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Dynamics of Early-Season Weed Management and Soybean Nutrition

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DYNAMICS OF EARLY-SEASON WEED MANAGEMENT AND SOYBEAN NUTRITION

by

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A Thesis
Submitted in Partial Fulfillment of the Requirements for the
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THESIS APPROVAL

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Approved by:

Dr. Bryan Young, Chair

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MAJOR PROFESSOR: Dr. Bryan G. Young

The popularity of growers using only postemergence (POST) herbicides for weed management in soybean was enabled by the commercialization of glyphosate-resistant soybean. The efficacy and flexibility provided by this technology diminished the use of soil residual herbicides and arguably, increased soybean yield loss from early-season weed competition. While, the rapid evolution and biogeographical spread of herbicide-resistant weeds, especially glyphosate-resistant biotypes, has renewed interest into the use of soil residual products, herbicide-resistant soybean technologies continue to be developed that may once again entice growers into POST-only weed management systems. The commercial interest in soybean yield advancements justifies further characterizing the benefits provided by early-season weed control beyond those of herbicide-resistance management. Furthermore, as awareness heightens regarding techniques that will enhance the sustainability of agro-ecosystems, specific focus on resource utilization will help to evaluate the viability of this weed management strategy.

Field experiments were conducted across four sites throughout southern Illinois in 2012 and 2013 to study the influence of early-season weed management strategies on soybean nutrient accumulation, grain yield parameters, and the acquisition of nutrients by broadleaved and grass weeds. Increasing periods of weed competition duration were established by removing weeds at heights of 10, 20, 30 or 45 cm with glyphosate. A weed-free treatment utilizing a comprehensive soil residual and POST herbicide program was included to implement a weed-free comparison.

Two standard herbicide management strategies that simulate common grower practices were also evaluated for comparison: flumioxazin PRE followed by glyphosate POST and two sequential POST glyphosate applications. Averaged across all 11 mineral nutrients analyzed in this experiment, broadleaved weeds accumulated 149 and 108% more nutrients than grasses in 2012 and 2013, respectively. Competition from 20-cm weeds reduced the acquisition of N, P, Ca, Mg, S, Fe, B, Cu, and Zn by soybean in 2012; these nutrients in addition to K and Mn were reduced by the same level of competition in 2013. N and Fe were the nutrients in soybean most notably impacted by weed interference. Reductions in soybean grain yield were the result of competition with 30-cm weeds in 2012, and 10-cm weeds in 2013; while, both standard herbicide regimens yielded less than the weed-free treatment in 2013 only. Additionally in 2013, average soybean seed weight and grain oil content was reduced when weeds were not removed before a height of 10 and 20 cm, respectively.

The rate of decomposition and nutrient release was measured for waterhemp and giant foxtail desiccated by glyphosate at heights of 10, 20, 30, and 45 cm in two southern Illinois soybean fields. Weed biomass was grown under greenhouse conditions to ensure homogeneity and litterbag methodology was utilized to track *in situ* mass and nutrient losses, expressed as a decay constant (k) regressed over time according to the single exponential decay model. The effect of specie and height both had a strong influence on the intrinsic properties of the weed biomass and the associated rate of decay. Concentrations of the recalcitrant cell wall components (cellulose, hemicellulose, and lignin) were generally greatest as weed height (plant age and development) increased and with giant foxtail compared with waterhemp. Ca, Mg, and S concentrations were greater in waterhemp, while N was greater in giant foxtail. N and K concentrations decreased with increasing weed height. After 16 weeks, 10-cm waterhemp and giant foxtail detritus had lost 10 and 12% more mass compared to the 45-cm height. Decomposition rates revealed mass loss was highest for 10-cm waterhemp ($k_{\mathrm{D}} = 0.022$) and lowest for 45-cm giant foxtail ($k_{\mathrm{D}} = 0.011$) and this process was negatively correlated to the overall amount of cell wall constituents ($r = -0.73$). Nutrient release rates followed a similar trend in that shorter (younger) weeds and waterhemp liberated nutrients more readily. Across all tested plant material, K was the nutrient most rapidly released, whereas, Ca was the most strongly retained nutrient.

Although the pressing challenge of managing herbicide-resistant weeds justifies the implementation of early-season weed control tactics, this research suggests there are ancillary benefits that are provided by this strategy. The use of a robust, broad-spectrum soil residual herbicide program in conjunction with timely POST applications provides the foundation for early-season weed management, thereby minimizing non-crop nutrient use and enhancing the nutrient acquisition capacity in soybean. This strategy facilitates more sustainable crop production by requiring fewer supplemental nutritional inputs while also protecting grain yield.

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CHAPTER 1

REVIEW OF LITERATURE

Weeds have been a nemesis to agricultural endeavors since ancient times. Prior to the utilization of modern, synthetic herbicides in the 20th century, the most effective means of weed control were through mechanical tillage and cultural practices such as crop rotation (Walker and Buchanan 1982). With the development of the herbicide 2,4-D in the early 1940's, producers were able to improve their levels of weed control thereby, stimulating an increase in production area of major crops (Zimdahl 2007). Weeds reduce not only the quantity of crop yields, but the quality as well. Early farmers were aware that weeds growing with crops decreased agronomic efficiency, however, not until the evolution of weed science research in the mid-1900's did the deleterious effects of weeds become more refined. Weeds act as a host to a variety of other pests such as nematodes, plant diseases, and insects (Aldrich 1984). Research during this time often attempted to study the effects of weed interference; a term developed to describe the allelopathic and competitive tendencies of weeds. Although the detrimental effect of allelopathy has been documented in greenhouse studies to reduce seedling germination and growth (Putnam 1983; Toai and Linscott 1979), in most production areas, the sole impact of weed competition tends to be of primary concern. Still today, weed competition continues to be one of the major restrictions to crop production systems in North America (Subedi and Ma 2009).

Competition exists "when two or more organisms seeks the measure it wants of any particular factor and when the immediate supply of the factor is below the combined demand of the organisms" (Clements et al. 1929). Weeds compete with crops for light, water, nutrients, space, and gases. Competition for these resources is dependent upon a variety of interactions and often follows the general ecological principle of Liebig's law of the minimum: a factor limits a physiological process only as long as no other factor overrules it (Liebig 1840). The quantification of the relative competitiveness of a given weed is made possible through the evaluation of competitive indices (CI's). Although no indices exist specifically for southern Illinois, the most recent publication in a geographically similar area is from Missouri by Bradley et al. (2007). With 10 being the most competitive, they formulated the following CI's for a variety of common weed species: common sunflower (*Helianthus annus*) 10; giant ragweed (*Ambrosia trifida*) 8.0; common cocklebur (*Xanthium strumarium*) 5.5; annual morningglory (*Ipomea* spp.) 5.5; velvetleaf (*Abutilon theophrasti*) 4.2; shattercane (*Sorghum bicolor*) 3.5; giant foxtail (*Setaria faberi*) 3.0; common waterhemp (*Amaranthus rudis*) 2.5; common ragweed (*Ambrosia artemisiifolia*) 1.5; and fall panicum (*Panicum dichotomiflorum*) 1.5. The level of competition is exaggerated by a variety of factors beyond weed species heterogeneity that impact the development and growth habit of either the crop and/or the weed such as: weed density (Bradley et al. 2007; Shurtleff and Coble 1985), crop species and cultivar (Knake and Slife 1965, Monks and Oliver 1988), cultural practices (Di Tomaso 1995), timing of emergence (Massinga et al. 2001), length of competition (Crook and Renner 1990), and environmental factors (Patterson 1995).

Weed Management Concepts

In 1996, Monsanto introduced Roundup Ready Soybeans® (*Glycine max* L.), which were genetically engineered to be resistant to the herbicide glyphosate, and followed with the public release of glyphosate-resistant cotton (*Gossypium hirsutum* L.) and corn (*Zea mays* L.) in 1997 and 1998, respectively (Monsanto 2010). This new technology facilitated the implementation of postemergent (POST) applications of glyphosate to be made over these crops and drastically altered commercial herbicide regimens. Prior to the release of glyphosate-resistant (GR) crops, the utilization of preemergent (PRE) herbicides was an essential part of an integrated weed management program as these soil residual herbicides alleviated pressure on POST applications by resulting in fewer, smaller weeds (Gonzini et al. 1999). However, after the commercialization of GR crops, the robust weed control attained by POST glyphosate applications lessened the dependence on PRE herbicides, particularly in soybean (Young 2006). Greater consistency in weed control was also achieved through the use of glyphosate because its effectiveness is not as dependent upon environmental and edaphic factors when compared to most soil residual herbicides. Consequently, in just over a decade, there has been a wide acceptance of utilizing GR crops. In 2010, 93% of soybean and 70% of corn hectares in the United States were planted with glyphosate-resistant seed (USDA 2010).

The greater reliance on POST herbicides with little to no soil residual activity stimulated interest as to the most appropriate time to implement weed control without a yield penalty (Knezevic et al. 2002). The critical weed-free period and critical duration of weed competition are concepts of two different approaches to weed management. The critical weed-free period is defined as the length of time from crop emergence weeds must be controlled in order to achieve a maximum crop yield. In corn and soybean, this period is typically from three to five weeks after crop emergence (Barrentine 1974, Van Acker et al 1993), with weeds emerging after this period having no effect on crop yield. The foundation of providing crops an earlier emergence date than weeds is supported by research that suggests weeds, themselves, are very intolerant of competition. Knake and Slife (1965) found that giant foxtail accumulated close to 0% growth when soybeans were allowed to emerge three weeks prior. Barnyardgrass (*Echinochloa crus-galli*) growth was reduced by 60% when competing with soybeans that had emerged one week earlier (Maun 1977). Furthermore, Palmer amaranth (*Amaranthus palmeri*) emerging with corn reduced grain yields 60% compared to 10% when emergence was delayed thirty days (Massinga et al. 2001). In soybean, CI's of weeds are greater for those allowed to emerge with the crop when compared to emergence at V1 (Hock et al. 2006).

The second approach to weed management, which focuses on the critical duration of weed competition, is the period weeds may grow with the crop until removal is necessary to achieve maximum grain yields. This phase typically varies from two to five weeks in corn and soybean; however, this period has been much more inconsistent than that of the critical weed-free period and is largely dictated by site-specific interactions (Van Acker et al. 1993; Page et al. 2012). A compilation of such studies by Zimdahl (1980) across an assortment of crops revealed a range of up to 22 weeks. Extensive work by Knezevic et al. (2009) in soybean indicated that crop row spacing can influence the critical time of weed removal. In 19-cm rows the ideal growth stage to implement weed control was V3; in 38-cm rows, V2; and in 76-cm rows, V1. The authors also reported a 2% yield penalty for every growth stage delayed past the critical removal timing up to R3 (beginning pod) at which point yield loss was even greater. There are inconsistencies as to how studies have reported the critical weed-free period and critical duration of weed competition; weed height, crop growth stage, and days after crop emergence have all been proposed (Knezevic et al. 2009; Van Acker et al. 1993).

As the dependency on POST applications of glyphosate grew, the widespread use of this single mode-of-action has selected for GR weeds. Currently, there are 14 GR weed biotypes in the U.S. and three in Illinois (Heap 2013). Such a great reliance on POST herbicides has led to a complacent understanding of proper weed management as the effectiveness of glyphosate provided the prospect of excellent control of weeds at heights that were previously unacceptable.

Weed management implies a holistic approach ranging from reducing the soil seed bank, limiting weed emergence with crops, and preventing weed competition with crops (Aldrich 1984). Focus, exclusively on weed control, meant that growers were allowing weeds to compete with crops often surpassing the critical duration of competition. Carey and Kells (1995) found that corn grain yields can be significantly reduced despite effectively controlling 15-cm weeds. As the shortcomings of POST-only weed control come to light, a more sound approach to weed and herbicide-resistance management has renewed interest into the utilization of soil residual herbicides and requires insight as to any additional benefits provided by early-season weed management.

Weed-Crop Nutrient Competition

Yet to be studied extensively in soybean, research has been conducted on the effect weed competition has on nutrient uptake in corn. Gonzalez Ponce and Salas (1995) found that a mix of grass and broadleaved weeds reduced the N, P, and K content of corn at harvest. Although the latter experiment evaluated all three primary macronutrients, much of the literature focuses solely on N. Nutrient competition appears to be dependent upon a variety of weed characteristics including weed species, density, and height. High densities (369 plants m^{-2}) of common waterhemp consistently reduced corn biomass N accumulation when allowed to reach heights between 38 and 46 cm (Cordes et al. 2004). Hellwig et al. (2002) publicized similar effects when no-tillage corn was allowed to compete with a mix of grass weed species at a density of 300 shoots m^{-2}. This grass population, consisting of giant foxtail, barnyardgrass, and large crabgrass (*Digitaria sanguinalis*) at heights of 31 cm and greater reduced corn dry weight and N content. Hans and Johnson (2002) found, despite ample control of shattercane at a height of 31 cm, corn N accumulation had already been hindered. These results suggest weed management will likely play an integral role as growers attempt to maximize the efficiency of nutrient applications.

Currently, Midwestern research has been limited to corn, nevertheless; the inherent anatomical and morphological differences that exist between corn and soybean make it difficult to extrapolate such findings. The bush growth habit and taproot system of soybean may enable competition with weeds to occur at a different time than that of corn (Aldrich 1984). The aboveground competition may be due in large part from the differential filtering of the available photosynthetically active radiation. Thus, a denser crop canopy increases the far-red:red light ratio and retards the germination and growth of weeds (Rajcan et al. 2004). Belowground resource competition is also likely to vary. Corn and soybean have very dissimilar rooting systems; grown in the same location, soybean root density is approximately 80% less than corn (Barber 1978). Moreover, influx of P and K into soybean roots was less than corn during early vegetative phases, yet greater than corn during later growth stages (Barber 1978). In addition, soybean roots have a mechanism in which they can circumvent the intertwining of other roots, thereby limiting direct physical competition (Raper and Barber 1970).

The nutrient requirements to meet the physiological demands of the leguminous soybean also vary from corn. Paramount in corn fertility, N is often thought to be of lesser importance in soybean. However, although a portion of the N needed for soybean production is fixated by their root nodules, it is estimated that 50% of their total N requirement must still be drawn from the soil solution indicating a greater availability of N may still increase soybean yields (Berglund and Helms 2003). Although soybean nutrient deficiencies are rarely a problem across many of the high-producing regions, there remain exceptions particularly within the context of micronutrients. Calcareous regions in the northern Corn Belt are subject to Fe deficiency

(Berglund and Helms 2003) while the *Cerrado* region of Brazil, one of the largest soybean production areas in the country, suffers from Zn, Cu, and Mn deficiencies across 70 to 80% of the area (Hitsuda et al. 2010). Therefore, elucidating the specific nutrient drawdown capacity from competing weeds in soybean may enable more efficient nutrient management decisions to be made and allow for greater sustainability.

Soybean-Weed Interactions

Numerous weed competition studies have been conducted in soybean. Most of these, however, have focused at any given time on the competitive effects of a single weed species. Barrentine (1974) found that common cocklebur populations can decrease soybean grain yields by up to 80% both as duration of competition and densities increase. At a density of 8 plants m^{-2}, Palmer amaranth, common waterhemp, and redroot pigweed (*Amaranthus retroflexus*) reduced soybean grain yields by 79, 56, and 38%, respectively (Bensch et al. 2003). In an area dominated by giant foxtail, soybean plant height was reduced by 10% while grain yields were only 68% of the weed-free control (Krausz et al. 2001). Loss of grain yield in soybean as a result of weed interference is likely caused by fewer pods per plant (Harris and Ritter 1987). Plant dry weight (Monks and Oliver 1988), shoot dry weight, height, and leaf area (Shurtleff and Coble 1985) are all non-yield components that have also been reduced by weed competition. Although single-species studies provide useful insight pertaining to weed-crop interactions, from a crop management standpoint, they are difficult to apply towards a typical agronomic scenario as most soybean fields are infested with a more heterogeneous weed species complex. Moreover, the competitive impact of weed species working in conjunction is not cumulative; as two weed species are allowed to infest a crop, the resulting impact on crop yield is generally less than the sum of their monoculture influence (Chu et al. 1978; Millar et al. 2007; Van Acker et al. 1997).

While, research regarding weed interference in soybean appears to be quite substantial, given the complexity of factors involved, these results are often dictated by site-specific interactions. Hence, further research is required that focuses on the competitive effects of mixed weed species populations in soybean and under a variety of environmental and edaphic influences.

Degradation of Weed Residue

Weed control strategies are often considered successful upon the cessation of physiological activity within the plant. However, the fate of the resources weeds possess and the lasting influences their decomposition will have both on the soil and the growing crop are often overlooked. The weed community has a large affinity for nutrient acquisition (Aldrich 1984). Mineral nutrition of weeds differs both among species (Hellwig et al. 2002; Majumder et al. 2008) and plant heights (Lindsey et al. 2013). Shattercane, at a height of 31 cm competing with corn accumulated as much as 20 kg N ha^{-1} before it was successfully controlled via herbicidal means (Hans and Johnson 2002). Large amounts of resources utilized by weeds and therefore, unavailable to crops not only cause reduction in grain yields, but also lessens the effectiveness of any nutrient management program. The fate of resources assimilated by weeds following successful control measures remains poorly understood and thus, justifies the need to characterize the rate and extent to which nutrients will be returned to the soil and how weed management strategies may play an integral role.

Decomposition of plant litter involves the physical, chemical, and biological processes that reduce detritus to its elemental chemical constituents (Aerts 2006). The general model of decomposition follows a two-step process: an initial, rather rapid loss of the water-soluble, labile nutrients, followed by a more prolonged phase in which the recalcitrant chemical elements are slowly broken down and stabilized as humus (Prescott 2005). The decay continuum can vary greatly as a result of the controlling factors and biological processes involved. The rate of decomposition is controlled largely by three factors: climate, litter quality (the chemical and physical attributes of plant matter), and soil organisms (Aerts 1997). Many have speculated as to the single, most important factor affecting the rate and completeness of litter decomposition. Aerts (2006), Swift et al. (1979), and Meentemeyer (1978) speculate that the climate is the major determinant while Berg (2008) and Prescott (2005) believe the type of vegetation present to be the primary factor. Coûteaux et al. (1995) suggest that under suitable weather conditions, the quality of the litter is the driving factor and under harsh weather conditions, the climatic influence prevails. It is important to note that much of the literature regarding the process of plant decomposition has been conducted in tundra, taiga, or tropical biomes. Therefore, care must be taken when extrapolating results from these areas across other ecosystems given the vastly different climatic conditions and diversity of species possible. Vazquez et al. (2003) and Parmelee et al. (1989) evaluated N mineralization of over-wintering weed residue in Ohio and Georgia. Majumder et al. (2008) performed a litterbag experiment to track nutrient release and fungal succession of weed biomass in India. However, Lindsey et al. (2013) is the only readily identifiable study in the Midwest that attempts to simulate in-season nutrient release from decaying weed residues.

Anatomical Interferences of Litter Decomposition

The plant cell wall is the largest obstacle of nutrient release due to insoluble components concentrated within the wall (Dickinson and Pugh 1974). An understanding of the anatomy and role of this structure in the plant cell is, therefore, crucial in studying litter degradation. The cell wall provides structural and mechanical support, regulates cell growth, provides carbohydrate storage, and acts as a physical barrier to pathogens. Many of the chemical compounds needed to fulfill such functions naturally contradict the destruction process and, thus, retard decomposition and nutrient release rates (Gilbert 2010). The anatomy of the cell wall is a diverse, intricate network consisting of cellulose and cross-linking glycans (hemicelluloses) that reside in a pectin polysaccharide matrix with associated structural proteins (Carpita and Gibeaut 1993). There are three regions of the cell wall: 1) the middle lamella is the outmost layer that primarily binds nearby cells; 2) the primary wall is deposited during active growth and division, and must allow for cell expansion; and 3) the secondary wall, which is deposited once active growth ceases on the interior of the primary wall (Carpita and Gibeaut 1993). While all plant cells have a middle lamella and primary wall, the secondary wall is utilized mainly for structural support and is not present in all cells.

The process of lignification can further intensify the cell wall network in certain cell types. Eleven different sugars comprised of four different linkage positions and two oxygen atom loci allow for a plethora of configuration options, all of which may impact degradation depending on their concentrations (Berg 2008). Upon the cessation of primary wall growth, the formation of the secondary wall begins. In certain cells, this is coupled with the deposition of lignin. Although lignin may appear in all layers of the cell wall, the largest concentration, 60 to 80%, is deposited within the secondary cell wall (Musha and Goring 1975). Lignin production is derived from phenylalanine via the shikimate biosynthesis pathway (Rippert et al. 2009). Upon cell differentiation, the lignin molecule forms strong covalent bonds to cellulose and other carbohydrate components (Vanholme et al. 2010). Hence, the lignification process increases cell wall rigidity by increasing the strength of the fibrous tissue. The final step of fortifying tissue strength in plants involves the biosynthesis of cutin. Cutin is concentrated in foliage and is produced, along with wax, by the epidermal cells of leaves to act as a barrier to prevent water loss and physical injury (Berg 2008). The ultrastructure of plant leaves reveals that the waxy layer comprised of long-chain alkanes, ketones, fatty acids, and alcohols overlays the cutin complex predominantly consisting of hydroxyl fatty acids (Northcote 1972). Cutin performs as a cement, binding the waxes to the cell wall. This function is achieved through the orientation of cutin as the lipophilic groups face outwards, thus, attracting the waxes while the hydrophilic portion is oriented towards the polysaccharide layers of the cell wall. As such, cutin is one of the most recalcitrant plant materials (Swift et al. 1979).

Cell Wall Dynamicity

Plant cell walls are the most plentiful sources of organic C in the world (Gilbert 2010). However, the organization and concentrations of these various C compounds are diverse throughout the plant kingdom. Cell walls are not static. An alteration to their orientation through chemical changes creates a dynamic structure that can adapt to adverse biotic and abiotic stimuli (Gilbert 2010). Evolutionary adaptation has led to cell walls with differing anatomies and chemical compositions. The nature of cell walls in plants comes in two forms, type I and type II. While various differences exist between these, the greatest distinction lies in their hemicellulose fraction (Carpita and Gibeaut 1993). Type I walls appear in the non-commelinoid monocots and most dicots. Here, xyloglucan is the predominant cross-linking glycan (hemicellulose) with the combination of cellulose-xyloglucan aggregates accounting for 50% of the cell wall composition (Carpita and Gibeaut 1993). Type II cell walls are found in the commelinoid monocots; this taxon contains most of the common grass species in the Poaceae family. Instead of xyloglucan dominance, glucuronoarabinoxylan is the primary hemicellulosic component. Furthermore, upon cell expansion, type II cell walls stimulate the production of the mixed-linkage β-D glucans (Carpita and Gibeaut 1993). Another important division that can occur within plant cell walls involves the chemical array of lignin. Lignin is a diverse compound that differs not only among species but also within species amid cell types (Vanholme et al. 2010). The lignification process is much slower than, for example, cellulose biosynthesis. Therefore, depending on the age of the tissue at senescence, the lignin fraction is likely to be the cell wall element with the greatest variability in concentration (Berg 2008). The plant cell wall consists primarily of high-molecular weight, water-insoluble compounds that are resistant to microbial depolymerization. Given the diversity and dynamicity of such a structure, it would seem plausible that these variances will serve as rate regulators of plant litter degradation.

The compounds discussed thus far have pertained to the plant cell wall and, while the majority of C compounds reside here, there are numerous other complexes that constitute plant matter. They can be divided into high-molecular weight substances such as complex fatty acids and phenols; and low-weight materials such as amino acids, short-chain fatty acids and lightweight phenolics. Foliar litter contains four main groups of soluble substances: sugars, phenolics, hydrocarbons, and glycerides (Berg 2008). The plant cell wall, consisting of vast networks of structural, interwoven compounds remains inherently, extremely porous. The porosity of this structure, however, only allows the passage of the lightweight materials while acting as a barrier to the more complex compounds. Hence, upon plant death, the latter will remain bound within the cells until acted upon by extracellular enzymes while the water-soluble components will be easily leached.

Nutrient Dynamics of Plant Litter

A more comprehensive view of plant cell stoichiometry reveals that the primary constituents are comprised of essential plant nutrients. The location of nutrients within a plant varies both across species and at the individual plant level among cell type. Some minerals are very specific in their functional role. For instance, the primary role of the nutrient B lies within strengthening of the cell wall (Matoh et al. 1996). Conversely, an element such as N is a crucial structural, genetic and metabolic mineral. Apart from C, H, and O, which are rarely limiting in abundance, N is the mineral nutrient required in the greatest quantities by plant life. For example, N is a component of the chlorophyll pigment, amino acids, ATP, and DNA. However, in plants, the most abundant source of N comes from the constituency of the enzyme Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase) where plants may devote as much as 50% of their leaf N (Ellis 1979). The differential allocation of nutrients occurs during the active growth of plants in order to satisfy various physiological demands (Lambers et al. 2008). Precisely which organs are the beneficiaries of this redistribution will likely influence the rate of decay and nutrient release due to aforementioned cell wall heterogeneity. For example, heavily lignified stem tissue will likely contain fewer nutrients and decompose more slowly than succulent, green vegetation.

Decomposition as a Process

As stated earlier, there are two primary stages of decomposition that detritus undergoes. The initial pattern of plant degradation is a loss of the water-soluble, labile compounds proceeded by a diminution of more complex, lignified compounds. The preponderance of research has focused on this stage for two main reasons: it is believed that the majority of the compounds and nutrients have been released by this point and logistical time constraints often deter long-term studies of humus dynamics. It has been proposed that plant matter will eventually reach a maximum level of decomposition upon which further decay of the newly-formed humus is extremely slow (Prescott 2005). Aber et al. (1990) and Melillo et al. (1989) suggest that this stage of decomposition begins at approximately 80% mass loss. Yet, there is evidence that initial litter quality can change the limit value of decomposition for a species. Van Vuuren et al.

(1993) and Magill and Aber (1998) found that initial biomass of high quality (narrow lignin:N) enters the humus stage with a greater amount of their initial mass remaining. Therefore, throughout the decay continuum, high quality litter will initially decompose at a more rapid pace than detritus of low quality but, ultimately, to a lesser degree of completeness.

The manner in which decomposition occurs appears to be a community-level process, defined by Reice (1974) as the interactions of several populations mediated by physical factors. As recently senesced plant matter falls to the soil surface, soil microbes and fungi begin to populate it. While these organisms break down litter at the cellular level, saprophages shred the material into smaller portions as they feed on it (Reice 1974; Swift et al. 1979). The primary decomposers are fungi and bacteria. The diversity and abundance of these microorganisms is prodigious; 1 gram of soil may contain 10 billion microbes associated with thousands of species (Rosselló-Mora and Amann 2001). Of the two, bacteria are both more species-rich and dynamic in functioning. Fungi are strictly aerobic organisms whereas, bacteria may be found in oxic or anoxic environments. Polysaccharides in plant litter can be degraded both aerobically and anaerobically with the former being favored and, furthermore, required for complete decomposition (Berg 2008).

Both fungi and bacteria are capable of degrading cellulose and hemicellulose while, the ability to completely degrade lignin is rare within the decomposer spectrum. The white-rot fungi, a class of basidiomycetes, and the actinomycete group of bacteria are part of the exclusive assemblage able to mineralize lignin (Romaní et al. 2006). These processes require a large amount of free O_2 and is generally why agronomic fields under conventional tillage have lower organic matter values than undisturbed sites. The nutrient content, particularly N and Mn, present in the microsite of lignin degradation has also been shown to influence the rate of decay.

High concentrations of N can have a suppressing effect on the lignolytic enzyme phenol oxidase as evidenced by Carreiro et al. (2000) and Keyser et al. (1978). Mn peroxidase, produced by the basidiomycete fungi, is an enzyme that oxidizes Mn^{+2} in the litter to the highly reactive and destructive Mn^{+3} ion. By utilizing and prolonging the lifespan of this ion, lignin degradation transpires to a greater extent (Hofrichter 2002). N enrichment to soils dominated by basidiomycete fungal populations have been correlated to soil organic matter increases, and may provide a greater capacity for C sequestration, however, these studies have been restricted to temperate and boreal forests (Sinsabaugh 2010).

Rate-Regulators of Decomposition

The initial stoichiometric properties of plant litter are often regressed against first-year mass loss in an attempt to identify which of these influence decomposition the most. The most extensive review of initial properties as rate-regulators of decomposition is by Berg (2008). By comparing studies across gradients of time, space, and species distribution, he was able to develop a few generalized patterns. While there is variation among species, the relationships involving N, P, and S have all shown to be significant. These three nutrients are essential constituents of nucleic acids and proteins. Therefore, it seems logical that these will in some way influence plant degradation given biota’s high demand for these elements. Other nutrients such as K, although appearing in relatively large amounts initially, do not perform well as an indicator of mass loss due to the high water solubility of K. Of the plant cell wall components, lignin may provide the best relationship because it is the most recalcitrant. For this reason, the lignin:N ratio appears to be superlative to the C:N ratio as an indicator of decomposition rate because it does not take into account the labile C in plant matter. An understanding of how litter quality affects decomposition provides useful rationale in the assumption that variations in species and plant heights will influence the rate at which biomass decays. Immature plants have lower C:N ratios and less lignin content (Muller et al. 1988, Nicolardot 2001). Moreover, as plants mature their cell walls become more heavily fortified with cellulose, hemicellulose, and lignin (Singh and Gupta 1977). Gupta and Singh (1980) expanded this concept across monocotyledonous and dicotyledonous plants and found that aboveground biomass of grasses decompose at slower rates than that of broadleaves. This is likely attributed to the higher N use efficiency of most grasses, thus, leading to a larger lignin:N ratio. Given the relationship between plant maturity and chemical constituency, this would suggest that not only variances in plant species but, height as well will influence the rate of biomass breakdown and nutrient return.

Temperature and moisture are the abiotic influences that have the greatest effect on the rate of plant litter decay (Swift et al. 1979). The ideal temperature range for plant decomposition is 30 to 40º C (Waksman and Gerretsen 1931). At these higher temperatures, the destruction of the plant cell wall components, particularly cellulose and lignin, greatly increases. After nine months of decomposition across a temperature gradient, the degradation of cellulose and lignin at 37º C increased by 96 and 60%, respectively, over 7º C (Waksman and Gerretsen 1931). Kirschbaum (1995) found that microorganism activity often doubles for every 10º C increase in soil temperature. Additionally, the presence of water in an ecosystem seems to have its largest impact on the activity of soil microorganisms with field capacity being the ideal edaphic level. Fluctuations in moisture regimes may generate more of a response in the decomposer community than the plant community because minute precipitation events that only affect the uppermost layer of soil can stimulate microbial activity (Austin 2002). Droughty conditions not only affect the activity of soil microorganisms but also plant growth as well; stressed plants tend to produce litter that is of lesser quality (i.e. resists decomposition). Assuming no other resources are limiting, a plant with sufficient access to water would likely generate tissue that is more nutrient-rich and readily degradable due to the less restrictive uptake of minerals from the soil. Therefore, decomposition rates increase along with rising temperatures and moisture levels (Meentemeyer 1978).

Contemporary Assessment of Weed Residue Nutrient Release

Stated previously, there is only one published study pertaining to in-season weed residue degradation in Midwestern agricultural landscapes. Conducted by Lindsey et al. (2013), this group evaluated N release from common lambsquarters (*Chenopodium album*), common ragweed, and giant foxtail grown at four N rates and two weed heights. Weeds were grown to 10- and 20-cm heights in corn plots receiving different N rates and then harvested. Residues were oven dried, finely ground, and then mixed with field soil to be placed in a laboratory incubator over a 12-week period. By tracking net mineralization and immobilization rates, they were able to determine which types of weed residues may contribute to the soil N pool within the same growing season. Giant foxtail released N more slowly than both common lambsquarters and common ragweed when grown without additional N. When N fertilizer amendments were made, residue release rates were positively correlated. Furthermore, weeds grown to 20 cm released N to a lesser extent when compared 10-cm weeds. Lindsey et al. (2013) concluded that weeds may contribute to the available soil N pool if controlled by the 10-cm height and furthermore, to avoid N immobilization, giant foxtail should be controlled before it reaches 20 cm in height.

There are several reasons care must be taken when extrapolating these results to *in situ* scenarios. First, N mineralization rates from laboratory incubations are usually greater than field experiments (Sanchez et al. 2001). The weeds utilized in the latter study were freshly cut and removed from the field rather than being controlled with a herbicide. Glyphosate is the most commonly used POST herbicide on corn and soybean hectares. Therefore, the majority of weed residues resulting from successful POST applications commercially are likely a result of the phytotoxic effects of this chemical. It is plausible that the weeds in this study may differ in their chemical constituency when compared to glyphosate-treated plants. The toxicity of glyphosate is generally attributed to the blocking of aromatic amino acid production, thus, causing insufficient protein synthesis. However, there is also evidence that it can stimulate a reallocation of carbohydrates towards the shikimate pathway due to the deregulation of the 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS) enzyme which, in turn, creates a C shortage in other plant parts (Servaites et al. 1987; Siehl 1997). This provides evidence that C compounds may be redistributed within the plant between the time of glyphosate uptake and weed death and the location of these carbohydrates in the affected specimen may differ from that of a freshly cut plant. Finally, the residue in this experiment (Lindsey et al. 2013) was ground to pass a 1 mm sieve and mixed with soil to facilitate degradation. However, *in situ*, this is not an accurate representation as much of the particle reduction of plant litter is carried out by saprophages. This research provides useful information regarding N release from various weed species residues and how it is impacted by plant height. Because research in this area is lacking, it is a step towards a better understanding of the dynamics involved with weed decomposition and nutrient release. However, there remains a need to quantify these parameters with methodology more closely adapted to field scenarios and broaden the scope of mineral release beyond that of N.

CHAPTER 2

INFLUENCE OF DURATION OF WEED COMPETITION ON SOYBEAN NUTRIENT ACQUISITION AND GRAIN YIELD PARAMETERS

Weed management implies a whole systems approach ranging from reducing the soil seed bank, limiting weed emergence with crops, and preventing interference with crops (Aldrich 1984). Weed interference encompasses the multitude of deleterious effects weeds elicit in crop production systems. The most economically detrimental of these is the reduction in quantity and quality of grain yield that may stem from the holistic impact of allelopathy and resource competition. Allelopathic effects of weeds can hinder the growth and development of neighboring crop plants (Toai and Linscott 1979), however, the overall influence of this on grain yield in agronomic crops is minor. Therefore, direct weed-crop competition for resources is generally regarded as that most strongly associated to yield losses and continues to be one of the major restrictions to crop production systems (Subedi and Ma 2009).

Weed-crop competition occurs when plants require resources such as water, light, nutrients, and gases that are limited in supply. The extent of competition depends on a variety of cultural practices and environmental conditions as well as the weed species spectra. For example, at a density of 1 plant m^{-2}, giant foxtail (*Setaria faberi*) can cause a 2.5 to 5% yield loss in soybean (*Glycine max*) compared to a 20 to 30% yield loss imposed by common cocklebur (*Xanthium strumarium*) (Bradley et al. 2007). Two important concepts utilized for determining the timing of weed control are the critical duration of weed competition and the critical weed-free period. The latter is the period of time from crop emergence weeds must be controlled to avoid yield losses. Allowing the crop to emerge before weeds provides a form of season-long suppression.

When giant foxtail emergence was delayed three weeks behind soybean, grass biomass accumulation was near 0% (Knake and Slife 1965). Emerging with corn (*Zea mays*), Palmer amaranth (*Amaranthus palmeri*) reduced grain yields by 60% compared to only 10% when emergence was delayed 30 days (Massinga et al. 2001). Furthermore, Hock et al. (2006) found that competitive indices of weeds are greater when emerging with soybean than when emerging at the V1 growth stage. Alternatively, the critical duration of weed competition may be defined as the length of time a grower can wait before making a postemergent (POST) herbicide application or tillage operation to eliminate weeds. This period is much more variable than the critical weed-free period (Zimdahl 1980) and is strongly associated to early-season growing environments with more favorable conditions requiring earlier implementation (Bradley et al. 2007). These two concepts form the rationale behind the preemergent (PRE) and POST herbicide use patterns as PRE applications are used to attain the critical weed-free period and POST applications used to comply with the critical duration of weed competition.

Perhaps the most drastic change in soybean weed management occurred following the commercial introduction of glyphosate-resistant (GR) soybean in 1996. Prior to the introduction of this technology, soil residual herbicide use had been the foundation for chemical weed control in soybean (Young 2006). The effectiveness and flexibility provided by glyphosate, however, drastically altered herbicide use patterns as many growers began to rely solely upon POST glyphosate applications; in 1995, 11 active ingredients were used on at least 10% of soybean hectares, but by 2002 this list was reduced to simply glyphosate (Young 2006). Although at this time growers were experiencing new peaks of in-crop weed control, they were also delaying POST applications that often exceeded the critical duration of weed competition. Another repercussion related to the wide adoption of POST-only glyphosate use was the extraordinary selection pressure put forth on weeds for herbicide resistance. Instead of utilizing this technology to supplement the already established use of PRE herbicides that offered varying sites of action, growers were quick to abandon PRE herbicide use altogether. Consequently, in just over a decade, there are now 14 GR weed biotypes in the U.S. and 3 in Illinois (Heap 2013). Thus, the utilization of glyphosate on GR soybean initially resulted in enhanced weed control, but ultimately facilitated the evolution of GR weeds and a diminished use of sound agronomic principles.

An extended period of weed-crop competition due to delayed POST herbicide applications arguably, increases the prevalence of grain yield reductions. Numerous studies have been conducted on this scenario in soybean, however, they are often restricted to the effects of a single weed species. Common cocklebur populations can decrease soybean yields by up to 80% as both duration of competition and densities increase (Barrentine 1974). Bensch et al. (2003) publicized the yield reducing capacity of three *Amaranthus* species in soybean: Palmer amaranth, common waterhemp (*Amaranthus rudis*), and redroot pigweed (*Amaranthus retroflexus*) at a density of 8 plants m^{-2} caused yield losses of 79, 56, and 38%, respectively. While single-species experiments provide insight into specific weed-crop interactions, they do not accurately represent practical scenarios as many growers are often plagued by a more heterogeneous weed species complex and, thus, justifies the characterization of mixed-species competition on soybean grain yield.

A possible causal explanation for yield reductions is nutrient drawdown from weed competition. Current evaluation of nutrient competition in common agronomic crops has been strictly limited to corn and has shown that weed interference can result in diminished nutrient levels in corn tissue; N, P, and K acquisition was limited by a mixed population of grass and broadleaved weeds (Gonzalez Ponce and Salas 1995), common waterhemp competing at a height of 38 cm reduced corn biomass N accumulation (Cordes et al. 2004), and competition from shattercane (*Sorghum bicolor*) can restrict N nutrition (Hans and Johnson 2002). Research regarding nutrient competition in soybean is non-existent and regardless the crop of interest, the scope of the nutrients investigated has been limited to the macronutrients or simply N. Therefore, given the varying nutrient demands and physiological differences between these two crops further research is required to elucidate soybean-specific nutrient drawdown from weed competition.

As growers strive to enhance soybean yields, a current trend is the use of foliar nutrient solutions, especially in calcareous regions where Fe deficiency is a concern (Rodríguez-Lucena et al. 2010). Furthermore, new herbicide-resistant technologies with POST utility are forthcoming likely within the decade. The flexibility of these programs may once again result in the heavy reliance on POST-only herbicide regimens by growers. The consequence of such a system could result both in a greater susceptibility to nutrient drawdown from early-season weed competition and expenditure in crop mineral nutrition. Perhaps if weed competition were eliminated altogether through the use of a comprehensive PRE/POST herbicide regimen the need for supplemental nutrients would be diminished and also procure sound herbicide resistance management tactics resulting in a more sustainable production system. Thus, the primary objective of this research is to characterize the influence of weed competition duration in soybean by 1) assessing the effect on soybean mineral nutrition, 2) quantifying the capacity of nutrient accumulation by broadleaved and grass weeds, and 3) determining the influence on soybean grain yield and yield components.

MATERIALS AND METHODS

Field experiments were conducted in 2012 and 2013 across four sites in southern Illinois located at the Belleville Research Center near Belleville, the Agronomy Research Center near Carbondale, Rend Lake College near Ina, and a producer field site near Ridgway. For each site and year, the previous crop was corn. The seedbed was conventionally tilled in order to establish a weed-free setting at planting. A regionally adapted, glyphosate-resistant soybean variety, treated with a fungicide and insecticide was planted in 76-cm rows at a target population of 346,000 seeds ha^{-1} approximately 3 cm deep (Table 2.1). Weed growth rates were calculated by using the days required from soybean planting to reach 45 cm in height. All weed species at each location were glyphosate-susceptible.

Herbicide Treatments. A PRE treatment consisting of sulfentrazone + *s*- metolachlor + fomesafen (140 + 1,378 + 70 g ai ha^{-1}) followed by a POST application of glyphosate + fomesafen[1] (1,100 g ae + 275 g ha^{-1}) provided weed-free conditions. Four separate treatments of glyphosate[2] (1,100 g ha^{-1}) applied at the 10-, 20-, 30-, or 45-cm average weed height allowed for increasing levels of weed competition duration. Two other treatments were implemented that enabled the comparison of two standard herbicide regimens commonly employed by growers. The first being a PRE application of flumioxazin[3] (70 g ai ha^{-1}) followed by a POST application of glyphosate (1,100 g ha^{-1}) while the second treatment consisted of sequential POST applications of glyphosate (1,100 fb 1,100 g ha^{-1}) at the 10 cm weed height and again at 21 days after treatment. All glyphosate applications contained ammonium sulfate[4] at 1% w/w and the

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[1] Flexstar GT 3.5, Syngenta Crop Protection, Inc., P.O. Box 18300, Greensboro, NC 27419-8300.
[2] Touchdown Total, Syngenta Crop Protection, Inc., P.O. Box 18300, Greensboro, NC, 27419-8300.
[3] Valor SX, Valent U.S.A., 1333 N. California Blvd., Walnut Creek, CA 94596.
[4] N-Pak AMS Liquid, Winfield Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164-0589.

fomesafen-containing POST treatment was applied with methylated seed oil[5] at 1% v/v. Herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to provide 140 L ha^{-1} at a pressure of 207 kPa through a 3-m wide hand-held boom equipped with XR 8002 flat fan nozzles[6] to ensure all four 76-cm soybean rows in a plot receive application.

Nutrient Competition. Once soybeans were planted, a biomass sampling schedule was implemented in order to track the nutrients accumulated by broadleaved weeds, grass weeds, and soybeans. Collection timings occurred at the 10-, 20-, 30-, and 45-cm weed heights. Both treatments receiving a PRE application were sampled at every collection date. The remaining treatments were only sampled on the same date they received the POST application with the exception being the 45-cm weed height timing in which all treatments were assessed. Biomass collection was performed prior to the herbicide application (Table 2.1). At each collection time, aboveground weed biomass was gathered from a representative area within the plot. The size of the area collected was documented and was at a minimum of 0.1 m^2; in order to obtain enough weed biomass for laboratory analysis, the area sampled occasionally varied due to low weed densities and immature weeds. The weeds from each sample location were then sorted into broadleaves and grasses and placed in paper bags. Six soybean plants from the outside two rows of the plot were also collected. All biomass was obtained by clipping specimens at the soil surface and carefully removing any soil that remained on the plant. After biomass collection, plots were then sprayed with the designated POST herbicide. The collected biomass was then oven-dried at 60° C until constant weight for dry mass determination and then analyzed for nutrient content[7]. Determination of total N was by the Dumas combustion method while P, K,

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[5] FS MSO Ultra, GROWMARK, Inc., 1701 Towanda Ave., Bloomington, IL 61701.

[6] TeeJet Technologies, 3062 104th St., Urbandale, IA 50322.

[7] Midwest Laboratories, Inc., 13611 B St., Omaha, NE 68144.

Mg, Ca, S, Fe, Mn, B, Cu, and Zn concentrations in the plant tissue were measured by inductively-coupled plasma emission spectroscopy (ICPES) following a microwave nitric acid digestion. Nutrient accumulation was then formulated as kg ha^{-1} by using the concentration of the ion in the plant and the area the biomass was collected from. Apart from assessing foliar nutrients in plant tissue, soil nutrient tests were also employed. Five soil cores from the center two rows of each plot were collected at planting and harvest and analyzed as a composite sample for N, P, K, Mg, Ca, S, Fe, Mn, B, Cu, and Zn. Total N was quantified by Dumas methodology, Bray P1 was determined by colorimetric means, and the remaining ions were measured via ICPES.

Soybean Grain Yield. Once soybeans had reached maturity, but prior to harvest, data were collected to provide indices of grain yield by first counting the number of plants in 1 m of row from the center two rows of the plot. From each meter of row, three representative plants were collected for a total of six plants per plot. These plants were then used for determination of number of pods per plant, and then hand harvested to calculate seeds per pod. At harvest, the center two rows were machine harvested. The entire grain sample of each plot was then bagged individually, weighed, and adjusted to 13% moisture for grain yield determination. A subsample was then analyzed for protein and oil content using a ZX-50 Near-Infrared Seed Analyzer[8].

Experimental Design and Analysis. Plots were 15 m long by 3 m wide and arranged in a randomized complete block design consisting of four replications. Soybean and weed nutrient accumulation were extrapolated to a kg ha^{-1} basis using the area collected, biomass dry weight, and nutrient concentration. To allow for a broader inference to be made of the results across the multiple locations, data were pooled across sites. However, due to the drastic differences in

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[8] Zeltex, Inc., 130 Western Maryland Pkwy, Hagerstown, MD 21740.

rainfall patterns between 2012 and 2013 (Table 2.2), years were analyzed separately. Soybean nutrient accumulation and grain yield parameters were subjected to analysis of variance using the PROC MIXED model in SAS[9] treating site as a random effect. Means were then separated using Fisher's protected LSD (α=0.05).

RESULTS AND DISCUSSION

Rainfall patterns varied greatly between the two years (Table 2.2) and thus, resulted in the planting and weed collection dates being adjusted as necessary (Table 2.1). During the first three months of the 2012 growing season only 41% of the precipitation was received compared to the 30-year average. Alternatively, 2013 received 22% more precipitation than the long-term average. Another repercussion associated with these environmental differences was fluctuations in the weed species spectra (Table 2.3). The most notable difference was a 433, 906, 330, and 54% increase in grass density in 2013 at Belleville, Carbondale, Ina, and Ridgway, respectively. Similarly, there was a 48% increase in broadleaved weed density at the Belleville location. Another major effect was a shift in the broadleaved weed species complex to more competitive species in 2013. The late plantings and droughty conditions in 2012 at Ina and Ridgway facilitated the establishment of carpetweed (*Mollugo verticillata*), a species with a competitive index (CI) of 0.1. Conversely, the following year these sites were infested with more competitive weeds such as morningglory (*Ipomea* spp.), Palmer amaranth, and waterhemp (*Amaranthus tuberculatus*) with CI's of 5.5, 4.0, and 2.5, respectively (Bradley et al. 2007; Coble 1998). Weed growth rates between sites ranged from 0.87 to 1.20 cm day^{-1} in 2012, from 0.82 to 1.09 cm day^{-1} in 2013 and on average, differed by less than 0.1 cm day^{-1} between years

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[9] SAS software, Version 9.3, July 2011, SAS Institute Inc., Cary, NC 27513.

(data not shown). Thus, competitive differences between the two years are more likely the result of a changing weed species spectrum and environmental conditions more conducive to weed-soybean competition. Competition from weeds did not result in any detectable differences in the soil nutrient analysis (data not shown) and is likely due to the inherent low sensitivity of these tests as reported by others (Hellwig et al. 2002).

Nutrient Accumulation by Weeds. Averaged across all minerals, broadleaved weeds assimilated 149% more nutrients than grasses in 2012 and 108% more in 2013 (Table 2.4). The greater congruency between the two in 2013 is likely due to higher grass densities during this year. The individual nutrients that showed the most disparity between grasses and broadleaves were Ca and B; both of which were accumulated more by broadleaved weeds. Ca and B both have critical roles in fortifying the plant cell wall and are rich within the pectin polysaccharide matrix. Because broadleaves contain more of this substance, their physiological demand for these ions is much greater than grasses (Hepler and Winship 2010; Hu et al. 1996). Nutrient acquisition by weeds was greater for all ions in 2013 than in 2012, except Fe and Mn. On average, the increase in nutrient acquisition was 29% for the primary macronutrients, 19% for the secondary macronutrients, and 11% for the micronutrients. Nutrient uptake in plants is influenced by a number of environmental conditions. The droughty conditions in 2012 may have impacted nutrient accumulation in a number of ways. First, when plants are under stress, their overall nutritional demand will be less than that of a rapidly growing plant. Also, the presence of soil moisture is required for effective nutrient uptake. Plants acquire labile nutrients such as NO_3^-, SO_4^{-2}, and BO_3^{-2} primarily via mass flow and uptake non-mobile ions such as Ca^{+2}, Mg^{+2}, and K^+ through diffusion. Both of these processes are dependent upon ample soil moisture levels either to transport anions in the soil solution or establish an interface by which cations may diffuse from the soil colloids.

Soybean Nutrient Assimilation. Concentrations of all nutrients in weed-free soybean plots were well within suggested sufficiency levels (Table 2.5) indicating adequate nutrient supplying power from each site. As the magnitude of nutrient accumulation (kg ha^{-1}) is ion-specific, data relating to soybean nutrition is presented as a percent relative to the weed-free treatment to enable a useful comparison across each nutrient. No differences in soybean nutrient uptake were observed between the standard herbicide regimens and the weed-free treatment. Therefore, only the effect of increasing weed heights will be discussed.

Primary Macronutrients. In 2012, soybean primary macronutrient acquisition was not reduced until weeds reached a height of 20 cm (Table 2.6). After this initial decline, N, P, and K uptake by soybean was not reduced further by extending the period of weed competition from 20 to 45 cm. In 2013, results were more pronounced with soybean N nutrition being reduced from competition with weeds at a height of 10 cm, whereas, P and K levels were not impaired until 20-cm weed competition. Unlike 2012, after the initial decline, further reductions in N and P accumulation were observed in 2013 by enabling weeds to compete up to a height of 45 cm. Competition with 45-cm weeds reduced N, P, and K accumulation by an average of 31% in 2012 and 39% in 2013 when compared to the weed-free treatment. Although P and K are generally regarded as the most important primary macronutrients in soybean nutrition, these results suggest during both years N was that most strongly affected by weed competition. Because uptake of N from the soil solution requires less energy than forming a symbiotic N-fixing relationship, this is the preferred form of acquisition by soybean (Berglund and Helms 2003) and accounts for approximately 50% of N within the plant (Kramer and Boyer 1995). This reduction in soybean

N nutrition may be a result of direct, physical competition for N ions or an interaction that alters soybean root architecture and root nodule formation.

Secondary Macronutrients. There was much less disparity between the individual secondary macronutrients as Ca, Mg, and S responded similarly to increasing durations of weed competition (Table 2.7). As with the primary macronutrients, soybean accumulation of the secondary macronutrients was not affected so long as weeds were removed before reaching 20 cm in height. Also, there was no significant additional impairment by competition from 45-cm weeds, although means continued to decline. The critical height to remove weeds to ensure the greatest uptake of Ca, Mg, and S did not change in 2013. However, by extending this period beyond 20 cm to 45 cm weed competition, further reductions in Mg and S occurred. Overall, the impact of weed competition on soybean secondary macronutrient nutrition was greater in 2013 than in 2012 with an average reduction by 45-cm weeds of 31% in 2012 and 37% in 2013.

Micronutrients. The acquisition of micronutrients by soybean in 2012 was altered by competition once weeds reached 20 cm in height, but beyond this height, no additional reductions occurred (Table 2.8). Competition from weeds in 2013 once again resulted in a greater reduction in overall micronutrient accumulation with a 33% loss in 2012 versus a 47% loss in 2013. In 2013, B, Cu, and Zn acquisition was impaired if weeds were not controlled by 20 cm in height, whereas Fe and Mn levels were reduced already by the 10-cm weed removal timing. Progressions in the duration of competition up to 45-cm weed heights further reduced the uptake of all micronutrients, except B. Soybean micronutrient accumulation, as impacted by weed competition, showed a greater response to the more favorable growing season of 2013 than the macronutrients. Due to the higher weed densities in this year, belowground competition was likely stronger and may have made it more difficult for soybean roots to extract the inherent low concentrations of micronutrients from the soil. Out of all 11 analyzed minerals in soybean, Fe was that most strongly impacted by weed competition in both years. In 2013, competition from 20-cm weeds produced soybean plants that contained only 40% the Fe of soybeans grown under weed-free conditions; this was less than any other nutrient in soybean, even from competition with 45-cm weeds. Under aerobic conditions, Fe exists in its ferric state. Although, normally present in sufficient quantities, this form of Fe is only slightly soluble and thus, very difficult for roots to assimilate. In high pH and calcareous soils, ferric ions become even more insoluble – the primary reason growers in some northern regions of the Corn Belt are plagued with Fe chlorosis (Berglund and Helms 2003). There are two strategies utilized by higher plants for Fe uptake. Strategy I, used by soybean and other non-graminaceous plants, relies on the solubilizing power provided by H^+-ATPase and the reducing capacity of ferric-chelate reductase within the cell wall (Kobayashi and Nishizawa 2012). Strategy II, employed by graminaceous species, is generally regarded as a more efficient form of Fe uptake because it requires less modification of the ferric ion via the use of Fe-scavenging phytosiderophores. The more resourceful uptake of Fe by grasses may explain soybean's particular susceptibility to reduced Fe accumulation in response to weed competition. Additionally, the more drastic impairment of Fe assimilation in 2013 may in part be explained by the 333% increase in grass weed density over 2012. In 2013, the difference in Fe accumulation between weed-free soybean and soybean competing with 45-cm weeds was 0.41 kg ha^{-1} (data not shown); this amount is within the range growers may apply as a foliar supplement (Diaz 2011; Goos and Johnson 2000). Therefore, by eliminating this level of weed competition, producers may be able to reduce the application rate or altogether avoid the use of foliar-applied Fe.

Correlation analysis was utilized between relative soybean nutrient accumulation and days of weed competition. These results concur with the ANOVA analysis using weed height as the independent variable; averaged across both years, N (r = -0.62) and Fe (r = -0.67) are the minerals most strongly impacted by increasing periods of weed competition duration (Table 2.9). For all nutrients, correlation coefficients were greater in 2013 than in 2012.

Soybean Grain Yield. Weed interference reduced soybean grain yields both years but the level of competition at which yield losses occurred differed. In 2012, competition from weeds 30 cm or greater in height reduced grain yield, whereas the onset of these losses came sooner in 2013 as competition from 10-cm weeds elicited the same effect (Table 2.10). The magnitude of reduction was greater in 2013 as competition from 45-cm weeds reduced grain yield by 13% compared to 7% in 2012. However, the average yield was slightly higher in 2012 (4%) and is likely due to the ample rainfall later in the growing season during pollination and pod fill (Table 2.2). For this experiment, the period of active competition between weeds and soybean occurred during the droughty period of 2012; hence, the less early-season precipitation received during this year is one probable explanation as to why yield reductions from weed competition were more pronounced in 2013. Other authors have noted the variability associated with determining the critical duration of weed competition in soybean and how this may be influenced by environmental conditions (Hagood et al. 1980; Halford et al. 2001; Patterson 1995; Van Acker et al. 1993). During a growing season with ample rainfall, Harris and Ritter (1987) noted a 15% soybean grain yield loss from a 4-week period of weed competition compared to only 4 and 0% losses during droughty years. The correlation coefficient (r) between yield and days of competition was -0.21 ($p=0.066$) in 2012 and -0.54 ($p<0.001$) in 2013 (Table 2.11). In a similar study in corn, Hans and Johnson (2002) reported a much stronger coefficient of -0.84 between days of weed competition and grain yield.

Compared to the weed-free treatment, the only yield reductions from the standard PRE/POST and POST/POST herbicide treatments occurred in 2013. Weed control ratings taken at the time of POST application for the PRE flumioxazin treatment were never greater than 82% (data not shown). The short half-life of flumioxazin under anaerobic conditions and the ample soil moisture in 2013 likely facilitated rapid degradation resulting in unsatisfactory control and enabled early-season competition from weeds. The timing of the first application in the sequential POST treatment coincided with the 10-cm weed removal height and yields of these treatments did not differ from each other. This indicates the second POST application may not have been warranted as it did not provide an enhancement in yield. However, it may still offer other benefits not assessed in this project such as preventing late-season weed escapes from producing seed.

Yield Components. Beyond overall grain yield, no differences between additional yield components were observed in 2012. Soybean seed weight and oil content responded to weed competition in 2013 (Table 2.10). A decline in seed weight occurred when weeds were not removed before reaching 10 cm in height while, oil content was not reduced until the 20-cm weed removal height. The ability of weeds to reduce soybean seed weight has been well documented (Burnside 1979; Eaton et al. 1976; Felton 1976); however, few have been able to establish a connection between weed competition and reduced oil content (Chhokar et al. 1995). Millar et al. (2007) found high levels of weed competition generally increased the concentration of protein in soybean seed, while, tending to reduce the oil content. Because oil is the most resource-consuming macromolecule synthesized by soybean (Rodriguez and Vivian 2011) it would seem logical that any stressor may alter the production of this vital seed component. Dombos and Mullen (1992) and Ghassemi-Golezani and Lotfi (2013) have illustrated this effect in response to salt and drought stress. Although weed competition had no effect on pods per plant or seeds per pod, other researchers have noted such findings (Burnside 1979; Eaton et al. 1976) with the largest losses generally attributable to fewer seeds per pod (Harris and Ritter 1987).

These results suggest the critical duration of weed competition in soybean is greatly dependent on climatic influences as it has both a direct effect on the growth and development of the crop and an indirect effect by altering the relative competitiveness of weeds through a changing species spectrum. There are discrepancies in how critical removal timings are reported. Crop growth stage, days after crop emergence (DAE), and weed height have all been suggested (Knezevic et al. 2009; Van Acker et al. 1993). Although this study focuses primarily on weed height at the time of removal, to facilitate the comparison across studies it seems imperative to include such information when reporting data (Table 2.12). In general for this study, to maximize nutrient availability to soybean, weeds should be managed prior to reaching 20 cm in height. This height corresponds to 33 to 34 DAE and the V2 to V4 growth stage. To circumvent yield losses, the critical removal timing was 30 cm (40 DAE, V4) in 2012 and 10 cm (27 DAE, V2) in 2013. Knezevic et al. (2003) reported the critical period of weed control for soybean planted in 76-cm rows to be during the V1 growth stage. Van Acker et al. (1993) epitomize the inherent variability associated with this concept as they report a range of 9 to 38 DAE.

The weed-free treatment utilizing a robust, broad-spectrum PRE/POST herbicide regimen provided the most consistent soybean nutrient and yield data across both years. These results, given such drastic climatic differences between 2012 and 2013, reveal one of the numerous benefits of utilizing comprehensive herbicide programs. As the evolution of herbicide-resistant weeds continue to challenge growers to adapt, more are adopting the implementation of PRE herbicides for resistance management reasons. However, the selection of soil residual products is frequently driven by economic decisions in an attempt to minimize input costs and often results in the underutilization of effective PRE options. Consequently, only partial weed control may be achieved resulting in escapes that must be dealt with through POST applications. These results show that early-season weed competition can hinder soybean nutrient uptake and grain yield. By eliminating this level of interference through the use of more dynamic, broad-spectrum soil residual herbicides, growers can circumvent these losses and may establish a more effective nutrient and herbicide-resistant weed management plan. Thus, sound weed management practices that include soil residual herbicides to minimize the duration of weed competition preserves soybean grain yield, mitigates the evolution of herbicide-resistant weeds, and reduces nutrient competition with soybean may help alleviate micronutrient deficiencies and the need for supplemental foliar fertilizers in some geographies and provide for an overall, more sustainable soybean production system.

Table 2.1. Year, location, soil characteristics, planting dates, soybean varieties, weed collection and herbicide application dates, and harvest dates for field experiments.

Year	Location	Soil class	Variety	Planting date[a]	Weed collection dates[b]				Harvest date
					10 cm	20 cm	30 cm	45 cm	
2012	Belleville	Pierron silt loam	NK S46-A1	22-May	15-Jun	20-Jun	24-Jun	30-Jun	25-Oct
	Carbondale	Stoy silt loam	NK S46-A1	24-May	24-Jun	29-Jun	6-Jul	14-Jul	29-Oct
	Ina	Wynoose silt loam	NK S39-U2	28-Jun	24-Jul	1-Aug	9-Aug	15-Aug	24-Oct
	Ridgway	Sexton silt loam	NK S39-U2	2-Jul	1-Aug	9-Aug	15-Aug	23-Aug	22-Oct
2013	Belleville	Pierron silt loam	NK S46-L2	15-Jun	5-Jul	13-Jul	18-Jul	22-Jul	22-Oct
	Carbondale	Stoy silt loam	NK S46-L2	19-May	17-Jun	23-Jun	26-Jun	4-Jul	24-Oct
	Ina	Wynoose silt loam	NK S46-L2	22-Jun	16-Jul	22-Jul	29-Jul	5-Aug	26-Oct
	Ridgway	Sexton silt loam	NK S46-L2	28-May	26-Jun	3-Jul	9-Jul	16-Jul	19-Oct

[a] Preemergent herbicide treatments applied at planting.

[b] Postemergent herbicide treatments applied on weed collection dates.

Table 2.2. Monthly rainfall at Ina, IL in 2012 and 2013.

Year	May	June	July	August	September	October
	---mm--					
2012	60	20	47	166	151	87
2013	143	87	143	83	25	125
30 Year Average	104	99	103	88	76	72

Table 2.3. Predominant broadleaf and grass weed species and mid-season densities for each location and year.

Year	Location	Broadleaf species	Density[a]	Grass species	Density
			plants m^{-2}		plants m^{-2}
2012	Belleville	giant ragweed waterhemp	29	fall panicum	6
	Carbondale	morningglory spp. giant ragweed	38	giant foxtail	16
	Ina	carpetweed	160	green foxtail	10
	Ridgway	carpetweed redroot pigweed	22	fall panicum large crabgrass	35
2013	Belleville	giant ragweed waterhemp	43	fall panicum	32
	Carbondale	morningglory spp. common ragweed	32	giant foxtail	161
	Ina	Palmer amaranth waterhemp	25	fall panicum	43
	Ridgway	waterhemp morningglory spp.	21	fall panicum large crabgrass	54

[a] When more than one species is listed, the density represents the average of the two.

Table 2.4. Broadleaf and grass weed nutrient accumulation at the 45-cm weed removal timing in 2012 and 2013, pooled across sites.

	2012		2013	
Nutrient	Broadleaf	Grass	Broadleaf	Grass
	----------kg ha^{-1}----------			
N	35.8	28.0	45.1	24.2
P	5.59	4.79	9.87	6.29
K	62.0	53.3	89.2	52.3
Ca	27.2	5.74	36.3	5.06
Mg	7.61	2.93	7.98	3.35
S	3.89	2.25	5.09	2.45
	----------g ha^{-1}----------			
Fe	931	363	236	121
Mn	289	145	115	64.7
B	39.7	5.16	102	4.67
Cu	12.3	11.9	18.7	10.0
Zn	56.5	41.0	83.9	40.3

Table 2.5. Soybean nutrient concentrations from foliar analysis for each site and year from weed-free plots.

Year	Location	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
		%						ppm				
2012	Belleville	3.46	0.48	4.27	1.46	0.38	0.30	175	47	46	10	47
	Carbondale	3.59	0.35	2.83	1.86	0.34	0.25	241	89	31	9	36
	Ina	3.66	0.37	2.29	1.76	0.49	0.23	305	72	29	8	23
	Ridgway	3.85	0.40	3.48	1.49	0.41	0.26	196	166	31	13	55
2013	Belleville	4.09	0.44	4.20	1.42	0.35	0.29	196	50	44	9	48
	Carbondale	3.99	0.49	3.45	1.69	0.37	0.29	361	82	37	11	32
	Ina	4.05	0.43	3.87	1.47	0.36	0.28	180	62	39	9	42
	Ridgway	4.71	0.40	3.50	1.25	0.34	0.28	122	74	32	8	34
Sufficiency level[a]		NA[b]	0.25	2.00	0.40	0.25	0.15	30	20	25	5	15

[a] Minimum nutrient concentrations for soybean according to the Illinois Agronomy Handbook (Fernández and Hoeft 2009).

[b] None listed

Table 2.6. Relative soybean primary macronutrient accumulation at the 45-cm weed removal timing in 2012 and 2013, pooled across sites.

Weed removal timing[a]	2012						2013					
	N		P		K		N		P		K	
	-----------------------------------% of weed-free-------------------------------											
10 cm	101	a[b]	104	a	110	a	90	b	100	ab	101	a
20 cm	73	b	79	b	80	cd	72	c	77	c	75	b
30 cm	74	b	78	b	93	b-d	68	cd	74	cd	73	b
45 cm	67	b	68	b	71	d	59	d	63	d	67	b
PRE/POST[b]	96	a	94	a	96	a-c	94	ab	106	a	103	a
POST/POST[b]	103	a	107	a	103	ab	90	ab	95	ab	94	a

[a] Means within each column followed by the same letter do not differ significantly from the weed-free according to Fisher's protected LSD (α = 0.05).

[b] Standard herbicide regimens

Table 2.7. Relative soybean secondary macronutrient accumulation at the 45-cm weed removal timing in 2012 and 2013, pooled across sites.

Weed removal timing	2012						2013					
	Ca		Mg		S		Ca		Mg		S	
	-----------------------------------% of weed-free-------------------------------											
10 cm	103	a[a]	101	a	103	a	97	ab	100	ab	96	a
20 cm	78	b	78	b	77	b	71	c	74	c	75	b
30 cm	78	b	77	b	79	b	69	c	72	cd	70	bc
45 cm	68	b	68	b	70	b	62	c	64	d	62	c
PRE/POST[b]	96	a	95	a	95	a	105	a	105	a	99	a
POST/POST[b]	108	a	107	a	107	a	90	b	90	b	92	a

[a] Means within each column followed by the same letter do not differ significantly from the weed-free according to Fisher's protected LSD (α = 0.05).

[b] Standard herbicide regimens

Table 2.8. Relative soybean micronutrient accumulation at the 45-cm weed removal timing in 2012 and 2013, pooled across sites.

Weed removal timing	2012					2013				
	Fe	Mn	B	Cu	Zn	Fe	Mn	B	Cu	Zn
	-----% of weed-free-----									
10 cm	91 a[a]	93 ab	101 ab	100 a	98 ab	71 bc	86 b	99 a	98 ab	104 a
20 cm	61 b	76 bc	80 d	73 b	78 cd	40 d	61 c	77 b	74 c	80 cd
30 cm	60 b	75 bc	84 cd	75 b	79 cd	37 d	57 cd	75 b	72 c	72 d
45 cm	51 b	71 c	76 d	65 b	73 d	31 d	47 d	67 b	60 d	60 e
PRE/POST[b]	90 a	93 a-c	94 bc	90 a	93 bc	83 b	102 a	102 a	102 a	107 a
POST/POST[b]	102 a	105 a	109 a	102 a	109 a	59 c	79 b	94 a	91 b	92 bc

[a] Means within each column followed by the same letter do not differ significantly from the weed-free according to Fisher's protected LSD ($\alpha = 0.05$).

[b] Standard herbicide regimens

Table 2.9. Pearson correlation coefficients of relative soybean nutrient accumulation and days of weed competition in 2012 and 2013, pooled across sites.

Nutrient	2012	2013
Nitrogen	-0.56[a]	-0.68
Phosphorus	-0.47	-0.57
Potassium	-0.28	-0.54
Calcium	-0.49	-0.60
Magnesium	-0.49	-0.61
Sulfur	-0.48	-0.70
Iron	-0.58	-0.76
Manganese	-0.38	-0.68
Boron	-0.34	-0.56
Copper	-0.49	-0.56
Zinc	-0.35	-0.52

[a] All coefficients are highly significant ($p<0.01$)

Table 2.10. Soybean grain yield characteristics in 2012 and 2013, pooled across sites.

Year	Weed removal timing	Yield		200 seed wt.		Pods		Seeds		Protein		Oil	
		kg ha^{-1}		g		plant^{-1}		pod^{-1}		%		%	
2012	Weed-free	3745	a[a]	35.1	a	42.9	a	2.29	a	39.3	ab	20.0	a
	10 cm	3788	a	35.0	a	43.3	a	2.20	a	39.1	b	20.0	a
	20 cm	3648	a-c	34.8	ab	40.6	ab	2.23	a	39.5	ab	19.9	a
	30 cm	3430	c	35.2	a	41.2	ab	2.30	a	39.7	a	19.9	a
	45 cm	3489	bc	35.3	a	39.1	b	2.28	a	39.4	ab	20.0	a
	PRE/POST[b]	3606	a-c	35.2	a	41.6	ab	2.31	a	39.1	b	19.9	a
	POST/POST[b]	3731	ab	33.9	b	44.2	a	2.26	a	39.2	b	19.9	a
2013	Weed-free	3716	a	33.7	a	42.6	ab	2.26	a	38.7	ab	21.6	a
	10 cm	3445	b	32.6	b	40.1	ab	2.16	ab	38.6	ab	21.5	ab
	20 cm	3456	b	32.7	b	37.7	b	2.22	ab	38.9	a	21.2	c
	30 cm	3456	b	32.4	bc	39.1	ab	2.19	ab	38.6	ab	21.2	c
	45 cm	3278	c	31.8	c	42.3	ab	2.14	ab	38.3	b	21.2	c
	PRE/POST	3520	b	32.5	b	44.2	a	2.14	ab	38.8	a	21.2	c
	POST/POST	3486	b	32.7	b	39.3	ab	2.17	ab	38.7	ab	21.3	bc

[a] Means within each column and for each year followed by the same letter do not differ significantly according to Fisher's protected LSD (α = 0.05).

[b] Standard herbicide regimens

Table 2.11. Pearson correlation coefficients of relative soybean yield parameters and days of weed competition in 2012 and 2013, pooled across sites.

Parameter	2012		2013	
	r	p	r	p
Grain yield	-0.21	0.066	-0.54	<0.001
Seed weight	0.08	0.478	-0.52	<0.001
Pods plant^{-1}	-0.23	0.037	-0.10	0.389
Seeds pod^{-1}	-0.04	0.703	-0.21	0.058
Protein	0.17	0.135	-0.07	0.531
Oil	-0.12	0.295	-0.39	<0.001

Table 2.12. Days after soybean emergence and soybean growth stage associated to each weed removal height.

Year	Weed removal height	Days after emergence	Soybean growth stage[a]
2012	10 cm	28	V2
	20 cm	34	V3-V4
	30 cm	40	V4
	45 cm	47	V5-R1
2013	10 cm	27	V2
	20 cm	33	V2-V3
	30 cm	38	V3-V4
	45 cm	45	V4-R1

[a] Differences in planting dates resulted in minor variances in soybean growth stage therefore, ranges are provided.

CHAPTER 3

DECAY AND NUTRIENT RELEASE PATTERNS OF WEED RESIDUES FOLLOWING POSTEMERGENT CONTROL

Successful postemergent (POST) weed management is often the result of timely herbicide applications made prior to the critical duration of weed competition. However, the temporal disconnect between when weeds *should* be controlled versus when weeds *can* be controlled often results in substandard weed management practices with ensuing yield losses. One possible explanation behind such yield detriments is nutrient competition between the weeds and crop. The propensity of weeds to accumulate nutrients differs both among species (Majumder et al. 2008) and plant heights (Lindsey et al. 2013). Known to be one of the most competitive weeds, giant ragweed (*Ambrosia trifida*) can accumulate up to 104 kg ha^{-1} of N during one growing season (Johnson et al. 2007). The exploitation of resources by weeds, therefore, threatens not only to hamper the immediate productivity of crops, but also the sustainability of production agronomic systems. While the ability of weeds to reduce yields is well established and their capacity to accumulate nutrients is marginally understood, knowledge regarding the fate of nutrients following POST herbicide control is absent. As concerns mount about the impact nutrients from agro-ecosystems have on the environment, it is imperative to thoroughly identify and quantify the sinks and sources of these nutrients and how weed dynamics such as specie and height may affect these processes. Granted, recent work by Lindsey et al. (2013) exposed N mineralization rates were influenced by these two factors and provides credence for further investigations, the methodology used in this experiment does not accurately mimic *in situ* processes; weeds were harvested fresh, finely-ground, mixed with soil, and then placed in a laboratory incubator. Because research in this area is lacking, Lindsey et al. (2013) provided a better understanding of the dynamics involved with weed decomposition and nutrient release. However, there remains a need to quantify these parameters with methodology more closely adapted to field scenarios and broaden the scope of mineral release beyond that of N. The prospective role weeds play in the nutrient cycling in agronomic fields may elucidate any ancillary effects provided by sound weed management practices and bolster a more efficient form of crop mineral nutrition by ensuring sustenance is available at the proper time.

Much of the literature regarding the decay continuum and nutrient release patterns of plant litter stems from work conducted in ecosystems that differ greatly from Midwestern agronomic settings. Yet, when looking across these studies, much can still be learned about the dynamics and processes involved. Decomposition of plant litter involves the physical, chemical, and biological processes that reduce detritus to its elemental chemical constituents (Aerts 2006). The decay continuum is generally regarded as a biphasic process: initially, there is a rapid loss of the water-soluble, labile compounds such as simple sugars; followed by a more persistent phase in which the recalcitrant cell wall compounds are enzymatically degraded (Berg 2008). The resulting product of plant litter degradation is stabilized humus; at which point further losses are immeasurably slow (Prescott 2005). For any given site, the primary rate regulator of decomposition is the quality of the litter; this may be viewed as the stoichiometric proportions of recalcitrant versus labile plant compounds. Van Vuuren et al. (1993) and Magill and Aber (1998) suggest that high quality litter (e.g., low lignin:N ratio) initially decomposes at a faster rate than litter of poor quality, yet, ultimately enters the humus stage with more mass remaining. There is much debate as to the single, most useful litter quality parameter in predicting the decay rate of plant matter. However, a comprehensive analysis across gradients of time, space, and specie distribution by Berg (2008) revealed a few generalized patterns as to which initial chemical constituents were most often strongly associated to decay rates. Because of their essential role in nucleic acid synthesis, N, P, and S tend to have the strongest positive correlations while; the cell wall components consisting of cellulose, hemicellulose, and lignin are often negatively correlated.

Weed specie and height are two critical aspects that influence the probability of successful POST herbicide applications. To examine how heterogeneity within these factors may affect the course of decomposition, a physiological understanding of the largest obstacle to this process is critical. The plant cell wall is the most abundant source of organic C in the world. The primary functions of this structure are to provide mechanical and structural support, regulate cell growth, provide energy storage, and inhibit pathogen invasion (Gilbert 2010). With such robust functions to fulfill, the cell wall inherently possesses the affinity to impede the process of decomposition. The cell wall is a dynamic structure consisting of three regions: the middle lamella, primary wall, and secondary wall (Dickinson and Pugh 1974). While the utility and composition of each region differ to some extent, as an entire entity, the cell wall can be viewed as an intricate network composed of cellulose and cross-linking glycans (hemicelluloses) residing in a pectin polysaccharide matrix with associated structural proteins (Carpita and Gibeaut 1993). The ultrastructure and chemical constituency of cell walls are not static throughout the plant kingdom. There exist two forms of walls that differ primarily in the hemicellulose fraction, type I and type II. Xyloglucan is the predominant hemicellulose in type I walls and is found in most dicots while, glucuronoarabinoxylan is that most commonly found in the type II walls of monocots. Furthermore, type II walls produce the mixed-linkage β-D glucans that further bolster structural support (Carpita and Gibeaut 1993).

Lignin is known to be one of the most recalcitrant plant substances. Lignin increases cell wall rigidity by forming covalent bonds to cellulose (Vanholme et al. 2010) and in some tissues may compose 60 to 80% of the secondary cell wall (Musha and Goring 1975). The lignification process also results in cell wall heterogeneity. Because this phase is much slower than cellulose biosynthesis, lignin suffices as the cell wall component most strongly associated to tissue maturity and plant height (Berg 2008). Hence, given the rate regulating capacity of the cell wall together with the dynamic nature of this structure, it is probable that decomposition and nutrient release rates will differ according to weed specie and plant height variances.

Two of the most pernicious and prolific weed species encountered by growers in the Midwestern U.S. are waterhemp (*Amaranthus tuberculatus*) and giant foxtail (*Setaria faberi*). The vast prevalence of these species coupled with their affinity to competitively reduce grain yields suggests these are exemplary weed species to be used in the characterization of weed biomass degradation and to expose the subsidiary effects of poor weed management due to delayed herbicide applications. A rapid loss of nutrients from weeds in-season would minimize the risk of environmental losses after harvest by liberating minerals early enough for them to still be utilized by the crop. Therefore, the purpose of this study was to quantify the rate of decomposition and nutrient release of weed residues following POST herbicide control. Specific objectives include 1) determine the effect of weed height at the time of herbicide application 2) evaluate the influence imposed by a grass versus broadleaf, and 3) examine the relationship between the initial chemical properties of the weed residue and the liberation of nutrients over time.

MATERIALS AND METHODS

Decomposition and nutrient release rates were determined for aboveground biomass of waterhemp and giant foxtail grown to heights of 10, 20, 30, and 45 cm in 2013 during the months of June through September at the Agronomy Research Center near Carbondale, IL and a producer field site near Ridgway, IL.

Weed Biomass Accumulation. In order to acquire sufficient biomass and achieve the appropriate weed heights for June implementation, plants were grown under greenhouse conditions starting in February. Waterhemp[10] and giant foxtail[11] were sown into pots containing field soil; this growing media was preferred due to a preliminary experiment that revealed the propensity of waterhemp to have a higher percentage of its dry weight allocated to foliage if grown in potting soil (data not shown). Soil pH was 6.5, soil organic matter was 1.15%, and cation exchange capacity was 8.73 cmol kg^{-1}. NO_3-N concentration in the soil was 27.5 mg kg^{-1} and NH_4-N was 2.7 mg kg^{-1}. Bray P1 was 72 mg kg^{-1} and Mehlich III extractable K, Ca, Mg, and S concentrations in the soil were 116, 986, 70, and 20 mg kg^{-1}, respectively. Pots were fertilized for plant maintenance every other week with a macro- and micronutrient-containing fertilizer[12]. Specimens were grown under 30º C conditions and placed under auxiliary lighting of 120 to 140 μmol m^{-2} s^{-1} provided by high pressure sodium bulbs to mimic a 16-hour day. To appropriately simulate a common grower practice for POST weed control, glyphosate[13] (1,100 g ae ha^{-1}) was applied once weeds reached the targeted heights of 10, 20, 30, or 45 cm. This particular glyphosate formulation did not contain an activator adjuvant; therefore, a nonionic

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[10] Collected from an indigenous field population near Belleville, IL 62221.

[11] Collected from an indigenous field population near Carbondale, IL 62901.

[12] Jack's Classic Professional, JR Peters, Inc., 6656 Grant Way, Allentown, PA 18106.

[13] Touchdown HiTech, Syngenta Crop Protection, Inc., P.O. Box 18300, Greensboro, NC 27419-8300.

surfactant[14] was included at 0.5% v/v. The herbicide application was made with a single-nozzle spray booth calibrated to deliver 140 L ha^{-1} at a pressure of 207 kPa. Specimens were then harvested 7 days after treatment by clipping the weeds at the soil surface. The biomass was then allowed to air-dry in the greenhouse at 35° C until constant weight.

***In situ* Degradation of Weed Litter.** A litterbag experiment (Cobo et al. 2002, Majumder et al. 2008, Swift et al. 1979) was conducted to track decomposition and nutrient release rates. Litterbags[15] were 20 x 20 cm, constructed of nylon, with a 2-mm mesh on the bottom and a 5-mm mesh on the upper side. The finer mesh keeps detritus in the bag, while the larger mesh facilitates macrofaunal entry and air circulation (Swift et al. 1979). Twenty bags for each treatment were filled with air-dry material equivalent to 5 g on a dry weight basis and then closed with plastic ties. For the 30- and 45-cm treatments, specimens were cut into two segments before being placed in a bag. Care was given to ensure the proportion of stems and leaves used accurately represented a whole plant sample. Furthermore, handling loss bags were filled for each species in order to account for any weight loss during transport (Swift et al. 1979). A larger, 10-g sample was also taken at this time and used for determination of the initial chemical characteristics of the plant materials. The experimental field area was conventionally tilled and then planted with soybeans[16] in 76-cm rows at a target population of 346,000 seeds ha^{-1} to simulate common agronomic practices. A blanket application of the herbicides sulfentrazone, *s*-metolachlor, and fomesafen was applied at 140, 1,378, and 70 g ai ha^{-1} prior to soybean emergence to limit initial weed pressure and were maintained weed-free via glyphosate applied at 1,100 g ae ha^{-1} at the V4 soybean growth stage.

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[14] Activator 90, Loveland Products Inc., P.O. Box 1286, Greeley, CO 80632.
[15] EFE & GB Nets, P.O. Box 1, Bodmin, Cornwall, UK, PL311YJ.
[16] NK S46-L2, Syngenta Seeds, 11055 Wayzata Blvd., Minnetonka, MN 55305.

Litterbags were placed into the field during the first week of June and anchored to the soil surface between two soybean rows using fabric staples. In order to capture the anticipated exponential decay, a geometric sampling schedule of 2, 4, 7, 11, and 16 weeks was implemented. At this time, one bag from each treatment was removed from the field and placed into a plastic bag for transport back to the laboratory. Weed residues were removed from the bags and sorted from other debris using forceps at which point they were rinsed with deionized water for no longer than 15 seconds to avoid the risk of leaching minerals from the plant material (Baker and Plank 1992). Detritus were then oven dried at 60º C until constant weight for dry weight determination and then ground and mixed using a Sample Prep 8000M mixer/mill[17] to pass a 1-mm screen before elemental analysis. The C and N contents were determined by flash combustion using a FLASH 2000 analyzer[18]. P, K, Ca, Mg, and S were measured using inductively-coupled plasma emission spectroscopy (ICPES) following a microwave nitric acid digestion. In order to correct for any contaminant that remained on the plant material after washing, ash content was measured to enable the use ash-free dry weights as a more suitable measure of mass (Cobo et al. 2002, Palm and Sanchez 1990). Ash content was determined by igniting the specimen in a muffle furnace at 500º C for two hours in order to oxidize the organic material. To quantify the cell wall components present in the initial plant material, neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin concentrations were measured by reflux methodology (Undersander et al. 1993, Van Soest et al. 1991). Cellulose concentrations were calculated by subtracting lignin from ADF while, the hemicellulose fraction was determined by subtracting ADF from NDF (Lindsey et al. 2013).

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[17] SPEX, 15 Liberty St., Metuchen, NJ 08840.

[18] Thermo Scientific, 81 Wyman St., Waltham, MA 02451.

Experimental Design and Analysis. Treatments were arranged in a randomized complete block design with four replications. Each block consisted of the 76-cm inter-row space between two soybean rows and spanned the length of 15 m. Litterbags were arranged in a serpentine line between the rows and spaced 10 cm apart. So as to fulfill the objectives of this experiment, data were pooled across both sites so that a larger inference may be formed as to the effect of each treatment. The mass and nutrients remaining at each collection time were analyzed using two-way factorial ANOVA, treating species and height as the main effects. The means were then separated using Fisher's protected LSD (α=0.05). In order to determine a single parameter useful in describing the rate of decay over the entire experimental period, decay constants, or *k* values, were derived according to the single exponential decay model:

$$-k = \ln(X/X_0)/t \qquad [1]$$

where X is the final dry weight or nutrient content, X_0 is the initial dry weight or nutrient content, and t is time (Olson 1963). To examine the association between decay constants and the initial chemical properties of the weed biomass, Pearson product-moment correlation was used. Finally, to establish which factor had a greater influence over both the initial stoichiometric properties of the plant material and the rate of decay, multiple regression analysis using weed species and height as the independent variables was employed. All statistical analyses were performed using SAS.[19]

RESULTS AND DISCUSSION

Weed Residue Quality. All initial quality parameters, excluding lignin, were influenced by the interaction of specie and height (α = 0.05) (data not shown). The 10-cm waterhemp contained

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[19] Version 9.3, July 2011, SAS Institute Inc., Cary, NC 27513

the lowest amounts of NDF, ADF, cellulose, hemicellulose, and lignin (Table 3.1). Conversely, 45-cm giant foxtail showed the highest levels of NDF, ADF, cellulose, and lignin. Generally, the amount of cell wall components was greater in taller weeds and in giant foxtail; illustrated by the positive values of β in Table 3.2. NDF, ADF, cellulose, and hemicellulose were all strongly associated to changes in plant height and weed species ($R^2 = 0.84 – 0.96$). The specie influence ($\beta = 0.87$) on NDF was twice as strong as height ($\beta = 0.42$) and even more pronounced on the amount of hemicellulose ($\beta = 0.96$ and 0.19, respectively). Marten and Andersen (1975) reported a greater abundance of cell wall constituents, particularly hemicellulose, in giant foxtail than in redroot pigweed (*Amaranthus retroflexus*)—a member of the same plant family as waterhemp. Lignin content was the only initial parameter not influenced by a specie effect ($p = 0.78$) and was instead, driven primarily by plant height. Initial nutrient concentrations of P, Ca, Mg, and S were generally greater in waterhemp, whereas N was greater in giant foxtail (Table 3.3). Concentrations of N and K decreased with increasing plant heights. A similar relationship was observed for N content in giant foxtail by Lindsey et al. (2013).

Decomposition and Nutrient Release. Each location received at least 25 mm of rainfall within the first week of litterbag deployment. There was little variation in the rainfall (< 20 mm) and temperature data between each site (data not shown), therefore, the average of the two across the entire experimental period are presented in Figure 3.1. Dry weight loss and nutrient release were subjective to the interaction of specie and height ($\alpha = 0.05$) (data not shown). The largest dry weight losses occurred during the first 4 weeks of the experiment with only minor subsequent losses and followed the anticipated exponential decay trend (Figure 3.2). At the end of 16 weeks, 10-cm waterhemp and giant foxtail had lost 10 and 12% more mass than the 45-cm weed height. Release of nutrients was similarly asymptotic (Figures 3.3 and 3.4), excluding Ca

(Figure 3.4a). Other researchers (Cobo et al. 2002; Palm and Sanchez 1990) have observed initial increases in Ca content and slower rates of release and has been attributed to the accumulation of Ca by fungi residing on the residues. Following a similar trend to overall dry weight loss, smaller weeds liberated nutrients to a greater extent than larger weeds and waterhemp more so than giant foxtail. For both species, 10- and 20-cm weeds had less than 20% of their initial N content remaining by 4 weeks; 30- and 45-cm waterhemp and giant foxtail did not reach this same level until 11 and 16 weeks of decomposition, respectively (Figure 3.3a). P release occurred much sooner for waterhemp than giant foxtail (Figure 3.3b). At 2 weeks, 10-cm waterhemp had only 19% P remaining compared to 39% in 10-cm giant foxtail. After 4 weeks, all treatments had less than 10% of their initial K remaining (Figure 3.3c). K is regarded as one of the most water-soluble plant compounds (Berg 2008) and given the ample rainfall received during the early stages of decomposition this nutrient was the most susceptible to leach from weed residue.

Decomposition rates, according to the single exponential decay model, showed that mass loss was highest in 10-cm waterhemp ($k_D = 0.022$) and lowest in 45-cm giant foxtail ($k_D = 0.011$) (Table 3.4). Nutrient release rates showed a similar response to the specie and height influence as mass loss. The highest k values were for K release ($k_K = 0.030 – 0.043$) while, Ca liberation was the slowest ($k_{Ca} = 0.009 – 0.025$). Release of nutrients from waterhemp followed the order of K > S > Mg > P > N > Ca and from giant foxtail, K > Mg > N > P > S > Ca. Rates of decay and nutrient release in this experiment are consistent with those of Murungu et al. (2011) in which grazing vetch, forage peas, and oats were evaluated. However, they tended to be slower than those presented by Cobo et al. (2002) in which a number of green manures were analyzed in a more tropical environment. These differences can likely be attributed to climatic variables as it is well established that temperature and precipitation can affect the rate of decomposition (Swift et al. 1979).

The influence of plant height and phylogenic class observed in this experiment concur with previous research. Lindsey et al. (2013) documented the affinity of 10-cm weeds to release N at a faster rate than 20-cm weeds. Moreover, there is substantial evidence that broadleaves tend to decompose and release nutrients sooner than grasses (Gupta and Singh 1981; Lindsey et al. 2013; Murungu et al. 2011). The specie influence was stronger than height variations for all *k* values except K and were greatest for P and S release (β = -0.83 and -0.87, respectively) (Table 3.5). For K release, the β weight for height was -0.61 compared to -0.41 for the specie influence. The negative values for β indicate faster decay and release rates for waterhemp compared to giant foxtail.

Rate Regulating Effect of Initial Chemical Characteristics. Significant negative correlations were found between NDF, ADF, cellulose, hemicellulose, and lignin and the rates of decomposition and release of all nutrients; while positive correlations were found for the initial concentrations of P, Ca, Mg, and S in the weed residue (Table 3.6). Across all *k* values, NDF appeared to be the best negatively correlated predictor and has been reported by others as an excellent indicator of decay rates (Cobo et al. 2002; Gupta and Singh 1981). P and S were the nutrients with the strongest correlation to the rate of decomposition. Given the essential role these play in amino acid synthesis, they are among the minerals most often limiting microbial growth (Lambers et al. 2008); hence, greater concentrations of them in the plant litter are likely to stimulate microbial activity and enhance degradation (Vivanco and Austin 2006). In contrast to other authors (Müller et al. 1988; Murungu et al. 2011), quality parameters such as N, and the ratios of lignin:N and C:N were very poorly correlated. The specie influence was stronger for most of the *k* values, yet lignin concentrations differed only according to weed height (Table 3.2). Therefore, those initial quality parameters that responded to both specie and height changes, such as NDF, ADF, cellulose, and hemicellulose, expressed a stronger relationship. The weeds investigated in this research were desiccated while still in the juvenile stage. Many of the studies that have identified lignin or the lignin:N ratio as the most suitable predictor of decomposition have dealt with more mature biomass such as leaf litterfall in forested areas (Aerts 1997; Meentemeyer 1978). Since lignin is a relatively expensive energy investment for plants, juvenile specimens often contain less of this substance. Therefore, while the use of lignin as a predictor of decay rates are adequate when studying mature plants, the use of NDF or other cell wall components, such as cellulose, may be better suited when juvenile plants are of interest and may have specific implications regarding the decomposition of cover crops as these are often terminated before reaching full maturity.

Decomposition integrates the effects of environmental processes and the biochemical constituency of plant matter. It is often difficult to distinguish whether differences in decay rates are simply due to intrinsic variances in initial litter quality or more by interactions that take place following plant desiccation. These results suggest the decomposition of weed residues are strongly regulated by the amount of cell wall components the plant has generated and the amount of these are influenced both by a weed specie and height effect. Research that combines the impact of both a change in specie and maturity has not previously been conducted *in situ*. The litterbag method is capable of quantifying the release of nutrients, but not the precise amount, that will be made plant-available; some will be utilized by soil microbes or in the case of N, lost due to volatility. Recent evidence even suggests that POST glyphosate applications may influence nitrous oxide emissions from weeds (Bailey and Davis 2013). Despite this caveat of litterbag methodology, the results obtained from this experiment are consistent with those of Lindsey et al. (2013), in which a similar project was performed using laboratory incubation methods to detect when N released from weeds would become plant-available. In both studies, a grass weed contained more recalcitrant plant compounds than a broadleaved weed and this also increased along with plant height. The previous authors concluded that N acquired by weeds may be recycled quickly enough to be utilized by the crop within the same growing season if weeds were controlled at a height of 10 cm and that early-season control was particularly critical for this to occur from the recalcitrant giant foxtail.

The weed heights used in this experiment span a range of POST application timings commonly used by growers, while the two species constitute only a small portion of the diversity of weeds encountered in agricultural fields. Given the large differences observed between the two species, avenues of future research could include elucidating decomposition and nutrient release rates for other common weed species and how cultural practices (crop species, row spacing, tillage type) may further impact these processes. Weed residues in this experiment were placed in the field at the same time, regardless of height, to ensure each treatment was exposed to identical environmental conditions. However, in practice this would not be the case as the maturity differences of the treatments would result in days to weeks of separation between the initial start of decomposition. Therefore, weed height affects both the intrinsic properties of weed biomass as evaluated in this study, as well as the temporal start of decomposition. In this way, the impact of weed height on the rate of decomposition is likely greater than what is reported here. Future research efforts should attempt to identify more precisely how both the maturity and time at which weeds are controlled dictate decay and nutrient release rates. For example, control of 45-cm weeds would not only occur later than 10-cm weeds, but this timing may also coincide with the more droughty summer months and, thereby, further impede decomposition. By further elucidating the complex interactions involved with the nutrient release of plant litter and how this responds to changing weed dynamics and cultural practices, growers may be able to make more informed weed management decisions enabling greater synchrony between weed nutrient release and crop utilization.

Table 3.1. Initial chemical constituency of waterhemp (AMATA) and giant foxtail (SETFA) at 10, 20, 30, and 45 cm weed heights.

Specie	Height	NDF[a]		ADF		CEL		HEM		L		L:N		C:N	
	cm	---				%				---					
AMATA	10	24.36	f[b]	14.96	e	13.41	d	9.40	f	1.55	c	0.62	c	16.20	d
	20	25.89	f	15.23	e	13.67	d	10.66	e	1.56	c	0.77	c	20.08	c
	30	37.29	e	24.26	d	21.79	c	13.03	d	2.47	ab	1.69	a	27.87	b
	45	40.64	d	26.47	c	23.97	b	14.17	d	2.50	ab	1.85	a	30.46	a
SETFA	10	47.98	c	25.25	cd	23.61	b	22.73	c	1.65	c	0.50	c	12.59	e
	20	50.39	b	24.34	d	22.71	bc	26.05	ab	1.63	c	0.53	c	13.77	e
	30	56.68	a	29.55	b	27.56	a	27.13	a	1.99	bc	0.74	c	15.76	d
	45	58.13	a	31.13	a	28.14	a	25.37	b	2.99	a	1.23	b	16.77	d

[a] Abbreviations: NDF, neutral detergent fiber, ADF, acid detergent fiber, CEL, cellulose, HEM, hemicellulose, L, lignin.

[b] Means within each column followed by the same letter do not differ significantly according to Fisher's protected LSD ($\alpha = 0.05$).

Table 3.2. Multiple regression analysis for specie and height influence on initial chemical characteristics of weed biomass.

Chemical Parameter	Variable	P	β[b]	R^2
NDF[a]	Height	<0.0001	0.42	0.94
	Specie[c]	<0.0001	0.87	
ADF	Height	<0.0001	0.65	0.84
	Specie	<0.0001	0.65	
CEL	Height	<0.0001	0.61	0.83
	Specie	<0.0001	0.69	
HEM	Height	<0.0001	0.19	0.96
	Specie	<0.0001	0.96	
L	Height	<0.0001	0.75	0.53
	Specie	0.78	0.03	

[a] Abbreviations: NDF, neutral detergent fiber, ADF, acid detergent fiber, CEL, cellulose, HEM, hemicellulose, L, lignin.

[b] Standardized estimates (β weights) enable the direct comparison between discrete and continuous data of different scales.

[c] Tests the change from waterhemp to giant foxtail (e.g. a positive β indicates a larger value associated with the chemical parameter in giant foxtail over waterhemp).

Table 3.3. Initial nutrient concentration of waterhemp (AMATA) and giant foxtail (SETFA) at 10, 20, 30, and 45 cm weed heights.

Specie	Height	N	P	K	Ca	Mg	S
	cm	-----------	-----------	-----------%	-----------	-----------	-----------
AMATA	10	2.52	0.32	2.27	1.05	0.65	0.34
	20	2.02	0.37	1.99	0.99	0.68	0.35
	30	1.48	0.27	1.74	0.88	0.52	0.25
	45	1.35	0.28	1.71	1.16	0.57	0.26
SETFA	10	3.31	0.19	2.50	0.40	0.37	0.21
	20	3.05	0.20	2.75	0.43	0.51	0.22
	30	2.68	0.17	1.46	0.45	0.47	0.19
	45	2.49	0.14	1.93	0.64	0.48	0.18
LSD[a]		0.18	0.02	0.16	0.09	0.04	0.02

[a] Fisher's protected LSD ($\alpha = 0.05$).

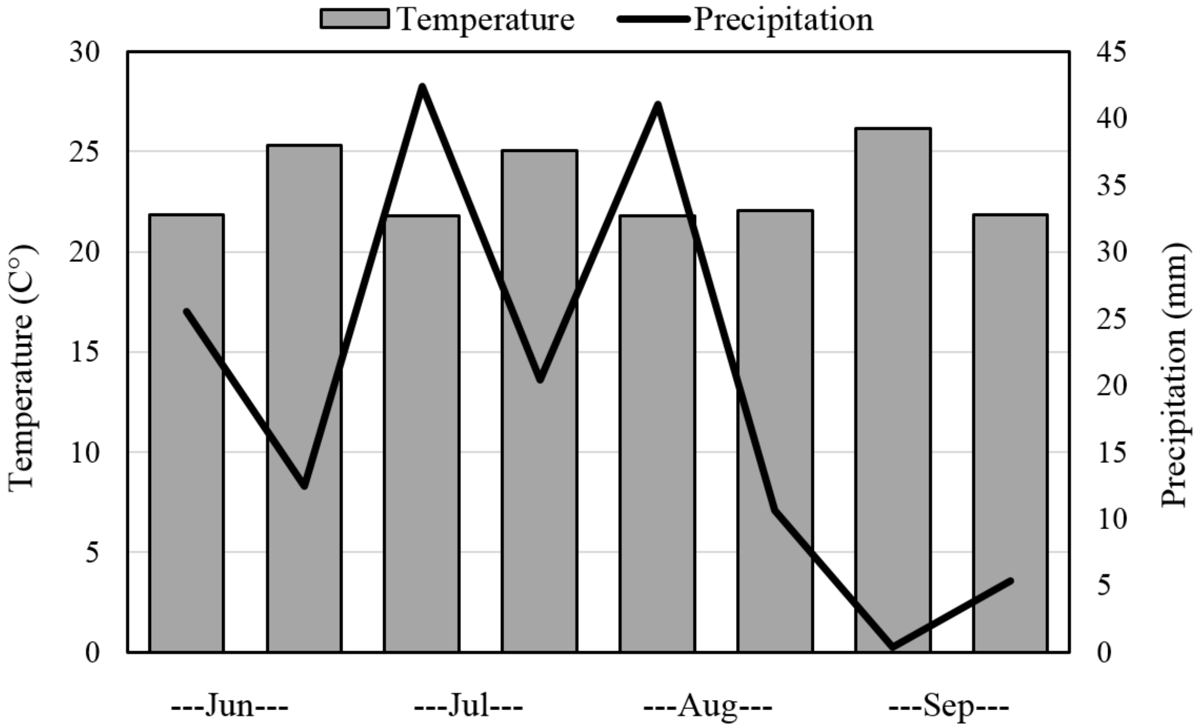

Figure 3.1. Climatogram illustrating bi-monthly mean temperature and precipitation received during the experimental period, averaged across Carbondale and Ridgway, in 2013.

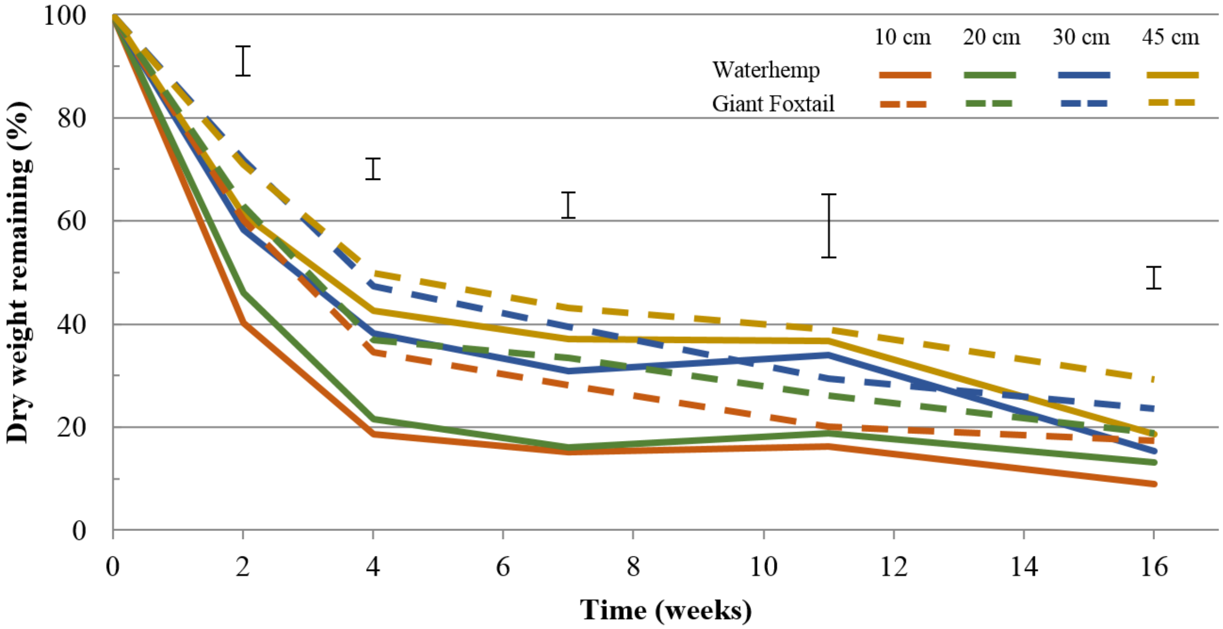

Figure 3.2. Dry weight loss from decaying waterhemp and giant foxtail residues, corresponding to weed removal timings of 10, 20, 30, and 45 cm plant heights. Vertical bars for each collection timing denote Fisher’s protected LSD (α = 0.05).

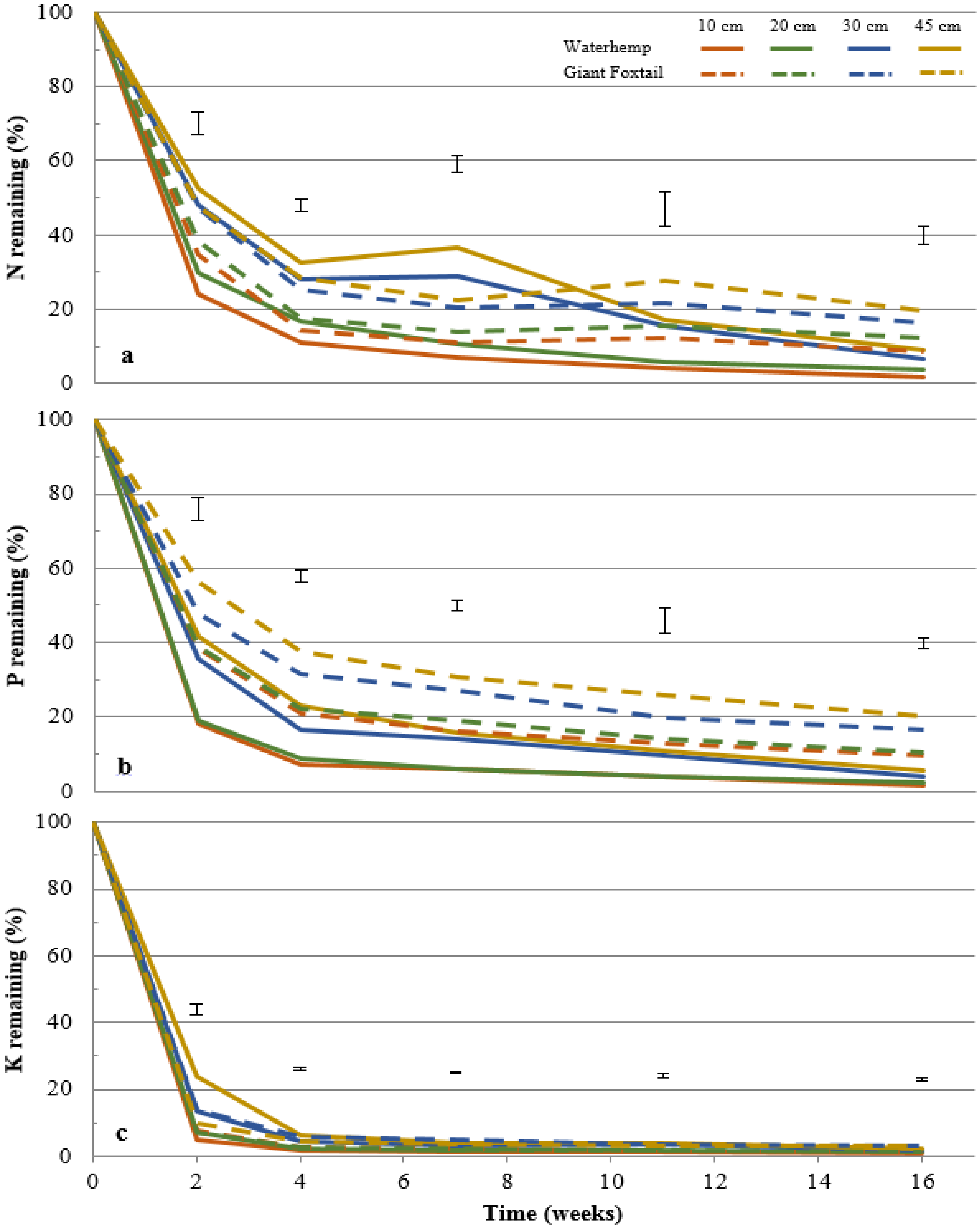

Figure 3.3. Release of primary macronutrients (N, P, K) from decaying waterhemp and giant foxtail residues corresponding to weed removal timings of 10, 20, 30, and 45 cm plant heights. Vertical bars for each collection timing denote Fisher's protected LSD (α = 0.05).

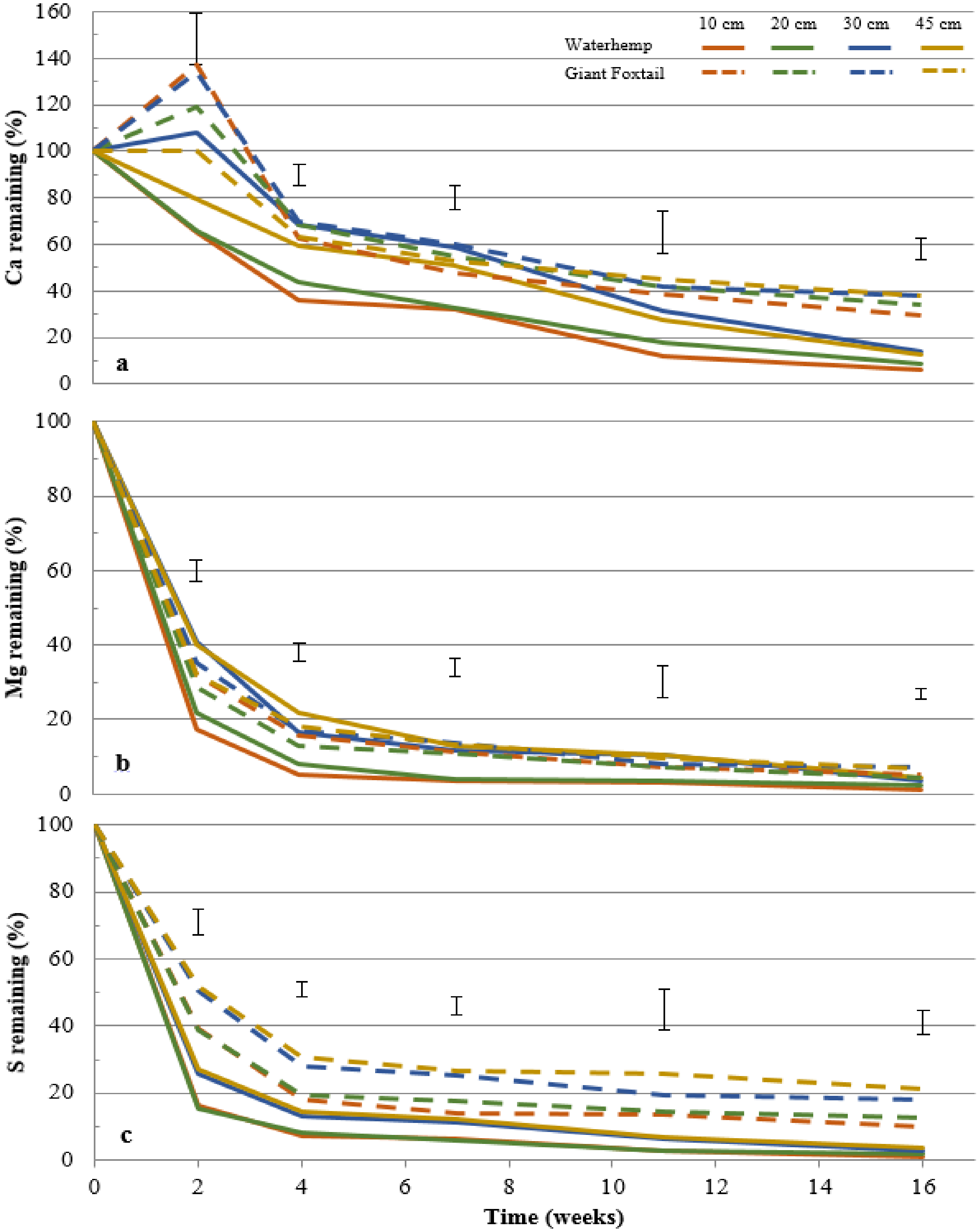

Figure 3.4. Release of secondary macronutrients (Ca, Mg, S) from decaying waterhemp and giant foxtail residues corresponding to weed removal timings of 10, 20, 30, and 45 cm plant heights. Verticals bars for each collection timing denote Fisher's protected LSD (α = 0.05).

Table 3.4. Decomposition (k_D) and N (k_N), P (k_P), K (k_K), Ca (k_{Ca}), Mg (k_{Mg}) and S (k_S) release rates for waterhemp (AMATA) and giant foxtail (SETFA) at 10, 20, 30, and 45 cm weed heights, obtained when fitting dry weight and nutrient remaining against time (d) according to the single exponential decay model (Olson 1963).

Specie	Height	k_D		k_N		k_P		k_K		k_{Ca}		k_{Mg}		k_S	
	cm	d^{-1}													
AMATA	10	0.022	a[a]	0.035	a	0.037	a	0.043	a	0.025	a	0.039	a	0.040	a
	20	0.018	b	0.029	b	0.034	b	0.039	b	0.022	b	0.034	b	0.037	a
	30	0.017	bc	0.024	c	0.029	c	0.036	cd	0.018	c	0.030	c	0.032	b
	45	0.015	cd	0.022	cd	0.026	c	0.034	d	0.018	c	0.028	cd	0.030	b
SETFA	10	0.016	c	0.022	cd	0.021	d	0.038	bc	0.011	d	0.026	de	0.021	c
	20	0.015	cd	0.019	de	0.020	d	0.038	bc	0.010	d	0.028	cd	0.018	cd
	30	0.013	de	0.016	e	0.016	e	0.030	e	0.009	d	0.024	e	0.015	de
	45	0.011	e	0.015	e	0.014	e	0.031	e	0.009	d	0.024	e	0.014	e

[a] Means within each column followed by the same letter do not differ significantly according to Fisher's protected LSD ($\alpha = 0.05$).

Table 3.5. Multiple regression analysis for specie and height influence on decomposition (k_D), and N (k_N), P (k_P), K (k_K), Ca (k_{Ca}), Mg (k_{Mg}) and S (k_S) release rates of weed biomass.

Decay/release constant	Variable	P	β^a	R^2
k_D	Height	<0.0001	-0.52	0.57
	Specie[b]	<0.0001	-0.56	
k_N	Height	<0.0001	-0.49	0.65
	Specie	<0.0001	-0.65	
k_P	Height	<0.0001	-0.41	0.85
	Specie	<0.0001	-0.83	
k_K	Height	<0.0001	-0.61	0.53
	Specie	<0.0001	-0.41	
k_{Ca}	Height	<0.0001	-0.26	0.68
	Specie	<0.0001	-0.79	
k_{Mg}	Height	<0.0001	-0.44	0.63
	Specie	<0.0001	-0.67	
k_S	Height	<0.0001	-0.31	0.85
	Specie	<0.0001	-0.87	

[a] Standardized estimates (β weights) enable the direct comparison between discrete and continuous data of different scales.

[b] Tests the change from waterhemp to giant foxtail (e.g. a negative β indicates a larger *k* value associated with waterhemp).

Table 3.6. Pearson correlation coefficients (r) between initial chemical characteristics of weed residue and their decomposition (k_D), and N (k_N),P (k_P), K (k_K), Ca (k_{Ca}), Mg (k_{Mg}) and S (k_S) release rates.

	k_D	k_N	k_P	k_K	k_{Ca}	k_{Mg}	k_S
NDF[a]	-0.73***	-0.81***	-0.93***	-0.66***	-0.84***	-0.83***	-0.91***
ADF	-0.74***	-0.79***	-0.86***	-0.73***	-0.74***	-0.83***	-0.80***
CEL	-0.74***	-0.80***	-0.88***	-0.72***	-0.76***	-0.84***	-0.82***
HEM	-0.66***	-0.75***	-0.90***	-0.55***	-0.84***	-0.75***	-0.92***
L	-0.50***	-0.45***	-0.42***	-0.57***	-0.27*	-0.44***	-0.32*
L:N	-0.17	-0.11	0.04	-0.29*	0.13	-0.11	0.17
C:N	0.06	0.11	0.32*	-0.09	0.36**	0.12	0.43***
N	-0.12	-0.19	-0.40**	0.06	-0.44***	-0.22	-0.50***
P	0.65***	0.72***	0.89***	0.56***	0.80***	0.75***	0.89***
K	0.21	0.15	0.06	0.47***	-0.04	0.17	-0.02
Ca	0.44***	0.55***	0.73***	0.30*	0.74***	0.59***	0.78***
Mg	0.51***	0.59***	0.75***	0.41***	0.71***	0.71***	0.73***
S	0.70***	0.79***	0.91***	0.63***	0.81***	0.82***	0.87***

[a] Abbreviations: NDF, neutral detergent fiber, ADF, acid detergent fiber, CEL, cellulose, HEM, hemicellulose, L, lignin.

*, **, *** = probabilities associated to Pearson correlation coefficients at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

CHAPTER 4

CONCLUSIONS

The evolution of herbicide-resistant weeds has resulted in a dramatic reassessment of weed management strategies in soybean. The efficacy provided by postemergent (POST) herbicides such as glyphosate is often no longer satisfactory to meet grower demands in areas plagued by these troublesome weed biotypes that may also have resistance to multiple other herbicide sites of action. The challenge of herbicide-resistant weeds in soybean production has led to a resurgent use of soil residual herbicides and other early-season weed management tactics to combat their spread. In regions that remain unaffected by glyphosate-resistant weeds, POST herbicides are still an effective and viable option for weed control; however, prior knowledge would suggest that such a great reliance on POST-only control measures are precisely the cause for the fruition of herbicide-resistant weeds. Furthermore, the flexibility provided by POST strategies would make it appear to be the most parsimonious choice, yet this can often result in a complacent understanding of what constitutes a timely herbicide application in order to avoid crop yield losses from prolonged weed competition. To facilitate the implementation of more sound weed and herbicide-resistant management tactics, an evaluation of additional benefits provided by early-season weed management in soybean was performed in this research.

The use of a broad-spectrum preemergent (PRE) and POST herbicide can provide early-season weed-free conditions that enhance nutrient uptake by the crop. Soybean establishment under these conditions affords the crop a competitive advantage over weeds and serves as a form of season-long weed suppression to realize maximum yield potential. When weeds are allowed to infest the crop, the magnitude of competition is regulated by the duration of this period and environmental influences. Competition from weeds, even at heights commonly found today, possess the capacity to diminish soybean acquisition of all 11 minerals analyzed in this research. Fertilizer recommendations are made based on the expected physiological demand by the crop yet, the accumulation of nutrients by weeds can be prodigious. Thus, growers interested in utilizing foliar applied nutrients and maximizing fertilizer use efficiency should first, and foremost, adopt sound weed management strategies to eliminate weed and nutrient competition. Under favorable growing conditions, the levels of nutrient competition and grain yield reductions elicited by weeds are intensified compared to droughty conditions, under which water appears to be the most-limiting resource. This in part, may be explained by the adaptive nature of the weed species complex. As the number dwindles for effective POST herbicide options in soybean for the control of herbicide-resistant broadleaved weeds, weed management decisions for this crop should place emphasis on the successful control of these species as they are also more effective competitors for nutrients than grasses as demonstrated with waterhemp in this research.

If the attempt to establish weed-free conditions fails, nutrient competition between the crop and weeds will ensue. Growers do not make fertilizer applications with the intent of a partial amount being used by weeds and unavailable to the crop. Given a finite amount of mineral resources in the soil, to maximize agronomic efficiency it is critical to ensure inputs intended for the crop are utilized by only the crop. By controlling weeds early in the growing season, the nutrient recycling process is accelerated and can result in the bioavailability of weed-bound nutrients during the same growing season. The rate at which these resources are returned from weed residues is surely dictated by the environmental status, but is also strongly regulated by the intrinsic properties of the weeds and future research efforts should attempt to gain a more comprehensive understanding of how species and site interactions influence these properties.

With greater insight of how weed dynamics effect the nutrient recycling process, more informed management decisions can be made that minimize post-harvest environmental losses.

The judicious and timely use of broad-spectrum PRE and POST herbicides are essential for mitigating the rapid development of herbicide-resistant weeds. This research concludes there is additional agronomic merit provided by this management strategy when used in soybean. Weed escapes from soil residual herbicides should be controlled in an urgent manner as delayed POST applications enable weeds to have a more pronounced impact on the nutrient status at a given site. Early-season weed management not only reduces the extent of nutrient competition between weeds and soybean, but also facilitates the speed at which minerals are recycled and contribute to the soil nutrient pool. As a result, control of early-season weeds suffices as a logical weed management strategy as it offers a more sustainable approach that suitably manages herbicide-resistant weeds, increases the efficiency of nutrient management systems, and enhances soybean yield potential.

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APPENDICES

APPENDIX A. Test of treatment as a fixed effect in 2012 generated from the mixed model design.

Dependent variable[a]	2013		2013	
	F Value	p	F Value	p
Nitrogen[b]	12.50	<0.001	18.51	<0.001
Phosphorus	10.00	<0.001	17.38	<0.001
Potassium	5.22	<0.001	13.01	<0.001
Calcium	11.45	<0.001	17.57	<0.001
Magnesium	7.31	<0.001	18.84	<0.001
Sulfur	11.18	<0.001	21.08	<0.001
Iron	8.91	<0.001	26.34	<0.001
Manganese	2.49	<0.001	27.01	<0.001
Boron	8.45	<0.001	13.98	<0.001
Copper	8.50	<0.001	16.61	<0.001
Zinc	6.44	<0.001	19.29	<0.001
Grain Yield	2.34	0.038	7.80	<0.001
Seed Weight	2.20	0.051	5.91	<0.001
Pods plant^{-1}	1.71	0.127	1.49	0.191
Seeds pod^{-1}	0.39	0.881	1.06	0.391
Protein	1.92	0.085	1.11	0.365
Oil	0.33	0.917	3.73	0.002

[a] Degrees of freedom: main effect = 6 ; error = 90

[b] Soybean nutrient accumulation

APPENDIX B. Progression of soybean nutrient accumulation in 2012 and 2013, pooled across sites.

Year	Weed height	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
		------------------------------kg ha^{-1}------------------------------						-------------------------g ha^{-1}-------------------------				
2012	10 cm	20.0	1.88	13.1	7.43	2.05	1.25	191	63.7	13.8	5.15	20.4
	20 cm	32.8	2.91	20.4	11.8	3.24	1.98	471	105	21.3	8.26	32.1
	30 cm	53.6	5.06	36.7	21.1	5.57	3.28	493	140	39.0	13.9	51.5
	45 cm	80.4	7.95	59.3	34.9	8.92	5.19	567	215	66.7	23.2	81.9
2013	10 cm	10.3	0.98	7.32	4.48	0.94	0.74	148	34.5	8.72	2.00	8.34
	20 cm	26.4	2.47	19.3	9.57	1.99	1.69	194	57.4	21.7	4.73	19.4
	30 cm	35.2	3.54	29.4	13.0	2.78	2.38	222	68.7	30.2	7.18	27.5
	45 cm	67.5	6.40	52.2	22.9	5.15	4.31	484	125	56.0	13.1	50.6

APPENDIX C. Progression of broadleaved weed nutrient accumulation in 2012 and 2013, pooled across sites.

Year	Weed height	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
		------------------------------kg ha^{-1}------------------------------						-------------------------g ha^{-1}-------------------------				
2012	10 cm	18.1	2.42	21.0	8.58	3.82	1.42	185	54.4	10.1	5.08	16.6
	20 cm	27.5	3.27	33.2	14.2	5.35	2.42	475	135	17.9	8.85	30.2
	30 cm	28.9	3.86	38.1	18.4	5.52	2.58	632	194	21.7	9.3	36.7
	45 cm	35.8	5.59	62.0	27.2	7.61	3.89	931	289	39.7	12.3	56.5
2013	10 cm	9.41	1.55	13.1	5.44	1.45	0.92	165	31.6	9.02	2.41	10.4
	20 cm	22.7	3.85	30.5	15.8	3.83	2.47	168	77.5	35.3	7.02	32.2
	30 cm	29.4	3.30	58.3	23.9	6.12	3.64	169	112	55.0	10.2	48.9
	45 cm	45.1	6.87	89.2	36.3	7.98	5.09	236	115	102	18.7	83.9

APPENDIX D. Progression of grass weed nutrient accumulation in 2012 and 2013, pooled across sites.

Year	Weed height	N	P	K	Ca	Mg	S	Fe	Mn	B	Cu	Zn
		-------------------------------kg ha^{-1}-------------------------------						--------------------------g ha^{-1}--------------------------				
2012	10 cm	9.92	1.01	10.3	1.23	0.81	0.65	89.7	28.2	1.14	2.97	10.8
	20 cm	15.7	1.92	22.6	2.34	1.47	1.07	152	46.1	1.89	5.27	19.9
	30 cm	13.3	1.72	19.4	1.78	1.24	0.96	164	50.4	1.24	4.72	14.5
	45 cm	28.0	4.79	53.3	5.74	2.93	2.25	363	145	5.16	11.9	41.0
2013	10 cm	7.24	1.10	9.12	1.11	0.55	0.54	51.9	13.5	0.75	2.05	6.13
	20 cm	16.3	3.36	26.0	2.89	1.61	1.31	96.1	38.9	1.98	5.73	17.5
	30 cm	20.2	4.62	36.7	4.04	2.39	1.81	115	47.5	3.01	8.19	25.1
	45 cm	24.2	6.29	52.3	5.06	3.35	2.45	121	64.7	4.67	10.0	40.3

APPENDIX E. Root mean square errors obtained while fitting the data according to the single exponential decay model of waterhemp (AMATA) and giant foxtail (SETFA) at 10, 20, 30, and 45 weed heights.

Specie	Height	k_D	k_N	k_P	k_K	k_{Ca}	k_{Mg}	k_S
	cm							
AMATA	10	0.103	0.045	0.040	0.013	0.098	0.034	0.041
	20	0.118	0.079	0.046	0.019	0.111	0.047	0.046
	30	0.155	0.120	0.076	0.033	0.173	0.076	0.068
	45	0.159	0.128	0.087	0.037	0.109	0.079	0.072
SETFA	10	0.111	0.088	0.100	0.019	0.311	0.065	0.098
	20	0.121	0.111	0.109	0.020	0.214	0.072	0.114
	30	0.098	0.133	0.128	0.037	0.298	0.076	0.130
	45	0.120	0.160	0.133	0.030	0.153	0.079	0.149

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