between male and female plants; pollination is required via insects, making them obligate out-crossers. Nuzzo (1997) noted that some male plants; approximately around 26%, are "hermaphrodites" that can produce some seed themselves. *Cirsium arvense* has evolved mechanisms for attracting the right insects to spread its pollen. Canada thistle produces a series of nineteen organic molecules that are known to have floral scents that help the thistle attract pollinators (El-Sayed et al., 2008). This is not without risk, however, because these scents also attract insect herbivores. This is what makes clonal reproduction important for Canada thistle as there is the possibility that pollen does not reach the female plants. However, when the thistle is pollinated a single female plant can produce 1500-4500 seeds in the same season (Gover et al., 2007; Wilson, 2009; Beck, 2013).

Plants depend on sexual reproduction to bring more variety to the gene pool. In some cases, without this, clonal species can be vulnerable to one disease that can wipe all of the species because they will have the same weakness. Two examples of this would be diseases similar to the potato famine and banana blight. Because genetics of Canada thistle were found to vary between different patches in even the same field, and on a larger scale difference between land use type (organic agriculture, conventional agriculture, roadsides, and continually disturbed areas), any sort of plant disease or herbicide will not completely eradicate the species (Bommarco et al., 2010). In the end, the importance of this knowledge is that while clonal rhizomes in the soil may represent the greater percentage of reproduction in the thistle, the population of Canada thistle seeds in the seed bank should not be ignored.

Long distance movement of the weed is accredited to contaminated crop seeds entering the country with immigrants. This is the accepted theory as to how Canada thistle arrived in the United States in the 1700s (Nuzzo, 1997). Guggisberg et al. (2012) found in a large genetic testing experiment that there were two main waves of introduction of *Cirsium arvense* into North America. The first seed was brought to the New World by French, Dutch and English settlers, accounting for genetic traits found in Western Europe origin sites (Guggisberg et al., 2012). The second wave came from Eastern Europe, where the weed seeds followed settlers from Ukraine or shipments of cereals to North America from Russia (Guggisberg et al., 2012). The result is that while there was a limitation in the diversity of the thistle in the beginning, it rebounded quickly with little evidence that there ever was a problem (Guggisberg et al., 2012).

When the thistle was brought in with crop seed as settlers passed through, the weed seeds were brought as contaminants (Guggisberg et al., 2012). Today, because of quality standards and certified seed, such seed contamination should not happen. Thistle still can be mobile in several ways. Canada thistles are known to be carried easily via livestock when the seeds stick to them while moving past patches (Drahota, 2010). The thistle also can be transported by farm implements that are known to move seeds and vegetation between fields. Canada thistle seeds also to have the ability to move by wind through its pappus, to move by water, and to move with human assistance (clothing, shoes, etc.). The only way to avoid some of these spreading issues is to "sterilize" equipment, animals, shoes, clothes etc, so no seeds are taken between fields (Gramig and Keene 2017).

Understanding the reproductive system of the plant can help be a guide to just how badly thistle is at halting crop production. Scanning through search results from the Web of Science, it becomes obvious that the thistles have been researched for all cereals, oilseed, legumes and specialty crops (such as blueberry). In Nebraska, research on the impact of Canada thistle is mainly focused on soybean, alfalfa and corn. Canada thistle infests approximately 375,000 acres in Nebraska. The presence of the weed has the ability to reduce corn yields by 80% and reduce soybean yields by 95% (Wilson, 2009). This totals to around three million dollars annually in Canada thistle infestation of crop land (Wilson, 2009). These totals do not include the allelopathic effects of Canada thistle, it also has a deadly ability to store high levels of nitrate, to serve as an alternative host for plant diseases, and the plants have the ability to act as a refuge for insect pests (Wilson, 2009). Weed plants frequently require more resources to grow than wanted plants. Because Canada thistle is an example of this, the thistle moves quickly to secure those needs. (Nuzzo, 1997).

With so much damage done by Canada thistle, a question becomes "What can be done to manage the damage and help lessen the financial losses when a weed becomes resistant to the current available methods of control?" Integrated Pest Management (IPM) provides multiple potential solutions (Gover et al., 2007; Wilson 2009; Beck 2013). The most common strategy suggested in the literature is to keep the plant stressed, reducing its ability to quickly reproduce, they suggest using multifaceted, multi-year plans (Gover et al., 2007; Wilson 2009; Beck 2013). As stated by Gover et al. (2007) and Beck (2013), one needs to be attacking the problem from different fronts.

Mechanical and cultural methods can be a sound baseline for starting management plans. Mowing is effective whenever plants first emerge as each time you destroy the above ground parts, the energy storage in the root system is taxed to provide for new growth. Likewise, if roots are exposed to the elements in winter via tilling, they will die (Gramig and Keene, 2017). Culturally, good practice for the management of many weeds is sterilizing equipment and minimizing contact of reproductive tissues with clothing and livestock.

Herbicide is a staple of Canada thistle control, by itself and in tandem with cultural, mechanical and biological control factors within an IPM plan. All the extension publications favor a similar approach with layering chemical control options interlaced based on season and stage of growth of crop and weed (Gover et al., 2007; Wilson 2009; Beck 2013), with emphasis on keeping stress on the plants. An interesting take comes from Drahota (2010) that during the growing season it really doesn't matter the approach to management that is taken, it's the same job for all options; however the fall application or management strategies become extremely important to overwintering health of the root system. Drahota (2010) goes on to note that a systematic chemical application is important to deplete energy stores in the plant, and also to address vegetative matter that had not been attached to shoots over the summer.

Chemical management cannot do this alone, however, which means that along with mowing and sterilization, available biological control options should be applied (Beck, 2013). The state of Idaho has two natural enemies unique to Canada thistle approved as biological control: *Hadroplontus litura* (Fabr.) (formerly classified as *Ceutorhynchus litura*) and *Urophora cardui* (L.L.) (Invasive Species of Idaho, 2019). *Hadroplontus litura* is a weevil known by the common name: Canada Thistle Stem Mining Weevil. The only real note for the beetle is that it can be a biological control for Canada thistle (Invasive Species of Idaho, 2019).

This is important because different weevils brought to North America for exotic thistle control are not always well researched and the introduced biological control sometimes becomes invasive (Louda et al., 1997). *Hadroplontus litura* can cause small injuries to the Canada thistle plants. This happens as a yearly progression where in the spring new beetles emerge and feed on the plants until the female mines into the vein of a leaf on a new rosette and deposits the eggs (Yellowhead County, Alberta, 2012). Gestation lasts a week, and the larvae feed on the stem and root collar. After feeding, the weevils will go into pupae around the radius of the thistle plant. They emerge as adults after two to three weeks and eat on the thistle until frost (Yellowhead County, Alberta, 2012). These weevils can be purchased and over a three-year period have the ability to clear small patches of thistle.

Figure 1. (Yellow Head County, Alberta, 2012)

As mentioned previously, the creeping nature of the thistle may extend to fifteen feet in a season, but the beetles move up to ninety meters in a six-year period (Yellowhead County, Alberta, 2012). Yellowhead County (2012) is on a mission to find and give relief for Canada thistle and other invasive species coming into and negatively impacting cropping systems. There is not any obvious ability for *Hadroplontus litura* to be the sole element of control for Canada thistle. Note the three-year timetable in the advertisement (Figure 1). The holes that the insects mine into the plant can add extra damage for allowing other thistle predators and diseases easier access, but actual damage by the beetle can only take a leaf or so per each batch of eggs. It is not convincing that the beetles can take more than a patch of the size of the patch in *Figure 1* over a three-year period.

There are other biological agents that can be introduced to help the weevil. For one, *Urophora cardui* comes in as a second thistle pest that is claimed to be synergistic with *Hadroplontus litura* (Invasive Species of Idaho, 2019). *Urophora cardui,* aka Canada thistle gall fly, does its damage when adults lay eggs in the stems of a plant, hatch, and start forming galls (Invasive Species of Idaho, 2019). Maximum injury to the weed plant depends on what root shoot position the larvae are in and that is the biggest factor determining the effectiveness of the fly (Invasive Species of Idaho, 2019). Beck (2013) notes effectiveness of the gall fly helps reduce seed setting by way of blocking terminal meristems, lowering how much seed the plant can make. Gall fly larvae can stress a plant so much that the plant dies (Gover, 2007). Nuzzo (1997), however, noted that the fly has little impact. This difference in effectiveness might be regional. Beck (2013) is in Colorado, and Nuzzo (1997) is in New York. However, this could be something that would fit in with Guggisberg et al. (2012) and the two seed origins from the Europe and Asia continents. One member of the group that came from Russia could be the ecotype that Beck (2013) is studying. Nuzzo (1997) could be looking at the strain that came from Western Europe.

Burns et al. (2013) compared using *Hadroplontus litura* paired with the common sunflower (*Helianthus annuus* L.) as a competitor of thistle, with the intent to look at what had the most effect on Canada thistle. This was meant to be a look into how a weak control agent paired with a resource competitor could work in an IPM plan with additional treatment comparing soil health and nutrient levels (Santin-Montanya er al., 2016). *Hadroplontus litura* did not do as much damage as the sunflower and nutrient treatments. Similarly, alfalfa (*Medicago sativa* L.) and perennial forage grasses can be good competitors with the thistle, especially when the thistle has been mowed and an herbicide treatment applied before planting the hay crop (Wilson, 2009).

There are many other species that can be considered as possible thistle control. In Nebraska there are many butterflies that can be natural enemy species that have caterpillars that exfoliate thistle, including Red Admiral (*Vanessa atalanta L.*), Viceroy (*Limenitis archippus* Cra.) and Painted Lady (*Vanessa cardui* L.). These caterpillars are leaf feeding and will defoliate plants (Wilson, 2009). This will weaken the plants that the caterpillars are on. However, unless the caterpillars do enough damage to cause winterkill, Canada thistle will rebound. There is research that is also looking at pathogens that could be biological control for Canada thistle: thistle rust, white mold, the bacterium *Pseudomonas syringae* (van Hall) and the rust fungus *Puccinia punctiformis* (Strauss) Röhlings (Wilson, 2009).

Gover et al. (2007), Beck (2013) and Burns et al. (2013) are in agreement that the larvae of any of the biological control species are not a complete measure of control because the most damage they inflict is limited to decreasing winter survival by reducing plant sugar and starch reserves in roots and rhizomes. However, because the weevils do not damage the vascular system of the plant, they do not stop the weed from growing (Burns et al. 2013). As Gover et al. (2007) put it: “There is no ‘silver bullet’ for Canada thistle control.”

Nuzzo (1997) ends her article by acknowledging that there are several other means that have potential when plans are made considering multifaceted approaches using chemicals, biological and mechanical/cultural practices. The tricky part and the key is to find the right combination and to continue to stress the plants until they cannot reproduce anymore and die. For this type of management to be successful, the grower needs to commit time and work over a multi-year plan. (Wilson, 2009).

Despite the limits of beetles, flies and other mentioned species, biological control application and performance should not be ignored. They can be instrumental in slowing down the spread of the thistle (A.W. Lenssen, pers. comm., 2019). The right biological control will always only go to the target. *Hadrosplontus litura* and *Urophora cardui* have a track record for remaining in an area and feeding only on Canada thistle. *Rhinocyllus conicus* (Froeh.)(Musk thistle beetle), was introduced as a biological control for exotic thistles such as musk thistle but has been found feeding on threatened or endangered native thistles (Louda et al., 1997). These species were very much studied for exotic control in those countries. However, the trials were not completely finished in the US, and the weevils were approved to release for Musk thistle (*Carduus nutans* L.). At that time the beetles appeared to have preference for the musk thistle (Louda et al., 1997). So, they were released into the United States in multiple states. Louda et al. (1997) conducted a study that lead to finding that the introduced species was preferentially going for the native thistle over the exotic. The problem is not isolated, Louda and O'Brien (2002) again discovered another weevil, *Larinus planus* (F.)(Canada thistle bud weevil), was also found to prefer the native thistle over the exotic thistle for which it was released. The weevil was released to control *Cirisium arvense,* and had instead targeted Tracy's thistle, *Cirisium undulatum* (Nutt.).

Because Musk thistle beetle and Canada thistle bud weevil were approved to treat Musk thistle and Canada thistle without full research on what it might do to local native thistle population, as such, local native species were more attractive to the two beetles and the already sparsely populated native thistles are becoming more rare. As those plants continue to be lost; diversity is lowered as invasive species go into niches. There are now laws concerning how long a potential biological management species must be researched be introduced and shown that will not destroy the native plants (Montgomery, 2012). It’s possible that if there is more research dollars spent on researching biological control elements that it could allow for independence from any one method of control.

When encountering a weed like Canada thistle, there needs to be more than one type of control element. Chemicals, biological and cultural methods are needed to keep stress on the plant. Reflecting on the past and other problem plants, there needs to be a way to handle thistle that is practical. Right now, this calls for a new strategy with a well-developed plan to work on the problem. This needs to be done to determine more options that may be present to help control the plant.

We need to find better ways to keep stress on the Canada thistle. As time goes on, this exhausting battle with many control methods could become useless as the weed becomes resistant to herbicide. A combination of many parts needs to be developed to create synergy between chemical, biological and mechanical controls. More research may give better insight to Canada thistle, including studying rhizome dynamics in the seed bank and searching for native plant species and crops that can compete with the thistle.

CHAPTER TWO

Field sandbur [*Cenchrus longispinus* (Hack.) Fern.]

Field sandbur, longspine sandbur, mat sandbur, grass bur, and burgrass are all aliases for a weed that most people recognize as a nuisance: *Cenchrus longispinus* (Hack) Fern. All of these common names are also applied to other members of *Cenchrus.* For the purpose of this review, Field sandbur or sandbur will be used to reference *Cenchrus longispinus*. Field sandbur is native to the lower 48 states with the exception of Idaho, as well as Quebec, Ontario, and British Columbia (USDA-NRCS, 2019).

Sandbur is considered noxious in California (as mat sandbur) as well as Washington (as longspine sandbur). Interestingly enough, the weed is listed as threatened/endangered in Maine (as long-spined sandbur) and New Hampshire (as burgrass) (USDA-NRCS, 2019). Sandbur is often misidentified as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] as a seedling. When the fruit starts developing with the forty or more spiny fruit from each spike, it is easy to identify (Agri and Nat Resources Univ. Calif, 2019). Sandbur grows well in sandy, well-drained soil, but also can do well in soils that are heavier. Some plants are able to move their shoots and leaves to reach sunlight, this is known as phototropism (Univ. Ill. Ext., 2000). Sandbur has this ability, which means that it does not have to compete for light, which is key to why it can be a very big competitor for other resources in row crops. (Soltani et al., 2009).

Sandbur most often is a problem when animals are let out to graze and the flowers are becoming fully developed (Stubbendieck, 2003). The spines can injure livestock most especially when they consume the burs, but also when the burs stick on flanks and legs where they can dig into skin causing discomfort and eventual major pain if the animal tries to remove the fruit. To that end, the seeds that leave the pasture via animals, clothing or equipment can pick up enough seed to start patches in other places (Agric. and Nat. Resources Univ. Calif., 2019). As one would infer from the fruit structure, its primary method of spread is catching rides on clothing, skin, equipment and animals therefore there is no surprise that the plant needs only seeds to reproduce (Strat et al., 2017).

Despite this status as being prolific in reproduction, sandbur has the reputation for being harmless, except for the annoyance of the sandbur in yards, on shoes, socks, and the dog. However, Field sandbur can cause issues in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] as well as other crops, including alfalfa (Soltani et al., 2008, Soltani et al., 2009). Just as Canada thistle is invasive to the United States, Field sandbur is invasive to the rest of the world. The European Plant Protection Organization (EPPO) listed *Cenchrus longispinus* as an invasive species to South America, Australia and EPPO countries such as Romania and Ukraine.

The EPPO put Field sandbur on its alert list in 2015 as a possible risk. The weed in Europe is as much of an issue as in North America, adaptive at finding places to grow and then spreads over a wide area. Sandbur has also become invasive to agricultural land in Australia. In

Belgium the seeds contaminate grain. In Ukraine the plant is taking over beaches and has invaded the Black Sea nature preserve (EPPO, 2018). In Romania the weed has become very aggressive and was first noted on the beaches of Mamaia resort. The mode of travel to Europe from North America is unknown. Something brought the seed into the resort; and the result is that beaches are infested with the plants.

In 2018, the EPPO lowered the watch status for sandbur, and the weed was moved to the Observation List after a review. This does not mean the watch status on sandbur is being ignored. It just means there is a lot of work ahead of us. The weed population is still there regardless. More time spent at the Mamaia resort will help to see how *Cenchrus longispinus* moves in sandy soil of the Black Sea (EPPO, 2018) compared to North America. As much as the weed has become considered a small nuisance in North America, the study of sandbur is hoped to give insight into the behavior of the sandbur. Perhaps the weed in Europe can be handled in the same way with the level of treatment that can make the plant no longer a threat as sandbur has in North America. The same tactics may work for Europe.

It is suggested that because sandbur has a continual cycle of germination, growth, and seed that placing slow release herbicides may be more effective for management. However, it was noted that this application only helps control the weed, there is no increase in yield from the crop (similar to what was reported from large crabgrass [*Digitaria ciliaris* (Retz.) Koeler] and green foxtail [*Setaria viridis* (L.) P. Beauv.] (Wick and Wilson, 1999).

Control measures for public places include cultural methods such as taking precautions when handling soil that may be contaminated with weed seeds, planting vegetation that is competitive with the weed, mowing and of course, herbicides (Stevens County Washington, 2015).

Soltani et al. (2008) constructed an experiment where applications of an herbicide (imazethapyr) were looked at for control of the sandbur in soybean. There were ten treatments from weed-free to untreated to spraying at five leaf stage of the weed. The study found that the two pre-emergent applications of imazethapyr showed no improvement in either soybean yield or weed control when compared to untreated control treatment; from emergence to five leaf there were improvements in both control and yield as compared to no control up to full application. The trial showed that application at emergence, one leaf and two leaf stages provided the best yields in the trial. The study also found that estimated that soybean yields were improved by 43% with treatment as opposed to no treatment for the weeds at all.

In a related experiment Soltani et al. (2009) looked at sandbur as a weed in corn applying treatments of herbicide at each stage of development and subsequent effects on corn yield. A set of eight experiments were performed in a two-year period with a goal of looking at data of weedy and weed-free control treatments as a baseline. The goal was to find what the baseline effect of sandbur was on the corn and then tested six pre-emergent treatments of different herbicides and seven post-emergent treatments. The weeds were visually inspected as the experiments progressed and at the end, corn yield was used as a way to assess sandbur control. Soltani et al. (2009) concluded the best corn yield was from post-emergent applications of the herbicides rimsulfuron, nicosulfuron, and a mix of the two herbicides.

Similarly, a study in Nebraska examined competition by sandbur in corn, originally done in 1974, which was last updated in 1999. The most vulnerable part of the state for sandbur competition is the North Platte Valley, where well drained sandy soils make the plant a better competitor in its home territory. Sandbur does best in its native sandy soils (Wicks and Wilson, 1999). Wicks and Wilson (1999) looked at how many weeks of weed control after planting were needed to maintain the best yield in corn. The first experiment looked at how many weeks of treatment returned the best yield came from any form of treatment. The answer was six weeks. Another experiment set of treatments were formed that included tandem-disk harrowing, preplant soil incorporated herbicides, pre-emergence herbicides, post-emergence herbicides. Each treatment of the herbicide was tested on sandbur to help determine the right herbicide for the job. At the end of each trial period each treatment was assigned a "weed control rating" for sandbur as described in a guide available in Extension offices of the University of Nebraska (Wicks and Wilson, 1999). The best control for sandbur is an herbicide coming from the Nebraska study is named Contour (a mix of atrazine and imazethapyr). It had the best control rating that was indicated in Wicks and Wilson (1999).

Sandbur has a surprising ability to compete that is not readily apparent as it is looked at as a nuisance weed where it is common. However, many articles were reviewed and there seems to have been no research or trials that have run from sandbur since 1990s and 2000s. With nothing new, are other weeds better to study? There is no sign or any new methods or that there are current efforts put into research or have been developed to a point that there is an ability for consistent management other than more pulling, mowing and spraying. How is it that a common weed thought of as a nuisance can cast a large amount of damage? With little new information in the literature there are no new answers that could applied to sandbur management. There are very few examples of anything pertaining to nuisance of the plant past the early 2010s. One would think California and Washington would have much more literature about control as Field sandbur is considered noxious in these states, but all there is, is a trail of broken links and websites. No one seems to be worried about sandbur and the problem is waved off as a nuisance in North America.

This is a situation where new research into sandbur can help develop better management techniques. In Europe research is considered in great need for help of aid in the efforts to manage invasive sandbur. Sandbur is easy to find in the seed bank, but the way the weed travels makes control and eradication difficult. Sandbur is in a situation where two different patches of the same genus may be completely different species. This is because of the presence of two types of seed; one that is more active and can go on to germinate within the year, and the second that can be viable in the soil for up to five years (EPPO, 2019). There have not been many studies that look into seed degradation in soil after those five years or if there is a way to take advantage of it as a long-term plan.

What strategies can help research to bring relief to both the domestic weed and the ones that became invasive? Is there a possibility to treat and remove the weed or detain sandbur seeds that will render them no longer a threat to Europe? Can the study of the soil seed bank help to find better control that does not necessarily need chemicals? Would studying degradation time of the seeds give us a window into optimum time to apply management techniques? Wick and Wilson (1999) mentioned slow release herbicides that could be used for weed control and while it would not be helpful in raising yields, is it an option for off season at the resort?

CHAPTER THREE

Volunteer Corn *(Zea mays* L.)

There is a disconnect in the concept that corn *(Zea mays* L.) could be a weed and do harm. However, last year's corn seeds can do actual harm to the current crop. Crop plants that do this are termed "volunteer". Corn in the soil seed bank is common in any corn field, due to inefficiency of harvest, broken stalks, spills, and other practices and events that leave seeds behind. Corn and soybean rotations are subject to volunteer corn even when the field has been planted with more corn.

A second misconception is that the herbicide resistant genes were not exclusively what made volunteer crops a problem. One journal article that says that the problem with volunteer corn was caused by plants dropping seeds and germinating because of no-till, as previous systems with tillage buried the seeds too deep to germinate (Marquard et al., 2013). Another journal article that reports 80% of dropped corn germinates when tilled, whereas a no-till system has only 10% of dropped seed germinating (Holman et al., 2011).

The answer from both gathered literature and experience is that volunteer corn has always been a problem when corn seeds are present. However, Nicolai et al., (2018) supports Holman et al. (2011), that seeds left on top of the soil have a higher probability to be damaged or eaten than with tillage, allowing a lower volunteer corn population to emerge. That dissonance could make for a new experiment.

Today, the majority of herbicide resistant volunteer corn is transgenic (most resistant to glyphosate or glufosinate) (Marquardt et al., 2013), which demonstrates that farmers favor the transgenic seed as it has proven itself. Marquardt et al. (2013) goes on to note that in past studies it was shown that 85% of resistant seed leave behind seeds that have the resistant traits. While not a prevalently used, there are also traditionally bred hybrids that are resistant to sethoxydim and imidazolinone (Marquardt et al., 2013). This makes herbicide resistance not just about the transgenic seeds, but also on traditional hybrids.

Volunteer corn is considered a weed primarily in soybean. In soybean, a population of 7000 volunteer corn plants per acre can cause a loss of 27% soybean yield (Jhala and Rees, 2018). In fields where whole cobs were left, clusters made from the cobs can produce groupings numbering 3500 plants and higher in the field; there can be over 40% soybean yield loss (Jhala and Rees, 2018). Corn following corn can find itself competing against the volunteer corn, as well as remnants of an attempt as a reseed. Jhala and Rees (2018) found fields of corn with over 7000 groupings of the volunteer corn per acre could result in a corn yield loss of 14%.

(Figure 2: Volunteer Corn in Soybean)

There is a time window where if plants are not emerging and any other options are not available, it might be appropriate to replant a shorter season corn crop. However, there are risks involved, including the new planting losing yield from the areas where the corn was replanted, and the initial corn emerged. The replanted corn will have two major problems. It will have to compete for resources against members of the first planting compounded by volunteer groupings in the field. With three sets of seeds causing issues such as smaller diameter plants, lodging, plant density will be subject to the next year of more volunteer corn. Alms et al. (2016) looked at plant density and showed that 3.4 volunteer corn plants in a square meter could cause losses of 62% corn yield.

Rotation of crops other than just corn in a management system can certainly help to enhance corn yield the following season after soybean or other legumes that help soil health by adding organic matter and more nitrogen to the soil (Shauck and Smeda, 2014). Replanting when the stand does not look good seems like a good option but has inherent problems and risks (Shauck and Smeda, 2014). Continuous corn is a tempting rotation as well, though it has its own set of challenges.

Volunteer corn in a soybean field can cost a lot in production and resources. The transgenic corn of the year before will have corn kernels germinating and eventually the corn plants create a canopy to choke the soybean by reducing the availability of light (Marquardt, 2012).

Volunteer corn removing resources is not the only way it causes injury to the following crop. There is also the issue of the pests that feed off the corn that are refugees in those fields. European corn borer (*Ostrinia nubilalis* Hbn), Southwestern corn borer (*Diatraea grandiosella* Dyar), fall armyworm (*Spodoptera frugiperda* Smith), Corn earworm (*Helicoverpa zea* Boddie), are all corn pests controlled by the Bt gene. When there is volunteer corn that was transgenic for Bt, eggs that hatch in the vicinity will be eating those corn plants, and those that survive into adulthood will have an unknown resistance to the Bt proteins (Bessin, 2010).

This comes back to two types of gene transference. Herbicide resistant crops and crops that produce its own resistance to corn pests. There are varieties that have both. These are the products of weed science that come with positives and negative experiences. These technologies were developed in the 1990s so with the current generation, most have always lived in a world that had Bt corn and herbicide resistance. Within that there lays the fact that technology, all of it, has always been here when they were children. There has never been a time where Bt and herbicide resistant crops did not exist for this generation. There were very few studies about volunteer corn before the 1990s. It is difficult to fathom a world without herbicide resistant crops and Bt crops.

The *Bacillus thuringiensis* Bt gene was first isolated from a soil bacterium in 1901 by a Japanese biologist and then again in 1911 by Ernst Berliner: Both scientists noted the bacteria separately while looking for a cause of death for silkworm *(Bombyx mori* Linn.) and Mediterranean flour moth (*Ephestia kuehniella* Zeller), respectively. The bacterium began to be marketed as a pesticide by the 1920s, however, the formulations had vast limitations and the mode of action was not clear (Chein, 2000). In the late 1950s it became apparent that the parasporal crystal, the active chemical made by bacteria was the cause of death for larval moth species that encountered it. It took very little time for the discovery to be licensed as a registered pesticide (Chein, 2000). Governments and industry started funding Bt research to develop the first transgenic plant, Bt corn, in 1995 (Chein, 2000). Bt corn has been a great discovery and tool. However, the risk of the chemical resistance to the pests of volunteer corn can generate those risk insects.

Marquardt et al. (2012) planted a soybean field impregnated with prepared volunteer corn mockup plants. These were put into the field which has already prepared with pest eggs in “cages”. Observations were taken as the experiment ran. At the end of the experiment, not only did the expected soybean yields fall, but every “volunteer” corn plant had adult western corn rootworm emerging in every trap. This was in a soybean field where Bt corn was grown over the last year. With that being the case, all the corn rootworms that emerged had survived plants that had varying levels of Bt toxin. This causes the corn pests to have an unknown level of Bt resistance, which will make some difficult decisions necessary in the future as it will be unknown how resistant the pests may be and could cause yield losses if not researched (Marquardt et al., 2012).

Consequently, there are two reasons to control volunteer corn: yield loss and pest resistance. Neither is a new issue, though there are more options coming from current study for learning to manage these issues. There needs to be a way to find better options. In conversations with a colleague, there has been speculation about a field just out of town near the plant. The field has a large volunteer corn in soybean problem. The conversation brought up the field history. It often continues for a bean/corn rotation, and how this field has a tendency for the volunteer corn (M. Jeppesen, pers. comm., 2019). This suggests that this farmer is using both glyphosate tolerant corn and glyphosate tolerant soybeans. There may be herbicides that can help control volunteer corn, but as tall as those plants are getting, the damage will be significant (M. Jeppesen, pers. comm., 2019).

Glyphosate is one of the most highly applied herbicides in the world. Of all the transgenic corn planted acres in the entire world, 90% of that corn planted in those fields is herbicide resistant; and most of those are glyphosate resistant (Duke, 2017). Glyphosate was a mistake that worked. This discovery "... was made after a conventional lead follow up program that had failed" (Franz, 1984). What followed the quote here was a long multistep organic/biochemical synthesis culminating with the glyphosate molecule. The chemical *N*-(phosphonomethyl)glycine, an organic acid and its salts were first labeled as a non-selective herbicide in 1971. They are also broad spectrum, and most importantly, post-emergent. Glyphosate binds to soil particles, so the chemical is not effective before the plant emergence from the soil. Glyphosate is an herbicide that is sprayed as a foliar application (Franz, 1984). Glyphosate was commercialized in 1974 at a time when new herbicide modes of action were developed every few years. Non-selectivity made Glyphosate work like paraquat and diquat but, those were quick to act where glyphosate slowly translocated into the plant, allowing the herbicide to make its way to the underground parts of the plant, rather than just quickly killing only the above ground portion of the weed (Duke, 2018). This description aligns with the statement by Franz (1984) on how glyphosate could destroy Canada thistle. Other contact or slow to move herbicides had ingredients that broke down to chemicals that made them became toxic. Whereas glyphosate broke down without worry of chemical hygiene (many herbicides break into toxic elements; however, glyphosate does not), this made glyphosate a better option. Even as a slow actor, a small amount of glyphosate on any plant will cause injury or death to the crop. A solution to this issue to control corn in soybeans is the wick applicator. Forms of the wick applicator find their origin in the beginning of the 1900s. In the 1970s usage increased with the discovery of glyphosate as a broad-spectrum herbicide. The tool worked through taking advantage of the height difference between soybean and corn. The mechanism here was a rod that used rope or canvas to hit the corn, while the soybean plants were mostly unscathed. The risk of this being that some can still get on the soybean.

Glyphosate resistance genes were not the first transgenic resistance seed. However, glyphosate was that one that worked and caught on. In 1996, the glyphosate resistant gene was released to the public as a variant of soybean (Duke, 2018). By 2007, the world had adopted many glyphosate resistant plants: canola, cotton, corn, alfalfa, and sugar beets. Glyphosate (RoundUp®) and glyphosate resistant crops (RoundUp Ready®) are affordable and do a lot of work when it comes to being able to spray as a whole spectrum, while there is no worry of getting injury on the crops (Duke, 2018). Duke (2018) refers to this period of ease of growing as the “Golden Age of Weed Control.” The title fits; there were very little problems from traditional weeds, little obvious harm to the environment and people, less fuel used, improving soil health from no-till, and over all a safer field for not having to use much more dangerous herbicides.

Volunteer corn today is the nuisance it has always been. Nothing can stop spills and broken plants and that is how as always has been. There is a problem with teaching producers to understand the products they are using. The first big question is: “How will it be possible to control weeds without glyphosate?” If RoundUp® herbicide and RoundUpReady® plants are the only method that solves weed issues, it reveals a more distressed second question: “How did the greater part of crop production get so dependent on one herbicide resistant gene?”

Nineteen countries have banned, used to have banned, or are considering banning glyphosate in the future (Baum et al., 2019). Cities in 26 states have banned glyphosate or are working on legislation to ban glyphosate (Baum et al., 2019).

Jhala and Rees (2018) have stated the only way for glyphosate resistant corn to be controlled in soybeans as a glufosinate resistant product (LibertyLink®). A relatively new herbicide resistance technology, Enlist® corn, has multiple genes resistant that each have a different way they work (Jhala and Rees, 2018). These products do have good use when there is a known need with weeds that need four modes of action to keep down. However, if the recent past has shown us, chemical solutions for controlling these weeds will not necessarily last very long. Assure II® is the only herbicide that works on Enlist® volunteer corn (Jhala and Rees, 2018). So a fair question is: What is going to happen when Assure II® does not control the volunteer corn anymore? Another is, if glyphosate is allegedly causing this many human health issues after over twenty years of being transgenic, and more than that when it was used for wicking, have the studies done already on any new herbicide been extensive enough?

DISCUSSION AND CONCLUSION

Each of these weedy plants have different strengths and weaknesses relative to their abilities of surviving and spreading. Because of this, different ways are required to manage them. Canada thistle has been well studied and there is a high number of articles that discuss it. Most of those articles are studies that have been explored management deeply. Canada thistle is very high up on the global watch list. Standard operating procedures lead to the right directions to look at multiple management types. There is cultural control by mowing, and biological control seems effective to a point with the mining weevils and gall fly; it is important to have a full vetting to avoid endangering native varieties. In cases with was required before they were released, and that did not happen because of pressure to release.

There is a big gap in papers and research after the early 2000s for Field sandbur. After not finding many chemical management systems for sandbur, there are only really spraying outside herbicides and mowing before the fruit develops are known to help with sandbur. However, there is really nothing that can be done about them. Even with developed control mechanisms, would it be usable internationally in the fields of Europe and beaches of the Black Sea where sandbur is now a noxious weed?

There is not a lot of good research on volunteer corn outside of how to manage it, with mostly recommended concentrations of herbicide options. A large dissonance occurred with my two sources that were completely opposite of one source claiming to how volunteer corn became a problem before herbicide resistance. The conclusion on this is that volunteer corn has always been a problem. It is just more visible now with herbicide resistant varieties, and the Bt genes. It is just a continual issue to find different mode of action herbicides. The creation of Enlist® is dangerous, especially when there is a shrinking number of new herbicides and a heightening level of weed tolerance of herbicide in minor weeds. However, there are good reasons behind the ideas that resulted in Enlist® even if the only herbicide that can kill volunteer Enlist® is Assure II®. Dr. Lenssen mentioned in discussion that many of the articles being referenced were by a lot of his friends. This might be related to the lack of research found. There seems to be less studying of weed science than there has been in the past. As one generation of scientists prepares for retirement, there appears to not be many scientists coming in to continue the research.

In the meantime, there are details that are imperative and there are opportunities that exist that can stop the sole dependence on herbicides. There needs to be multiple modes of action for a true IPM plan to work. The problem here is there's not much we can currently do to volunteer corn and sandbur other than using herbicides. As far as the research shows us is that sandbur only has biological control as grazing until the flowers emerge, otherwise the livestock will injury itself. With volunteer corn, there may not be any other way then changing to a longer rotation. Financial assistance on this may be a motivator in systems that are only corn and soybean.

It will be imperative to become smarter when it comes to using biological controls and the research on it. There could be cultural and mechanical ways to do things that we haven't thought of yet. It is also vital that greater care is taken when it comes to handling seeds that are easily spread, as Europe has seen it with the sandbur. These problems have the potential to be solved by coming by better study on seed mechanisms, how sandbur and corn break down overtime (and any other problem seeds), and studies on transgenics/biochemicals. There’s lots of avenues that should be explored. For that better future, weed science will be imperative, so it is important to start now.

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I guess we know how Clover feels about Citations

This paper would have never become complete without her, especially when she executed her duty to eat post-its, textbooks, notebooks, the style manual, laptop cords, the sensor bar that makes the Wii work, and most especially any piece of paper that hit the floor during the creation of this document.