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Critical Time for Weed Removal in Corn (*Zea mays* L.) as Influenced by Pre Herbicides

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CRITICAL TIME FOR WEED REMOVAL IN CORN (*Zea mays* L.) AS INFLUENCED BY PRE HERBICIDES

by

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CRITICAL TIME FOR WEED REMOVAL IN CORN (*Zea mays* L.)

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A weed control program that utilizes PRE herbicides and ensures a timely post-emergence weed removal could protect growth and yield of corn. The use of pre-emergence (PRE) herbicides for weed control could reduce the need for multiple POST applications of glyphosate in glyphosate-tolerant (GT) corn and provide an additional mode of action for combating glyphosate-resistant weeds. Thus, field studies were conducted in 2017 and 2018 at Concord, NE with the following objectives develop weed management recommendations that considers soil applied herbicides and determine proper timing of glyphosate based on the crop growth stage.

Therefore the material in this thesis is presented in three chapters: Chapter 1 outlines the integrated weed management, critical period of weed control, and pre-emergence (PRE) or post-emergence (POST) herbicide use in corn. Chapter 2 determines the critical time for weed removal in glyphosate-tolerant corn without pre-emergence (PRE) herbicide and atrazine or Verdict-Zidua applied pre-emergence (PRE). Chapter 3 determines how the timing of weed removal and PRE herbicides application could influence growth and yield of glyphosate-tolerant corn.

DEDICATION

This thesis is dedicated to my parents Selami Ulusoy and Vecihe Ulusoy, to my sister Gamze Nur Ulusoy, to my brothers Yunus Ulusoy and Emre Ulusoy; for all their unconditional love, support, sacrifices, and encouragement throughout my education to give me the best.

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CHAPTER 1:

INTRODUCTION AND PROJECT OBJECTIVES

Integrated Weed Management (IWM)

In most crop production systems, there is a need for alternative management tactics to make crop protection more sustainable (Chandler et al., 2011). Integrated pest management (IPM) is a systems approach that includes multiple crop protection practices by monitoring of pests and their natural enemies (Flint and Bosch, 2012). The definition of integrated pest management (IPM) proposed by Kogan (1998): “IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment”. Bajwa and Kogan (2002) claimed that integrated pest management (IPM) is a sustainable agricultural approach with a sound ecological foundation. Ecological and economical concerns associated with a heavy reliance on pesticides in cropping systems has led to the development of integrated pest management (IPM). Integrated pest management (IPM) has improved greatly since the introduction of “integrated control” defined as “applied pest control which combines biological and chemical control” (Stern, Smith, Van den Bosch, and Hagen, 1959). The integrated pest management (IPM) concept was initially developed by entomologists faced with indiscriminate broad-spectrum insecticide use and insect outbreaks caused by the elimination of natural enemies and the emergence of pesticide resistance. The integrated pest management (IPM) applies to all aspects of crop protection at present. (Barzman et al., 2015).

Integrated weed management (IWM) is an essential component of integrated pest management (IPM) system, which is an interdisciplinary approach that can involve agronomy, horticulture, entomology, plant pathology, nematology, ecology, and weed science. (Thill et al., 1991; Knezevic, 2014). As a part of integrated pest management (IPM), integrated weed management (IWM) became a commonly used scientific term in the early seventies (Walker and Buchanan 1982), and since then definition of the term was determined in many different ways (Thill et al., 1991; Shaw 1982; Swanton and Weise 1991; Knezevic 2014). Buchanan defined integrated weed management (IWM) as a combination of mutually supportive technologies to control weeds (Buchanan 1976; Knezevic 2014), whereas Swanton and Weise described it as a multidisciplinary approach in order to control weeds utilizing the application of numerous alternative control measures (Swanton and Weise 1991; Knezevic 2014). Knezevic points out that in practical terms, integrated weed management means developing a weed management program using a combination and integration of preventive, cultural, mechanical, and chemical practices. It does not mean abandoning chemical weed control program, however relying on it less (Knezevic 2014). None of the individual control program can provide complete weed control and give a satisfactory solution to the weed problems in crop production system. However, when various components of integrated weed management strategies are implemented in a systematic manner, then significant advances in weed control technology can be achieved (Swanton and Weise 1991; Jhala et al. 2014). Broadly, four methods are employed for weed management which are cultural, mechanical, biological, and chemical. Each of weed control methods has certain advantages and disadvantages (Figure 1-1.)

By virtue of this philosophy, an integrated weed management (IWM) system is designed to be economically, environmentally, and socially acceptable (Swanton and Murphy, 1996). Integrated weed management (IWM) involves the progressive implementation of combination of crop and weed management practices that favor the growth, development, and yield of the crop over the weeds (Walker and Buchanan 1982).

The IWM approach advocates the use of all available weed control options that include:

1. Selection of a well-adapted crop variety or hybrid with good early-season vigor and appropriate disease and pest resistance
2. Appropriate planting patterns/spacing and optimal plant density, improved timing, placement, and amount of nutrient application
3. Appropriate crop rotation, tillage practices, and cover crops
4. Suitable choice of mechanical, biological, and chemical weed control methods
5. Alternative weed control tools (flaming, steaming, infrared radiation, sand blasting, etc.)

Integration old and new weed management strategies into the cropping system is an approach to weed management based on crucial knowledge for its implementation and focus on crop health. The important part to the implementation of IWM is knowledge. The essential knowledge base which is necessary for the achievement of and IWM system includes key components. The critical period for weed control is one of the important components that can provide growers with the knowledge to make good decisions in their weed management strategy (Swanton et. al., 2008).

Critical Period of Weed Control (CPWC)

One of the first steps in implementing a successful integrated weed management (IWM) system is to define the length of time that weed control strategies are required to optimize yield. It is this need that has prompted researchers to investigate the appropriate timing of weed control efforts more formally referred to as the critical period for weed control (CPWC). Knowledge of the CPWC in major crops is essential in the development of a successful IWM system because it provides a framework for optimizing the effectiveness of weed control measures (Swanton and Weise 1991). The CPWC was defined by Swanton and Weise as the time interval when it is essential to maintain a weed-free environment for preventing crop yield losses. (Knezevic 2014). The CPWC has been defined as "a span of time between that period after seeding or emergence, when weed competition does not reduce crop yield, and the time period after which weed competition will no longer reduce crop yield" (Zimdahl 1988). Knezevic et al. has described the CPWC as a window in the crop growth cycle during which weeds must be controlled to prevent unacceptable yield losses. (Knezevic et al. 2002; Knezevic 2014). Practically speaking, the CPWC provides a biological basis for determining the need for and appropriate timing of weed control based on the crop's perspective (Knezevic et al. 2002).

Knowing the CPWC is useful to make a decision on the need for, and timing of, controlling weed, depending on the specific crop in agricultural system (Knezevic & Datta 2015). The concept of CPWC was introduced in 1968 by Nieto et al. Since that time, numerous CPWC studies have been reported in a variety of crops worldwide to determine the CPWC for a number of vegetable and grain crops (Zimdahl 1980, 1988;

Van Acker et al. 1993; Evans et al. 2003; Knezevic et al. 2003; Arslan et al. 2006; Uremis et al 2009; Knezevic et al 2013; Tursun et al. 2015, 2016), including corn (*Zea mays* L.) (Knake and Slife 1968; Sibuga and Bandeen 1980; Wilson and Westra 1991; Hall et al. 1992; Carey and Kells 1995; Ghosheh et al. 1996; Ferrero et al. 1996; Bedmar et al. 1999; Strahan et al. 2000; Halford et al. 2001; Evans et al. 2003; Norsworthy and Oliveira 2004; Dogan et al. 2004; Isik et al. 2006; Williams 2006; Mahmoodi and Rahimi 2009; Page et al. 2009; Gantoli et al. 2013; Tursun et al. 2016), soybean [*Glycine max* (L). Merr.] (Knake and Slife 1968; Barrentine 1974; Coble and Ritter 1978; Rathmann and Miller 1981; Young et al. 1982; Williams and Hayes 1984; Harris and Ritter 1987; Crook and Renner 1990; Van Acker et al. 1993; Franey and Hart 1999; Chhokar and Balyan et al. 1999; Mulugeta and Boerboom 2000; Halford et al. 2001; Eyherabide and Cendoya 2002; Knezevic et al. 2003; Keramati et al. 2008; Ghanizadeh et al. 2010; Green-Tracewicz et al. 2012), sunflower (*Helianthus annuus* L.) (Knezevic et al. 2013), grain sorghum [*Sorghum bicolor* (L.) Moench] (Burnside and Wicks 1967), rice (*Oryza sativa* L.) (Chauhan and Johnson 2011; Anwar et al. 2012), cotton (*Gossypium* L. spp.) (Papamichail et al. 2002; Bukun 2004; Tursun et al. 2015; Korres and Norsworthy 2015), canola (*Brassica napus* L.) (Martin et al. 2001), peanut (*Arachis hypogaea* L.) (Agpstinho et al. 2006; Everman et al. 2008), carrot (*Daucus carota* L.) (Swanton et al. 2010), sugar beets (*Beta vulgaris*) (Dawson 1970), white bean (*Phaseolus vulgaris* L.) (Dawson 1970; Woolley et al. 1993; Ngouajio et al. 1997; Burnside et al. 1998; Ghamari and Ahmadvand 2012), tomato (*Solanum lycopersicum* L.) (Weaver and Tan 1987), potato (Bazirakamakenga and Leroux 1994; Ahmadvand et al. 2009), leek (*Allium porrum* L.) (Tursun et al. 2007), red pepper (*Capsicum annum* L.) (Tursun et al. 2012), lentil (*Lens culinaris* Medik.) (Erman et al. 2008; Fedoruk et al. 2011; Smitchger et al. 2012), and chickpea (*Cicer arietinum* L.) (Mohammadi et al. 2005; Tepe et al. 2011).

In concept, the CPWC represent the time interval between two separately measure competition components (Figure 1-2.): (I) the maximum weed infested period (critical duration of weed interference), which is the length of time before early emerging weeds may grow and interfere with the crop before the resulting yield losses become important; and (II) the minimum weed-free period, which is the length of time required from the time of seeding or emergence that the crop must be maintained weed-free before yield losses caused by subsequent emerging weeds is negligible (Weaver and Tan 1983). An extensive review of the concept of the CPWC has been provided previously (Knezevic et al. 2002). The first component is known as the critical time for weed removal (CTWR), based on the so-called weedy curve (Figure 1-2.A). Knezevic claims that the CTWR is estimated to determine the ‘‘beginning’’ of the CPWC. The second component is known as the critical weed-free period (CWFP) based on the so-called weed-free curve (Figure 1-2.B). This component determines the ‘‘end’’ of the CPWC. Results from both components are required and are typically combined to determine the CPWC, regardless of crop species (Figure 1-2.C) (Knezevic et al. 2002). Knezevic determines theoretically, weed control before and after the CPWC does not significantly contribute to the conservation of crop yield potential. The beginning and end of the CPWC determined using the regression approach to generate both the weedy and weed-free curves depend on the level of acceptable yield loss (AYL) used to predict its beginning and end (Figure

1-2.). Many studies determined the beginning and end of the CPWC based on the maximum AYL level between 2.5 and 10% (Knezevic et al. 2002).

Many studies have been conducted in order to determine the CPWC or one of its components (CWFP or CTWR). There are several examples of studies that determined CPWC. Tursun et al. 2016 reported that the CPWC ranged from 175 to 788 growing degree days (GDD) in 2013 which corresponded to V2-V12 corn growth stages, and 165 to 655 GDD (V1-V10 growth stages) in 2014 based on the 5% acceptable yield loss (AYL) level (Tursun et al. 2016). In popcorn, Tursun et al. 2016 reported that the CPWC ranged from 92 to 615 GDD (VE to V10 growth stages) in 2013 and 110 to 678 GDD (V1 toV10 growth stages) in 2014. In sweet corn, the CPWC ranged from 203 to 611 GDD in 2013 (V2 to V10 growth stages) and 182 to 632 GDD (V2 toV10 growth stages) in 2014 (Tursun et al., 2016). These findings could help corn producers improve the cost effectiveness and efficacy of their weed management programs.

Other researchers conducted studies that determined critical time for weed removal (CTWR) with and without use of PRE herbicides. Knezevic et al. 2013 demonstrated that the CTWR without PRE herbicide treatment ranged from 14 to 26 d after emergence (DAE) corresponding to the V3 (three leaves) to V4 stages compared to 25 to 37 DAE, which corresponded to the V6 to V8 stages with PRE herbicide. The CTWR in IMI-resistant sunflower grown with PRE herbicide can be delayed by an additional 6 to 12 d compared to the crop grown without PRE herbicide under the present experimental conditions. The practical implication of this study is that the use of PRE herbicide could extend post-herbicide treatments by another 6 to 12 d with respect to the critical time required for weed removal without PRE herbicide in IMI-resistant sunflower. (Knezevic et al. 2013). It is confirmed that application of PRE herbicides delayed CTWR in crops. More recently, the CTWR without PRE herbicides was determined to be around the V1 to V2 (14 to 21 d after emergence [DAE]) growth stage in soybean study (Knezevic et al. 2019). The use of PRE-applied herbicides delayed CTWR from about the V4 (28 DAE) stage up to the R5 (66 DAE) stage. These results suggest that the use of PRE herbicides in GR soybean could delay the need for POST application of glyphosate by 2 to 5 wk, thereby reducing the need for multiple applications of glyphosate during the growing season. Additionally, the use of PRE herbicides could provide additional modes of action needed to manage GR weeds in GR soybean (Knezevic et al. 2019).

Weed Control Methods

Preventive Methods

The preventive practices are essential, but often overlooked, component of any integrated weed management (IWM) strategy (Thill and Mallory-Smith, 1997). The saying ‘An ounce of prevention is better than a pound of cure’ is indeed very applicable to weed management. Weed prevention strategies aim at preventing: (i) initial introduction; (ii) infestation development; and (iii) dispersal of weeds and their propagules. Because of their role in reproduction and dissemination and their ability to withstand extreme environments, seeds represent an important stage in the life cycle of many weeds (Teasdale et al. 2007). Stevan points out that the practice of weed prevention strategies are usually the least expensive however routinely the most overlooked.

Cultural Control

The row spacing plays an important role affecting weed control in integrated weed management because corn plants in narrow rows shade soil surface earlier than corn plants in wider rows. Very little light reaches the soil surface when the canopy has closed. The value of early canopy closure to control weeds is especially evident when weed control program in corn is dependent on post-emergence herbicides only (Jhala et al. 2014). Hock et al. 2006 reported that soybean planted in 19-cm rows had less total weed dry matter than weed species grown with soybean planted in 76-cm rows. In addition, the researchers observed that weeds caused less soybean yield losses when grown in 19-cm than 76-cm soybean rows. They reported that the difference between soybean yield losses in 76-cm versus 19-cm rows was 29% and 31% for common sunflower (*Helianthus annuus*) and velvetleaf (*Abutilon theophrasti*), respectively (Hock et al, 2006).

Cover Crops

The other method to manage weed species is cover crops. Cover crops (e.g. rye, hairy vetch, red clover, sweetclover, velvetbean, cowpea) are increasingly being used to provide multiple ecosystem services that sustain and enhance soil and water quality and reduce pest management inputs (O'Connell et al. 2014; Singer et al. 2007), suppress weed (Akemo et al., 2000; Blackshaw et al., 2001; Ross et al., 2001) during several crop production phases.

Cover crops can be grown in rotation system, during a fallow period, during an off-season winter period which is a more acceptable approach for many farmers, or simultaneously during the life cycle of a cash crop (Teasdale 2007). In the following cash crop, cover crop residues retained on the soil surface can directly limit germination and growth of weeds (Mirsky et al. 2011; Ryan et al. 2011; Teasdale and Mirsky 2015). Cover crops planted between cash crops can offset the need for an early-season herbicide application or tillage before cash crop planting in conventional systems (Norsworthy et al. 2012). Teasdale determined that cover crops are able to control weeds mainly by absorbing photosynthetically active radiation and by lowering the red: far-red ratio of transmitted light, which in turn influences the germination of light-requiring weed seeds. Furthermore, cover crops also reduce soil erosion by wind and water, help to improve soil structure, increase soil organic matter content, and influence the soil's nutrient status, nutrient cycling, soil biology, pests and diseases in addition to controlling weeds (Blackshaw et al., 2005).

Rye, sorghum, mustards, velvetbean, black walnut are known to release chemicals which can influence associated species either directly by influencing their growth or seed germination, or indirectly by affecting soil biology such as by inhibiting mycorrhizal inoculation potential (Inderjit and Keating, 1999; Weston and Duke, 2003). This phenomenon is called allelopathy and can be used to suppress weeds by using rotational crops, mulching with plant residues, applying plant extracts, or by incorporating allelopathic potential in crop cultivars using plant improvement techniques (Einhellig and Leather, 1988; Weston, 1996, 2005; Inderjit and Bhowmik, 2002).

Mechanical Weed Control

As for the mechanical weed control, tillage is the most common method. It can be divided into two categories: (I) preplant tillage and (II) in-row cultivation. The aim of preplant tillage is to kill all the weeds present before planting corn to give the crop a better start to compete with weed species during the initial stage. Field cultivators and discs are commonly used by growers, and they are highly effective to control weed seedlings when used properly. The in-row cultivation is used to remove weeds after the crop has been planted, usually using rotary hoe or an interrow cultivator. According to an economic study done in Quebec, mechanical weed control is just as cost-effective as conventional chemical methods (St-Pierre 1993). A mechanical weed management program usually entails three or four passes a season. The rotary hoe, although its cost falls in the mid-range, is the least expensive tool to operate per hectare because it can be used at high speeds.

Chemical Control

When we look at the chemical control, application of herbicides is the most important method of weed control in corn. Herbicides have been adopted by a majority of corn growers in the United States and many other parts of the world as well because herbicides are effective and economical. At different time intervals, such as before the crop is planted (preplant), after the crop is planted but before emergence (preemergence), and after crop emergence (postemergence) herbicides can be applied. The choice of herbicide application timing depends on many factors and varies from grower to grower and field to field in cropping system. Many corn growers use more than one herbicide applications that may provide a season-long weed control (Jhala et al. 2014).

Herbicides applied after corn planting, however before emergence and having soil residual activity, are known as preemergence herbicides. Soil-applied preemergence herbicides may either be broadcast on the field or be applied in bands over the planted crop rows. Preemergence herbicides require irrigation or rainfall within seven to ten days of application to activate herbicides and enter the weed germination zone by water infiltration (Hoeft et. al., 2000). Without rainfall or lack of irrigation source, mechanical incorporation by a rotary hoe can move some of the herbicide into the weed germination zone. The preemergence herbicides will have little or no foliar activity, so they will not be effective for the control of already emerged weeds at the time of application. If weeds are emerged at the time of application, preemergence herbicide can be tank-mixed with foliar active herbicides to expand weed control spectrum. Excess rainfall can reduce weed control efficacy of preemergence herbicides and increase the risk of corn injury. Several preemergence herbicides have been registered for weed control in corn (Figure 1-3.). Due to wet soil conditions or other factors, it is quite often that many corn growers are not in a position to apply preemergence herbicides prior to corn emergence. Several residual preemergence herbicides can be applied after corn emergence (Figure 1-4.). For example, herbicides (e.g., atrazine and mesotrione) have foliar activity on small, emerged weeds. Metolachlor, alachlor, and dimethenamid are acid amide herbicides, also known as chloroacetamide herbicides. The acid amide herbicides have much more activity on grass weeds, such as crabgrass (*Digitaria sanguinalis* [L.] Scop.), barnyardgrass (*Echinochloa crus-galli* [L.] Beauv.), and broadleaf signalgrass (*Urochloa platyphylla* [Munroex C. Wright]). Tank-mixing these herbicides with atrazine-applied preemergence can provide effective broad-spectrum weed control for about 3 weeks after application. Soil texture, pH, and organic matter content are the soil properties most commonly used to determine the application rates of preemergence herbicides. To illustrate, isoxaflutole, a preemergence herbicide of corn, showed a considerable crop injury (Knezevic et al. 1998; Simmons 2003). It was concluded that isoxaflutole rates should be carefully selected for soils with low organic matter and high pH (Wicks et al. 2007)). In the past few years, several preemergence herbicides have been tank-mixed with postemergence herbicides and are now available as a prepackaged mixture that expands weed control spectrum and provides more flexibility with application timing (Figure 1-3. and 1-4. by Jhala et al., 2014) (Guide for weed management in Nebraska). Postemergence (POST) herbicides registered for weed control in corn is needed to apply based on application timing to get better control in weed. (Figure 1-5. by Jhala et al., 2014) (Guide for weed management in Nebraska).

In conclusion, developing methods and techniques for integrated weed management is essential for better agricultural production, manufacturing, management of agricultural farms, and ecological balance of surrounding environments. By improving existing and developing novel weed management methods with scientific rigor, the researchers can estimate the capability of developed scientific techniques in reaching future crop manufacturing requirements (Westwood et. al., 2018). This scientific rigor would also guide in identify and modify selected areas in the integrated weed management program to reach maximum attainable levels of future crop manufacturing requirements.

PROJECT OBJECTIVES

I. Develop weed management recommendations that considers soil applied herbicides

II. Determine proper timing of glyphosate based on the crop growth stage.

The main purpose of this research was to develop weed management recommendations that considers soil applied herbicides. This project directly showed the benefit of using PRE herbicides for control of the early germinating weeds, which are the most competitive against the crop for the sun light, soil nutrition, space, and water. Also, control of early germinating weeds allowed farmers to properly time application of the POST herbicides. The use of soil herbicides directly reduced the need for multiple post application of herbicides. Moreover, the use of soil applied herbicides provided an additional mode of action for combating glyphosate resistant weeds in corn.

Literature Cited

Agostinho, F. H., Gravena, R., Alves, P. L. C. A., Salgado, T. P., & Mattos, E. D. (2006). The effect of cultivar on critical periods of weed control in peanuts. *Peanut science*, *33*(1), 29-35.

Ahmadvand, G., Mondani, F., & Golzardi, F. (2009). Effect of crop plant density on critical period of weed competition in potato. *Scientia horticulturae*, *121*(3), 249-254.

Anwar, M. P., Juraimi, A. S., Samedani, B., Puteh, A., & Man, A. (2012). Critical period of weed control in aerobic rice. *The Scientific World Journal*, *2012*.

Bajwa, W. I., & Kogan, M. (2002). Compendium of IPM definitions (CID). What is IPM and how is it defined in the worldwide literature, 15.

Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., ... & Lamichhane, J. R. (2015). Eight principles of integrated pest management. Agronomy for sustainable development, 35(4), 1199-1215.

Bedmar, F., Manetti, P., & Monterubbianesi, G. (1999). Determination of the critical period of weed control in corn using a thermal basis. *Pesquisa Agropecuária Brasileira*, *34*(2), 188-193.

Bukun, B. (2004). Critical periods for weed control in cotton in Turkey. *Weed Research*, *44*(5), 404-412.

Burnside, O. C., Wiens, M. J., Holder, B. J., Weisberg, S., Ristau, E. A., Johnson, M. M., & Cameron, J. H. (1998). Critical periods for weed control in dry beans (Phaseolus vulgaris). *Weed science*, 301-306.

Chandler, D., Bailey, A. S., Tatchell, G. M., Davidson, G., Greaves, J., & Grant, W. P. (2011). The development, regulation and use of biopesticides for integrated pest management. Philosophical Transactions of the Royal Society B: Biological Sciences, 366(1573), 1987-1998.

Chauhan, B. S., & Johnson, D. E. (2011). Row spacing and weed control timing affect yield of aerobic rice. *Field Crops Research*, *121*(2), 226-231.

Chhokar, R. S., & Balyan, R. S. (1999). Competition and control of weeds in soybean. *Weed Science*, 107-111.

DOĞAN, M. N., Ünay, A., Boz, Ö., & Albay, F. (2004). Determination of optimum weed control timing in maize (Zea mays L.). *Turkish Journal of Agriculture and Forestry*, *28*(5), 349-354.

Erman, M., Tepe, I., Buuml, B., Yergin, R., & Taşkesen, M. (2008). Critical period of weed control in winter lentil under non-irrigated conditions in Turkey. *African Journal of Agricultural Research*, *3*(8), 523-530.

Evans, S. P., Knezevic, S. Z., Lindquist, J. L., Shapiro, C. A., & Blankenship, E. E. (2003). Nitrogen application influences the critical period for weed control in corn. *Weed Science*, *51*(3), 408-417.

Everman, W. J., Clewis, S. B., Thomas, W. E., Burke, I. C., & Wilcut, J. W. (2008). Critical period of weed interference in peanut. *Weed Technology*, *22*(1), 63-67.

Eyherabide, J. J., & Cendoya, M. G. (2002). Critical periods of weed control in soybean for full field and in-furrow interference. *Weed Science*, *50*(2), 162-166.

Fedoruk, L. K., Johnson, E. N., & Shirtliffe, S. J. (2011). The critical period of weed control for lentil in Western Canada. *Weed science*, *59*(4), 517-526.

Flint, M. L., & Van den Bosch, R. (2012). Introduction to integrated pest management. Springer Science & Business Media.

Gantoli, G., Ayala, V. R., & Gerhards, R. (2013). Determination of the critical period for weed control in corn. *Weed Technology*, *27*(1), 63-71.

Ghanizadeh, H., Lorzadeh, S., & Ariannia, N. (2010). Critical period for weed control in corn in the south-west of Iran. *Asian Journal of Agricultural Research*, *4*(2), 80-86.

Ghamari, H., & Ahmadvand, G. (2012). Weed interference affects dry bean yield and growth. *Notulae Scientia Biologicae*, *4*(3), 70-75.

Ghosheh, H. Z., Holshouser, D. L., & Chandler, J. M. (1996). The critical period of johnsongrass (Sorghum halepense) control in field corn (Zea mays). *Weed Science*, *44*(4), 944-947.

Green-Tracewicz, E., Page, E. R., & Swanton, C. J. (2012). Light quality and the critical period for weed control in soybean. *Weed science*, *60*(1), 86-91.

Gunsolus, J. L. (1990). Mechanical and cultural weed control in corn and soybeans. *American Journal of Alternative Agriculture*, *5*(3), 114-119.

Halford, C., Hamill, A. S., Zhang, J., & Doucet, C. (2001). Critical period of weed control in no-till soybean (Glycine max) and corn (Zea mays). *Weed Technology*, *15*(4), 737-744.

Hall, M. R., Swanton, C. J., & Anderson, G. W. (1992). The critical period of weed control in grain corn (Zea mays). *Weed science*, *40*(3), 441-447.

Hock, S., Knezevic, S., Martin, A., & Lindquist, J. (2006). Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Science, 54*(1),38-46.

Hoeft, R. G., Aldrich, S. R., Nafziger, E. D., & Johnson, R. R. (2000). Modern corn and soybean production.

Isik, D., Mennan, H., Bukun, B., Oz, A., & Ngouajio, M. (2006). The critical period for weed control in corn in Turkey. *Weed Technology*, *20*(4), 867-872.

Jhala, A. J., Knezevic, S. Z., Ganie, Z. A., & Singh, M. (2014). Integrated weed management in maize. In *Recent Advances in Weed Management* (pp. 177-196). Springer, New York, NY.

Keramati, S., Pirdashti, H., Esmaili, M. A., Abbasian, A., & Habibi, M. (2008). The Critical Period of Weed Control in Soybean (Glycine max (L.) Merr.). *Pakistan Journal of Biological Sciences*, *11*(3), 463-467.

Knezevic, S. Z., Evans, S. P., Blankenship, E. E., Van Acker, R. C., & Lindquist, J. L. (2002). Critical period for weed control: the concept and data analysis. *Weed science*, *50*(6), 773-786.

Knezevic, S. Z., Evans, S. P., & Mainz, M. (2003). Row spacing influences the critical timing for weed removal in soybean (Glycine max). *Weed Technology*, *17*(4), 666-673.

Knezevic, S. Z. (2014). Integrated weed management in soybean. In *Recent Advances in Weed Management* (pp. 223-237). Springer, New York, NY.

Knezevic, S. Z., & Datta, A. (2015). The critical period for weed control: revisiting data analysis. *Weed Science*, *63*(SP1), 188-202.

Knezevic, S. Z., Elezovic, I., Datta, A., Vrbnicanin, S., Glamoclija, D., Simic, M., & Malidza, G. (2013). Delay in the critical time for weed removal in imidazolinone-resistant sunflower (Helianthus annuus) caused by application of pre-emergence herbicide. *International journal of pest management*, *59*(3), 229-235.

Knezevic, S. Z., Pavlovic, P., Osipitan, O. A., Barnes, E. R., Beiermann, C., Oliveira, M. C., ... & Jhala, A. (2019). Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. *Weed Technology*, 1-7.

Knezevic, S. Z., Sikkema, P. H., Tardif, F., Hamill, A. S., Chandler, K., & Swanton, C. J. (1998). Biologically effective dose and selectivity of RPA 201772 for preemergence weed control in corn (Zea mays). *Weed technology*, 670-676.

Kogan, M. (1998). Integrated pest management: historical perspectives and contemporary developments. Annual review of entomology, 43(1), 243-270.

Korres, N. E., & Norsworthy, J. K. (2015). Influence of a rye cover crop on the critical period for weed control in cotton. *Weed science*, *63*(1), 346-352.

Mahmoodi, S., & Rahimi, A. (2009). Estimation of critical period for weed control in corn in Iran. *World Academy of Science, Engineering and Technology*, *49*, 67-72.

Martin, S. G., Van Acker, R. C., & Friesen, L. F. (2001). Critical period of weed control in spring canola. *Weed Science*, *49*(3), 326-333.

Mohammadi, G., Javanshir, A., Khooie, F. R., Mohammadi, S. A., & Zehtab Salmasi, S. (2005). Critical period of weed interference in chickpea. *Weed Research*, *45*(1), 57-63.

Mulugeta, D., & Boerboom, C. M. (2000). Critical time of weed removal in glyphosate-resistant Glycine max. *Weed Science*, *48*(1), 35-42.

Ngouajio, M., Foko, J., & Fouejio, D. (1997). The critical period of weed control in common bean (Phaseolus vulgaris L.) in Cameroon. *Crop Protection*, *16*(2), 127-133.

Norsworthy, J. K., & Oliveira, M. J. (2004). Comparison of the critical period for weed control in wide-and narrow-row corn. *Weed science*, 52(5), 802-807.

Page, E. R., Tollenaar, M., Lee, E. A., Lukens, L., & Swanton, C. J. (2009). Does the shade avoidance response contribute to the critical period for weed control in maize (Zea mays)?. *Weed Research*, *49*(6), 563-571.

Papamichail, D., Eleftherohorinos, I., Froud-Williams, R., & Gravanis, F. (2002). Critical periods of weed competition in cotton in Greece. *Phytoparasitica*, *30*(1), 105-111.

Shaw, W. C. (1982). Integrated weed management systems technology for pest management. Weed science, 30(S1), 2-12.

Simmons, J. T., & Kells, J. J. (2003). Variation and inheritance of isoxaflutole tolerance in corn (Zea mays). *Weed technology*, *17*(1), 177-180.

Singh, H. P., Batish, D. R., & Kohli, R. K. (Eds.). (2006). *Handbook of sustainable weed management*. CRC Press.

Smitchger, J. A., Burke, I. C., & Yenish, J. P. (2012). The critical period of weed control in lentil (Lens culinaris) in the Pacific Northwest. *Weed science*, *60*(1), 81-85.

Stern, V. M. R. F., Smith, R., Van den Bosch, R., & Hagen, K. (1959). The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. Hilgardia, 29(2), 81-101.

Swanton, C. J., Mahoney, K. J., Chandler, K., & Gulden, R. H. (2008). Integrated weed management: knowledge-based weed management systems. *Weed Science*, *56*(1), 168-172.

Swanton, C. J., & Murphy, S. D. (1996). Weed Science Society of America. *Weed science*, 44(2), 437-445.

Swanton, C. J., O'sullivan, J., & Robinson, D. E. (2010). The critical weed-free period in carrot. *Weed Science*, *58*(3), 229-233.

Swanton, C. J., & Weise, S. F. (1991). Integrated weed management: the rationale and approach. Weed Technology, 5(3), 657-663.

TEPE, I., Erman, M., Yergin, R., & Bükün, B. (2011). Critical period of weed control in chickpea under non-irrigated conditions. *Turkish Journal of Agriculture and Forestry*, *35*(5), 525-534.

Thill, D. C., Lish, J. M., Callihan, R. H., & Bechinski, E. J. (1991). Integrated weed management–a component of integrated pest management: a critical review. Weed Technology, 5(3), 648-656.

Tursun, N., Bükün, B., Karacan, S. C., Ngouajio, M., & Mennan, H. (2007). Critical period for weed control in leek (Allium porrum L.). *HortScience*, *42*(1), 106-109.

Tursun, N., Datta, A., Tuncel, E., Kantarci, Z., & Knezevic, S. (2015). Nitrogen application influenced the critical period for weed control in cotton. *Crop Protection*, *74*, 85-91.

Tursun, N., Datta, A., Sakinmaz, M. S., Kantarci, Z., Knezevic, S. Z., & Chauhan, B. S. (2016). The critical period for weed control in three corn (Zea mays L.) types. *Crop protection*, *90*, 59-65.

Van Acker, R. C., Swanton, C. J., & Weise, S. F. (1993). The critical period of weed control in soybean [Glycine max (L.) Merr.]. *Weed Science*, *41*(2), 194-200.

Walker, R. H., & Buchanan, G. A. (1982). Crop manipulation in integrated weed management systems. Weed science, 30(S1), 17-24.

Weaver, S. E., & Tan, C. S. (1983). Critical period of weed interference in transplanted tomatoes (Lycopersicon esculentum): growth analysis. *Weed Science*, *31*(4), 476-481.

Weaver, S. E., & Tan, C. S. (1987). Critical period of weed interference in field-seeded tomatoes and its relation to water stress and shading. *Canadian Journal of Plant Science*, *67*(2), 575-583.

Westwood, J. H., Charudattan, R., Duke, S. O., Fennimore, S. A., Marrone, P., Slaughter, D. C., ... & Zollinger, R. (2018). Weed management in 2050: Perspectives on the future of weed science. *Weed science*, *66*(3), 275-285.

Wicks, G. A., Knezevic, S. Z., Bernards, M., Wilson, R. G., Klein, R. N., & Martin, A. R. (2007). Effect of planting depth and isoxaflutole rate on corn injury in Nebraska. *Weed Technology*, *21*(3), 642-646.

Williams, M. M. (2006). Planting date influences critical period of weed control in sweet corn. *Weed Science*, *54*(5), 928-933.

Woolley, B. L., Michaels, T. E., Hall, M. R., & Swanton, C. J. (1993). The critical period of weed control in white bean (Phaseolus vulgaris). *Weed Science*, *41*(2), 180-184.

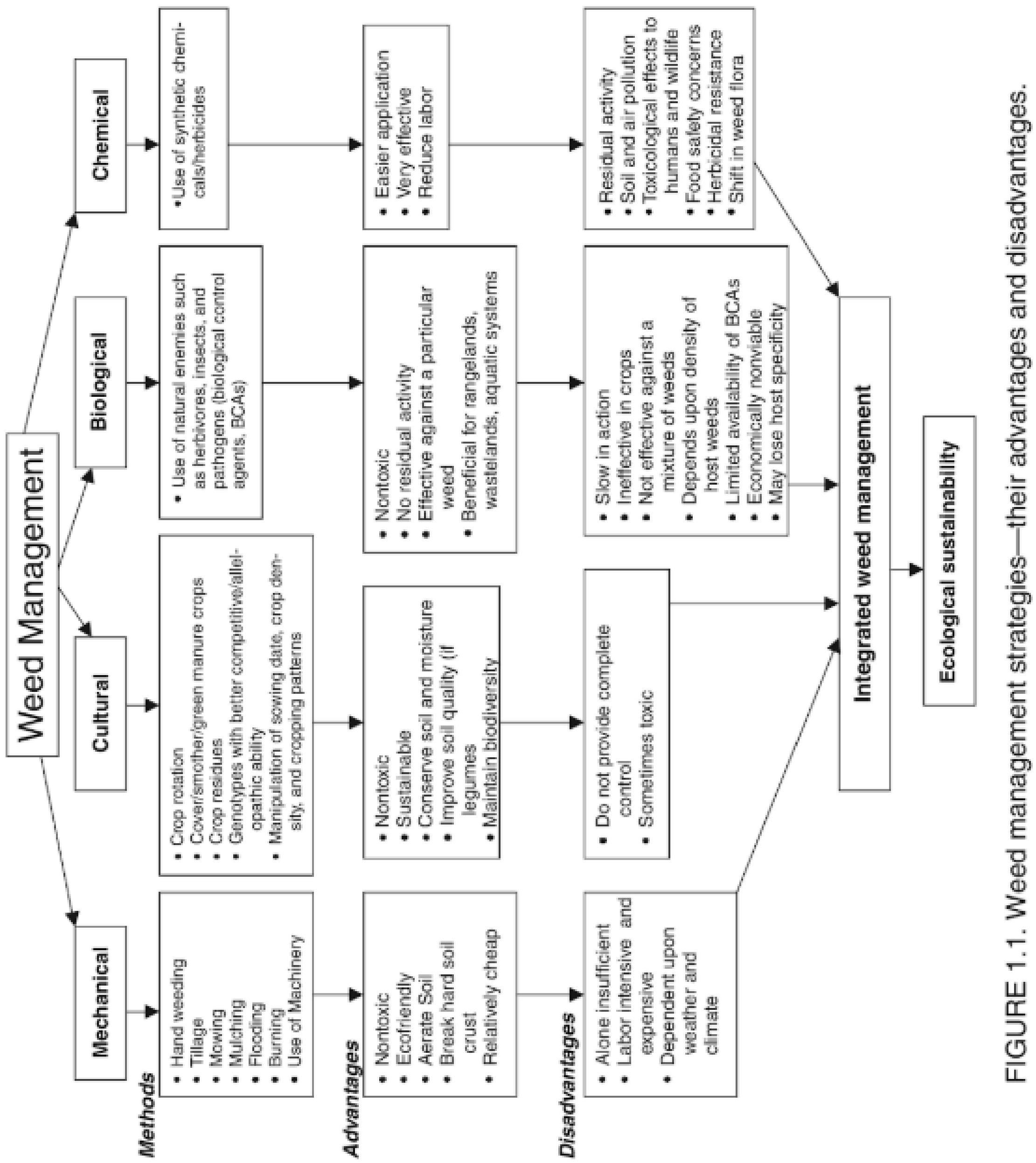

Figure 1-1. Weed management strategies (Source: Singh et al., 2006)

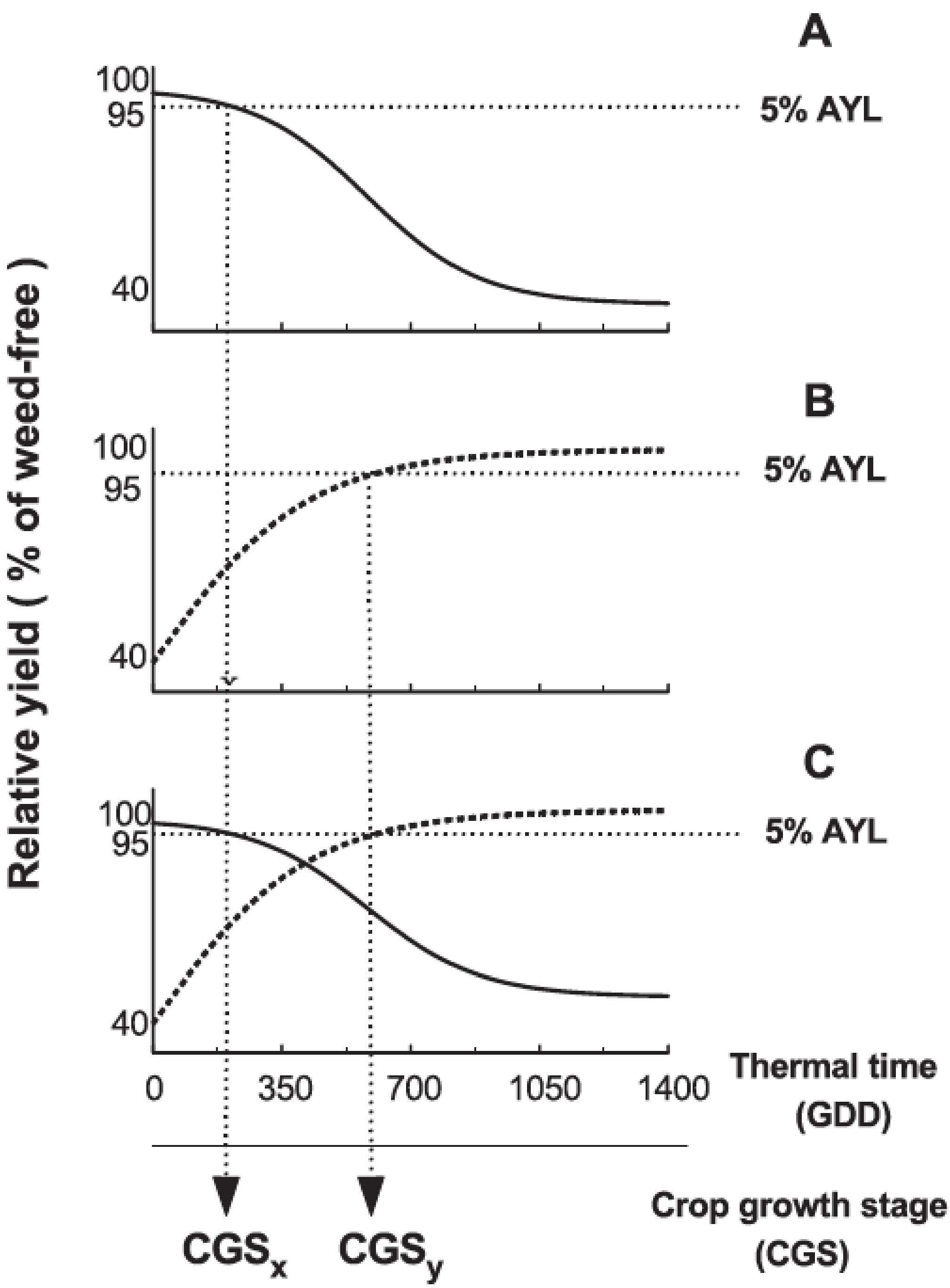

Figure 1-2. Functional approach used for determination of the critical period for weed control (CPWC). (A) The critical time for weed removal (CTWR) is determined from the so-called weedy curve (—; descending line), fit to data representing an increasing duration of weed interference. (B) The critical weed-free period (CWFP) is determined from the weed-free curve (- - -; ascending line), fit to data representing the increasing duration of the weed-free period. (C) The value of the x-axis that

corresponds to the 95% relative yield or an acceptable yield loss (AYL) of 5% is determined for both curves and related to crop growth stage (CGS). The CPWC is then defined as the time between the two crop growth stages (CGSx to CGSy) and represents the length of weed control required to protect the crop yield from more than a 5% yield loss. (Source: Knezevic et al. 2015)

Table 8.2 List of preemergence herbicides registered for weed control in corn [64]

Herbicide	Commercial product kg per hectare		
	Sandy loam	Silt loam	Silty-clay Loam
	<1% OM	1–2% OM	>2% OM
Atrazine[a]	[b]Do not use	1.12–2.46	1.12–2.46
Isoxaflutole[b]	0.21	0.21–0.35	0.21–0.42
Isoxaflutole[b]+	0.07–0.21	0.21–0.35	0.21–0.42
Atrazine[a]	1.12	1.45	1.70
S-metolachlor+atrazine[a]	4.06	4.06–4.74	4.74
Mesotrione alone or with	0.42	0.42	0.42
S-metolachlor+atrazine	1.13	1.46	1.46
Thiencarbazone+isoxaflutole[b]	0.23	0.23–0.40	0.23–0.40
Thiencarbazone+isoxaflutole+trazine[a]	2.26	2.26	2.26
Acetochlor	2.60–3.61	3.61–4.52	3.61–4.52
Acetochlor+atrazine[a]	6.10	7.91	7.91
S-metolachlor+benoxacor	1.13	1.46	1.46
S-metolachlor+glyphosate+atrazine[a]	5.65	6.78	8.47
Flumioxazin+pyroxasulfone	0.21	0.21	0.21
Encapsulated acetochlor+atrazine[a]	5.65–6.10	6.10–7.45	6.78–7.91
Dimethenamid-P+atrazine[a]	2.26	2.82	3.95
Dimethenamid-P+atrazine[a]	2.71–3.16	3.16–3.84	3.84–4.52
Acetochlor+MON 13900 safener	1.41–1.97	1.97–2.54	1.97–2.54
Acetochlor+atrazine+MON 13900 safener	4.06	4.06–5.19	4.52–5.19
Flumetsulam+clopyralid	0.28	0.28	0.28–0.35
Acetochlor+atrazine+dichlormid	4.97–5.42	5.42–6.32	5.87–6.78
S-metolachlor+mesotrione+atrazine	6.78	6.78	6.78
S-metolachlor+mesotrione+atrazine	5.65	5.65	5.65–6.78
Dimethenamide-P	0.70–0.98	0.98–1.12	1.12–1.26
Rimsulfuron+isoxaflutole	Do not use	0.11–0.17	0.11–0.18
Pendimethalin+atrazine	Do not use	4.06	4.06
Rimsulfuron+atrazine	Do not use	0.07–0.10	0.07–0.10
Saflufenacil	0.14	0.17	0.21
Acetochlor+dichlormidsafener+flumet-sulam+clopyralid	1.70	1.70–1.97	2.26
Acetochlor+dichlormidsafener	1.70–2.82	1.70–2.82	1.70–3.10
Acetochlor+dichlormidsafner alone or with	2.26	4.52–5.65	5.08–6.78
atrazine	1.23	1.45	1.68
Clopyralid+flumetsulam+acetochlor	1.70	1.97	2.26
Saflufenacil+dimethenamid-P	0.7	0.91	1.12
S-metalochlor+mesotrione+benoxacor (safener)	4.52	4.52	4.52

OM organic matter

[a] Do not apply atrazine within 20 m of where water runoff from a field will enter a stream, river, or standpipe. The total amount of atrazine (active ingredient per hectare) applied cannot exceed 2.8 kg ai/ha per calendar year. Use no more than 1.80 kg ai/ha on highly erodible land with less than 30% crop residue. Using atrazine on soils with less than 1% organic matter increases carryover injury risk to susceptible crops, especially high pH soils. Do not use on sandy soils if water table is less than 30 ft

[b] Do not use isoxaflutoleon coarse-textured soils of less than 2% organic matter if the water table is less than 7.6 m. Do not use on fields prone to runoff or flooding. Crop response is most likely to occur where soils are coarse, organic matter content is less than 1.55%, and the pH is greater than 7.4. Corn seed must be covered with 3–5 cm inches of soil. Avoid planting when soil surface is wet

Figure 1-3. List of preemergence (PRE) herbicides registered for weed control in corn from Jhala et al., 2014.

Table 8.3 List of preemergence herbicides also registered for postemergence (in-crop) application in corn [64]

Herbicide	Crop stage	Maximum weed stage
Atrazine	0–30 cm	4 cm
Isoxaflutole[a]	V2	4 cm
S-metolachlor + atrazine	0–30 cm	Two-leaf
Acetochlor + atrazine + dichlormid	0–28 cm	Unemerged
Mesotrione[b]	0–76 cm	13 cm
Thiencarbazone + isoxaflutole	V2	4 cm
Acetochlor	0–28 cm	Unemerged
Acetochlor + atrazine	0–28 cm	Two-leaf
S-metolachlor + benoxacor	0–101 cm	Unemerged
S-metolachlor + glyphosate + atrazine	0–30 cm	15 cm
Encapsulated acetochlor + atrazine	0–28 cm	Unemerged
Dimethenamid-P + atrazine	0–30 cm	4 cm
Acetochlor + atrazine + MON 13900 safener	0–28 cm	Two-leaf
Flumetsulam + clopyralid	0–5 cm	20 cm
Acetochlor + atrazine + dichlormid	0–28 cm	Unemerged
S-metolachlor + mesotrione + atrazine	0–30 cm	7 cm
Dimethenamide-p	0–30 cm	Unemerged
Pendimethalin	0–76 cm	3 cm
Flumetsulam	0–51 cm	15 cm
Rimsulfuron	0–30 cm	7 cm
Atrazine + metolachlor	0–13 cm	Two-leaf
Acetochlor + dichlormidsafener + flumetsulam + clopyralid	0–28 cm	5-cm broad leaves
Acetochlor + dichlormidsafener	0–28 cm	Unemerged
Atrazine + metolachlor	0–13 cm	Two-leaf
Actochlor + atrazine + safener	0–28 cm	Unemerged

[a] If isoxaflutole is applied after the corn has emerged, do not add oil concentrate

[b] Severe injury may occur if mesotrione is applied postemergence to corn that has been treated with Counter. Do not tank-mix with any organophosphate or carbamate insecticide. Do not cultivate within 7 days of application

Figure 1-4. List of preemergence (PRE) herbicides also registered for (POST) postemergence (in-crop) application in corn from Jhala et al., 2014.

Table 8.4 List of postemergence herbicides registered for weed control in corn [64]

Herbicide	Rate kg per hectare	Application time
2,4-D ester or 2,4-D amine	0.56–1.12	Spike to 91 cm corn; broadleaf weeds 2–6 leaves
Nicosulfuron	0.05	Corn 10–91 cm (V10); if greater than 50 cm, use drop nozzle
Nicosulfuron + atrazine[a]	0.06 1.23	With atrazine, corn less than 30 cm
Carfentrazone-ethyl	0.03	Corn less than V14, but if greater than V8, use drop nozzles; broadleaves 2–10 cm; velvetleaf up to 90 cm
Atrazine[a]	1.60–2.5	Corn less than 30 cm; broadleaves 5–15 cm; grass weeds 2 cm or less
Atrazine[a] + dicamba[b]	0.62–1.12+ 0.63–1.12	Corn less than V5
Rimsulfuron (50 %) + thifensulfuron (25 %)	0.02	Corn spike to V2; grasses 2–5 cm; broadleaves 2–8 cm
Primisulfuron 75 %	0.03–0.05	Corn 10–50 cm; shattercane 10–30 cm; broadleaves 2–10 cm; grasses 2–8 cm
Bromoxynil + atrazine[a]	1.13–1.70+ 0.61–1.23	Corn three-leaf to 30 cm Broadleaves 5–15.24 cm
Bromoxynil + dicamba[b]	1.13–1.70+ 0.60	
Fluthiacet-methyl	0.04–0.06	Corn emergence to 120 cm
Mesotrione	0.21	Corn to 75 cm or V8; broadleaves less than 12 cm
Mesotrione + atrazine[a]	0.17 + 0.56	Corn less than 30 cm
Thiencarbazone-methyl tembotrione	0.21	V1–V6
Clopyralid + MCPA	2.26	Spike to V4
Dicamba[b]	0.56–1.12	Spike to 90 cm; if greater than 20 cm, use drops
Dicamba[b] + 2,4-D ester or amine	0.56 + 0.3 or0.30	Broadleaves 2–6 leaves
Diflufenzopyr + dicamba	0.42 + 0.30	Corn 10–25 cm; corn 25–60 cm; if 60–90 cm, use drops
S-metolachlor + glyphosate[c] + atrazine (glyphosate-resistant corn only)	6.21–8.50	Corn 0–30 cm
Glyphosate[c](glyphosate-resistant corn only)	Up to 3.40	Corn to 122 cm (V12); if over 60 cm, use drops
S-metolachlor + glyphosate[c] + mesotrione (glyphosate-resistant corn only)	4.10–4.52	Corn to 76 cm (V8); before weeds exceed 10 cm
Flumetsulam + clopyralid	0.14–0.35	Spike to 50 cm, if greater than 50 cm use drops; broadleaf weeds less than 20 cm
Topramezone	0.05–0.07	Broadleaf weeds 5–15 cm; for corn 60–71 cm, apply with drop nozzles
Topramezone + atrazine[a]	0.05+ 0.33–1.80	Corn less than 30 cm

Figure 1-5. List of postemergence (POST) herbicides registered for weed control in corn by Jhala et al., 2014.

Table 8.4 (continued)

Herbicide	Rate kg per hectare	Application time
Tembotrione	0.21	Corn emergence V8; broadleaf weeds less than 15 cm; grass weeds less than 8 cm
Tembotrione + atrazine[a]	+0.56	Corn less than 30 cm; weeds 2–8 cm
Tembotrione + bromoxynil	0.14 + 0.42	Corn less than 30 cm; weeds 2–15 cm
Glufosinate (Liberty Link hybrid required)	1.54–2.03	Corn at 60 cm (V7); for corn 60–90 cm, use drop nozzles to avoid spraying in whorl
Glufosinate (Liberty Link hybrid required) + tembotrione	1.54–1.70 0.10–0.21	Up to 60 cm (broadcast) or 75 cm (drops); weeds 2–10 cm
Imazethapyr + imazapyr alone (Clearfield hybrid required) or with dicamba[b]	0.08 0.56–1.12	Corn up to 50 cm (V6); weeds up to 10 cm; weeds to 10 cm
Foramsulfuron	0.09–0.12	Corn 0–90 cm, if greater than 40 cm, use drops; weeds less than 10 cm
Halosulfuron	0.05–0.09	Corn spike lay-by greater than 50 cm use drops; broadleaf weed 5–15 cm
Rimsulfuron + mesotrione	0.28	Corn up to 50 cm or V7
Rimsulfuron + dicamba[b]	0.28	V2–V7 corn; 2–8 cm weeds
Rimsulfuron + thifensulfuron	0.08	Corn up to 50 cm or V7
Flumiclorac	0.28–0.42	Corn V2–V10; broadleaf weeds less than 10 cm
Rimsulfuron	0.07	Corn up to 30 cm or V6, whichever is most restrictive
Prosulfuron + primsulfuron	0.07	Corn 10–60 cm; if greater than 50 cm (V6), use drops; weeds 5–20 cm
Fluroxypry + bromoxynil	0.45	VE–V5 corn; sweet corn up to V4; weeds less than 20 cm
Diflufenzo-pyr + dicamba[b] + isoxadifen	0.17	Corn 10–90 cm
Nicosulfuron + rimsulfuron	0.05–0.10	Corn to 50 cm or V6; weeds 5–10 cm
Nicosulfuron + acifluorfen	0.05–0.10	Corn to 40 cm or V5
Fluroxypyr + clopyralid	1.50	Corn spike to V5; weeds less than 20 cm
Halosulfuron + dicamba[b]	0.28–0.56	Spike to 90 cm; weeds 2–15 cm

OM organic matter

[a] Do not apply atrazine within 66 ft of where water runoff from a field will enter a stream, river, or standpipe. The total amount of atrazine applied (active ingredient per hectare) cannot exceed 2.8 kg ai/ha per calendar year. Use no more than 1.8 kg ai/ha on highly erodible land with less than 30% crop residue. Using atrazine on soils with less than 1% organic matter increases carryover injury risk to susceptible crops, especially high pH soils. Do not use on sandy soils if water table is shallower than 30 ft

[b] Dicamba rates are based on a 4.5–3.4 kg ae/ha formulation

[c] Glyphosate rates are based on a 4.5–3.4 kg ae/ha formulation

Figure 1-5 (continued). List of postemergence (POST) herbicides registered for weed control in corn by Jhala et al., 2014.

CHAPTER 2:

CRITICAL TIME FOR WEED REMOVAL IN CORN AS INFLUENCED BY PRE-HERBICIDES (*Zea mays* L.)

ABSTRACT

The use of PRE herbicides for weed control could reduce the need for multiple POST applications of glyphosate in glyphosate-tolerant (GT) corn and provide an additional mode of action for combating glyphosate-resistant weeds. Thus, field studies were conducted in 2017 and 2018 at Concord, NE, to evaluate the influence of PRE herbicides on critical time of weed removal (CTWR) in GT corn. The studies were arranged in a split-plot design with three herbicide regimes as main plot treatments and seven weed removal timings as subplot treatments in four replications. The herbicide regimes included no-PRE and two PRE herbicide treatments which were atrazine and Verdict®-Zidua® (saflufenacil plus dimethenamid plus and pyroxasulfone) in 2017 and 2018. The weed removal timings were at V3, V6, V9, V12, and V15 corn growth stages, as well as weed-free and weedy season long treatments. The relationship between relative corn yields and weed removal timings was described by a four-parameter log-logistic model, and the CTWR was estimated based on 5% yield loss. Delaying weed removal time significantly reduced corn yield, particularly without PRE application of herbicides. In 2017, the CTWR started at V3 without PRE herbicide while PRE application of atrazine and Verdict®-Zidua® delayed the CTWR to V5 and V10, respectively. In 2018, the CTWR started at V3 without PRE herbicide, and application of atrazine and Verdict®-Zidua® delayed the CTWR to V5. The studies confirmed that PRE application of herbicides could delay the need for application of POST herbicides for weed control in GT corn.

INTRODUCTION

Corn (*Zea mays* L.) is one of the most important cereal crops in the world. Weed control is a vital management practice that should be carried out to ensure optimum grain yield for corn production (Gantoli et al. 2013). Globally, 10% loss of the agricultural output is because of a competitive effect of weeds despite intensive control of weeds in most agricultural systems (Zimdahl, 2004). In general, weeds cause the highest loss potential (37%), followed by insects (18%), fungal and bacterial pathogens (16%) and viruses (2%) (Oerke, 2006). Integrated weed management (IWM) is a combination method of cultural, mechanical, biological, and chemical for effective and economical weed control (Swanton and Weise, 1991). The principles of IWM should provide the foundation for developing optimum weed control systems and efficient use of herbicides. The understanding of the critical period for weed control (CPWC) is an essential part of an IWM program.

Knowing the CPWC is necessary to develop management strategies that reduce weed interference during critical plant production times (Norsworthy and Oliveira 2004). The concept of CPWC was introduced in 1968 by Nieto et al. Since that time, numerous CPWC studies have been reported in a variety of crops worldwide to determine the CPWC for a number of vegetable and grain crops (Van Acker et al. 1993; Evans et al. 2003; Knezevic et al. 2003; Arslan et al. 2006; Uremis et al 2009; Knezevic et al 2013; Tursun et al. 2015, 2016), including corn (*Zea mays* L.) (Hall et al. 1992; Ghosheh et al. 1996; Bedmar et al. 1999; Halford et al. 2001; Evans et al. 2003; Norsworthy and Oliveira 2004; Dogan et al. 2004; Isik et al. 2006; Williams 2006; Mahmoodi and Rahimi

2009; Page et al. 2009; Gantoli et al. 2013; Tursun et al. 2016). The CPWC is the time-period the crop growth cycle during which weeds must be controlled to prevent unacceptable yield loss in the field (Evans et al. 2003). The CPWC is useful to make a decision on the need for proper timing of controlling weed to maintain optimum crop yield (Knezevic et al. 2002). In general, the CPWC has a beginning and an end. Weeds that emerge before or after the CPWC may not represent a threat to crop yields (Knezevic et al. 2002). For instance, it has been estimated that corn should be kept weed-free from the 1st to 10th leaf stage (Knezevic et al. 2003; Tursun et al. 2016) to avoid 5% unacceptable yield loss. However, the duration of CPWC can be influenced by several factors, including crop characteristics, weed composition, environmental condition, cropping practices as well as pre-emergence weed control tactics (Hall et al. 1994; Knezevic et al. 2002). Early emerging weeds are known to be most competitive with corn and often determines the beginning of CPWC. A pre-emergence weed control tactics that control early emerging weeds would potentially delay the critical time for weed removal (CTWR) and possibly reduce post-emergence weed control inputs (Weaver and Tan 1983) or post-emergence treatments become unnecessary if preemergence treatment combined well with mechanical methods (Wagner et al. 2006). CTWR is the maximum length of time before early emerging weeds can grow and interfere with the crop before unacceptable yield loss is incurred (Weaver and Tan, 1983). Knezevic claimed that the CTWR is practically the beginning of CPWC (Knezevic et al. 2003).

Several soil-applied pre-emergence (PRE) herbicides have been reported to provide 90 to 100 percent early emerging weed control in corn (Janak and Grichar, 2016; Jha et al. 2015; Ganie et al., 2017; Odero et al., 2014) for up to 21 days after herbicide application.

In addition to providing early weed control, PRE-herbicides also provide an alternative mode of action for weed control which is essential in minimizing the development of herbicide-resistant weed populations.

There is a lack of information on how early weed control by PRE-herbicides could influence CTWR and need for post-emergence weed control inputs in corn. Therefore, the objectives of the study are to develop weed management recommendations that consider soil-applied herbicides and to determine the proper timing of the POST application based on the crop growth stage.

MATERIALS AND METHODS

Experimental site description and design

Field experiments were conducted at the Haskell Agricultural Laboratory (HAL), Concord, Nebraska, USA (42.37°N, 96.95°W), during the 2017 and 2018 corn growing seasons. The soil texture of the field study was a clay silt loam with a combination of 35% sand, 38% clay, 27% silt, and 18% organic matter with ph 7.7. Each study was arranged in a split-plot design with 21 treatments (3 herbicide regimes as main plots × 7 weed removal times as subplots) in 4 replications. The main plots were no-PRE and PRE application of two herbicides (Atrazine or Verdict®-Zidua®). Verdict plus Zidua has three active ingredients: saflufenacil (6.24%), dimethenamid (55.04%), and pyroxasulfone (85%).

Weed removal timings were conducted at the following growth stage of corn: V3, V6, V9, V12, and V15 by glyphosate application and hand weeding for the remainder of the season. There were also season-long weed-free and weedy plots. Each subplot was 3 m by 7.62 m with 4 rows. The width was 0.76 m between two rows.

For each of the V3 to V15 weed removal timing, weeds were allowed to grow with the crop for increasing periods of time before the weeds were removed and the corn plants were maintained weed-free for the remainder of the season.

Calculation of growing degree days

Air GDDs were calculated using the method described by Gilmore and Rogers (1958). For accumulation of GDD, the time of crop emergence (DAE) was used the reference point

$$GDD= \sum [(T_{max}+T_{min})/2]-T_b$$

where, T_{max} and T_{min} are daily maximum and minimum temperatures (^oC), respectively, and T_b is the base temperature (10 ^oC) for corn growth. Daily rainfall and air temperature (maximum and minimum) from May to October were obtained from the meteorology station. Total monthly precipitation and average temperature for those months in 2017 and 2018 were recorded (Table 2-1.). Growing degree days (GDD) were calculated as the mean of the daily minimum and maximum temperature minus a base temperature. The base temperature was selected as 10^{o}C. (McMaster and Wilhelm, 1997; Yang et al., 2004).

Data collection

A natural infestation of velvetleaf (*Abutilon theophrasti*), common lambsquarters (*Chenopodium album* L.), green foxtail (*Seteria viridis* L.), and common waterhemp

(*Amaranthus rudis* L.) were seen in the trial. In general, weed density, weed biomass, and species composition were assessed at the time of weed removal. At each weed removal timing, weed species were counted within a 0.5 m × 0.5 m quadrat placed between two middle-rows in each plot. The counted weed species were harvested, dried at 50^{o}C for 7 days and weights recorded. Combined harvester (Almaco SP40, Nevada, IA, USA) was used to harvest corn in the two middle rows of each plot in each year, with yields reported at 15% moisture. The corn yield curves were developed to compare the pre-emergence weed control option with or without PRE herbicides.

Statistical analyses

A four parameter log-logistic regression model was used to describe the relationship between relative corn yields, yield components or yield losses, and weed removal timings (in GDD) using the following equation (Knezevic et al. 2007):

$$Y = \frac{C + (D - C)}{\{1 + exp\,[B(logX - logE)\,]\}}$$

where *Y* is the response (yield, yield components, or yield loss); *C* is the lower limit; *D* is the upper limit; *X* is the GDD calculated after corn emergence; *E* is the GDD at the inflection point (also abbreviated as ED_{50} or I_{50}), and *B* is the slope of the line around the inflection point.

The GDD (and the corresponding DAE [days after emergence] and corn growth stage required for 5% yield loss (ED_5) for no-PRE and PRE herbicide treatments were calculated from the regression curves and compared using standard errors (Knezevic et al. 2018). The ED_5 was considered the critical time for weed removal. In order to

determine the CTWR, all regression analyses and graphs were performed using the dose-response curves ('drc') statistical package in R program (Knezevic and Datta 2015).
The yield was collected in each plot and analyzed using regression procedures in R statistical package and drc package. The crop yields collected from the 7 weed removal timings provided basis for fitting the regression curve to determine the CTWR (based on 5% yield loss threshold). In particular, crop yields and yield loss (y-axis) were plotted against the duration of weedy periods according to the leaf stage of the crop (x-axis) based on growing degree days (GDD). The regression curve analysis provided the answer for the best timing for weed removal in corn grown with and without soil applied herbicides. The estimated timings of weed removal were expressed in crop growth stage (based on GDD) and days after corn emergence.

RESULTS AND DISCUSSION

Weed density and species composition

Weed density and species composition varied with years and treatment regimes (Table 2-2.). During both growing seasons dominated four weed species, including velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.), waterhemp (*Amaranthus rudis*), and green foxtail [*Setaria viridis* (L.) P. Beauv.].
In plots without PRE herbicides in 2017, the dominant weed species was common lambsquarters (*Chenopodium album* L.), with 78.57% of the overall weed population (Table 2-2.). During the 2018 growing season, green foxtail (*Setaria viridis* L.) had the highest density among the other species with 164 plants m^{-2} and 50.62% of the overall

weed population in plots without PRE herbicide application, while lambsquarters (*Chenopodium album* L.) averaged at about 63 plants m^{-2} and 19% of the overall weed population.(Table 2-2.).

The application of atrazine in one of the two PRE herbicide blocks resulted in decrease of overall weed density compared to no-PRE plots in both years. Atrazine provided good control of common lambsquarters (*Chenopodium album* L.) (eg. density of 0 plants/m^2, compared to poor control of waterhemp (*Amaranthus rudis*) (density of 10 plants/m^2). The application of Verdict-Zidua resulted in the overall lowest weed density in both years (Table 2-2.). For example, waterhemp (*Amaranthus rudis*) and green foxtail (*Seteria viridis* L.) were recorded 0 plants m^{-2} in 2017 while waterhemp (*Amaranthus rudis*) and common lambsquarters (*Chenopodium album* L.) were recorded 0 plants m^{-2} in 2018.

Corn Yield Loss

Postponing weed removal time caused major yield loss of corn. The plots without the application of PRE herbicides had higher yield losses than the ones with PRE herbicides. In 2017, weedy season-long corn had yield loss up to 99% without PRE herbicide compared to 35% and 33% with atrazine and Verdict-Zidua respectively (Figure 2-1., Table 2-3.).

In 2018, corn yield losses were lower compared to previous year. The weed interference throughout the corn growing season resulted in 14% corn yield losses without PRE herbicides compared to 14% and 10% with Atrazine and Verdict-Zidua, respectively. (Figure 2-1.; Table 2-3.). The likely reason for such yield loss difference between two years was the number and types of weed species and rainfall.

Critical time for weed removal

The CTWR in corn was estimated utilizing the 5% acceptable yield loss threshold. In 2017, the CTWR ranged from 157 to 371 growing degree days (GDD) which corresponds to V3 to V10 corn growth stages, depending on the herbicide regimes. Without PRE herbicide, CTWR started at V3 corn growth stage (157 GDD; 11 DAE) (Figure 2-1.; Table 2-4.). The PRE application of Atrazine delayed the CTWR to V5 corn growth stage (208 GDD; 16 DAE), while the PRE application of Verdict-Zidua (saflufenacil, dimethenamid, and pyroxasulfone) provided the longest delay up to V10 corn growth stage (371 GDD; 32 DAE) (Figure 2-1.; Table 2-4.); coinciding with canopy cover. Overall, the use of PRE herbicides Atrazine and Verdict-Zidua (saflufenacil, dimethenamid, and pyroxasulfone) resulted in significant delays of the CTWR by 5 and 21 days, respectively.

In 2018, the CTWR based on 5% yield loss ranged from 144 to 203 GDD which corresponds to V3 to V5 corn growth stages, depending on the herbicide regimes. Without application of PRE herbicide, CTWR started early, which was at V3 corn growth stage (144 GDD; 11 DAE) (Figure 2-2.; Table 2-4.). However, PRE application of Atrazine delayed the CTWR to V5 corn growth stage (198 GDD; 14 DAE) while PRE application of Verdict-Zidua (saflufenacil, dimethenamid, and pyroxasulfone) delayed the CTWR up to V5 corn growth stage (203 GDD; 15 DAE) (Figure 2-2.; Table 2-4.).

In both years (2017 and 2018), lack of PRE herbicides made corn more vulnerable to weed presence, which resulted in earlier CTWR (V3 stage, 11 DAE). The application of PRE herbicides helped suppress early emerging weeds directly helping corn crop and resulting in delayed CTWR to V5 growth stages for atrazine and Verdict-Zidua (saflufenacil, dimethenamid, and pyroxasulfone) in 2018. This analysis suggests a significant impact of PRE herbicides application on CTWR for corn.

MANAGEMENT IMPLICATIONS

After introduction of glyphosate-tolerant corn hybrids, many farming systems mostly utilized the POST herbicides, primarily glyphosate-based weed management programs. Such practices resulted in the development of glyphosate-resistant weeds. To prevent the repeated use of the glyphosate, alternative weed management approaches must implement the programs, which also should include PRE herbicides (Lamichhane et. al., 2017). Results of our study directly showed the benefit of using PRE herbicides for controlling the early germinating weeds, which are the most competitive against the corn. This research suggests that the application of PRE herbicide could eliminate the need for multiple use of glyphosate herbicides in corn. Moreover, the using of PRE herbicides in weed management programs will provide also alternative mode of action, which is necessary to manage glyphosate resistant weeds.

Literature Cited

Arslan, M., Uremis, I., & Uludag, A. (2006). The critical period of weed control in double-cropped soybean. *Phytoparasitica*, *34*(2), 159-166.

Bedmar, F., Manetti, P., & Monterubbianesi, G. (1999). Determination of the critical period of weed control in corn using a thermal basis. *Pesquisa Agropecuária Brasileira*, *34*(2), 188-193.

DOĞAN, M. N., Ünay, A., Boz, Ö., & Albay, F. (2004). Determination of optimum weed control timing in maize (Zea mays L.). *Turkish Journal of Agriculture and Forestry*, *28*(5), 349-354.

Evans, S. P., Knezevic, S. Z., Lindquist, J. L., Shapiro, C. A., & Blankenship, E. E. (2003). Nitrogen application influences the critical period for weed control in corn. *Weed Science*, *51*(3), 408-417.

Ganie, Z. A., Lindquist, J. L., Jugulam, M., Kruger, G. R., Marx, D. B., & Jhala, A. J. (2017). An integrated approach to control glyphosate-resistant Ambrosia trifida with tillage and herbicides in glyphosate-resistant maize. *Weed Research*, *57*(2), 112-122.

Gantoli, G., Ayala, V. R., & Gerhards, R. (2013). Determination of the critical period for weed control in corn. *Weed Technology*, *27*(1), 63-71.

Ghosheh, H. Z., Holshouser, D. L., & Chandler, J. M. (1996). The critical period of johnsongrass (Sorghum halepense) control in field corn (Zea mays). *Weed Science*, *44*(4), 944-947.

Halford, C., Hamill, A. S., Zhang, J., & Doucet, C. (2001). Critical period of weed control in no-till soybean (Glycine max) and corn (Zea mays). *Weed Technology*, *15*(4), 737-744.

Hall, M. R., Swanton, C. J., & Anderson, G. W. (1992). The critical period of weed control in grain corn (Zea mays). *Weed science*, *40*(3), 441-447.

Isik, D., Mennan, H., Bukun, B., Oz, A., & Ngouajio, M. (2006). The critical period for weed control in corn in Turkey. *Weed Technology*, *20*(4), 867-872.

Janak, T. W., & Grichar, W. J. (2016). Weed control in corn (Zea mays L.) as influenced by preemergence herbicides. *International journal of agronomy*, *2016*.

Jha, P., Kumar, V., Garcia, J., & Reichard, N. (2015). Tank mixing pendimethalin with pyroxasulfone and chloroacetamide herbicides enhances in-season residual weed control in corn. *Weed technology*, *29*(2), 198-206.

Knezevic, S. Z., & Datta, A. (2015). The critical period for weed control: revisiting data analysis. *Weed Science*, *63*(SP1), 188-202.

Knezevic, S. Z., Elezovic, I., Datta, A., Vrbnicanin, S., Glamoclija, D., Simic, M., & Malidza, G. (2013). Delay in the critical time for weed removal in imidazolinone-resistant sunflower (Helianthus annuus) caused by application of pre-emergence herbicide. *International journal of pest management*, *59*(3), 229-235.

Knezevic, S. Z., Evans, S. P., Blankenship, E. E., Van Acker, R. C., & Lindquist, J. L. (2002). Critical period for weed control: the concept and data analysis. *Weed science*, *50*(6), 773-786.

Knezevic, S. Z., Evans, S. P., & Mainz, M. (2003). Row spacing influences the critical timing for weed removal in soybean (Glycine max). *Weed Technology*, *17*(4), 666-673.

Knezevic, S. Z., Osipitan, O. A., & Scott, J. E. (2018). Sensitivity of grape and tomato to micro-rates of dicamba-based herbicides. *J. Hort*, *5*(229), 2376-0354.

Knezevic, S. Z., Streibig, J. C., & Ritz, C. (2007). Utilizing R software package for dose-response studies: the concept and data analysis. *Weed Technology*, *21*(3), 840-848.

Lamichhane, J. R., Devos, Y., Beckie, H. J., Owen, M. D., Tillie, P., Messéan, A., & Kudsk, P. (2017). Integrated weed management systems with herbicide-tolerant crops in the European Union: lessons learnt from home and abroad. *Critical reviews in biotechnology*, *37*(4), 459-475.

Mahmoodi, S., & Rahimi, A. (2009). Estimation of critical period for weed control in corn in Iran. *World Academy of Science, Engineering and Technology*, *49*, 67-72.

Norsworthy, J. K., & Oliveira, M. J. (2004). Comparison of the critical period for weed control in wide-and narrow-row corn. *Weed science*, *52*(5), 802-807.

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, *144*(1), 31-43.

Page, E. R., Tollenaar, M., Lee, E. A., Lukens, L., & Swanton, C. J. (2009). Does the shade avoidance response contribute to the critical period for weed control in maize (Zea mays)?. *Weed Research*, *49*(6), 563-571.

Singh, K., Kaur, T., Bhullar, M. S., & Brar, A. S. (2018). The Critical period for weed control in spring maize in North-West India. *Maydica*, *61*(1), 7.

Swanton, C. J., & Weise, S. F. (1991). Integrated weed management: the rationale and approach. *Weed Technology*, *5*(3), 657-663.

Tursun, N., Datta, A., Tuncel, E., Kantarci, Z., & Knezevic, S. (2015). Nitrogen application influenced the critical period for weed control in cotton. *Crop Protection*, *74*, 85-91.

Tursun, N., Datta, A., Sakinmaz, M. S., Kantarci, Z., Knezevic, S. Z., & Chauhan, B. S. (2016). The critical period for weed control in three corn (Zea mays L.) types. *Crop protection*, *90*, 59-65.

Uremis, I., Uludag, A., Ulger, A., & Cakir, B. (2009). Determination of critical period for weed control in the second crop corn under Mediterranean conditions. *African Journal of Biotechnology*, *8*(18).

Van Acker, R. C., Swanton, C. J., & Weise, S. F. (1993). The critical period of weed control in soybean [Glycine max (L.) Merr.]. *Weed Science*, *41*(2), 194-200.

Wagner, G., & Nadasy, E. (2006). Effect of pre-emergence herbicides on growth parameters of green pea. *Communications in agricultural and applied biological sciences*, *71*(3 Pt A), 809-813.

Weaver, S. E., & Tan, C. S. (1983). Critical period of weed interference in transplanted tomatoes (Lycopersicon esculentum): growth analysis. *Weed Science*, *31*(4), 476-481.

Williams, M. M. (2006). Planting date influences critical period of weed control in sweet corn. *Weed Science*, *54*(5), 928-933.

Zimdahl, R.L. (2004). *Weed crop competition: A review*, pp. 109-130. Oxford, UK, Blackwell Publishing

Table 2-1. Total monthly precipitation and average temperature from May to October in 2017 and 2018 at Concord (HAL), NE.

	Precipitation			
	2017		2018	
Month	mm	Temperature (°C)	mm	Temperature (°C)
May	94	14.4	78	18.7
June	14	22.2	370	22.7
July	39	24.2	41	22.6
August	246	19.4	27	21.6
September	49	18.0	16	18.5
October	88	12.7	59	8.7

Table 2-2. Average weed density and species composition with and without application of PRE herbicides in 2017 and 2018 at Concord (HAL), NE.

Treatment	Year	Weed species	Type	Density	Total population
				plants m^{-2}	%
NO-PRE	2017	*Abutilon theoprasti*	Broadleaf	7	1.61
		Chenopodium album	Broadleaf	341	78.57
		Amaranthus rudis	Broadleaf	83	19.12
		Seteria viridis	Grass	1	0.23
		Others		2	0.46
	2018	*Abutilon theoprasti*	Broadleaf	63	19.44
		Chenopodium album	Broadleaf	63	19.44
		Amaranthus rudis	Broadleaf	33	10.19
		Seteria viridis	Grass	164	50.62
		Others		1	0.30
ATRAZINE	2017	*Abutilon theoprasti*	Broadleaf	2	15.38
		Chenopodium album	Broadleaf	0	0
		Amaranthus rudis	Broadleaf	10	76.92
		Seteria viridis	Grass	1	7.69
		Others		0	0
	2018	*Abutilon theoprasti*	Broadleaf	48	19.35
		Chenopodium album	Broadleaf	4	1.61
		Amaranthus rudis	Broadleaf	9	3.63
		Seteria viridis	Grass	187	75.40
		Others		0	0
VERDICT-ZIDUA	2017	*Abutilon theoprasti*	Broadleaf	1	25
		Chenopodium album	Broadleaf	3	75
		Amaranthus rudis	Broadleaf	0	0
		Seteria viridis	Grass	0	0
		Others		0	0
	2018	*Abutilon theoprasti*	Broadleaf	2	15.38
		Chenopodium album	Broadleaf	0	0
		Amaranthus rudis	Broadleaf	0	0
		Seteria viridis	Grass	11	84.61
		Others		0	0

Table 2-3. Regression parameters and estimation of critical time for weed removal (CTWR) for no-PRE and PRE herbicide applications in corn.

Year	PRE Application of Herbicide	Regression Parameters (SE)[a]				CTWR[b]		
		Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
2017	NO-PRE	D (%)	99 (2.1)	46.344	< 2.2e-16 ***	157 (4)	11	V3
		I_{50} (GDD)	301 (7.7)	39.268	< 2.2e-16 ***			
	ATRAZINE	Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
		D (%)	35 (3.6)	9.7555	3.541e-10 ***	208 (21)	16	V5
		I_{50} (GDD)	554 (55.4)	10.0132	2.063e-10 ***			
	VERDICT-ZIDUA	Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
		D (%)	33 (2.3)	14.249	8.525e-14 ***	371 (16)	32	V10
		I_{50} (GDD)	606 (26.7)	22.651	< 2.2e-16 ***			
2018	NO-PRE	Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
		D (%)	14 (3.1)	4.4693	0.0001601 ***	144 (92)	11	V3
		I_{50} (GDD)	325 (82.7)	3.938	0.0006161 ***			
	ATRAZINE	Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
		D (%)	14 (4.2)	3.3953	0.002211 **	198 (60)	14	V5
		I_{50} (GDD)	545 (166.7)	3.2707	0.003022 **			
	VERDICT-ZIDUA	Parameters	Estimate (SE)	t-value	p-value	GDD (SE)	DAE	CGS
		D (%)	10 (2.3)	4.5886	0.0001182 ***	203 (43)	15	V5
		I_{50} (GDD)	541 (114.4)	4.7335	8.178e-05 ***			

[a]Parameters D and I_{50} represent maximum percentage yield loss and growing degree days at 50% yield loss (GDD), respectively.

[b]The CTWR was estimated based on GDD at 5% yield loss. DAE, days after emergence; CGS, corn growth stage.

Table 2-4. The CTWR based on 5% yield loss with and without PRE herbicide.

Year	Treatment	GDD(SE)[1]	DAE[2]	Corn Growth Stage
2017	No-PRE Herbicide	157 (4)	11	V3
	Atrazine	208 (20)	16	V5
	Verdict-Zidua	371 (16)	32	V10
2018	No-PRE Herbicide	144 (92)	11	V3
	Atrazine	198 (60)	14	V5
	Verdict-Zidua	203 (43)	15	V5

[1] GDD: Growing Degree Days

[2] DAE: Days After Emergence

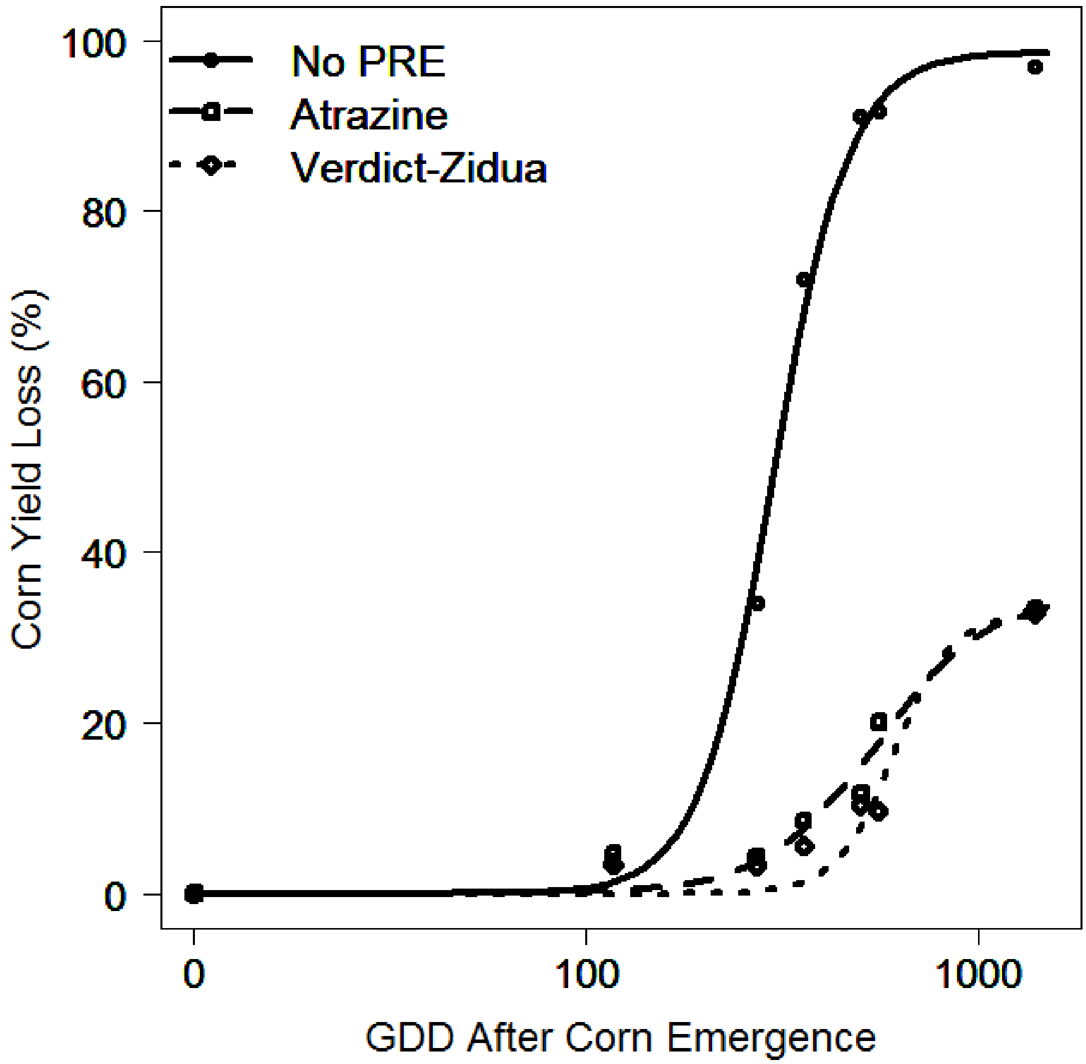

Figure 2-1. The CTWR in corn grown with and without PRE herbicide application in 2017 at Concord, NE.

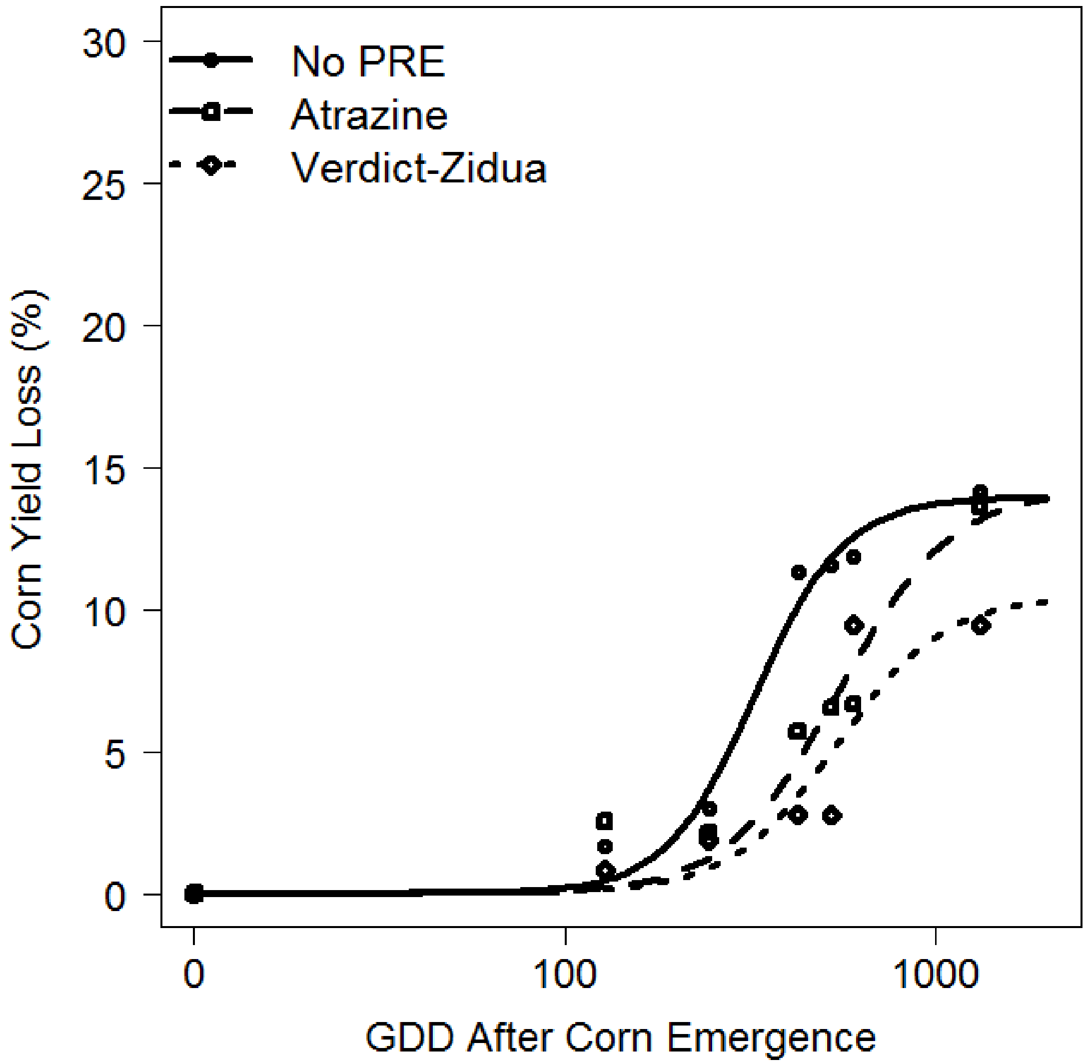

Figure 2-2. The CTWR in corn grown with and without PRE herbicide application in 2018 at Concord, NE.

CHAPTER 3:

THE EFFECTS OF TIMING OF WEED REMOVAL AND PRE HERBICIDES ON GROWTH AND YIELD OF CORN (*Zea mays* L.)

ABSTRACT

A weed control program that utilizes PRE herbicides and ensures a timely post-emergence weed removal could protect growth and yield of corn. Field study was conducted at Haskell Agricultural Laboratory, Concord, Nebraska in 2017 and 2018, with the objective to evaluate how the timing of weed removal and PRE herbicides application could influence growth and yield of glyphosate-tolerant corn. The studies were arranged in a split-plot design with three herbicide regimes (no-PRE and PRE application of two herbicides) as main plots and seven weed removal times (V3, V6, V9, V12, V15 corn growth stages as well as weed-free and weedy season long) as sub-plots in 4 replications. The two PRE herbicides were Atrazine and Verdict®-Zidua® (saflufenacil plus dimethenamid plus pyroxasulfone) in 2017 and 2018. Corn growth parameters such as plant height, leaf area per plant, leaf area index and corn plant dry weight were collected at corn tasseling stage (VT growth stage). Corn yield and yield components such as number of kernels per ear, 100 kernel weight and grain yield were collected at physiological maturity. In 2017, 5% reduction in corn dry weight occurred when weed removal was delayed until 91 GDD after emergence (V2 growth stage) without PRE herbicide, while the PRE application of Atrazine or Verdict®-Zidua® allowed corn to grow until 162 GDD (V4 growth stage) and 302 GDD (V7 growth stage) respectively, to reach the same 5% threshold. However, in 2018, the 5% corn dry weight reduction was caused by a delay in weed removal until 126 GDD after emergence (V3 growth stage) without PRE herbicide. With PRE-applied Atrazine or Verdict®-Zidua®, the 5% reduction in corn dry weight was caused by a delay in weed removal until 215 GDD (V5

growth stage) and 323 GDD (V7 growth stage), respectively. The results demonstrated that timely removal of weed was necessary to prevent yield reduction in corn.

INTRODUCTION

Corn (*Zea mays* L.) is grown in all over the world (Ranum et al., 2014). The Food and Agriculture Organization (FAO) reported that the United States of America (USA) is the top country in production of corn then followed by China and Brazil (FOASTAT, 2017). In the USA, corn was grown on an area of 33,469,080 hectares with the production of 370,960,390 tonnes and with average grain yield of 110,837 hg ha^{-1} in the USA (FOASTAT, 2017). Corn production in the USA is concentrated in the Heart-land region which is the Midwest area including Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Ohio, Nebraska, North Dakota, South Dakota, and Wisconsin. Iowa, Illinois, and Nebraska are the top corn producing states with 63,726,885 tonnes, 57,876,956 tonnes, and 45,405,405 tonnes, respectively (USDA, 2018).

Genetically modified herbicide-resistant corn crops has become the main form of corn cultivated in many nations by growers (Ranum et al. 2014) including the United States, where about 90 % of domestic corn cultivated acres are planted with herbicide-resistant seeds (Dodson L. 2019). The herbicide-resistant corn crops were quickly adopted by growers due to more suitable weed control, decrease labor and manufacturing costs, extended environmental benefits, and good points in profitability (Cao et al. 2010). Growing herbicide-resistant corn offers producers the choice, depending on the hybrid cultivated, to use glyphosate or glufosinate herbicides for in-season weed control (Zuver et al. 2006), cost reduction of weed management (Duke, S. O. 2015) and makes weed control easier (Colbach et al. 2017). The producers selected glyphosate-resistant corn crops due to the fact glyphosate made weed management less difficult and extra effective, elevated the profits, required less tillage, and did no longer avoid crop rotations (Green J. M., 2009). Glyphosate is a non-selective herbicide and used for vegetation management in the glyphosate-resistant corn crops. However, the only using of POST treatment of glyphosate might not give satisfactory control when weeds keep growing after the herbicide application (Curran et al. 1999; Hamill et al. 2000; Johnson et al. 2000; Zuver et al. 2006). In corn production, effective weed management programs are crucial as weed interference is usually the most significant factor in influencing grain yield (Rajcan and Swanton 2001). Maize is particularly susceptible to weed interference during the early stage of vegetative development, highlighting the benefits of efficient soil-applied herbicide programs preventing the development of weeds in the early season (Green 2012; Page et al. 2012). Soil-applied herbicides may decrease the population density and the competitiveness of early-emerging weeds. Resulting in a lower risk of yield reduction when the application of POST glyphosate is postponed due to weather or to control late-emerging weeds (Weaver 1991). Effective POST herbicides is important elements of integrated corn weed management; however, the effectiveness of herbicides depends on the timing of the application (Metzger et al., 2019).

The information is lacking on the influence of soil-applied herbicides and weed removal timing on the corn growth and corn yield. A greater understanding of the yield benefits of early weed removal timing and PRE herbicides application is needed to refine weed control recommendations for glyphosate-resistant corn. The objective of this study were (1) to develop weed management recommendation that considers soil applied herbicides, and (2) to determine the effects of weed removal timing and PRE herbicides on growth and yield of corn (*Zea mays* L.).

MATERIAL AND METHODS

Experimental site description and design

A field experiment was conducted in 2017 and 2018 at the Haskell Agricultural Laboratory near Concord, NE, US. The study was arranged in a split-plot design with herbicide regimes as the main plot and weed removal timings as the subplot with four replications of each treatment. The three herbicide regimes included no-PRE and PRE application of two herbicides (Atrazine or Verdict®-Zidua®). The active ingredients of Verdict plus Zidua were saflufenacil, dimethenamid, and pyroxasulfone. Verdict plus Zidua is group 14, 15 herbicides. (PPO inhibition and long-chain fatty acid inhibitor, respectively.) Atrazine was an active ingredient and Photosystem II inhibitor. This study had 21 treatments, and each treatment represents different weed removal timing. Weed removal timings were conducted at the following growth stage of corn: V3, V6, V9, V12, and V15 by POST application and hoeing for the remainder of the season. There were also season-long weed-free and weedy plots created as part of the weed removal timings. Each main plot had seven sub-plots, and individual sub-plot was 3 m wide, and 7.62 m long consisted of four corn rows. The two middle rows of each plot were used for corn data collection. The Roundup Ready corn hybrid Pioneer P0636AM 26000 seeds per acre was planted on May 16, 2017, and May 28, 2018. At the same day, after planting PRE herbicides was applied by CO_2 backpack sprayer with six nozzles boom. The nozzle type was AIXR and size was 10002. After PRE, the first application of the POST herbicide which is Roundup PowerMax was applied at V3 corn growth stage. For each of the V3 to V15 weed removal timing, weeds were allowed to grow with the crop for increasing periods of time before the weeds were removed and the crop was maintained weed-free for the remainder of the corn growing season. When the corn plants were at the V10 stage, the POST herbicide was not applied anymore. The last post application was on V9 corn growth stage. It was observed that the corn canopy cover occurred at the V10 growth stage.

Data collection

A natural infestation of velvetleaf (*Abutilon theophrasti*), common lambsquarters (*Chenopodium album* L.), green foxtail (*Seteria viridis* L.), and common waterhemp (*Amaranthus rudis* L.) were seen in the trial. Weed species were counted from a 0.5 m × 0.5 m quadrat per plot and then clipped, and dried for seven days at 50^{o}C and dry weight measured. Weed density, weed biomass, and species composition were assessed just prior to the time of weed removal.

Total of three corn plants were sampled at the tasseling stage for the leaf area index from 0.75 m^2 area in each plot. Leaves and stems dried and corn biomass recorded. At maturity, corn was hand harvested from the middle rows on November 4 and 5, 2017 and October 19, 2018. The kernels per ear, the number of rows per ear, the seed per rows, and the seeds per ear were recorded for each plots. Grain yield (bu/ac) and grain yield (kg/ha) was determined. Final corn harvest yield components included seed ear^{-1} and 100 seed weight.

Statistical analyses

Statistical analysis was performed in R (R Core Team 2018) using the base packages and the drc: Analysis of Dose-Response Curves package (Ritz et al. 2015). Data were subjected to ANOVA to test for significance of fixed effects (treatments) and random effects (replications nested in years). Data were analyzed using the four-parameter log-logistic model (Knezevic et al. 2007):

$$Y = \frac{C + (D - C)}{\{1 + exp\,[B(logX - logE)\,]\}}$$

where Y is the dependent variable (yield [kg ha−1], plants per meter of row, ears per plant, seeds per ear, or hundred-seed weight (g)); C is the lower limit; D is the upper limit; X is time expressed in GDD that corresponds with weed-removal timings and controls (weed-free control, V3, V6, V9, V12, V15, and non-treated control);
E is the ED50 (i.e., GDD where 50% response between lower and upper limit occurs; inflection point); and B is the slope of the line at the inflection point.
Air GDDs were calculated using the method described by Gilmore and Rogers (1958). For accumulation of GDD, the time of crop emergence (DAE) was used the reference point

$$GDD = \sum [(T_{max} + T_{min})/2] - T_b$$

where, T_{max} and T_{min} are daily maximum and minimum temperatures (^{o}C), respectively, and T_b is the base temperature (10 ^{o}C) for corn growth. Daily rainfall and air temperature (maximum and minimum) from May to October were obtained from the meteorology station. Total monthly precipitation and average temperature for those months in 2017 and 2018 were recorded (Table 3-1.). Growing degree days (GDD) were calculated as the mean of the daily minimum and maximum temperature minus a base temperature. The base temperature was selected as 10^{o}C. (McMaster and Wilhelm, 1997; Yang et al., 2004).

RESULTS AND DISCUSSION

Corn Yield

There was a significant impact of weed removal timing and PRE herbicides on yields of corn. The corn yields varied between years, 2017 was lower than 2018 in all treatments. In weed-free plots without application of PRE herbicide, corn yielded 11479 kg ha^{-1} in 2017 and 12987 kg ha^{-1} in 2018. Delaying weed removal timing in no-PRE plots affected the corn yield negatively. Without PRE herbicide, the corn yield in weedy season long plots were 332 and 11150 kg ha^{-1} in 2017 and 2018, respectively (Figure 3-1; Figure 3-2). The corn yield was positively influenced by application of PRE herbicides (Atrazine or Verdict®-Zidua®) in both years. In weed-free plots with PRE application of Atrazine, the corn yield was 11022 and 13228 kg ha^{-1} in 2017 and 2018, respectively. For atrazine in weedy season long plots, the corn yield was 7320 and 11431 kg ha^{-1} in 2017 and 2018, respectively (Figure 3-1; Figure 3-2).

In weed-free plots with PRE application of Verdict®-Zidua®, the corn yield was 10825 and 13110 kg ha^{-1} in 2017 and 2018, respectively. The application of Verdict®-Zidua® in weedy season long plots yielded 7257 and 11868 kg ha^{-1} in 2017 and 2018, respectively (Figure 3-1; Figure 3-2).

A 5% reduction in corn yield was caused by a delay in weed removal until 142 GDD (V3 stage) or 84 GDD (V2stage), without PRE herbicide in 2017 and 2018, respectively (Table 3-2). With PRE-applied Atrazine, a 5% reduction in corn yield was caused by a delay in weed removal until 204 GDD (V5 stage) or 135 GDD (V3 stage) in 2017 and 2018, respectively. With PRE-applied Verdict®-Zidua®, a 5% reduction in corn yield was caused by a delay in weed removal until 393 GDD (V10 stage) or 179 GDD (V4-stage) in 2017 and 2018, respectively (Table 3-2).

Corn Yield Components

There was an impact of weed removal timing and PRE herbicides on the number of kernels per ear and hundred-seed weight. That was especially the case in 2017 compared to 2018. That was likely due to the lack of soil moisture resulting in competition for water between early emergence weeds and corn plants in the plots where no-PRE herbicide was applied in 2017. It caused the corn plant become weak in the plots where weed removal timing was late or weedy season-long when no PRE herbicide was applied. The number of kernels per ear varied between years, 2017 was lower than 2018 in all treatments. The number of kernels per ear ranged from 590 to 638 in weed-free plots compared to 5 to 577 in weedy season long plots in 2017 corn growing season (Figure 3-3; Figure 3-4).

Without PRE herbicides, the number of kernels per ear averaged 590 and 597 in 2017 and 2018, respectively, in weed-free plots compared to 5 and 542 in 2017 and 2018, respectively in weedy season long plots (Figure 3-3; Figure 3-4).

With PRE-applied Atrazine in weed-free plots, the number of kernels per ear was 638 and 582 in 2017 and 2018, respectively whereas the number of kernels per ear was 577 and 551 in 2017 and 2018, respectively, in weedy season long plots (Figure 3-3; Figure 3-4).

The number of kernels per ear averaged 603 and 607 in 2017 and 2018, respectively, in weed-free plots where Verdict®-Zidua® was applied PRE. Similar to weed-free plots, the application of Verdict®-Zidua® in weedy season long plots have 573 and 597 kernels per ear in 2017 and 2018, respectively (Figure 3-3; Figure 3-4). Similarly to CTWR, the 5% reduction in the number of kernels per ear was caused by a delay in weed removal until 235 GDD (V5 stage) or 193 GDD (V5 stage), without PRE herbicide in 2017 and 2018, respectively. With PRE-applied Atrazine, a 5% reduction in corn yield was caused by a delay in weed removal until 273 GDD (V6 stage) or 252 GDD (V6 stage) in 2017 and 2018, respectively (Table 3-3).

The corn hundred-seed weight ranged from 32 to 36 grams in weed-free plots whereas there was only 5 to 31 in weedy season long plots in 2017 (Figure 3-5). In 2018, the corn hundred-seed weight was around 30 grams in weed-free plots while corn hundred-seed weight ranged 24 to 30 grams in weedy season long plots based on the treatment regimes (Figure 3-6).

Without application of PRE herbicides, the corn hundred-seed weight averaged 36 grams and 30 grams in 2017 and 2018, respectively, in weed-free plots. However, the corn hundred-seed weight decreased in weedy season long plots without PRE herbicides by 5 grams and 24 grams in 2017 and 2018, respectively (Figure 3-5; Figure 3-6). With PRE-applied Atrazine in weed-free plots, the corn hundred-seed weight was 32 and 30 grams in 2017 and 2018, respectively whereas the corn hundred-seed weight was around 30 grams in 2017 and 2018, respectively, in weedy season long plots (Figure 3-5; Figure 3-6).

The corn hundred-seed weight averaged 32 and 30 grams in 2017 and 2018, respectively, in weed-free plots where Verdict®-Zidua® was applied PRE. Similar to weed-free plots, the application of Verdict®-Zidua® in weedy season long plots had 30 around 30 grams corn hundred-seed weight in 2017 and 2018, respectively (Figure 3-5; Figure 3-6).

Similarly to CTWR, a 5% reduction in corn hundred-seed weight was caused by a delay in weed removal until 313 GDD (V7 stage) or 629 GDD (V15 stage), without PRE herbicide in 2017 and 2018, respectively. With PRE-applied Atrazine and Verdict Zidua, the corn seed weight was protected (Table 3-4).

Corn Leaf Area Index (LAI)

Corn leaf area measurements were taken at corn tasseling (VT) stage. Greater corn leaf area index (LAI) was observed in the application of PRE herbicides (Atrazine or Verdict®-Zidua®) in both years. Corn leaf area index in weed-free treatments was higher in the application of PRE herbicides (2.3) than in no-PRE herbicides (1.7) in 2017 (Figure 3-7).

The 2018 corn leaf area index (LAI) was higher than 2017 ones. In 2018, LAI ranged from 3.4 to 3.7 in weed-free treatments based on the herbicide regimes (Figure 3-8). The higher leaf area index was most likely due to the rainfall (370 mm) i.e. corn was well supplied with rainfall in June in the early corn growing season in 2018 (Table 3-1.). A 50% reduction in the corn leaf area index was caused by a delay in weed removal until 278 GDD (V6 stage) or 491 GDD (V11 stage), without PRE herbicide in 2017 and 2018, respectively. With PRE-applied Atrazine, a 50% reduction in corn leaf area index was caused by a delay in weed removal until 465 GDD (V11 stage) or 481 GDD (V11 stage) in 2017 and 2018, respectively (Table 3-5). The PRE-applied Verdict®-Zidua® did not cause any reduction of corn leaf area index in 2017 and 2018 corn growing season (Figure 3-7; Figure 3-8; Table 3-5).

Corn Biomass

A 5% reduction in corn dry weight was caused by a delay in weed removal until 91 GDD (V2 growth stage) to 126 GDD after corn emergence (V3 growth stage) without PRE herbicide in 2017 and 2018, respectively. However, with PRE-applied Atrazine, 5% reduction in corn dry weight occurred when weed removal was delayed until 162 GDD (V4 growth stage) to 215 GDD (V5 growth stage) in 2017 and 2018, respectively whereas the PRE application of Verdict®-Zidua® allowed corn to grow until 302 GDD (V7 growth stage) and 323 GDD (V7) respectively, to reach the same 5% threshold in 2017 and 2018, respectively (Figure 3-9; Figure 3-10; Table 3-6).

Corn Height

Corn height was recorded at tasseling (VT) stage. In general, corn plants were significantly shorter in plots without herbicides compared to the ones grown with PRE herbicides. For example, in weedy plots, the corn height averaged 87 cm without PRE herbicides compared to 200 cm and 214 cm in the plots applied with PRE herbicides Atrazine and Verdict-Zidua, respectively in 2017. Similarly, without PRE herbicide the corn plants were shorter in weed free plots than the ones applied with PRE herbicides (Figure 3-11).

Corn height in weed-free plots was higher than in weedy season long plots without PRE herbicides (eg. 185 cm and 87 cm respectively, in 2017). A 5% reduction in corn height was caused by a delay in weed removal until 199 GDD (V5 stage) or 221 GDD (V5 stage), without PRE herbicide in both, the 2017 and 2018, respectively. (Figure 3-11; Figure 3-12; Table 3-7).

However, delaying time for weed removal in PRE-applied Atrazine affected the corn plant height in 2018. A 5% reduction in corn plant height was caused by a delay in weed removal until 356 GDD (V8 stage) in 2018 with PRE-applied Atrazine (Table 3-7). The corn plant height was kept in the same level through corn growing season by PRE-applied Verdict®-Zidua® in 2017 and 2018 corn (Figure 3-11; Figure 3-12; Table 3-7).

CONCLUSION

Delay in weed removal timing significantly reduced leaf area index, corn dry weight, number of kernels per ear, and yield of corn especially in no-PRE treatment plots. A 50% reduction in shoot dry weight occurred when weed removal was delayed until 242 GDD after corn emergence without PRE herbicide, and 435 GDD with PRE application of Atrazine, and 497 GDD with PRE application of Verdict-Zidua in 2017. The number of kernels per ear was reduced by 50% when weed removal was delayed until 357 GDD without PRE herbicide application in 2017. Weed interference reduced hundred-seed weight in no-PRE plots whereas there was no significant reduction in plots treated by PRE-applied herbicides. For example, hundred-seed weight was reduced by 5% when weed removal was delayed until 313 GDD (V7 stage) or 629 GDD (V15 stage), without PRE herbicide in 2017 and 2018, respectively.

These results clearly demonstrated that application of PRE herbicides and timely removal of weed was necessary to protect growth and yield of corn. The use of PRE herbicide also protected the number of kernels per ear, hundred-seed weight, corn plant height, dry weight and leaf area index. PRE application of herbicide could delay the need for POST application of glyphosate for weed control in corn to protect crop yield and help in managing weed resistance.

Literature Cited

Cao, M., Sato, S. J., Behrens, M., Jiang, W. Z., Clemente, T. E., & Weeks, D. P. (2010). Genetic engineering of maize (Zea mays) for high-level tolerance to treatment with the herbicide dicamba. *Journal of agricultural and food chemistry*, *59*(11), 5830-5834.

Colbach, N., Fernier, A., Le Corre, V., Messéan, A., & Darmency, H. (2017). Simulating changes in cropping practises in conventional and glyphosate-tolerant maize. I. Effects on weeds. *Environmental Science and Pollution Research, 24*(12), 11582-11600.

Curran, W. S., D. D. Lingenfelter, and E. L. Werner. 1999. Glyphosate versus glufosinate: what have we learned? Proc. North Cent. Weed Sci. Soc. 54:105–106.

Dodson, Laura. "Recent Trends in GE Adoption." *USDA ERS - Recent Trends in GE Adoption*, 18 Sept. 2019, www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx.

Duke, S. O. (2015). Perspectives on transgenic, herbicide-resistant crops in the United States almost 20 years after introduction. *Pest management science*, *71*(5), 652-657.

[FAOSTAT] Food and agriculture organization of the United Nations (2017). http://www.fao.org/faostat/en/#data/QC Accessed: September 22, 2019

[FAOSTAT] Food and agriculture organization of the United Nations (2017). http://www.fao.org/faostat/en/#data/QC/visualize Accessed: September 22, 2019

Green, J. M. (2009). Evolution of glyphosate-resistant crop technology. *Weed Science*, *57*(1), 108-117.

Green, J. M. (2012). The benefits of herbicide-resistant crops. *Pest management science*, *68*(10), 1323-1331.

Hamill, A., S. Z. Knezevic, K. Chandler, P. H. Sikkema, F. J. Tardif, A. Shrestha, and C. J. Swanton. 2000. Weed control in glufosinate-resistant corn (*Zea mays*). Weed Technol. 14:578–585.

Johnson, W. G., P. R. Bradley, S. E. Hart, M. L. Buesinger, and R. E. Massey. 2000. Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays* L.). Weed Technol. 14:57–65.

Metzger, B. A., Soltani, N., Raeder, A. J., Hooker, D. C., Robinson, D. E., & Sikkema, P. H. (2019). Influence of application timing and herbicide rate on the efficacy of tolpyralate plus atrazine. *Weed Technology*, *33*(3), 448-458.

Page, E. R., Cerrudo, D., Westra, P., Loux, M., Smith, K., Foresman, C., Wright, H., & Swanton, C. J. (2012). Why early season weed control is important in maize. *Weed Science*, *60*(3), 423-430.

Rajcan, I., & Swanton, C. J. (2001). Understanding maize–weed competition: resource competition, light quality and the whole plant. *Field Crops Research*, *71*(2), 139-150.

Ranum, P., Peña-Rosas, J. P., & Garcia-Casal, M. N. (2014). Global maize production, utilization, and consumption. *Annals of the New York Academy of Sciences*, *1312*(1), 105-112.

[USDA] United States Department of Agriculture National Statistics Service (2019) Quick stats. https://quickstats.nass.usda.gov/results/51C92D6D-D2AB-3D62-BBDD-ED81F5810A51 Accessed: September 29, 2019

[USDA] United States Department of Agriculture National Statistics Service (2019) Quick stats. https://quickstats.nass.usda.gov/results/6B00E965-2846-3B12-AAD5-3CE867DE9758 Accessed: September 29, 2019

[USDA] United States Department of Agriculture National Statistics Service (2019)

Quick stats. https://quickstats.nass.usda.gov/results/03E0C0BD-F90D-38D7-9BCD-BE268D426EE8 Accessed: September 29, 2019

[USDA] United States Department of Agriculture National Statistics Service (2018) Quick stats. https://quickstats.nass.usda.gov/results/03BE552F-DC57-3EB6-800D-49778285840D Accessed: September 20, 2019

[USDA] United States Department of Agriculture National Statistics Service (2018) Quick stats. https://quickstats.nass.usda.gov/results/1C349AEE-99B9-3E07-846F-9809E4F53472 Accessed: September 20, 2019

[USDA] United States Department of Agriculture National Statistics Service (2018) Quick stats. https://quickstats.nass.usda.gov/results/95553B48-5199-35E3-B84F-62D20FA8C70C Accessed: September 20, 2019

Zuver, K. A., Bernards, M. L., Kells, J. J., Sprague, C. L., Medlin, C. R., & Loux, M. M. (2006). Evaluation of postemergence weed control strategies in herbicide-resistant isolines of corn (Zea mays). *Weed technology*, *20*(1), 172-178.

Table 3-1. Total monthly precipitation and average temperature from May to October in 2017 and 2018 at Concord (HAL), NE.

	Precipitation			
	2017		2018	
Month	mm	Temperature (°C)	mm	Temperature (°C)
May	94	14.4	78	18.7
June	14	22.2	370	22.7
July	39	24.2	41	22.6
August	246	19.4	27	21.6
September	49	18.0	16	18.5
October	88	12.7	59	8.7

Table 3-2. The 5% yield reduction as a result of delayed weed removal with and without PRE herbicide in 2017 and 2018 at Concord (HAL), NE.

Year	**Treatment**	**GDD(SE)[1]**	**DAE[2]**	**Corn Growth Stage**
2017	No PRE Herbicide	142 (4)	11	V3
	Atrazine	204 (58)	16	V5
	Verdict-Zidua	393 (25)	34	V10
2018	No PRE Herbicide	84 (30)	6	V2
	Atrazine	135 (44)	11	V3
	Verdict-Zidua	179 (63)	13	V4

[1]GDD, growing degree days; SE, standard error;

[2] DAE, days after corn emergence.

Table 3-3. The 5% reduction in number of kernels per ear as a result of delayed weed removal with and without PRE herbicide application in 2017 and 2018 at Concord (HAL), NE.

Year	**Treatment**	**GDD(SE)[1]**	**DAE[2]**	**Corn Growth Stage**
2017	No PRE Herbicide	235 (11)	19	V5
	Atrazine	273 (82)	22	V6
	Verdict-Zidua	-	-	-
2018	No PRE Herbicide	193 (26)	14	V5
	Atrazine	252 (100)	20	V6
	Verdict-Zidua	259 (71)	20	V6

[1]GDD, growing degree days; SE, standard error;

[2] DAE, days after corn emergence.

Table 3-4. The 5% reduction in corn hundred-seed weight as a result of delayed weed removal with and without PRE herbicide application in 2017 and 2018 at Concord (HAL), NE.

Year	Treatment	GDD(SE)[1]	DAE[2]	Corn Growth Stage
2017	No PRE Herbicide	313 (48)	25	V7
	Atrazine	-	-	-
	Verdict-Zidua	-	-	-
2018	No PRE Herbicide	629 (192)	47	V15
	Atrazine	-	-	-
	Verdict-Zidua	-	-	-

[1]GDD, growing degree days; SE, standard error;

[2] DAE, days after corn emergence.

Table 3-5. Regression parameter showing 50% reduction in corn leaf area index (LAI) for no-PRE and PRE herbicide applications in corn.

Year	PRE Application of Herbicide	Regression Parameter (SE)[a]			
		Parameter	Estimate (SE)	t-value	p-value
2017	No-PRE	I_{50} (GDD)	278 (21)	13.395	6.566e-13 ***
	Atrazine	I_{50} (GDD)	465 (126)	3.6866	0.001371 **
	Verdict-Zidua	I_{50} (GDD)	8.3355e+03	NA	NA
2018	No-PRE	I_{50} (GDD)	491 (146)	3.3625	0.002585 **
	Atrazine	I_{50} (GDD)	481 (79)	6.0764	2.824e-06 ***
	Verdict-Zidua	I_{50} (GDD)	3.5608e+03	NA	NA

[a]Parameter I_{50} represent at 50% loss by showing growing degree days (GDD).

Table 3-6. The 5% corn dry weight reduction as a result of delayed weed removal with and without PRE herbicide in 2017 and 2018 at Concord (HAL), NE.

Year	**Treatment**	**GDD(SE)[1]**	**DAE[2]**	**Corn Growth Stage**
2017	No PRE Herbicide	91 (7)	8	V2
	Atrazine	162 (34)	13	V4
	Verdict-Zidua	302 (93)	25	V7
2018	No PRE Herbicide	126 (75)	10	V3
	Atrazine	215 (76)	15	V5
	Verdict-Zidua	323 (93)	26	V7

[1]GDD, growing degree days; SE, standard error; [2] DAE, Days after corn emergence.

Table 3-7. The 5% corn plant height reduction as a result of delayed weed removal with and without PRE herbicide in 2017 and 2018 at Concord (HAL), NE.

Year	**Treatment**	**GDD(SE)**[1]	**DAE**[2]	**Corn Growth Stage**
2017	No PRE Herbicide	199 (10)	18	V5
	Atrazine	-	-	-
	Verdict-Zidua	-	-	-
2018	No PRE Herbicide	221 (55)	6	V5
	Atrazine	356 (66)	11	V8
	Verdict-Zidua	-	-	-

[1]GDD, growing degree days; SE, standard error;

[2] DAE, days after corn emergence.

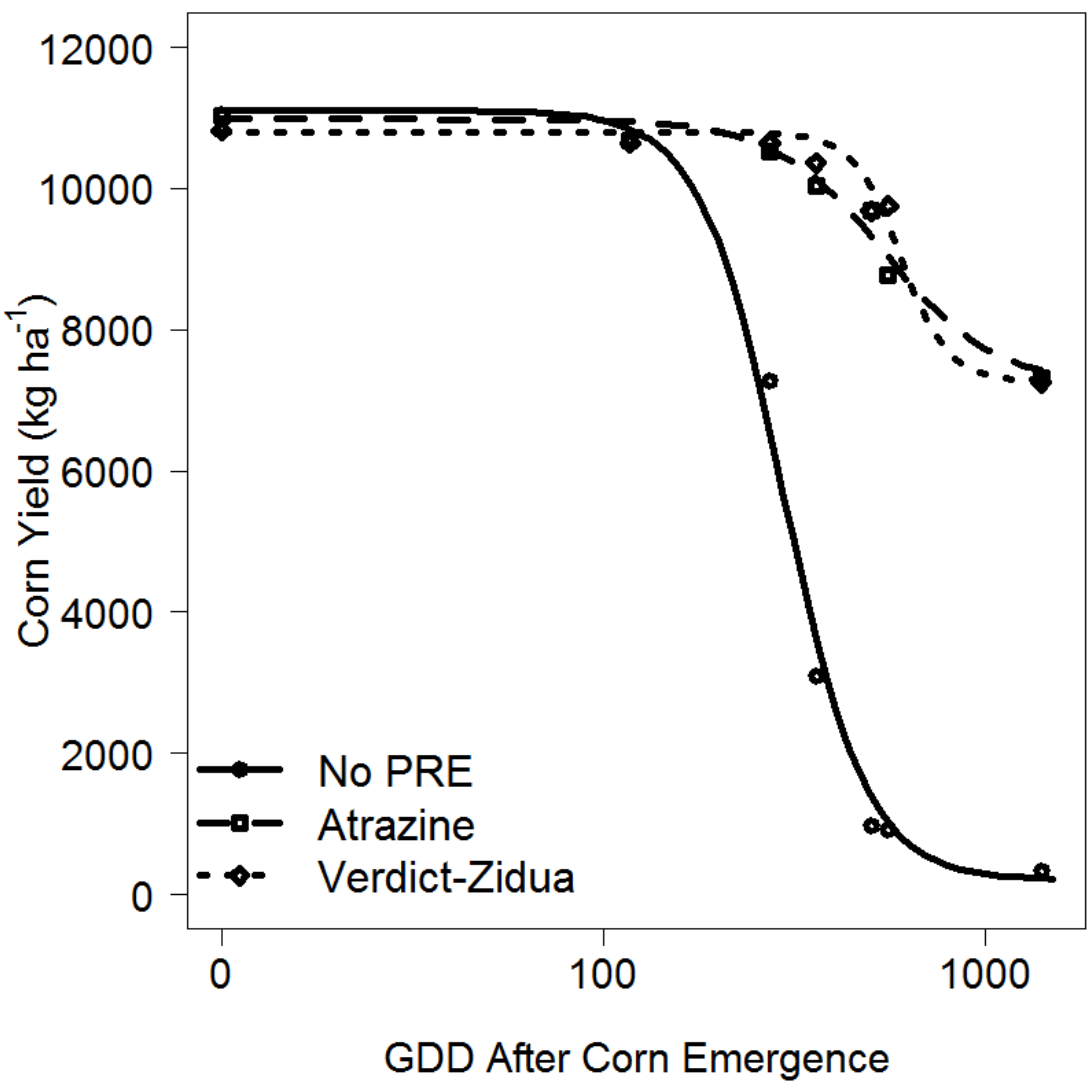

Figure 3-1. Corn yield (kg/ha) for no-PRE and PRE herbicide applications in 2017 at Concord, NE.

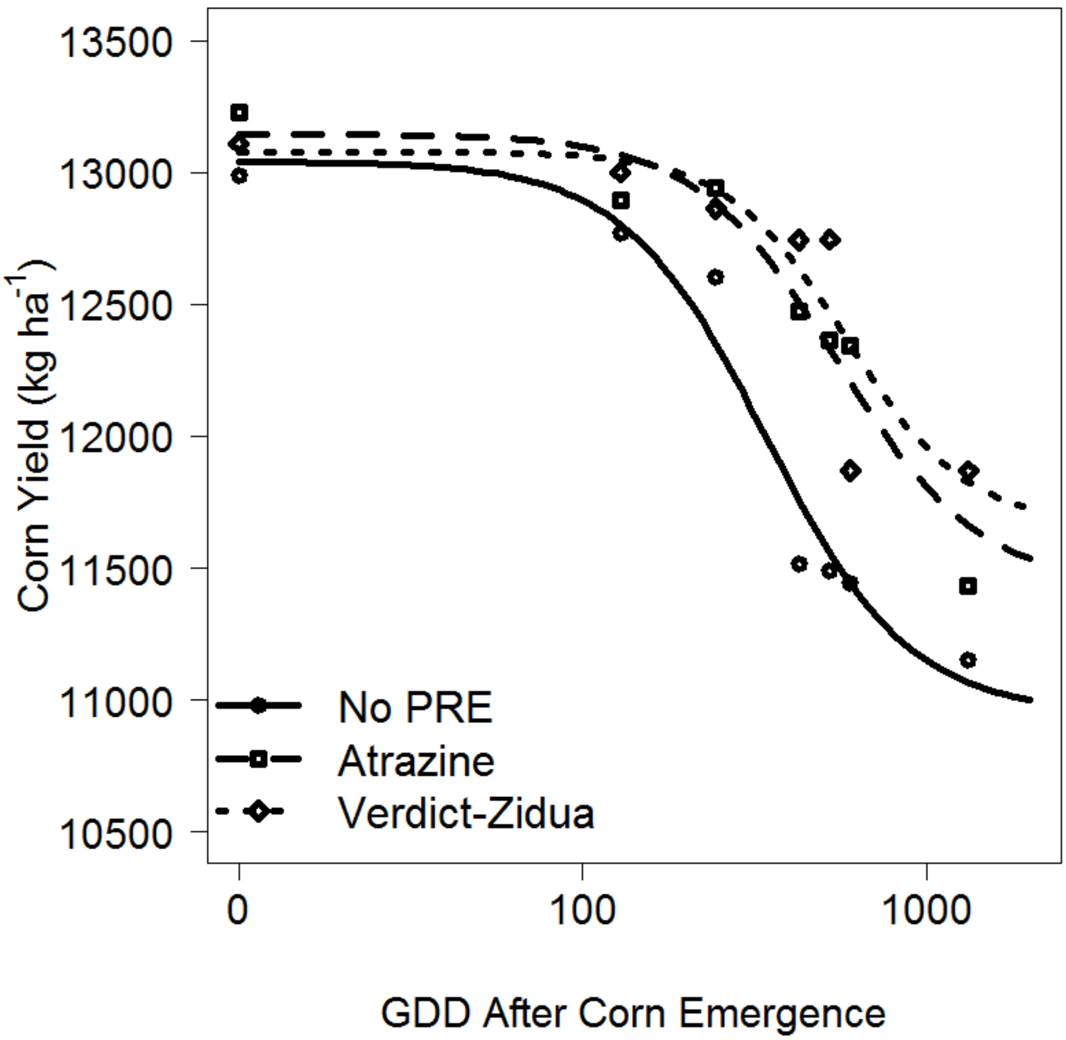

Figure 3-2. Corn yield (kg/ha) for no-PRE and PRE herbicide applications in 2018 at Concord, NE.

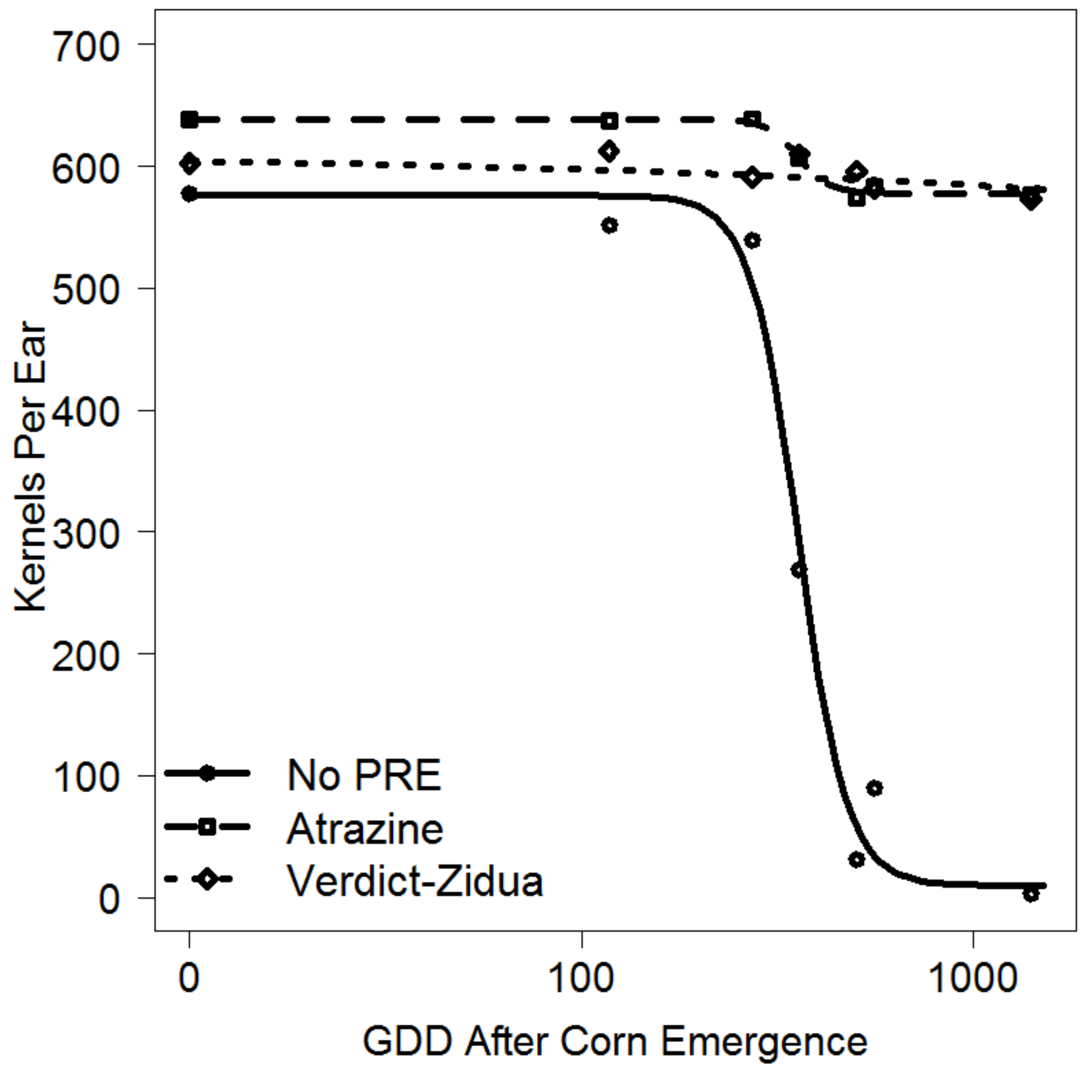

Figure 3-3. Kernels per ear for no-PRE and PRE herbicide applications in 2017 at Concord, NE.

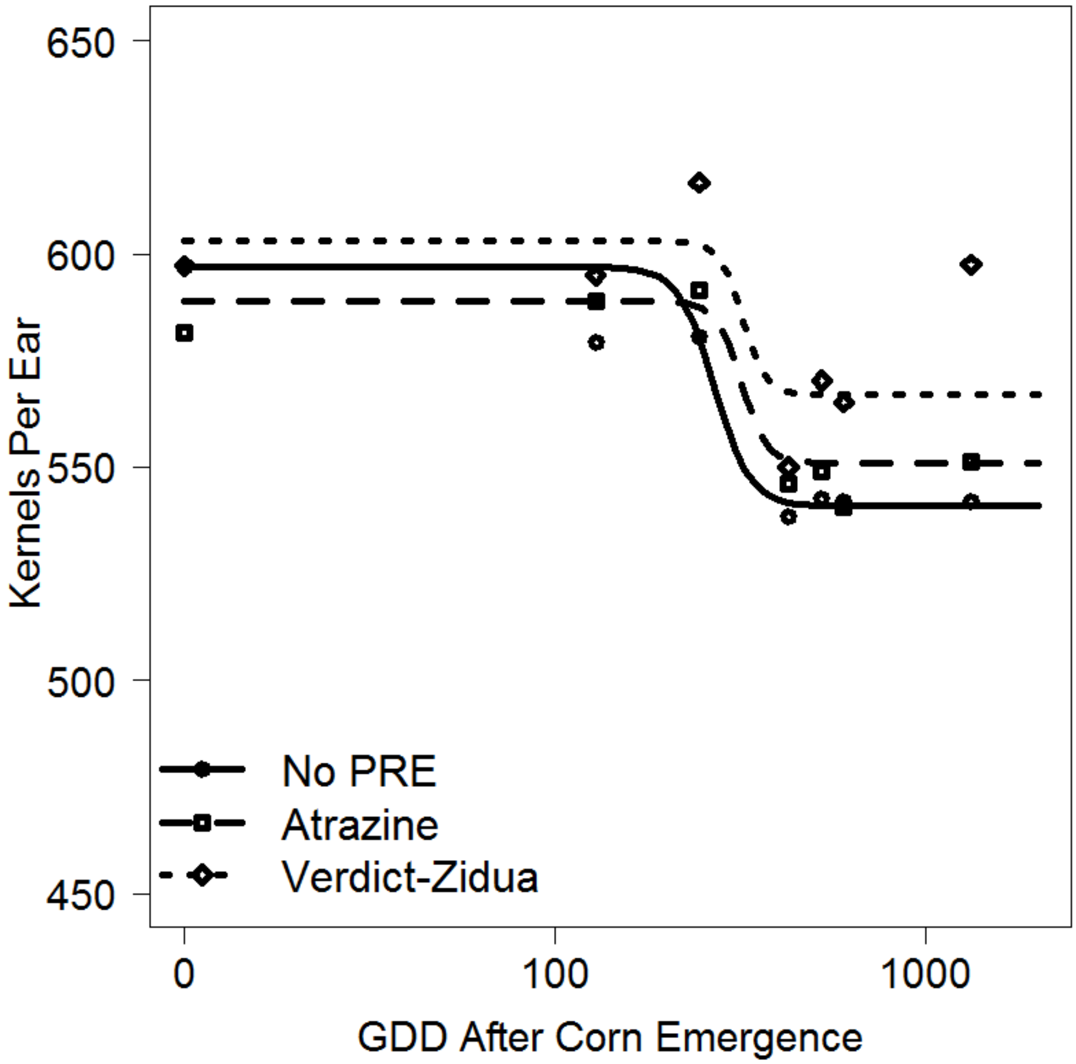

Figure 3-4. Kernels per ear for no-PRE and PRE herbicide applications in 2018 at Concord, NE.

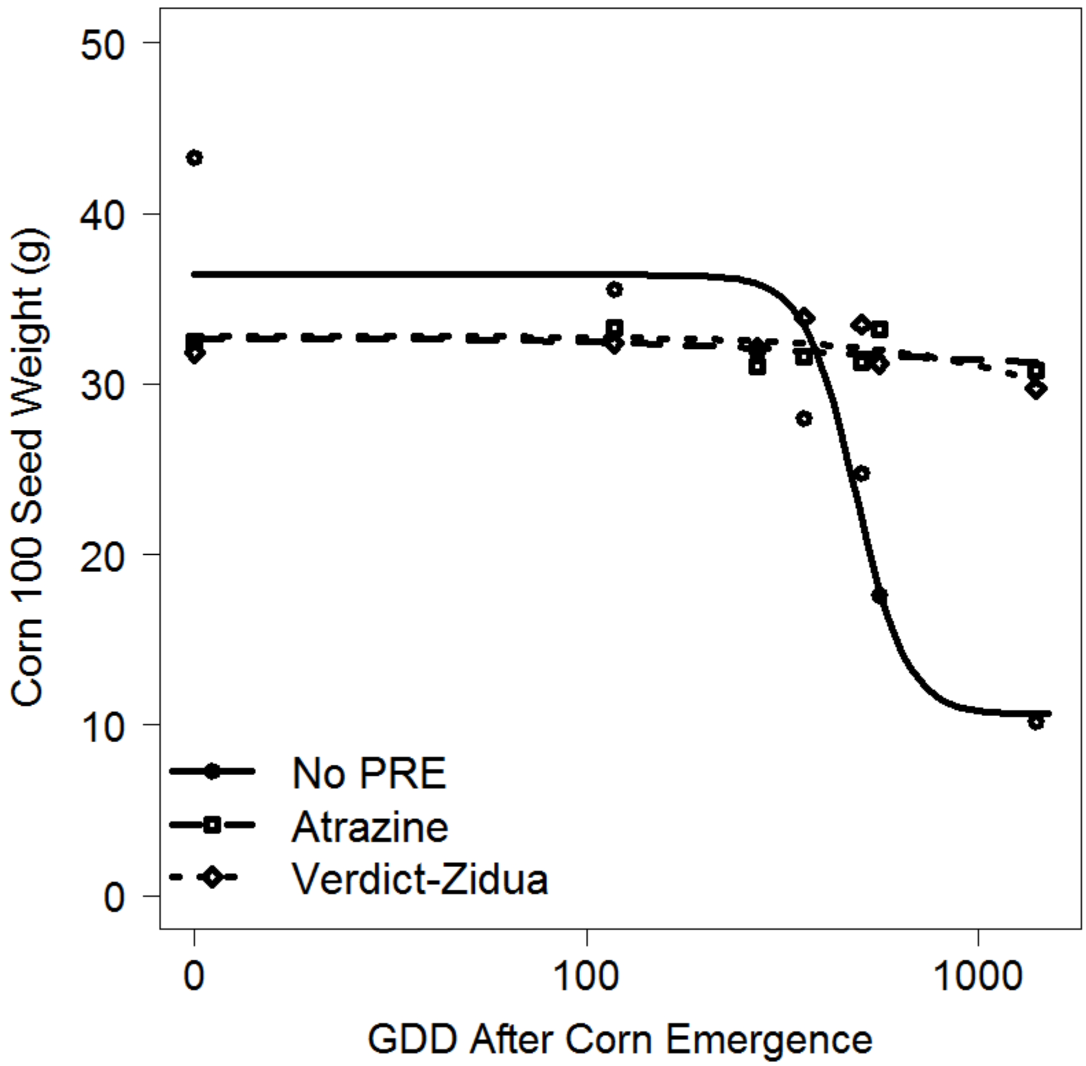

Figure 3-5. Corn 100 seed weight with and without PRE herbicide application in 2017 at Concord, NE.

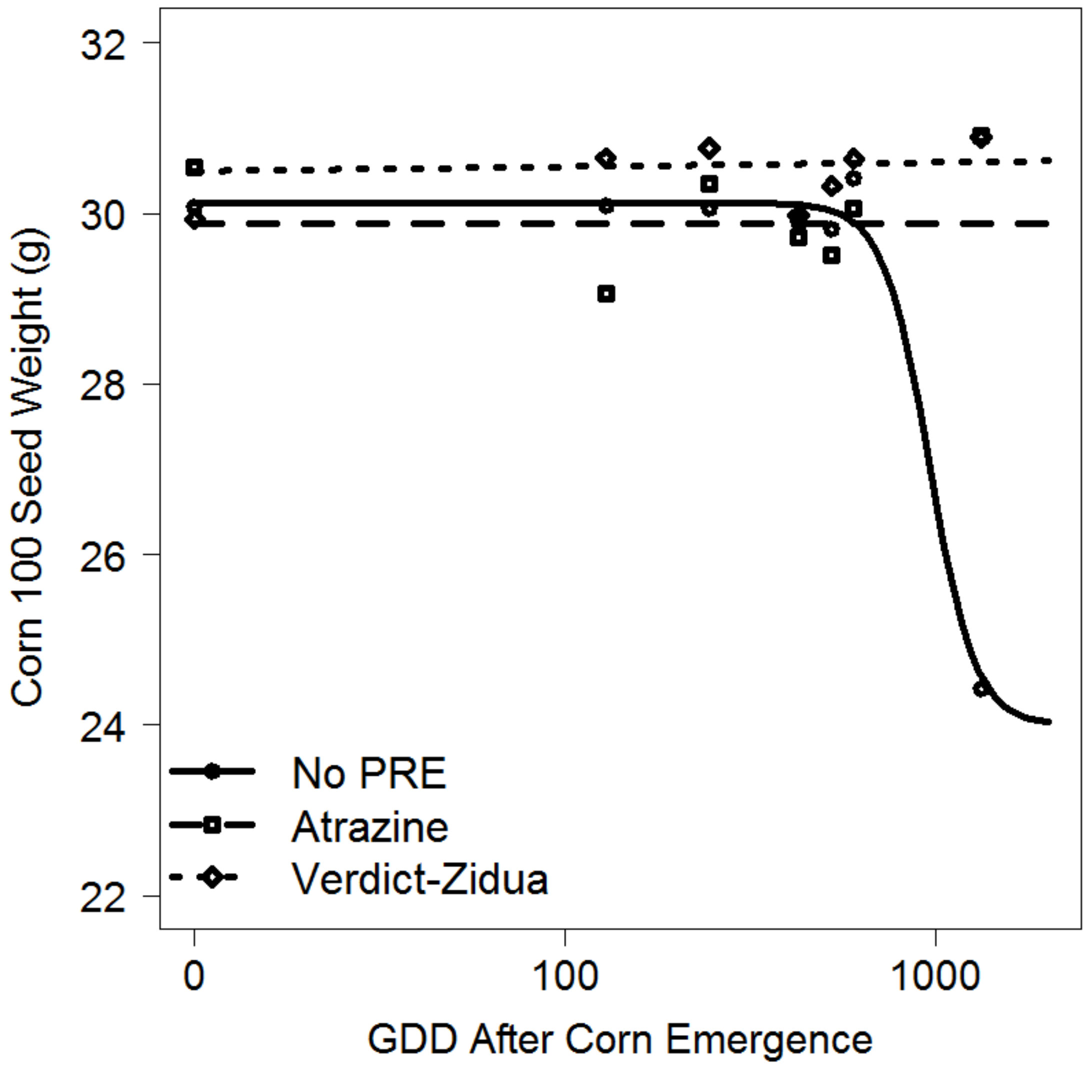

Figure 3-6. Corn 100 seed weight with and without PRE herbicide application in 2018 at Concord, NE.

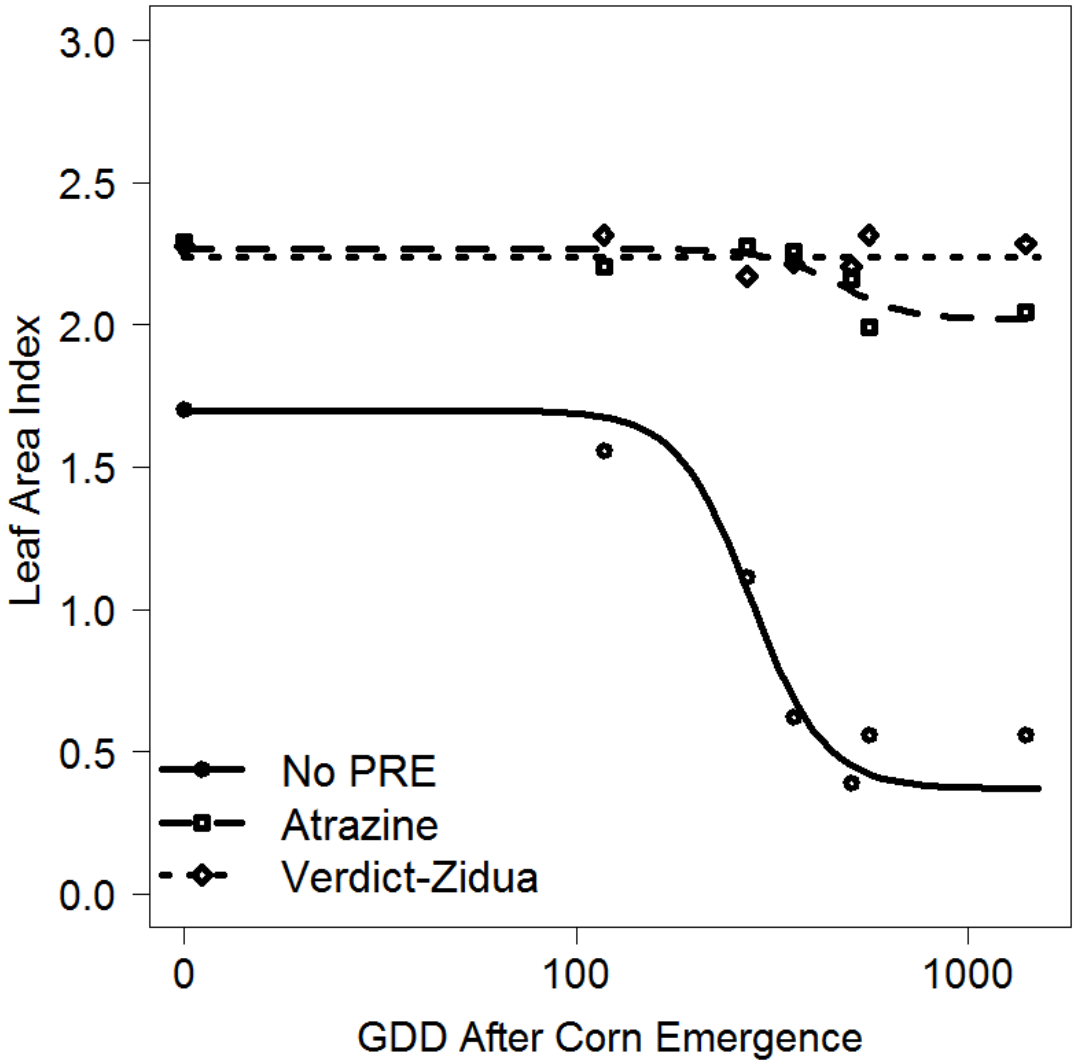

Figure 3-7. Corn leaf area index at corn tasseling (VT) stage for no PRE and PRE herbicide applications in 2017 at Concord, NE.

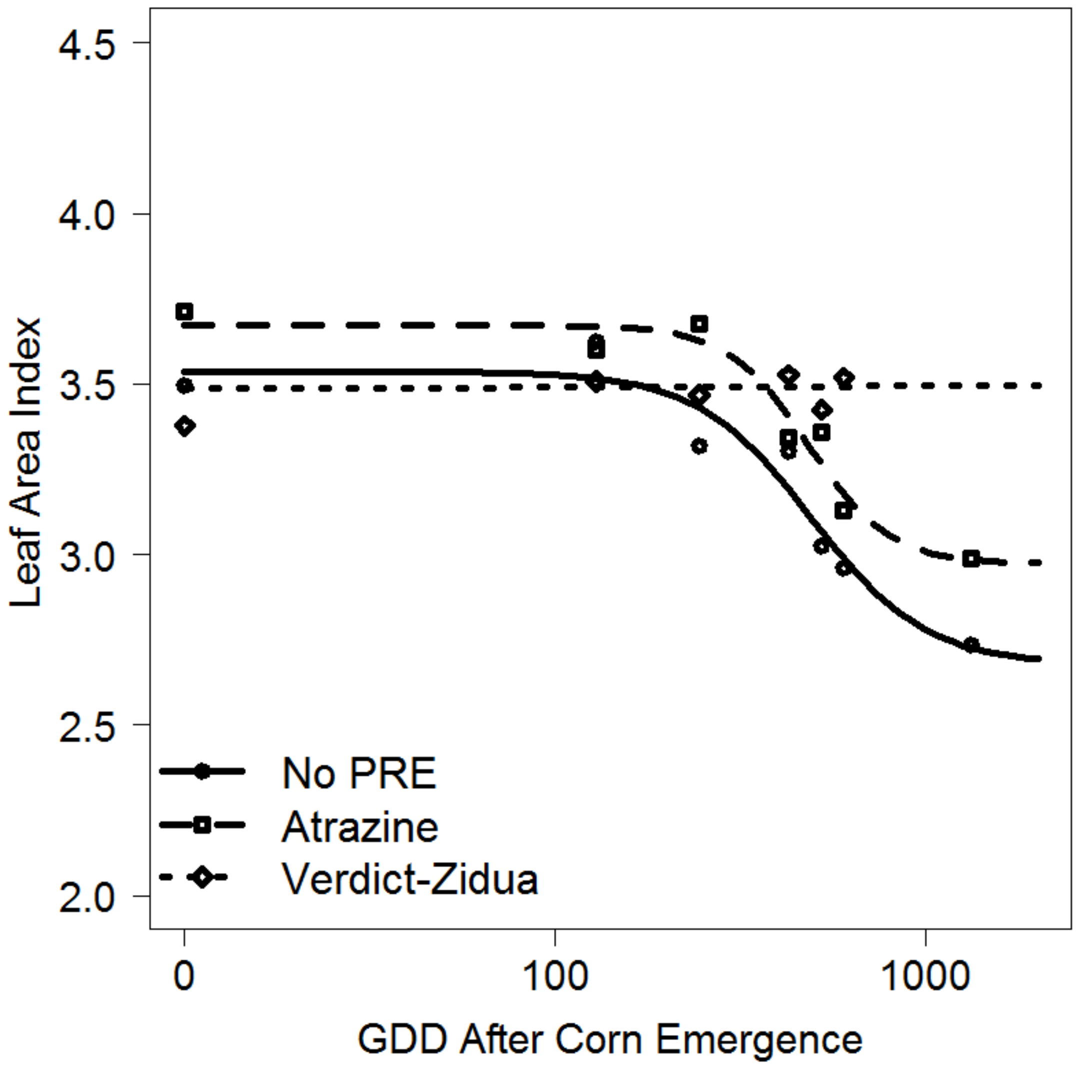

Figure 3-8. Corn leaf area index at corn tasseling (VT) stage for no PRE and PRE herbicide applications in 2018 at Concord, NE.

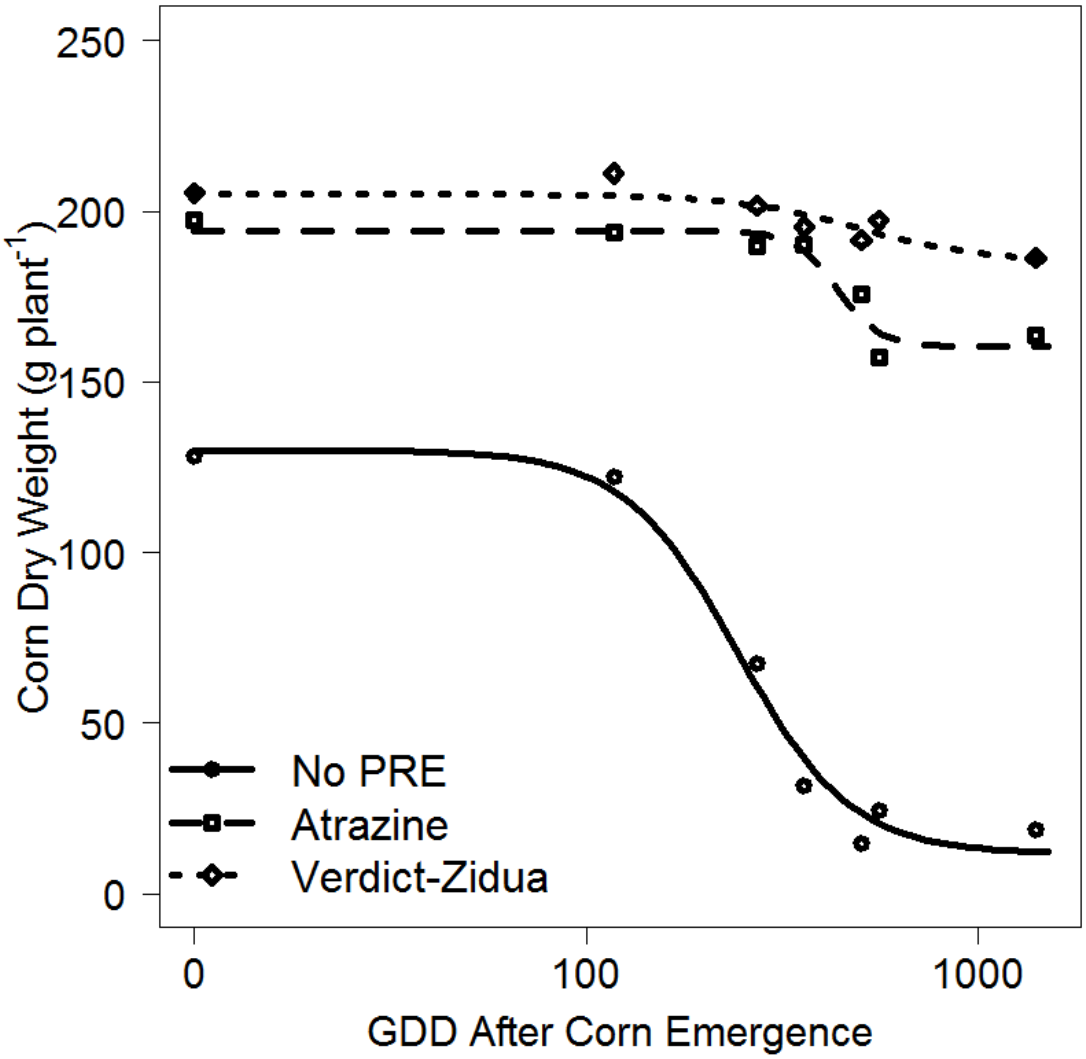

Figure 3-9. Corn dry weight with and without PRE herbicide applications in 2017 at Concord, NE.

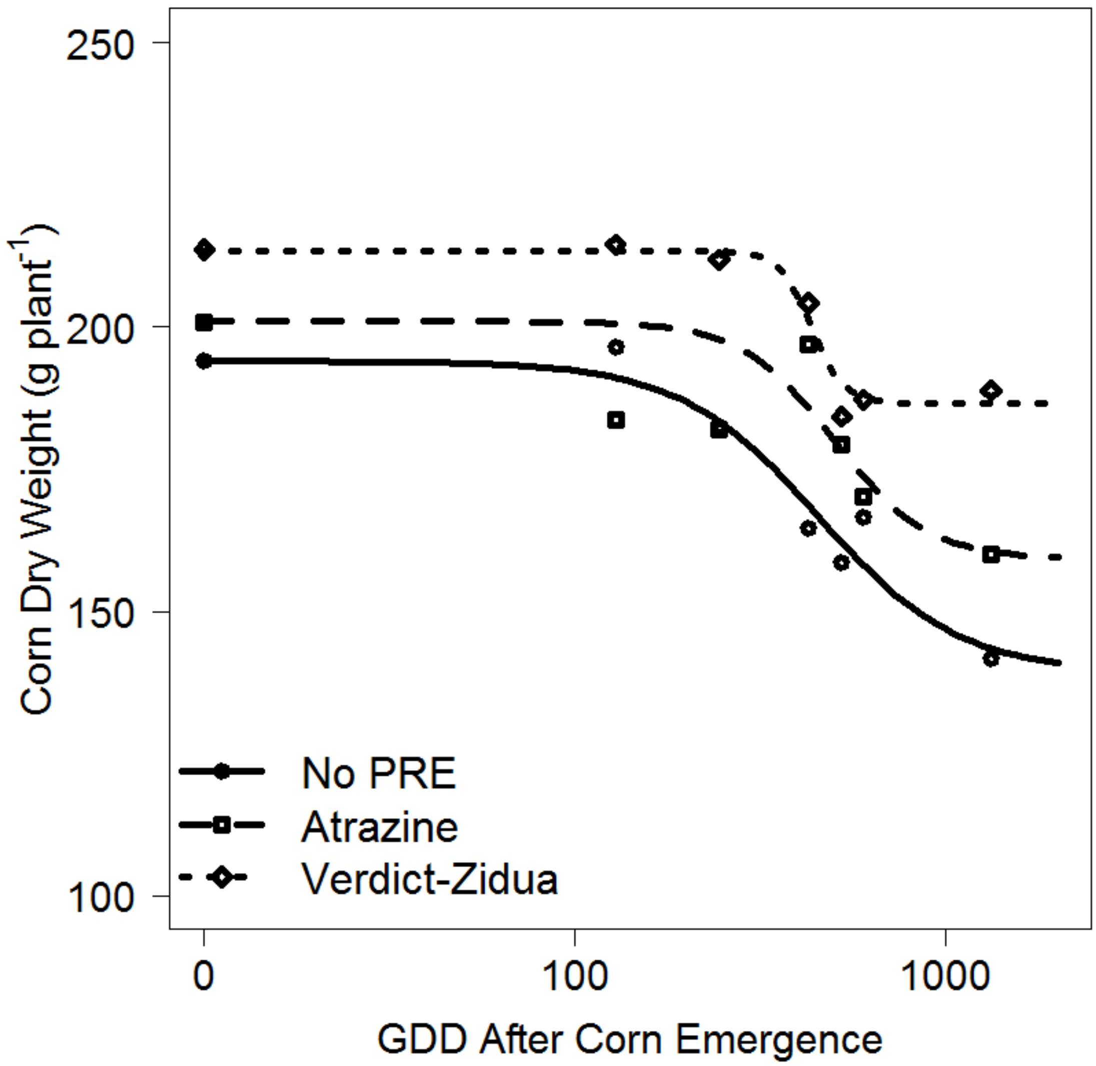

Figure 3-10. Corn dry weight with and without PRE herbicide applications in 2018 at Concord, NE.

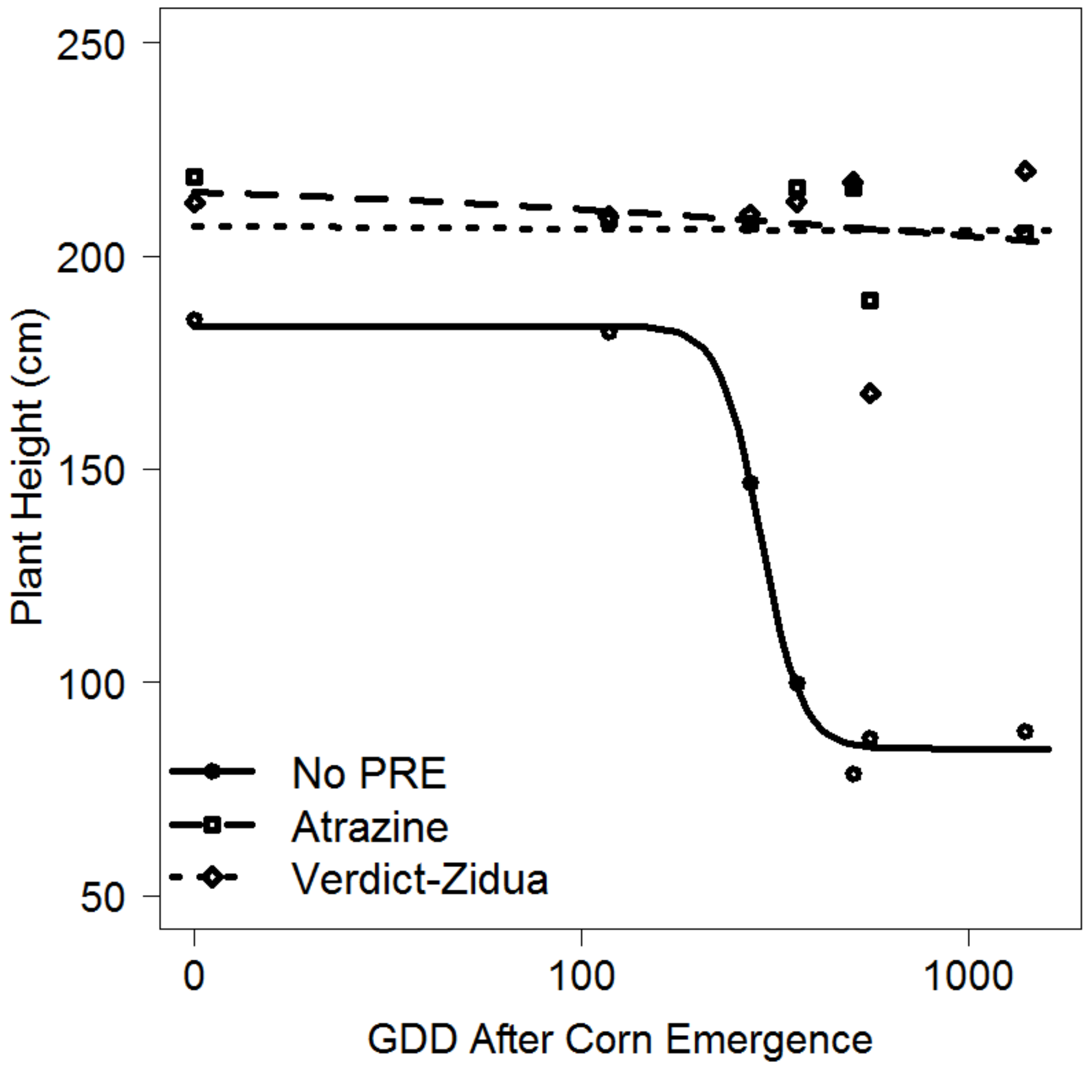

Figure 3-11. Corn plant height for no PRE and PRE herbicide applications in 2017 at Concord, NE.

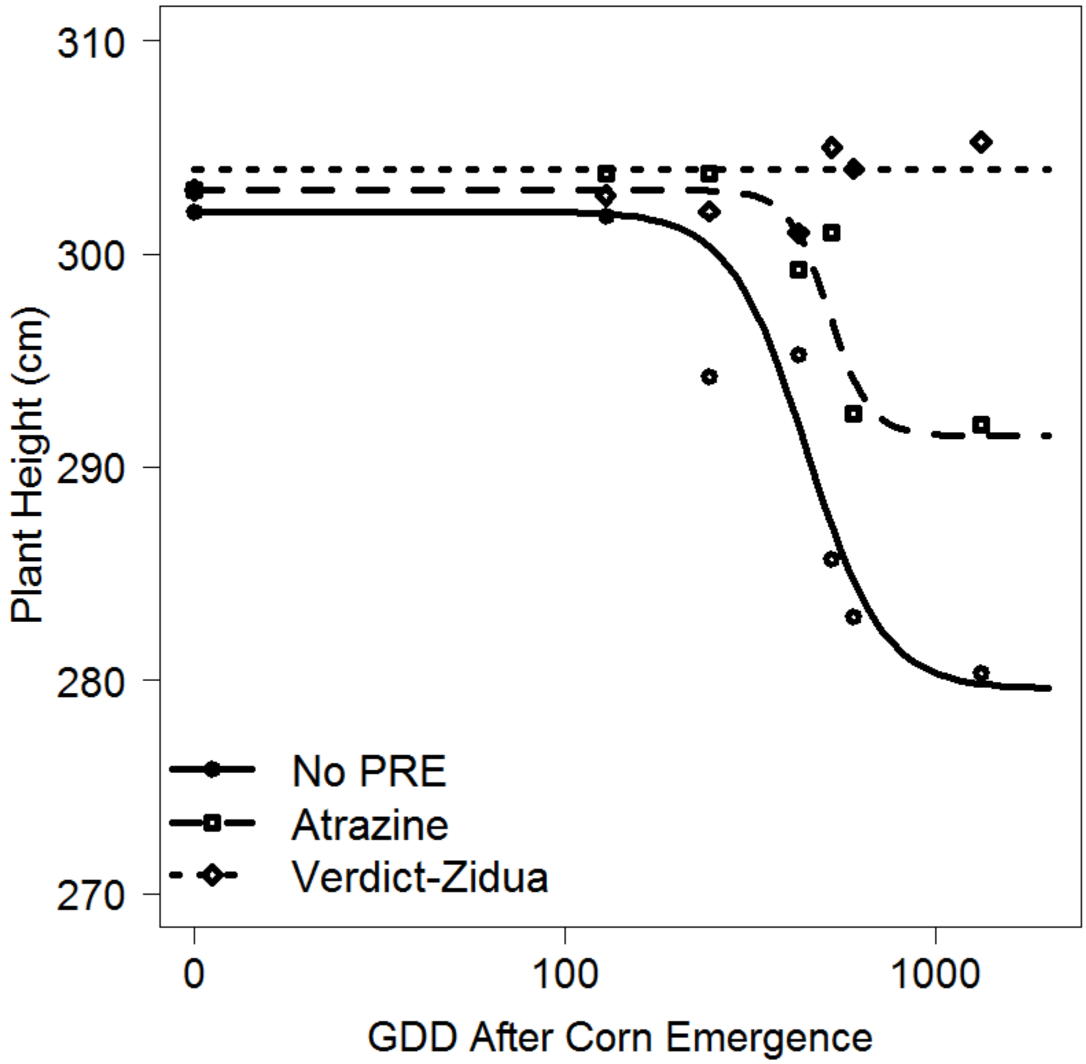

Figure 3-12. Corn plant height for no PRE and PRE herbicide applications in 2018 at Concord, NE.