COMPETITION AND MANAGEMENT OF VOLUNTEER CORN (*Zea mays* L.) IN CORN

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DEDICATION

… To my wife: Heather Jane Davis

Without your love, support, and guidance I would have never succeeded. I will never forget that you saw potential in me when others didn't and encouraged me to set goals higher than I had ever imagined. Thank you for reviewing papers, critiquing presentations, and being understanding as well as patient. When I thought I couldn't, you told me I could. Your love and unyielding drive to accomplish the most daunting goals inspire me every day.

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Corn Production

Corn *(Zea mays* L.*)* is one of the most important food and feed crops in the world with a significant portion also used for ethanol production. Theorized to be a descendent of teosinte *(Zea mexicana)*, corn is native to Central and South America, and was domesticated by Native Americans as a food source (Galinat 1971). Piperno and Flannery (2001) aged maize cobs in highland Mexico to be 6,250 years old. Currently, there are corn hybrids that are produced for food, food products, livestock feeds, plastics, and fuels. In 2010, a total of 318,934,000 acres were planted in the U.S. with the principle crops: corn, sorghum *(Sorghum bicolor* L.*)*, oats *(Avena sativa* L.*)*, barley *(Hordeum vulgare)*, winter wheat *(Triticum aestivum)*, rye *(Lolium multiflorum)*, Durum wheat *(Triticum turgidum)*, other spring wheat, rice *(Oryza sativa* L.*)*, soybeans *(Glycine max* L.*)*, peanuts *(Arachis hypogaea* L.*)*, sunflower *(Helianthus* L.*)*, cotton *(Gossypium)*, dry edible beans, potatoes *(Orogenia S.* Watson*)*, sugar beets *(Beta vulgaris* L.*)*, canola *(Brassica napus* L.*)*, and proso millet *(Panicum miliaceum)*. Approximately 28% (87,872,000 acres) of the total acreage was planted with corn (NASS 2010).

Since the adoption of corn as a food crop, many genetic improvements have occurred. Genetic selection has been practiced since corn domestication. Initial characteristics included seeds that would not shatter and larger ears (increased yield) (Troyer 2004). Movement from tropical to temperate areas, as well as colonization and land ownership, which made land a limited resource, required selection for early maturity and higher yields (Troyer 2004).

Corn plants have the ability to self-pollinate or cross-pollinate, due to both male and female reproductive systems separated but on the same plant (ARS 2011). When two separate varieties of corn are cross-pollinated, the offspring is called a hybrid, which typically has attributes from both parent plants (ARS 2011). Corn hybrid breeding began in the early 1900's when scientists discovered that crossing two inbred parents created a more vigorous hybrid. The hybrids planted today are vigorous and produce large ears. By 1960, hybrid corn accounted for approximately 95% of the corn acreage planted in the U.S. (ARS 2011). This allowed 20% more corn production on 25% fewer acres than in 1930 (ARS 2011). Some hybrids are genetically modified to be resistant to commonly used herbicides, as well as insects and pathogens. These genetically modified plants contribute to production of a higher quantity and quality of grain on fewer acres with fewer inputs and less labor.

Weed Competition

The use of herbicides on transgenic corn hybrids is one of the most common methods to reduce weed competition, which is one of the major factors in reducing yield potential. Competition is defined as, "when two or more organisms seeks the measure it wants of any particular factor or things and when the immediate supply of the factor or things is below the combined demand of the organisms" (Clements et al. 1929). In corn production systems, weeds compete with corn plants for water, nutrients, and light.

Different weed species exert different levels of competitiveness, which depends upon their growth rate, size, canopy shape, and time of emergence (Bradley et al. 2007). A scale of 1 to 10 depicts the competitive index of weed species found commonly in

Missouri: common cocklebur *(Xanthium strumarium)* 5.5; hemp dogbane *(Apocynum cannabinum)* 1.0; giant foxtail *(Setaria faberi)* 3.0; ivyleaf and pitted morningglory *(Ipomea hederacea and I. lacunosa)* 5.5; fall panicum *(Panicum dichotomiflorum)* 1.5; common ragweed (*Ambrosia artemisiifolia*) 1.5; giant ragweed *(Ambrosia trifida*) 8.0; shattercane *(Sorghum bicolor)* 3.5; common sunflower *(Helianthus annuus)* 10.0; velvetleaf *(Abutilon theophrasti)* 4.2; and common waterhemp *(Amaranthus rudis)* 2.5 (Bradley et al. 2007). According to Purdue University, common weeds found in corn and soybean fields in Indiana, which would be similar to those found in Missouri include: giant foxtail, giant ragweed, velvetleaf, common lambsquarter *(Chenopodium album*), common ragweed, common cocklebur, Canada thistle *(Cirsium arvense)*, johnsongrass *(Sorghum halepense)*, fall panicum, and marestail *(Conyza Canadensis)* (Childs 1996).

The competitive ability of weeds in corn has been estimated using mixtures of weed species or with specific weeds at different densities. A publication by the University of Missouri Extension has estimated yield losses in corn due to weeds dependent upon the species found and their densities (Bradley et al. 2007). Densities of less than 22 weeds per 9.3 m^2 resulted in yield losses of 8% (753 kg ha^{-1}). High densities (over 1,000 weeds per 9.3 m^2) resulted in yield losses of 53% (5,017 kg ha^{-1}) (Bradley et al. 2007). Beckett et al. (1988) reported shattercane at a density of 6.6 clumps per meter of corn row, with 2 to 3 plants per clump, reduced corn yield by 22%; giant foxtail at 13.1 clumps per meter of corn row, with 5 to 8 plants per clump, reduced corn yield by 18%. For broadleaf weeds, common cocklebur at 4.7 and 6.6 plants per meter of corn row reduced corn yield by 27 and 10% respectively; common lambsquarters at 4.9 plants per meter of corn row reduced corn grain yield by 12% (Beckett et al. 1988). Ghosheh et al. (1996a) conducted experiments with rhizome johnsongrass in corn; a density of 3 plants per 9.8 m of corn row reduced corn yield by 4.9%.

The impact of weed competition depends upon the duration of competition. This can be classified in two ways; critical duration of weed competition and critical weed-free period. The critical duration of weed competition is defined as the amount of time weeds are allowed to compete with corn, prior to removal, without effecting grain yield (Zimdahl 2007). The critical weed-free period is defined as the amount of time that corn must be kept weed-free to preclude grain yield loss (Zimdahl 2007). Halford et al. (2001) reported that the critical time during corn production when weeds must be controlled ranges from the 6-leaf stage to the 9- to 13-leaf stage. Norsworthy and Oliveira (2004) reported the critical time in corn to range from the 1- or 2-leaf stages to the 8- or 10-leaf stages. Ghosheh et al. (1996b) identified the critical period for johnsongrass in corn to range from 3 to 6.5 weeks after corn emergence. Once weeds begin to impact grain yield, delaying control can account for a 2% loss in grain yield for every leaf stage produced (Knezevic et al. 2003).

Production system characteristics, such as crop density and row spacing also influence weed competition. Norsworthy and Oliveira (2004) found weed competition was similar in narrow (48 cm) versus wide (97 cm) row corn when plant densities were the same. However, increasing the corn density in narrow rows may provide competitive advantage over wide rows.

Nitrogen is the most limiting nutrient for optimal grain yield. Nitrogen is essential for plant growth, tasseling, silking, and production of grain. Nitrogen requirements by corn vary due to residual soil nitrogen and use efficiency (Meisinger

1984). Nitrogen fertilizer recommendations should be made site and crop specific to reduce the risk of over-or under-application (Lory and Scharf 2003). The University of Missouri nitrogen rate recommendation for corn is based upon grain yield goal, seed population, and soil organic matter (Scharf 2001). The formula used by the University of Missouri to calculate the nitrogen rate needed is: N rate (kg ha^{-1}) = (yield goal X 16) + (population ha^{-1} X 0.0018) – (g kg^{-1} organic matter X 2) (Scharf 2001). Lambert et al. (2000) reported nitrogen removal by corn in grain ranged from 78.4 to 193.8 kg N ha^{-1}. Hellwig et al. (2002) reported grass weeds accumulated 59 kg N ha^{-1}, when allowed to compete with corn until 31 cm tall. According to Vengris et al. (1953), corn takes up less nitrogen, phosphorus, and potassium compared to pigweed, common lambsquarters, Pennsylvania smartweed *(Polygonum pensylvanicum)*, ragweed, and large crabgrass *(Digitaria sanguinalis)*. Hellwig et al. (2002) found that nitrogen accumulation in the corn plant and grain yield were reduced when grass weed interference was not removed before corn was 23 cm tall. Delayed application of nitrogen may benefit corn competition with weeds. Harbur and Owen (2004) found that leaf areas were reduced in velvetleaf, giant foxtail, and corn by 64, 41, and 25%, respectively with a POST compared to a PRE application of nitrogen. Therefore, delayed application of nitrogen may limit nitrogen availability to weeds, but limitations to corn may also decrease grain yield.

Weed Management

Weed management in corn has evolved from hand removal to mechanical cultivation to herbicides. The introduction of herbicides, beginning with 2, 4-D in the early 1940's, allowed growers to increase production areas while also improving levels of weed control (Zimdahl 2007). Herbicides have also promoted no tillage practices, which reduces soil erosion. However, overuse of herbicides has selected many resistant biotypes (Heap 2008).

Among the corn herbicides used today, atrazine, an inhibitor of photosynthesis in many broadleaf and some grass plants, is one of the most commonly used. Over 75% of the corn acreage in the U.S. is treated with atrazine (U.S. EPA 2010). Atrazine effectively reduces weed pressure in corn, but alternative herbicides are necessary to preclude weed competition season-long. Also, there are concerns over water quality with atrazine. Due to water solubility, detection of residues in ground and surface water has resulted in the banning of atrazine use in France, Germany, Italy, and Sweden (Swanton et al. 2007). Belluck et al. (1991) found atrazine in the groundwater of 25 U.S. states, and claimed atrazine is the most frequently found pesticide in groundwater systems. Environmental concerns over residual herbicides such as atrazine have encouraged development of postemergence herbicides.

One of the more recent trends in weed management is the introduction of herbicide-resistant crops. Herbicide-resistant crops are genetically modified to allow producers to selectively remove weeds with no risk for crop injury. One of the most successful herbicide-resistant crops has been glyphosate-resistance (Roundup Ready®). In 1996, Monsanto publicly released glyphosate-resistant soybeans; transgenic corn hybrids were introduced in 1998 (Monsanto 2010). In 2010, Gly-R crops accounted for approximately 93% of soybean (*Glycine max* L.), 70% of corn, and 78% of cotton (*Gossypium hirsutum*) acreage planted in the U.S. (Owen 2010).

For a number of reasons, glyphosate is highly desirable for weed control. Glyphosate is strictly a postemergence herbicide for effective management of a broad spectrum of plants. Glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase in the shikimate pathway, and blocks the production of the aromatic amino acids tyrosine, tryptophan, and phenylalanine (Sikorski & Gruys 1997). Glyphosate is systemic, improving control of perennial plants over contact herbicides (Zimdahl 2007). Glyphosate is registered for use in more than 130 countries and is approved for use in more than 100 crops (Monsanto 2005). Corbett et al. (2004) reported use rates of glyphosate at 1.12 kg ai ha^{-1} resulted in 90% visual control of many species. Glyphosate is also used for control of existing weeds prior to crop planting (burn down). With limited to no soil activity and very low mammalian toxicity, glyphosate poses very little health and environmental risks (Zimdahl 2007).

Another herbicide-resistant crop that is widely adopted is glufosinate-resistant (LibertyLink®) corn. Glufosinate is a non-selective postemergence herbicide that controls a broad spectrum of broadleaf and grass weeds including glyphosate-resistant weed species (Bayer CropScience US 2010). Initially, glufosinate was isolated from two species of Streptomyces fungi (Anonymous 1998). The active ingredient in synthetic glufosinate inhibits glutamine synthetase in plants (Bayer CropScience 2010). Glufosinate works more rapidly than glyphosate, but must be applied at earlier growth stages. Corbett et al. (2004) found effective rates of glufosinate ranged from 0.29 to 0.41 kg ai ha^{-1}.

Although over 95% of herbicide-resistant crops are represented by glyphosate- and glufosinate-resistant corn hybrids, imidazolinone-tolerant (Clearfield®) corn is also available. Imidazolinones are non-selective postemergence herbicides that control many grass and broadleaf weeds, and also exhibit residual activity (Alister and Kogan 2005). Imazethapyr and imazapyr are representative herbicide of imidazolinones, a family that targets the plastid enzyme acetolactate synthase (ALS), also known as aceto hydroxy acid synthase (AHAS). ALS is a key enzyme in the synthesis of the branched chain amino acids, leucine, isoleucine, and valine. Imidazolinones are effective at low application rates (0.01 to 0.1 kg ai ha^{-1}), exhibit low mammalian toxicity, and pose little environmental risk (Tan et al. 2005). Imidazolinone-tolerant corn was released initially in 1992 (Tan et al. 2005). Imazethapyr mixed with imazapyr (Lightning®) is the intended herbicide to be used on transgenic corn.

Widespread effectiveness of herbicides developed for herbicide-resistant crops has led to strict use of a single mode of action over an extended period of time. This has led to widespread incidences of herbicide-resistant weeds. Currently, 21 different weeds have been identified with glyphosate-resistance in 16 different countries (Heap 2011). In Missouri, there are 6 weed species with confirmed resistance to glyphosate. Over 40 ALS-resistant weed species have been reported in the United States (Heap 2011); Missouri has 3 reported weeds with ALS-resistance. To date, there are no confirmed cases of glufosinate-resistant weeds.

Volunteer Corn

Volunteer corn is corn that emerges following production of corn on a given area, and is considered a weed if emergence occurs during the following growing season, independent of the desired crop. Volunteer corn results from many different factors.

Each year corn seed is left in the field due to lodging and ear dropping, which can be induced by weather, insects, and poor stalk quality, as well as harvest inefficiencies. Lodging describes whole corn plants that have fallen to the ground. The majority of corn lost originates from corn kernels or ears which are dropped in the field during harvesting.

Inefficiencies in harvesting are often the result of limited time for growers to harvest large areas. According to the 2007 Census of Agriculture, the average farm is 169 hectares (USDA 2007). Combines are used to separate ears from plants and individual seeds from ears. Combines are typically quite efficient; 8 to 14 plant rows are harvested at once and the speed of travel is approximately 4.8 kilometers per hour (Shay et al. 1993). Mechanized harvesting will inevitably result in some loss. Iowa State University surveyed harvest losses from 84 different combines in central Iowa, and found the average loss to be approximately 1,248,081 kernels ha^{-1} (5.8 bu A^{-1}) (Vagts 2003). Harvesting losses due to combines cannot be reduced to zero, but the skill of the operator can minimize losses to less than 5% of total yield (Shay et al. 1993 and Schuler 1997). Shay et al. (1993) described four areas of harvest loss for combines. The first revolves around speed of the combine, inaccurate driving, or improper height of the header, which is necessary to remove corn ears from plants. Another type of loss results when kernels are removed from the cobs by mechanical action; proper adjustment should reduce losses in this area. A third source for loss occurs when rotors and the concave clearance is inadequate to remove all remaining kernels off the cob; incorrect settings will leave kernels on the cob or result in kernel breakage. Finally, some individual kernels do not pass through sieves, and are dropped behind the combine; losses can be reduced with correct sieve and blower adjustments (Shay et al. 1993).

Once corn kernels are lost in the field, numerous factors influence whether kernels will become volunteer plants. Conventional tillage, mowing, and no-tillage place corn kernels in varying levels of contact with the soil, which influences emergence. Fall tillage and mowing spread residue over kernels, protecting seed from feeding wildlife. Ferguson (2008) reported that spring tillage may be used to eliminate emerged volunteer corn prior to planting. However, excess spring moisture can delay planting if tillage is desired.

Climatic conditions are also factors that impact volunteer corn emergence after harvest. Fall rain and warm soil temperatures stimulate emergence. Soil temperatures in the upper five centimeters of soil must exceed 10 C for corn to germinate (Nielsen 2004). Generally, any volunteer corn that emerges in the fall will die following exposure to freezing temperatures.

Volunteer corn can be a significant weed problem in subsequent cropping systems. Thomas et al. (2007) found that volunteer corn formed a canopy over cotton as early as 25 days after cotton planting and a density of 5.2 plants per meter of cotton row decreased plant height by 49, 24, and 28% at three different locations, respectively. One glyphosate-resistant volunteer corn plant per meter of crop row reduced cotton yield by 5 to 8% at three different locations (Thomas et al. 2007.) Clewis et al. (2008) reported volunteer glufosinate-resistant corn was taller than glufosinate-resistant cotton as early as 11 days after planting. A density of 5.2 plants per meter of crop row reduced late season cotton height by 38 to 43% at three different locations (Clewis et al. 2008). One glufosinate-resistant corn plant per meter of crop row reduced cotton yield by 5 to 7% at three different locations (Clewis et al. 2008).

Volunteer corn also impacts soybean development, a crop commonly rotated with corn. Andersen et al. (1982) used clumps of volunteer corn with 7 to 10 corn plants per clump to determine competitive effects in soybeans. Densities of 0.4, 0.8, and 1.6 clumps per meter of soybean row reduced yields by 31, 58, and 83% respectively (Andersen et al. 1982.) Beckett and Stoller (1988) reported volunteer corn reducing soybean yield up to 25% at densities of 5,380 clumps per hectare with 10 plants per clump.

Volunteer corn is also a competitive weed in corn, and may be detrimental to corn yield if not managed (Jeschke and Doerge 2008). Jeschke and Doerge (2008) reported grain yield losses ranging from 1.5 to 13% when volunteer corn was competing with row corn at densities ranging from 0.5 to 4 plants m^{-2}. Alms et al. (2008) also reported grain yield losses of 9 and 40% when volunteer corn was competing with row corn at densities of 3.5 and 8.5 plants m^{-2}, respectively.

Removal of Volunteer Corn

As volunteer corn represents a "weed", removal is necessary to preclude competitive affects. Traditional corn as a volunteer weed is easily removed or eradicated with the use of herbicide-resistant crops. Increasing use of transgenic corn hybrids exhibiting herbicide-resistance will lead to greater areas of herbicide-resistant volunteer seed. When present in broadleaf cropping systems, there are several effective herbicides. If the broadleaf crop and volunteer corn are both genetically modified for herbicide-resistance, removal is possible with the chemical labeled for use on the broadleaf crop, provided it is different than the resistance trait exhibited by the volunteer corn. Control of glyphosate-resistant volunteer corn in glyphosate-resistant soybeans is accomplished with selective grass herbicides. Deen et al. (2006) reported the selective control of glyphosate-resistant volunteer corn in soybean with quizalofop-p-ethyl, clethodim, and fenoxaprop-p-ethyl. Soybean yields were similar to control plants with volunteer corn removed by hand (Deen et al. 2006).

In a continuous corn production system with glyphosate-resistant corn as the hybrid used, there are no selective herbicides for removal of volunteer corn. If glyphosate-resistant volunteer corn may be a concern, a rotation system with glufosinate-resistant or imidazolinone-tolerant corn hybrids may provide effective control. Corbett et al. (2004) reported glufosinate at 0.29 and 0.41 kg ai ha^{-1} resulted in at least 90% control of glyphosate-resistant corn at 8 to 10 cm tall. Johnson et al. (2001) reported 60 to 95% control of glyphosate-resistant volunteer corn with imazethapyr plus imazapyr at 0.063 kg ai ha^{-1} when corn was 10 to 15 cm tall.

Cultural practices can be used to remove volunteer corn between crop rows. Ferguson (2008) stated that spring tillage prior to corn planting can remove initial volunteer corn seedlings. While cultivation is an effective control method, it may reduce profitability due to increased costs in fuel, time, and labor.

Justification

Volunteer corn has been found to be a problematic weed which can impact yields and contaminate seed. The impact of volunteer corn is dependent upon the amount of corn remaining in a production field. Few surveys have been conducted to determine the amount of corn remaining in the field following harvest. Additionally, little research has been conducted to determine which combine, crop, and environmental factors influence harvest losses.

Volunteer corn is a competitive plant in subsequent cropping systems. However, there is little research on the competitive ability of volunteer corn in corn. With high-yielding corn hybrids, competition by volunteer corn can limit the availability of water and nutrients, which reduces grain yield and limits profitability. In a continuous corn production system, competition effects of volunteer corn need to be determined so control measures may be implemented cost effectively.

In cropping systems where a glyphosate-resistant corn is followed by a glyphosate-resistant corn, there are no herbicide treatments to effectively remove volunteer plants. The presence of other herbicide-resistant or -tolerant corn crops such as, glufosinate-resistant and imidazolinone-tolerant corn may be used in rotation with glyphosate-resistant corn. However, little to no research has been conducted on the ability of glufosinate and imidazolinone herbicides to remove glyphosate-resistant volunteer corn.

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Chapter II

Survey of Corn (*Zea mays* L.) Harvest Losses in Central Missouri

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Abstract. Harvest inefficiencies in corn (*Zea mays* L.) can lead to volunteer plants in subsequent cropping systems. Weather, insects, diseases, and harvest equipment can influence the quantity of kernels lost during harvest. Field surveys were conducted in the fall of 2008, 2009, and 2010 in central Missouri to determine the amount of corn remaining following harvest. Thirty fields harvested by different producers using unique combines were surveyed. Sixty individual areas, each measuring 1 m^2, were surveyed in each field; individual kernels, ears, and kernels attached to ears were counted. Corn left in the field ranged from 62,241 to 986,552 kernels ha^{-1} (0.3 to 4.6 bu A^{-1}). Crop, combine, and environmental information was obtained from producers for each field. Combine age and header width were the only combine factors that influenced harvest losses. Newer combines resulted in 51% fewer kernels than older combines, and 8-row headers resulted in 46% less loss than 6-row headers. Environmental factors contributed to differences in losses between years; losses in 2009 and 2010 were approximately 2.4-fold and 1.9-fold higher than losses in 2008, respectively. As percent seed moisture decreased from a range of 21-24% to 13-16%, harvest losses increased from 197,701 to 413,495 kernels ha^{-1}, respectively. Overall, many factors contributed to the loss of kernels which may result in up to 99 volunteer plants m^{-2}.

Nomenclature: corn, *Zea mays* L.

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Key Words: Volunteer corn; combine inefficiency; seed moisture.

Introduction

Volunteer corn *(Zea mays* L.*)* results from corn kernels remaining in the field following harvest. Factors contributing to unharvested corn kernels include: lodging, ear dropping, and harvest inefficiencies. Lodging and ear dropping may be induced by weather, insects, and diseases (Flint-Garcia et al. 2003; Zuber and Kang 1978), while harvest losses may result from human error and mechanical factors (Shay et al. 1993; Schuler 1997).

Both lodging and ear dropping result in the deposition of many kernels in one location on the ground. Stalk lodging is one of the most problematic stresses in corn, and reduces grain yield by 5 to 20% annually (Flint-Garcia et al. 2003; Zuber and Kang 1978; and Hondroyianni et al. 2000). Weather events, such as high winds, heavy rain, and hail storms may physically damage plants and result in lodging and ear dropping (Carter and Hudelson 1988; Sandell and Bernards 2010). Other factors contributing to plant lodging are insect feeding and stalk rot pathogens. Common insects include: European corn borer (*Ostrinia nubilalis* Hubner) and western corn rootworm (*Diabrotica virgifera virgifera*) (Martin et al. 2004; Hodgson 2008). Detrimental pathogens include: Gibberella stalk rot (*Gibberella zeae* (Schwein) Petch); Anthracnose stalk rot (*Colletotrichum graminicola* (Ces.) G.W. Wils.); and Fusarium stalk rot (*Fusarium verticillioides* (Sacc.) Nirenberg) (Gatch et al. 2002).

Mechanized harvesting will inevitably result in some grain losses. Harvest losses can be reduced below 5% of total yield by the skill of the operator (Shay et al. 1993; Schuler 1997). During 2003, a survey of harvest losses from 84 different combines in central Iowa found the average loss to be 1,248,081 kernels ha^{-1} (5.8 bu A^{-1}) (Vagts

2003). Pre-harvest losses were 451,891 kernels ha^{-1} (2.1 bu A^{-1}) and combine harvesting losses were 796,190 kernels ha^{-1} (3.7 bu A^{-1}).

Several moving parts on combines can influence grain harvest efficiency. Initially, the header separates ears from the plant and guides them through the gathering snouts (openings on the header). If the gathering snout is 10 to 13 cm off-center, grain losses can reach approximately 525,000 kernels ha^{-1} (UADA 2008). Snapping bars, snapping rolls, and gathering chains then remove the ear from the stalk. Ears and chaff (stalks and leaves) are moved to the feederhouse where they enter the threshing drum. Losses at the header may originate from speed of travel, inaccurate driving, improper height of gathering snouts, and improper settings of snapping bars and snapping rolls (Shay et al. 1993). Additionally, ears may be missed by the header unit while harvesting on a hillside. Self-leveling headers may help to reduce losses while harvesting on non-level ground. Combines equipped with self-leveling mechanisms such as a Contour-Master[1] will automatically adjust the feederhouse and header unit, up to 4 degrees laterally, to follow the contour of the ground (Anonymous 2010b).

After passing through the header, corn ears and plant material enter the threshing drum. Threshing drums separate kernels from ears by mechanical action (conventional), or centrifugal force (rotary). Sieves then separate kernels from large chaff, allowing kernels to fall into a gathering hopper while a blower moves air across the falling kernels to remove small chaff. Remaining chaff is then scattered behind the combine. Losses due to threshing may originate from improper cylinder or rotor speeds, concave clearance, sieves settings, and blower settings (Shay et al. 1993).

[1] Contour-Master®: Deere & Company World Headquarters, One John Deere Place, Moline, Illinois 61265

Once corn kernels are left in the field, numerous factors can influence the germination of kernels. Harvest date, tillage practices and environmental conditions influence the density of volunteer corn emergence in the fall (Anonymous 2010a; Anonymous 2010d; Sandell and Bernards 2010). Early harvesting when soil temperatures are above 10 C will stimulate fall emergence, whereas late harvesting after soil temperatures drop may encourage spring emergence (Nielsen 2004). Heavy predation by Canada geese (*Branta Canadensis*) and whitetail deer (*Odocoileus virginianus*) may decrease the number of kernels remaining, reducing seed for germinating the following spring (Anonymous 2008; Nixon et al. 1970). One report suggests 23% of kernels lost during harvest will germinate as volunteer corn the following year (Anonymous 2010d).

There is little research on the contribution of harvest and equipment factors to grain losses. The objectives of this research were to determine the number of corn kernels left in fields following harvest in central Missouri, and the relative importance of combine, crop, and environmental factors in contributing to harvest losses.

Materials and Methods

Field surveys were conducted in the fall of 2008, 2009, and 2010 in central Missouri. Ten corn fields were selected randomly each year throughout six counties: Audrain, Boone, Chariton, Howard, Randolph, and Saline (Figure 2.1). All fields were a minimum of 10 hectares in size and were surveyed within three days following harvest. Each field was harvested by a different operator using a unique combine. Kernels, ears, and kernels attached to ears were counted randomly from 60, one square meter quadrants per field. End rows and areas with obstacles that hindered normal harvesting were avoided.

Production, operation, and mechanical combine information was provided by crop producers for each field surveyed. Harvest information collected included: date of harvest; mean grain yield of field; and seed moisture percentages. Combine information included: make, model and year of manufacture of combine; mean combine speed at harvest; threshing mechanism (conventional or rotary); presence or absence of self-leveling header; header width (number of rows); and header year of manufacture (Table 2.1). Due to variable production, operation and mechanical combine characteristics, information was grouped into similar levels for some factors: a) combine year of manufacture: 1989-1992, 1996-1999, 2001-2006, 2007-2010; b) header year of manufacture: 1978-1992, 1994-1998, 2000-2004, 2006-2008; c) harvest speed: 4-6, 6.4-7.6, 8, 8.9-9.7 km h^{-1}; d) seed moisture: 13-16, 16.5-20, 21-24%; and e) grain yield: 5500-7500, 8000-9800, 10000-11800, 12000-14000 kg ha^{-1}.

Sixty samples per field were collected to calculate average losses (kernels ha^{-1}), which were then subjected to analysis.

$$\frac{A-(B+C)}{58} * 10{,}000 = \text{Avg. kernels ha}^{-1} \qquad [1]$$

Where A is the sum of kernels per field, B is the maximum number of kernels per quadrant, and C is the minimum number of kernels per quadrant.

Because the data collected are losses of kernels from randomly selected fields, treatments in this research are the crop, combine, and environmental factors that may have influenced losses in a given field. Factors considered included: survey year, combine year of manufacture, header year of manufacture, header width, harvest speed, threshing mechanism, presence of self-leveling header, seed moisture, harvest date, and grain yield. Each field was considered a unique observation and not a replication; therefore, there were unequal observations for each factor tested and the experimental design was completely randomized. Prior to analysis, Bartlett's test for equal variance was performed; harvest losses were not transformed due to homogeneity of variances (SAS 2010). A simple one-way ANOVA was used to determine the importance of each treatment independently. Harvest losses were analyzed in SAS using a GLM procedure; least square means were calculated and P-values used for testing mean differences between treatment levels (P=0.10) (SAS 2010). Harvest losses were also analyzed in SAS using Pearson's correlation coefficients to determine the relationship for the number of ears recorded with harvest loss and harvest factors (harvest date, seed moisture, harvest speed) (SAS 2010).

Results and Discussion

The loss of corn kernels at harvest varied widely within and between surveyed fields (Table 2.1). Average harvest losses for 2008, 2009, and 2010 were 170,831 (0.8), 406,569 (1.9), and 336,224 kernels ha^{-1} (1.6 bu A^{-1}), respectively. Harvest losses from all fields ranged from 62,241 to 986,552 kernels ha^{-1} (0.3 to 4.6 bu A^{-1}) and averaged 304,540 kernels ha^{-1} (1.4 bu A^{-1}). Mean grain losses were minimal compared to grain yields; 0.1 to 0.8% in 2008; 0.4 to 3% in 2009; and 0.5 to 2% in 2010.

Harvest conditions and harvest equipment also varied widely between fields (Table 2.1). Combine and header year of manufacture ranged from 1992 to 2010 and 1978 to 2008, respectively. Header width ranged from 6 to 12 rows, seed moisture at harvest ranged from 13 to 24%, and harvest dates ranged from September 16 to December 1.

The uniqueness of each field, harvest equipment, and environmental factors made it difficult to assess the importance of each variable independently. However, survey year, header width, presence of self-leveling header, and seed moisture were significant factors in an ANOVA (Table 2.2). Overall losses appeared related to the year the survey was taken, with losses in 2009 and 2010 about 2.4-fold and 1.9-fold higher, respectively compared to 2008. As header width increased from 6 to 8, mean grain losses were reduced by 46%; only one 12 row header was used among the 30 fields. Self-leveling headers also resulted in reduced losses, with 34% fewer kernels lost than headers that were not self-leveling. Seed moisture impacted grain yield losses, with kernel losses reduced by 35 and 52% as seed moisture increased from 16.5-20 and 21-24%, respectively compared to 13-16%. Newer combines, newer headers, rotary threshers, and harvest dates in October or November also appeared to result in lower harvest losses. However, individually these factors were not statistically significant.

Harvest loss was also a factor in the number of ears left in the field, which was influenced by percent seed moisture. Pearson's correlation coefficients indicate significant relationships for the number of ears recorded with harvest losses and percent seed moisture (Table 2.3). As percent seed moisture decreased, the number of ears recorded and harvest losses increased.

Differences in harvest loss between survey years were due to environmental factors; rainfall and temperatures likely influenced percent seed moisture and harvest dates (Figure 2.2). During 2008, harvest began in late September and ended by late

October. Corn fields were harvested as seed moisture ranged from 15 to 23.9%, and harvest losses ranged from 62,241 to 366,207 kernels ha^{-1}. During 2009, 3 fields were harvested in mid-September; however, high rainfall and low temperatures from late September to late October delayed harvest of the remaining 7 fields until mid-November. Seed moisture of the 3 fields harvested early ranged from 15.25 to 16.5% and harvest losses ranged from 480,862 to 986,552 kernels ha^{-1}. Seed moisture of the 7 fields harvested late ranged from 15.75 to 24% and harvest losses ranged from 103,103 to 460,345 kernels ha^{-1}. During 2010, harvest began in late September and ended by late October. Fields were harvested as seed moisture ranged from 13 to 17.5%, and harvest losses ranged from 165,345 to 631,379 kernels ha^{-1}.

Results from this survey indicate that a number of factors contribute to grain losses. Among them, specific equipment (header width, presence of self-leveling header) and environmental (year of survey, seed moisture) factors were most important. Combines with wider headers that were self-leveling appeared important in influencing grain losses. This indicates that growers may manipulate combine factors to reduce losses. Rainfall and temperatures varied by year; therefore, seed moisture and harvest date were factors that could not be controlled by the producer. In-season lodging typically becomes a problem when soils are saturated by precipitation (Carter and Hudelson 1988). However, during harvest, as corn plants dry they become more susceptible to stalk lodging and ear dropping (Brandon 2009; Elmore and Abendroth 2010; Anonymous 2010c). Data indicates that harvest losses were lower following high rainfall events (Figure 2.2). High amounts of rainfall and low temperatures delayed kernel dry down, which may have resulted in lower harvest losses. Losses may be more prevalent during dry conditions; as seed moisture decreased the number of dropped ears and harvest losses increased. This is supported by Brandon (2009), Elmore and Abendroth (2010), and Anonymous (2010c) who reported, as percent seed moisture decreases, plants become more susceptible to lodging and ear dropping leading to harvest losses.

While individual kernel losses were high for some fields, this was relatively low considering overall grain yields. Shay et al. (1993) and Schuler (1997) stated that harvest losses cannot be reduced to zero, but the skill of the operator can minimize losses to less than 5% of total yield. Flit-Garcia et al. (2003), Zuber and Kang (1978), and Hondroyianni et al. (2000) stated that stalk lodging reduces grain yield by 5 to 20% annually. For all fields surveyed, harvest losses were ≤ 3% of total yield. However, even when yield losses are minor, resulting volunteer corn densities may be high.

Regardless of the factors responsible for harvesting losses, corn kernels were dropped in every field. Average harvest losses from 84 different combines in central Iowa (Vagts 2003) were approximately 2.6-fold higher (796,190 kernels ha^{-1}) than average losses we determined in central Missouri (304,540 kernels ha^{-1}). Kernels dropped in 30 central Missouri corn fields during 2008 to 2010 indicates that potential volunteer corn densities may range from 6.2 to 98.7 plants m^{-2}. One report suggests 23% of kernels lost during harvest will germinate as volunteer corn the following year (Anonymous 2010d). This would suggest that volunteer corn densities the following year may range from 1.2 to 19.7 plants m^{-2}.

In conclusion, harvest losses may result in potentially high densities of volunteer corn. This survey suggests that harvesting losses are ultimately a result of the producer's skill in maintaining, setting, and operating their combine, as well as the environment. Crop producers should consider that some volunteer corn will emerge in subsequent crops, and be prepared to implement management practices.

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Table 2.1. Combine, crop, and environmental factors, as well as mean losses (kernels on soil surface and on dropped ears from 60 samples field^{-1}) following harvest. Ten fields surveyed each year from 2008 to 2010 (30 different fields) in central Missouri to determine average harvest losses and factors contributing to harvest losses.

Field #	Combine (year/make[a]/ model)	Header Year	Header Width (rows)	Speed (kph)	Conventional /Rotary[c]	Self-Leveling Header	Seed Moisture %	Date Harvested	Yield (kg ha^{-1})	Yield (bushels A^{-1})	Total Ears[d]	Mean Loss (kernels ha^{-1})	Loss (bushels A^{-1})	Standard Deviation
2008														
1	1996 JD 9600	1990	8	6.9	conventional	no	17.5	9/30/2008	12,518	200	0.5	326,897	1.50	473,246
2	1991 JD 9610	1998	8	4.0	conventional	no	20	10/1/2008	10,640	170	2	198,966	0.92	360,996
3	2006 JD 9660	2008	8	7.6	rotary	yes	15	9/30/2008	6,008	96	2.5	78,488	0.37	109,413
4	1998 NH TR98	1988	8	6.4	rotary	no	19.5	10/13/2008	11,579	185	0	184,483	0.85	124,141
5	2007 CIH 7010	2007	8	7.2	rotary	no	23.9	10/9/2008	11,767	188	0	122,931	0.55	38,067
6	2006 JD 9660 STS	2006	8	8.9	rotary	no	21	10/13/2008	13,456	215	0	366,207	1.70	195,948
7	--[b]	--	--	--	--	--	--	--	--	--	0	134,655	0.65	79,211
8	2004 JD 9750 STS	--	12	4.8	rotary	yes	22.5	10/6/2008	12,080	193	0	80,862	0.40	51,920
9	2007 CIH 2588	2007	8	6.4	rotary	yes	23	10/4/2008	12,518	200	1	152,586	0.70	57,049
10	2004 JD 9650	2000	8	6.8	rotary	yes	21	10/20/2008	14,082	225	0	62,241	0.29	42,054
2009														
11	2009 JD 9670	2003	8	7.2	rotary	yes	16.5	9/16/2009	5,758	92	2	480,862	2.23	506,776
12	1992 JD 9400	1992	6	6.0	conventional	no	15.4	9/22/2009	10,014	160	3	624,138	2.90	881,375
13	1989 JD 9600	--	6	6.8	conventional	no	15.25	9/22/2009	9,513	152	10	986,552	4.58	1,789,829
14	2006 JD 9760	2006	8	8.0	rotary	yes	24	11/15/2009	9,388	150	1	401,379	1.87	370,237
15	2001 JD 9650 STS	2001	8	8.0	rotary	yes	17	11/15/2009	7,511	120	1	106,207	0.49	54,703
16	2004 JD 9760	2004	8	8.0	rotary	yes	20	11/15/2009	--	--	1	103,103	0.48	44,572
17	2004 CIH 2388	1994	6	8.0	rotary	no	18.75	12/1/2009	12,831	205	4	460,345	2.14	977,377
18	1998 JD 9610	1997	8	9.7	conventional	yes	20	11/29/2009	9,388	150	0	180,000	0.84	114,693
19	1991 JD 9550	1991	6	7.2	conventional	no	18.5	11/24/2009	8,449	135	0	333,793	1.55	307,963
20	1996 JD9500	1996	6	6.0	conventional	yes	15.75	11/30/2009	8,762	140	1	389,310	1.81	580,562
2010														
21	2004 JD 9560	1994	8	5.6	rotary	yes	17.5	9/26/2010	9,263	148	0	313,448	1.46	193,623
22	1990 JD 9400	1978	6	6.4	conventional	no	15	9/28/2010	7,448	119	0	244,655	1.14	231,738
23	2010 JD 9570 STS	2003	6	8.0	rotary	yes	14	10/11/2010	7,010	112	1	236,552	1.10	147,723
24	1999 CIH 2388	1997	6	8.0	rotary	yes	14.5	10/18/2010	8,136	130	4.5	436,379	2.03	781,821
25	--[b]	--	--	--	--	--	--	--	--	--	0	165,345	0.77	105,335
26	2004 GLNR r65	2004	6	8.9	rotary	no	13	10/20/2010	6,885	110	5	501,379	2.33	1,128,519
27	2007 JD 9660 STS	2007	8	8.0	rotary	yes	13.5	10/26/2010	9,764	156	1	166,034	0.77	351,168
28	2002 JD 9650 STS	2002	8	6.0	rotary	yes	16.2	10/27/2010	8,888	142	7	631,379	2.93	1,305,233
29	1997 GLNR r62	2006	8	8.0	rotary	no	15.3	10/10/2010	10,828	173	4	397,241	1.85	767,478
30	1996 GLNR r72	2006	8	9.7	rotary	no	14.9	10/15/2010	11,704	187	0	269,828	1.25	145,680

[a] Abbreviations: JD = John Deere (Deere & Company, One John Deere Place, Moline, Illinois 61265), NH = New Holland (New Holland Agriculture, 120 Brubaker Avenue, New Holland, PA 17557), CIH = Case International Harvester (Case IH Max Service, c/o CNH America LLC, 621 State Street, Racine, WI 53402), GLNR = Gleaner (AGCO, 4205 River Green Parkway, Duluth, GA 30096).
[b] Producers crop and or combine information was not provided.
[c] Types of threshing drums that separate kernels from cobs.
[d] Ears found during survey with kernels attached: full ears counted as 1 and partial ears counted as 0.5.

Table 2.2. Comparison of harvest losses with combine, crop, and environmental factors by ANOVA. Least square means were calculated and P-values used for testing mean differences between levels of each factor (P=0.10). Ten fields were surveyed each year from 2008 to 2010 (30 different fields) in central Missouri.

Factors[a]	Pr > F	Levels[b]	# of observations	Mean loss (kernels ha^{-1})
Survey year:	0.0254[c]	2008	10	170,831 B[d]
		2009	10	406,569 A
		2010	10	336,224 A
Combine (year manufactured):	0.2585	1989 - 1992	5	477,621
		1996 - 1999	7	312,019
		2001 - 2006	11	282,276
		2007 - 2010	5	231,793
Header (year manufactured):	0.5149	1978 – 1992	3	400,862
		1994 – 1998	6	329,741
		2000 – 2004	7	303,103
		2006 - 2008	10	246,607
Header width (# of rows):	0.0149[c]	6	9	468,123 A
		8	18	252,349 B
		12	1	80,862 B
Harvest speed (kph):	0.8902	4.0 – 6.0	6	373,017
		6.4 – 7.6	10	297,348
		8.0	8	288,405
		8.9 – 9.7	4	329,354
Threshing mechanism:	0.1305	Conventional	8	410,538
		Rotary	20	277,597
Self-leveling header:	0.0976[c]	No	13	385,955 A
		Yes	15	254,589 B
Seed moisture (%):	0.0752[c]	13 – 16	12	413,495 A
		16.5 – 20	10	268,810 B
		21 – 24	6	197,701 B
Harvest Date:	0.2713	September	7	436,433
		October	14	271,933
		November	6	252,299
		December	1	460,345
Yield (kg/ha):	0.3307	5500 – 7500	6	274,691
		8000 – 9800	9	426,475
		10000 - 11800	6	299,598
		12000 - 14000	6	241,522

[a] Factors, other than survey year, were combined across all three years.
[b] Levels: different levels of each attribute recorded from all fields surveyed.
[c] Significant effect at $\alpha = 0.10$.
[d] Letters following means within a column and attribute indicate significant differences between levels.

Table 2.3. Pearson's correlation coefficients generated in SAS from a correlation procedure comparing the number of ears recorded with harvest losses and harvest factors. Harvest factors (date, seed moisture, speed) are those that may have been influenced by environmental factors (rainfall, temperature) which had an effect on harvest losses. Ten fields surveyed each year from 2008 to 2010 (30 different fields) in central Missouri.

Factor	Pearson's correlation coefficients	Pr > F	# of observations[a]
Harvest loss (kernels ha^{-1})	0.80964	<0.0001[b]	30
Harvest date (month)	-0.14953	0.4476	28
Seed moisture (%)	-0.49893	0.0069[b]	28
Harvest speed (kph)	-0.05949	0.7636	28

[a] Thirty possible observations; not all observations could be used for some factors because some producers did not provide harvest information.
[b] Significant effect at $\alpha = 0.01$.

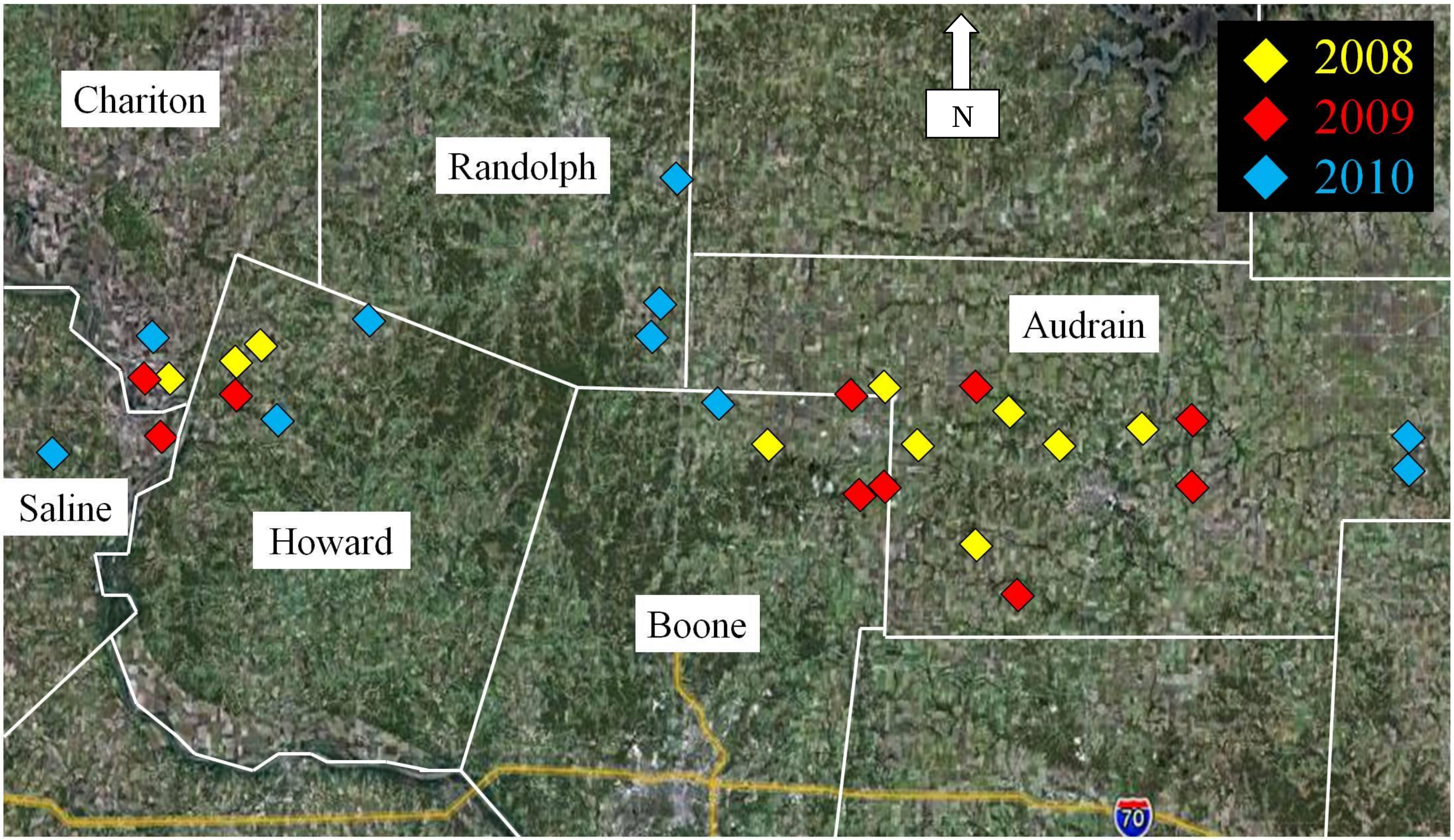

Figure 2.1. Location of fields surveyed for grain losses during harvest in six counties of central Missouri from 2008 to 2010. Losses (kernels on soil surface and on dropped ears from 60 samples field^{-1}) were determined within three days following harvest.

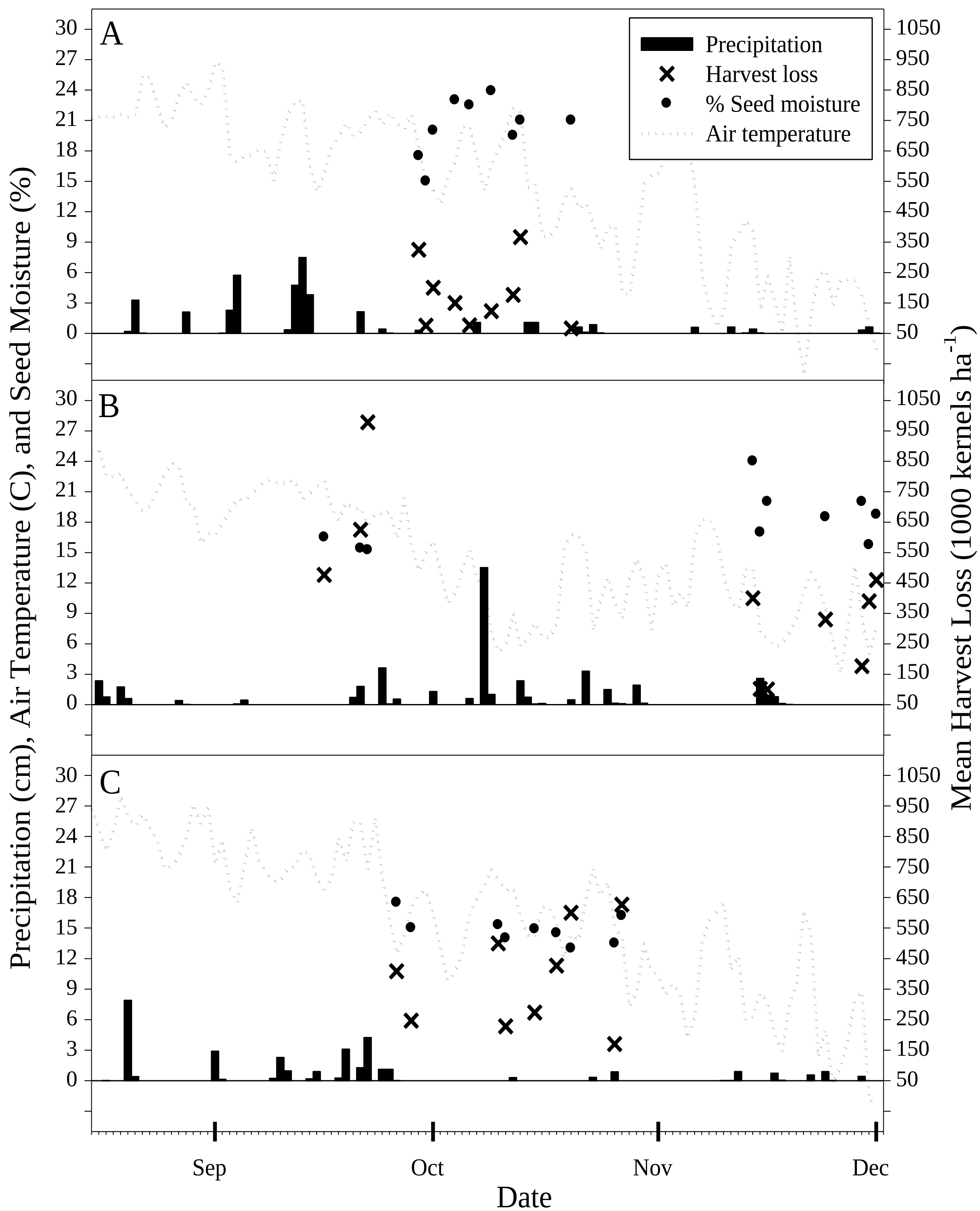

Figure 2.2. Daily precipitation and average temperature, harvest loss, percent seed moisture, and harvest date for ten corn fields surveyed in 2008 (A), 2009 (B), and 2010 (C) in central Missouri. Weather data recorded in Columbia, Missouri. Bars indicate total daily precipitation (cm). Dotted lines indicate average daily temperatures (C).

Chapter III

Competitive Effects of Volunteer Corn *(Zea mays* L.*)* in Corn

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Abstract. Volunteer corn (*Zea mays* L.) is a competitive weed in a number of agronomic crops, but little is known about its interference in corn. Field trials were established in central and northeast Missouri during 2008, 2009, and 2010 to determine the impact of volunteer corn in corn. Glyphosate-resistant corn was planted in 76 cm rows, with glyphosate-resistant volunteer corn established between rows at densities of 0 to 8 plants m^{-2} and allowed to compete season-long. Volunteer density was negatively correlated with leaf nitrogen, stalk diameter, and grain yield of row corn. At V6, V8, and VT growth stages, a SPAD meter demonstrated that leaf nitrogen levels were reduced by 5 to 40% compared to control plants with no competition. Row corn stalk diameters at the VT growth stage were reduced by volunteer corn from 4 to 38%; closely following the impact of volunteer corn on leaf nitrogen. Grain yield losses of row corn were reduced strongly by volunteer corn, with losses ranging from 14 to 93%. Both stalk diameters and grain yields were correlated with leaf nitrogen levels; 84 to 96% accuracy at 4 of 5 site years. Significant reductions in leaf nitrogen, stalk diameter, and yield were first observed at low densities of 0.5 to 1.6 plants m^{-2}. Every volunteer corn plant in a square meter resulted in approximately 11% (587 kg ha^{-1}, 9.4 bu A^{-1}) loss in grain yield in that area. To minimize negative impacts on row corn, volunteer corn should be managed at all densities.

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Nomenclature: volunteer corn, *Zea mays* L.

Key Words: grain yield, leaf chlorophyll content, stalk diameter.

Introduction

Optimization of corn grain yield depends upon many factors, including nutrients such as nitrogen. Nitrogen is required for many plant cell components; limited quantities result in reduced grain production (Taiz and Zeiger 2006; Cordes et al. 2004; Gonzalez and Salas 1995; Hellwig et al. 2002). Lambert et al. (2000) found as nitrogen fertilizer rates decreased from 269 to 0 kg N ha^{-1}, grain yield of corn decreased from 11,328 to 6,134 kg ha^{-1}. Monitoring nitrogen levels in the plant throughout the growing season facilitates the application of additional nitrogen when deficiencies occur. A Minolta SPAD-502[1] meter is a unit-less estimate of chlorophyll content in plant leaves; results provide accurate assessment of nitrogen status (Scharf et al. 2006; Vetsch and Randall 2004). Scharf et al. (2006) determined that relative chlorophyll measurements from V5 to R5 were related directly to yield response to nitrogen fertilizer and had coefficients of determination of 0.53 to 0.76 from 24 trials over 4 years across 7 north-central states. Sampling is non-destructive and the SPAD meter displays values of 0 to 99.9. In addition to predicting nutrient deficiencies, a SPAD meter can also quantify the competitive potential of weeds in corn (Lindquist et al. 2010).

One aspect of weed competition is the reduction of available soil nitrogen, resulting in grain yield losses. Lindquist et al. (2010) found available soil nitrogen was reduced by 50% when 80 to 364 weeds m^{-2} were competing with corn. Tollenaar et al. (1994a; 1994b) reported corn leaf chlorophyll was reduced up to 51% with high (133 to 150 weeds m^{-2}) weed densities. Hellwig et al. (2002) and Johnson et al. (2002) stated that grass weeds accumulated up to 59 and 38 kg N ha^{-1}, respectively when competing

[1] Minolta USA, 101 Williams Drive, Ramsey, NJ 07446 68

with corn until plants were 31 cm tall, which resulted in grain yield losses. Ghosheh et al. (1996) reported grain yields were reduced 47% by johnsongrass (*Sorghum halepense* L. Pers.) at a density of 12 plants per 9.8 m of row. Beckett et al. (1988) stated grain yield was reduced 18 and 22% following season-long competition of corn with giant foxtail (*Setaria faberi*) at 65 to 105 plants m^{-1} row, and shattercane (*Sorghum bicolor*) at 13 to 20 plants m^{-1} row, respectively.

In addition to reductions in available nutrients, weeds can also cause detrimental effects to corn stalks. Weeds reduce available light for corn plants resulting in taller corn with smaller diameter stalks (Anonymous 2010b; Westhoven 2010). Moolani et al. (1964) found stalk diameters were reduced by as much as 29% with high densities of smooth pigweed (*Amaranthus hybridus* L.); resultant grain yields were reduced by 39%. Thomison (2010) stated that thicker stalks had overall greater stalk strength and resistance to lodging. Reduced stalk diameter and strength may result in stalk lodging, which is one of the most problematic stresses in corn, reducing grain yield by 5 to 20% annually (Flint-Garcia et al. 2003; Zuber and Kang 1978; Hondroyianni et al. 2000).

Volunteer corn can be considered a weed, and can impact the yield in subsequent crops. Andersen et al. (1982) as well as Beckett and Stoller (1988) reported volunteer corn reduced soybean yields by 25 and 83% when volunteer corn densities were approximately 5 and 19 volunteer plants m^{-2}, respectively. Clewis et al. (2008) and Thomas et al. (2007) discovered cotton lint yield was reduced by 5 to 8% when competing with 1 volunteer corn plant m^{-1} cotton row.

Although corn and soybean are often rotated, Daberkow et al. (2008) reports that continuous corn is planted in some areas, which can result in problematic densities of volunteer corn. To date, there has been little research describing the competitive potential of volunteer corn in corn. The objectives of this research were to determine the effects of volunteer corn densities on nitrogen availability of row corn throughout the growing season, stalk diameters of row corn, and row corn grain yield.

Materials and Methods

Field trials were established in 2008, 2009, and 2010 at multiple locations in Missouri. During 2008, trials were conducted at the Greenley Research Center near Novelty (hereafter referred to as Novelty). In 2009, trials were conducted at the Bradford Research and Extension Center near Columbia (hereafter referred to as Columbia) and at Novelty. During 2010, trials were established at Columbia and at a producer's crop field near Mokane (hereafter referred to as Mokane). Columbia is located in central Missouri, Novelty is located approximately 150 km northeast of Columbia, and Mokane is located approximately 70 km southeast of Columbia. Soil at Novelty was a Putnam silt loam (Fine, smectitic, mesic Vertic Albaqualfs) with 2.9 and 2.3% organic matter and pH of 5.6 and 6.1 in 2008 and 2009, respectively. Soil at Columbia was a Mexico silt loam (Fine, smectitic, mesic Vertic Epiaqualfs) with 1.8 and 2.8% organic matter and pH of 6.3 and 6.3 in 2009 and 2010, respectively. Soil at Mokane was a Treloar (Sandy over loamy, mixed, superactive, calcareous, mesic Oxyaquic Udifluvents) - Haynie (Coarse-silty, mixed, superactive, calcareous, mesic Mollic Udifluvents) complex with 1.4% organic matter and a pH of 7.0. Experimental areas were maintained under no-till conditions and the previous crop was soybean at Novelty in 2007, Columbia in 2008, and Mokane in 2009 and corn at Novelty in 2008 and Columbia in 2009.

Glyphosate-resistant (Gly-R) corn [‘DKC 63-42 (VT3)’] was established in 76 cm rows at a depth of 3.8 cm and plant population of 69,190 seeds ha^{-1}. Each plot included four rows of corn (3 m total width) for a length of 13.7 m. Planting dates were: May 20, 2008 and May 22, 2009 at Novelty; May 21, 2009 and April 19, 2010 at Columbia; and April 21, 2010 at Mokane. Prior to or immediately after planting, glyphosate at 0.87 kg ae ha^{-1}, atrazine at 0.6 kg ai ha^{-1}, and s-metolachlor at 0.37 kg ai ha^{-1} were applied to plot areas to preclude competition with non-corn plants. Glyphosate at 0.87 kg ae ha^{-1} and mesotrione at 0.17 kg ai ha^{-1} were applied postemergence to remove any weed competition other than volunteer corn. All herbicides were applied at a speed of 4.8 km h^{-1} with a CO_2 pressurized backpack sprayer equipped with XR8002 TeeJet[2] flat fan nozzle tips calibrated to deliver 140 L ha^{-1} at 138 kPa. Ammonium nitrate was broadcasted at 167 kg N ha^{-1} at Novelty before planting corn in 2008, and at 140 kg N ha^{-1} on May 22, 2009. A rate of 140 kg N ha^{-1} was applied on April 22, 2009 and April 19, 2010 at Columbia, and April 13, 2010 at Mokane. Scharf and Lory (2006) stated that on average U.S. corn producers apply 1.12 kg N ha^{-1} (1 lb N A^{-1}) for each 62.5 kg ha^{-1} (1 bushel A^{-1}) of corn produced. Average grain yields for northeast and central Missouri counties ranged from 6,635 to 9,513 kg ha^{-1} from 2008 to 2009 (USDA 2009; USDA 2010b). Therefore, a nitrogen rate of 140 kg N ha^{-1} is an acceptable rate for a projected grain yield of approximately 7,823 kg ha^{-1} (125 bushels A^{-1}).

Volunteer corn was planted using a jab planter at a depth of 2.5 to 3.8 cm randomly throughout each plot at the time of planting row corn. ‘DKC 63-42 (VT3)’ was used as volunteer corn. Volunteer corn is typically a filial 2 (F_2) generation and exhibits less vigor than hybrid corn. Cross-pollination of hybrid corn creates genetic variability in

[2] TeeJet® : Spraying Systems Co. World Headquarters, P.O. Box 7900, Wheaton, IL, 60187-7900

the F_2 population, which could skew results in this experiment. Therefore, a hybrid (F_1) was used for uniform germination and growth.

Plot treatments included nine intended volunteer corn planting densities: 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 plants m^{-2} in 2008 and 0, 0.5, 1, 2, 3, 4, 6, 7, and 8 plants m^{-2} in 2009 and 2010. Volunteer corn densities were estimated after corn emergence to determine actual densities in each plot. In 2009, volunteer corn emergence was low at both locations. At Novelty, densities of volunteer corn were low; corn was replanted. However, at Columbia volunteer corn was not replanted due to the rapid growth of row corn; therefore, densities remained low, ranging from 0 to 3.4 plants m^{-2}.

Estimates of the competitiveness of volunteer corn with row corn included leaf chlorophyll measurements, stalk diameters, and yield of row corn. Fifteen plants from the two center rows of each plot were randomly selected and tagged to allow repeated measurement from the same plants throughout the growing season. Leaf chlorophyll measurements were taken at the V6, V8, and VT growth stages with a Minolta SPAD chlorophyll meter. Measurements were taken on the apex of the youngest mature leaf, one-half way between the midrib and leaf margin. Stalk diameters were recorded from the tagged plants at the VT growth stage using an electronic caliper on the widest axis of the stalk on the internode directly above the corn ear leaf. Prior to grain harvest, volunteer corn was removed from each plot. Grain was harvested from the two center rows of each plot, with moisture levels adjusted to 15.5%. Yields were taken at Novelty on October 10 and November 3, in 2008 and 2009, respectively. Yields at Columbia were taken on November 6 and October 5, in 2009 and 2010, respectively. Grain yield at Mokane was taken on October 20, 2010.

Experiments were designed as a randomized complete block with treatments (volunteer corn density) replicated four times at all site years, except for Mokane in 2010 where treatments were replicated six times. For leaf chlorophyll and stalk diameters, sub-samples were averaged to compute a mean for each plot. Leaf chlorophyll estimates were analyzed separately for each growth stage. A GLM procedure in SAS (2010) was used to determine effects on row corn leaf chlorophyll, stalk diameters, and row corn grain yield. Leaf chlorophyll, stalk diameters, and grain yields were then regressed across volunteer corn densities. A GLM procedure in SAS (2010) was also used to determine the order of polynomial orthogonal contrast for volunteer corn densities with the aforementioned data. Due to significant effects by locations, years, and location by year interactions, all site years were analyzed separately. Mean differences were determined using Fisher's Protected LSD at P=0.05.

Results and Discussion

Volunteer corn density influenced leaf chlorophyll of row corn at all growth stages (Table 3.1). Volunteer corn density was a significant factor at 3 of 5 site years for the V6 growth stage and at all site years for the V8 and VT growth stages. A quadratic relationship was found between volunteer corn densities and leaf chlorophyll at 1 or 2 growth stages for 2 of 5 site years (Appendix Table A.1). All other growth stages and site years were determined to exhibit a linear relationship.

Leaf chlorophyll was reduced due to volunteer corn competition at all densities throughout the growing season (Figure 3.1). At 2 of 3 site years (Novelty 2009 and Mokane 2010), chlorophyll measurements were similar across volunteer corn densities for the V6 and V8 growth stages. At all 3 site years, leaf chlorophyll measurements were 10 to 45% lower at the VT growth stage than the V6 and V8 growth stages. Densities of 0.5 to 4 plants m^{-2} reduced chlorophyll by 5 to 22% at 2 of 3 site years compared to the untreated across all growth stages. Densities of 6 to 8 plants m^{-2} reduced chlorophyll by 13 to 40% at all site years compared to plants without competition. With low volunteer corn densities (Novelty 2008 and Columbia 2009), reductions in leaf chlorophyll were less prevalent at the V6 growth stage (Figure 3.2). For Novelty 2008, chlorophyll measurements were similar across all densities of volunteer corn at V6. For the V8 and VT growth stages, reductions ranged from 8 to 20% at densities of 2 to 4 plants m^{-2} compared to the untreated control. For Columbia 2009, leaf chlorophyll reductions at all growth stages were variable, ranging from 3 to 20% at volunteer densities ranging from 0.45 to 3.4 plants m^{-2} compared to the untreated control.

Row corn stalk diameters were reduced significantly following competition with volunteer corn (Figure 3.3). For three of the site years, a linear relationship between stalk diameter and volunteer corn density was found; a quadratic relationship was determined for the other two site years (Appendix Table A.2). At Novelty 2009 and Mokane 2010, there were differences in stalk diameter reductions when comparing low and high densities of volunteer corn. With low densities (0.5 to 4 plants m^{-2}) row corn stalk diameters were reduced 1 to 5 mm compared to the untreated control, and with high densities (6 to 8 plants m^{-2}) stalk diameter were only reduced an additional 1 to 2 mm. At Novelty 2009, Columbia 2010, and Mokane 2010 densities of 0.5 to 4 plants m^{-2} reduced stalk diameters by 4 to 24% compared to the untreated control (Figure 3.3). The highest densities of 6 to 8 plants m^{-2} reduced stalk diameters by 20 to 38%. At site years with low volunteer corn densities, reductions in stalk diameters were not significant at densities below 0.5 plants m^{-2} (Figure 3.4). Densities of 0.7 to 1.6 plants m^{-2} reduced stalk diameters by 12 to 15%, and densities of 2 to 4 plants m^{-2} reduced stalk diameters by 13 to 24% compared to the untreated control.

Reductions in row corn yield were observed with all densities of volunteer corn for studies with 0 to 8 plants m^{-2} (Figure 3.5). Grain yield was related linearly to volunteer density at two site years, and a quadratic relationship was determined at two site years (Appendix Table A.3). Grain yield losses of 8 to 17% compared to the untreated control were observed at low densities of 0.5 to 1 plant m^{-2} (Figure 3.5). At Novelty 2009 and Mokane 2010, densities of 0.5 to 4 and 6 to 8 plants m^{-2} resulted in grain yield losses of 14 to 68 and 62 to 81%, respectively. At Columbia 2010 reductions in grain yield were variable, ranging from 8 to 56% for densities of 1 to 4 plants m^{-2}, and densities of 6 to 8 plants m^{-2} resulted in grain yield losses of 83 to 93%. For trials where volunteer corn densities only ranged from 0 to 4 plants m^{-2}, the impact on grain yield was inconsistent (Figure 3.6). For Novelty 2008, grain yield was similar across the range of volunteer corn densities. One likely explanation is the higher nitrogen fertilizer rate (167 kg N ha^{-1}) used at this site year, which may have minimized yield losses at volunteer corn densities $\leq$ 4 plants m^{-2}. At Columbia 2009, 140 kg N ha^{-1} was applied and grain yield was 21% lower at densities as low as 0.45 plants m^{-2}, and 62% lower at 3.4 plants m^{-2}.

Corn leaf chlorophyll levels are an indicator for potential grain yield. Scharf et al. (2006) demonstrated that a chlorophyll meter was a useful tool to relate corn yield to nitrogen; limits in available nitrogen reduce grain yield potential. Weed competition can reduce available nitrogen. Tollenaar et al. (1994a; 1994b) reported that corn leaf chlorophyll was reduced by 51% when competing with 133 to 150 weeds m^{-2}; subsequent grain yields were reduced 34%. Cordes et al. (2004) discovered corn leaf chlorophyll was reduced by 4 to 8% and grain yield reduced 4 to 41% with common waterhemp (*Amaranthus rudis*) densities of 369 to 445 plants m^{-2}. Hellwig et al. (2002) found the nitrogen content of corn biomass and grain yield was reduced by 35 and 26%, respectively when competing with 300 plants m^{-2} of giant foxtail (*Setaria faberi*), barnyardgrass (*Echinochloa crus-galli*), and large crabgrass (*Digitaria sanguinalis*). Our findings suggest volunteer corn is a competitive weed for available nitrogen, with reductions in late-season corn leaf nitrogen of 20 to 30% at 4 and 8 plants m^{-2}, respectively (Figure 3.1).

Leaf chlorophyll estimates were relatively low in all plots, including untreated plots. Scharf et al. (2006) determined that SPAD chlorophyll estimates in corn at VT generally ranged from 50 to 65 for corn with sufficient levels of nitrogen. Corn requiring additional nitrogen exhibited chlorophyll estimates below 50 (Scharf et al. 2006). In this research, chlorophyll estimates in untreated plots at VT ranged from 26 to 43, indicating nitrogen deficiencies prior to volunteer corn competition. This deficiency could have been due to adequate but lower rates of nitrogen applied or high rainfall during the growing season. In Missouri, average nitrogen fertilizer rates for corn were 157 and 174 kg N ha^{-1} for 2001 and 2005, respectively (USDA 2010a); a rate of 140 kg N ha^{-1} was used at 4 out of 5 site years in this experiment. Rainfall during the growing season reduces the amount of available nitrogen by moving nitrogen away from the root zone. Rainfall was 13 to 31cm higher throughout the growing season (April – September) during 2008 to 2010 compared to 30 year average rainfall amounts for Missouri (USDA 2000; USDA 2011).

Competition for light and reduced nitrogen availability may have impacted stalk diameter. As the amount of nitrogen in the leaf decreased, stalk diameters also decreased (Appendix Figure A.1). White et al. (1978) reported stalk diameters of corn were reduced by 15% when nitrogen was a limiting factor. Stalk diameter of corn is also an indicator of weed competition with corn. Moolani et al. (1964) found stalk diameters of corn were reduced by as much as 29% following competition with high densities of smooth pigweed (*Amaranthus hybridus* L.); corn yield was ultimately reduced 39%. With increased competition, corn plants likely respond by growing taller resulting in smaller diameter stalks (Anonymous 2010b; Westhoven 2010). However, stalk lodging and yield loss may result from this response. Stalk lodging reduces corn grain yield by 5 to 20% annually (Flint-Garcia et al. 2003; Zuber and Kang 1978; and Hondroyianni et al. 2000). Losses could contribute additional kernels to harvested fields, increasing the likelihood of volunteer corn in subsequent cropping systems. However, increased plant height and lodging were not estimated in this experiment; reduced stalk diameter likely reflected limited nitrogen availability.

Grain yields indicate low densities of volunteer corn reduced grain yields. The threshold where volunteer corn first reduced yields was at densities of 0.5 to 1.6 plants m^{-2} for site years that received 140 kg N ha^{-1}. Previous research using F_2 volunteer corn has suggested significant yield losses may not be an issue until high densities of volunteer corn are present. In North Dakota, Alms et al. (2008) found grain yield losses from volunteer corn ranged from 0 to 9% and 0 to 40% when volunteer corn was competing at densities of 0 to 3.5 and 0 to 8.5 plants m^{-2}, respectively. At densities of 0.1 and 0.5 plants m^{-2}, Jeschke and Doerge (2008) in MN, SD, and IA predicted yield losses to be 0.4 and 1.5%, respectively, based on a pooled analysis of university data (4 trials: 2 in MN, 1 in SD, 1 in IA). A technology development publication by Monsanto (Anonymous 2010a) predicted grain yield losses at volunteer densities of 0.25 to 5 plants m^{-2} to be 0.6 to 11.8%, respectively (test locations: MN, SD, IA, NE, KS, CO).

Leaf chlorophyll and stalk diameters were strongly correlated at all site years (Appendix Figure A.1). This indicates that both parameters were prediction variables for volunteer corn competition. At 4 site years, every 1 SPAD meter unit reduction in leaf chlorophyll resulted in a grain yield loss of 345 to 412 kg ha^{-1} (Figures 3.7 and 3.8). Also at 4 site years, each 1 mm loss in stalk diameter resulted in a loss of 543 to 807 kg ha^{-1} grain yield (Figures 3.9 and 3.10).

Our results indicate volunteer corn should be considered a significant weed problem in subsequent corn cropping systems. Volunteer corn reduces the available nitrogen to row corn, impacting grain yield. Stalk diameter of row corn is also reduced by increasing densities of volunteer corn. This decreased stalk diameter could also weaken overall stalk strength, potentially resulting in lodging (Thomison 2010). Crop producers should consider limiting the presence of volunteer corn in row corn to preserve grain yield.

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Table 3.1. ANOVA of volunteer corn density[a] influence on SPAD meter levels of row corn at three growth stages (V6, V8, and VT). Chlorophyll levels were estimated at three locations: Novelty (NE MO; 2008, 2009), Columbia (central MO; 2009, 2010), and Mokane (central MO; 2010).

	Pr > F				
Growth Stage	Novelty 2008	Columbia 2009	Novelty 2009	Columbia 2010	Mokane 2010
V6	0.8030	0.0131	0.0128	0.1940	<0.0001
V8	0.0060	0.0007	<0.0001	0.0003	<0.0001
VT	0.0156	0.0026	<0.0001	<0.0001	<0.0001

[a] Volunteer corn density: 0 to 4 plants m^{-2} (Novelty 2008), 0 to 3.4 plants m^{-2} (Columbia 2009), 0 to 8 plants m^{-2} (all other site years).

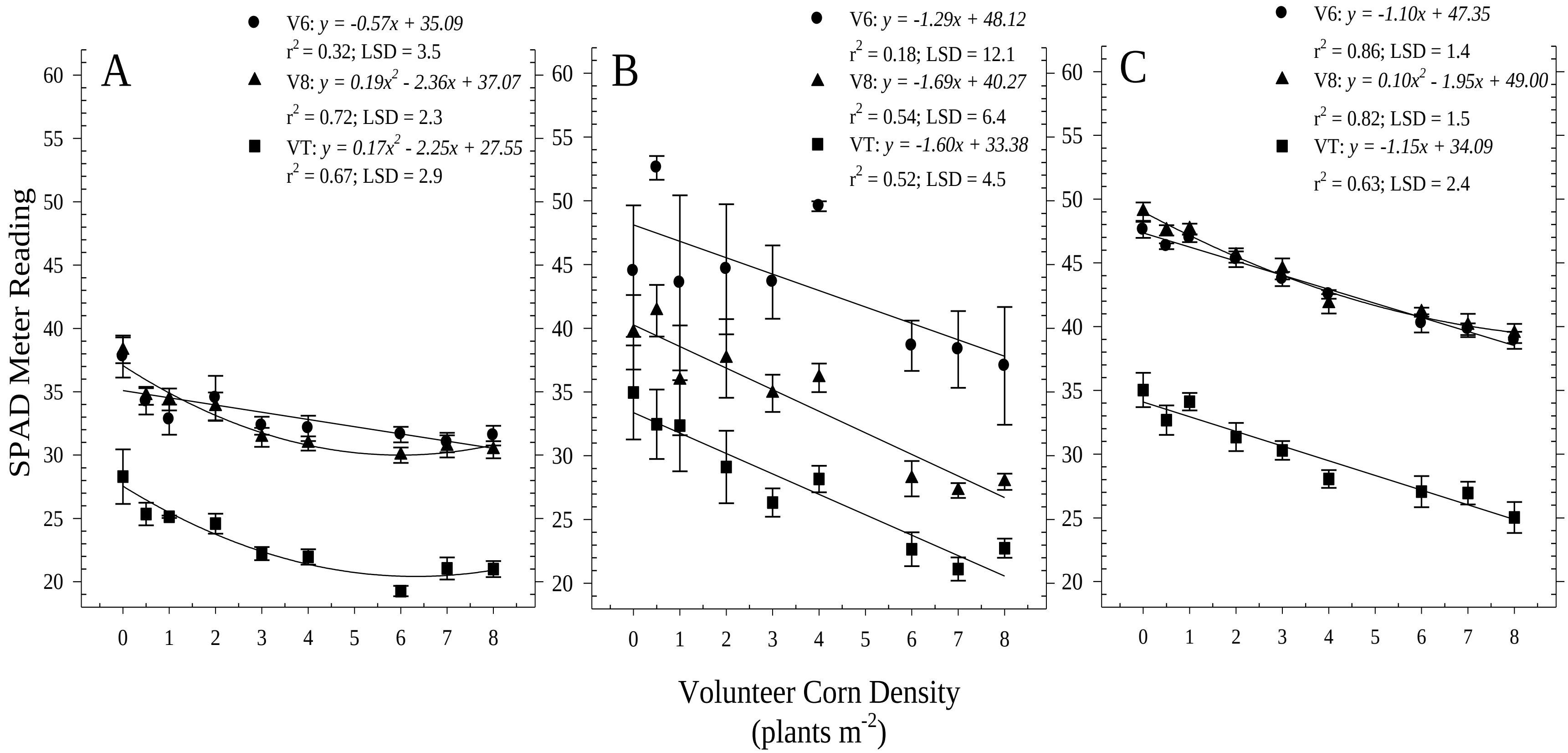

Figure 3.1. SPAD meter readings for Novelty 2009 (A), Columbia 2010 (B), and Mokane 2010 (C). Measurements represent the mean of 15 row corn plants in each plot with values recorded at three growth stages (V6, V8, VT). Volunteer corn densities ranged from 0 to 8 plants m^{-2}. Vertical lines above and below each point indicate standard errors. Points within the LSD range are not significantly different using Fishers Protected LSD at P=0.05.

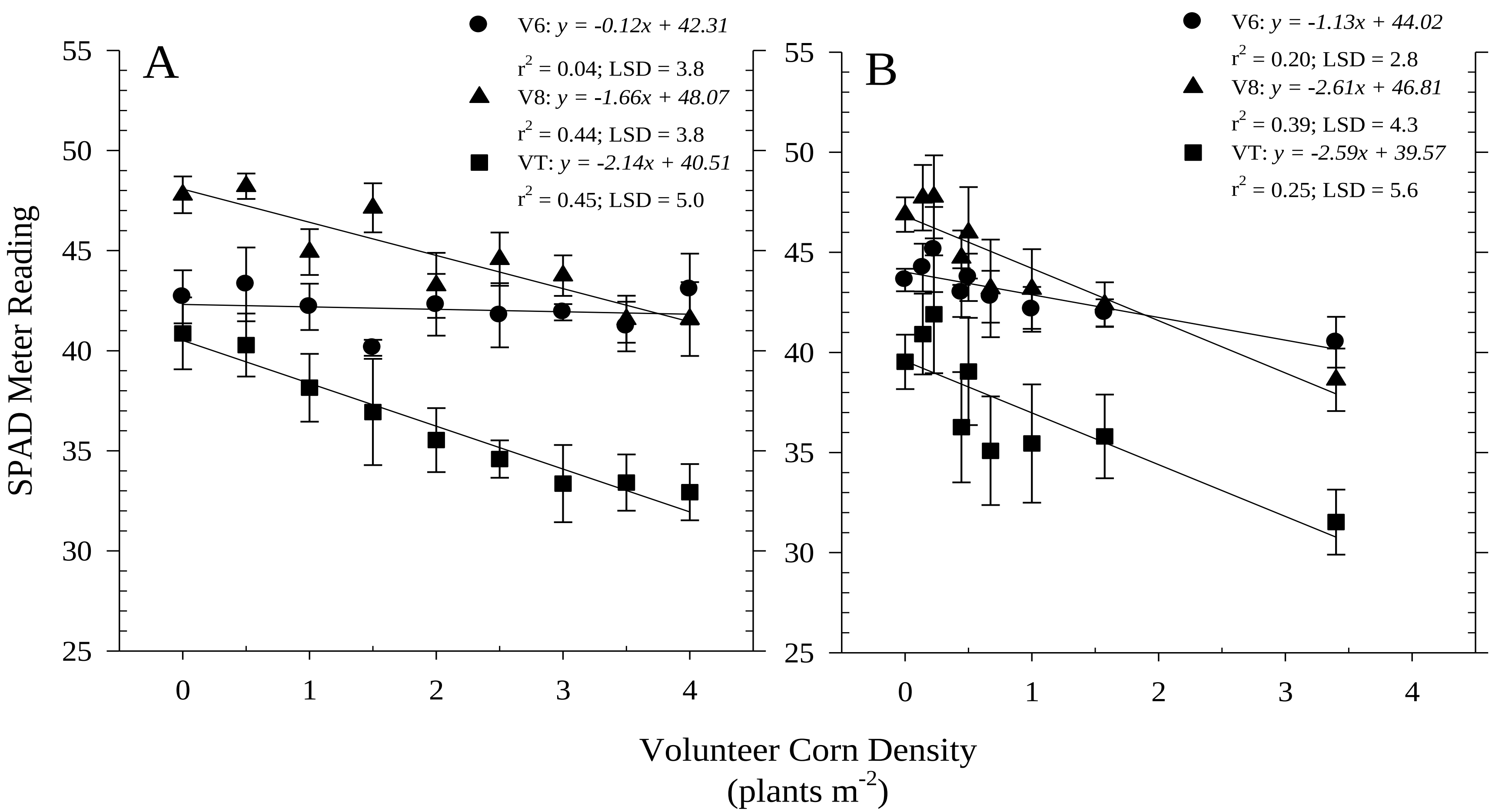

Figure 3.2. SPAD meter readings for Novelty 2008 (A) and Columbia 2009 (B). Measurements represent the mean of 15 row corn plants in each plot with values recorded at three growth stages (V6, V8, VT). Volunteer corn densities ranged from 0 to 4 plants m^{-2} (A) and 0 to 3.4 plants m^{-2} (B). Verti cal lines above and below each point indicate standard errors. Points within the LSD range are not significantly different using Fishers Protected LSD at P=0.05.

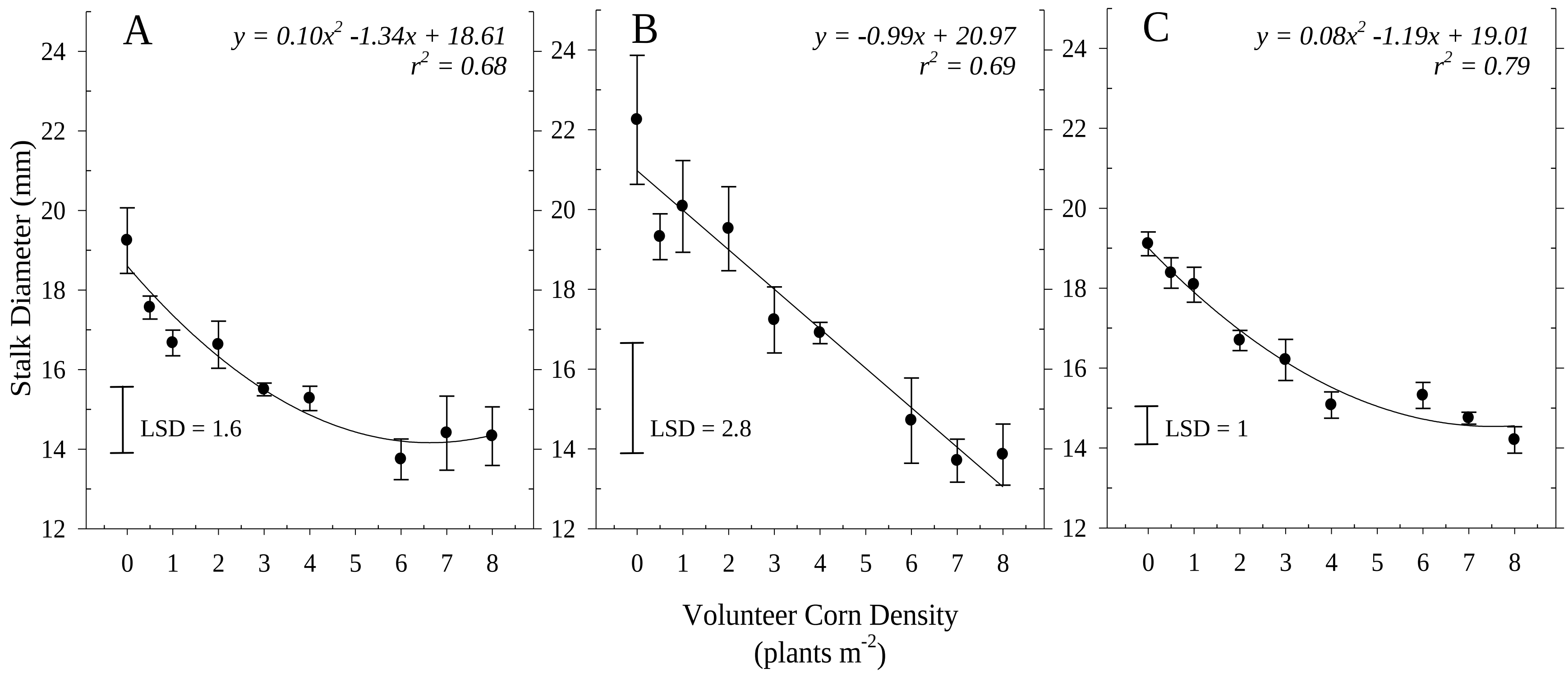

Figure 3.3. Diameter of row corn stalks following season-long competition with volunteer corn, at Novelty 2009 (A), Columbia 2010 (B), and Mokane 2010 (C). Stalk diameters measured from 15 row corn plants in each plot at the VT growth stage with an electronic caliper. Volunteer corn densities ranged from 0 to 8 plants m^{-2}. Vertical lines above and below each point indicate standard errors. Points within the LSD vertical line bar are not significantly different using Fishers Protected LSD at P=0.05.

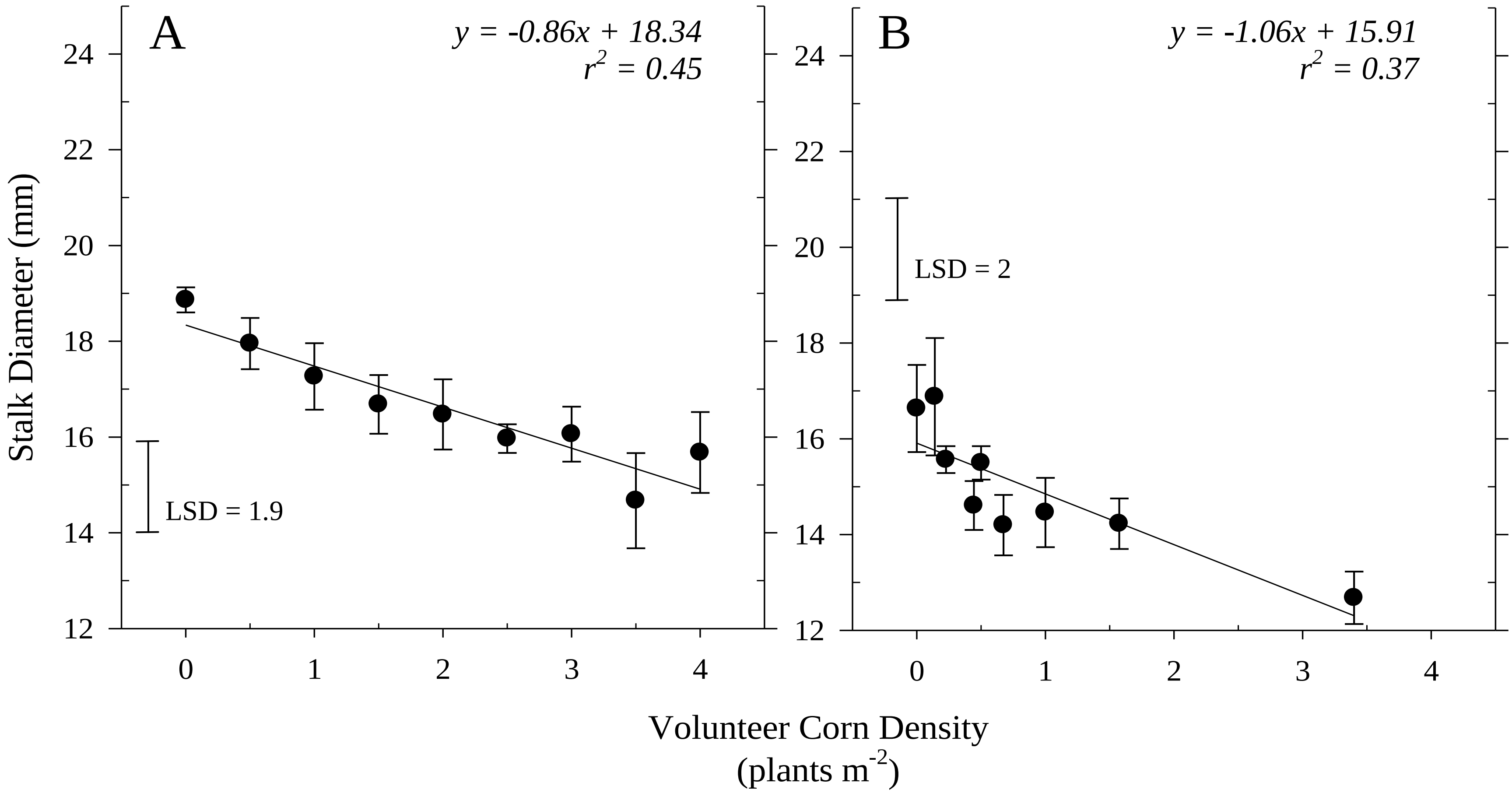

Figure 3.4. Diameter of row corn stalks following season-long competition with volunteer corn, at Novelty 2008 (A) and Columbia 2009 (B). Stalk diameters measured from 15 row corn plants in each plot at the VT growth stage with an electronic caliper. Volunteer corn densities ranged from 0 to 4 plants m^{-2} (A) and 0 to 3.4 plants m^{-2} (B). Vertical lines above and below each point indicate standard errors. Points within the LSD vertical line bar are not significantly different using Fishers Protected LSD at P=0.05.

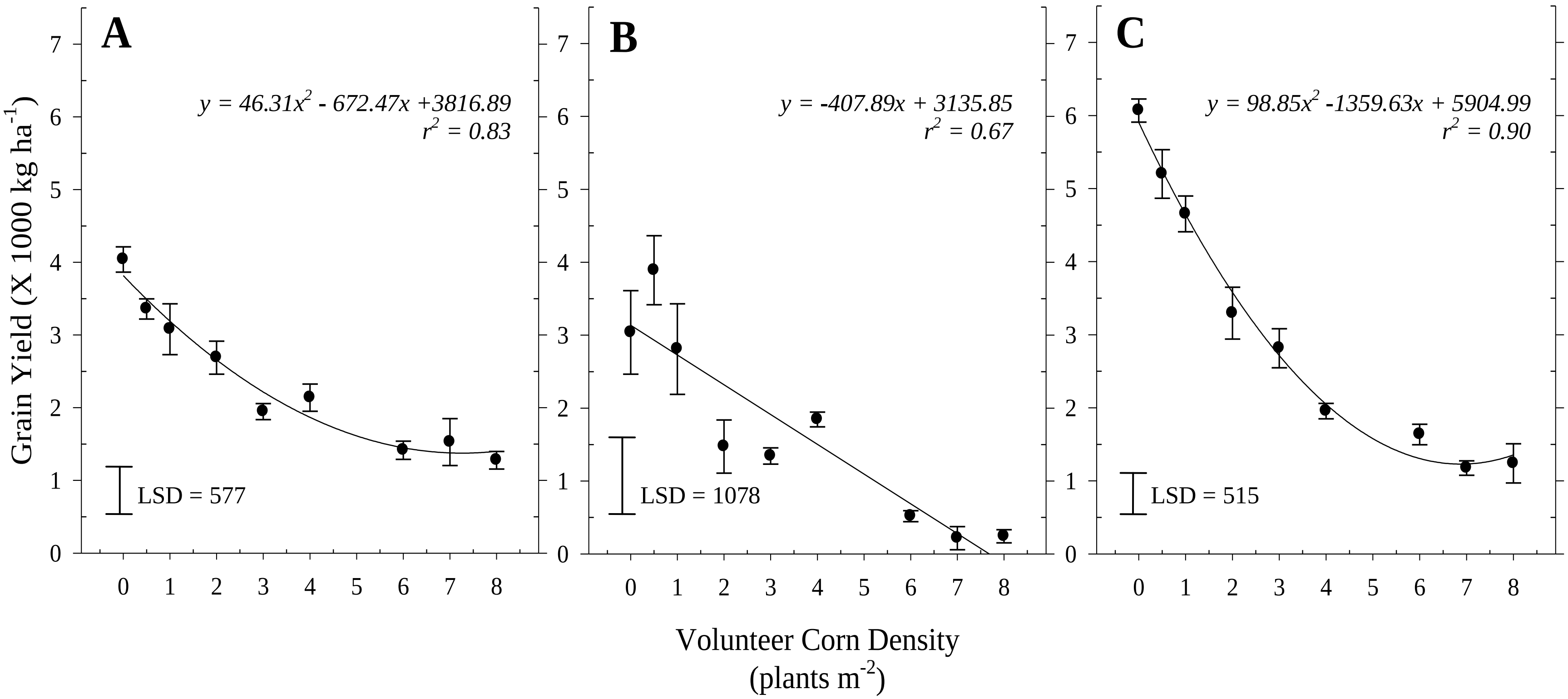

Figure 3.5. Row corn yield, following season-long competition with volunteer corn, at Novelty 2009 (A), Columbia 2010 (B), and Mokane 2010 (C). Grain yield estimated from the two center rows of each plot and adjusted to 15.5% moisture. Volunteer corn densities ranged from 0 to 8 plants m^{-2}. Vertical lines above and below each point indicate standard errors. Points within the LSD vertical line bar are not significantly different using Fishers Protected LSD at P=0.05.

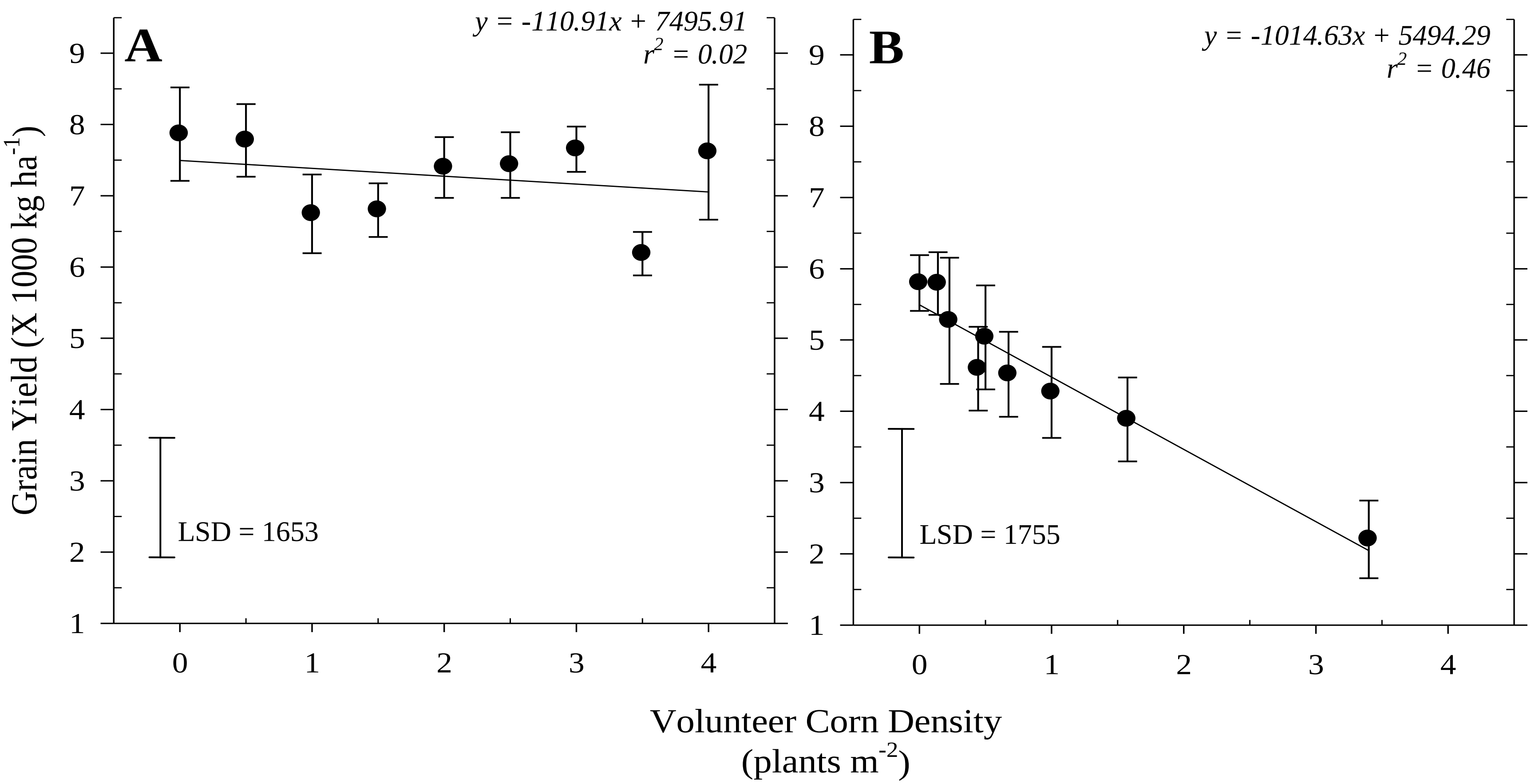

Figure 3.6. Row corn yield, following season-long competition with volunteer corn, at Novelty 2008 (A) and Columbia 2009 (B). Grain yield estimated from the two center rows of each plot and adjusted to 15.5% moisture. Volunteer corn densities ranged from 0 to 4 plants m^{-2} (A) and 0 to 3.4 plants m^{-2} (B). Vertical lines above and below each point indicate standard errors. Points within the LSD vertical line bar are not significantly different using Fishers Protected LSD at P=0.05.

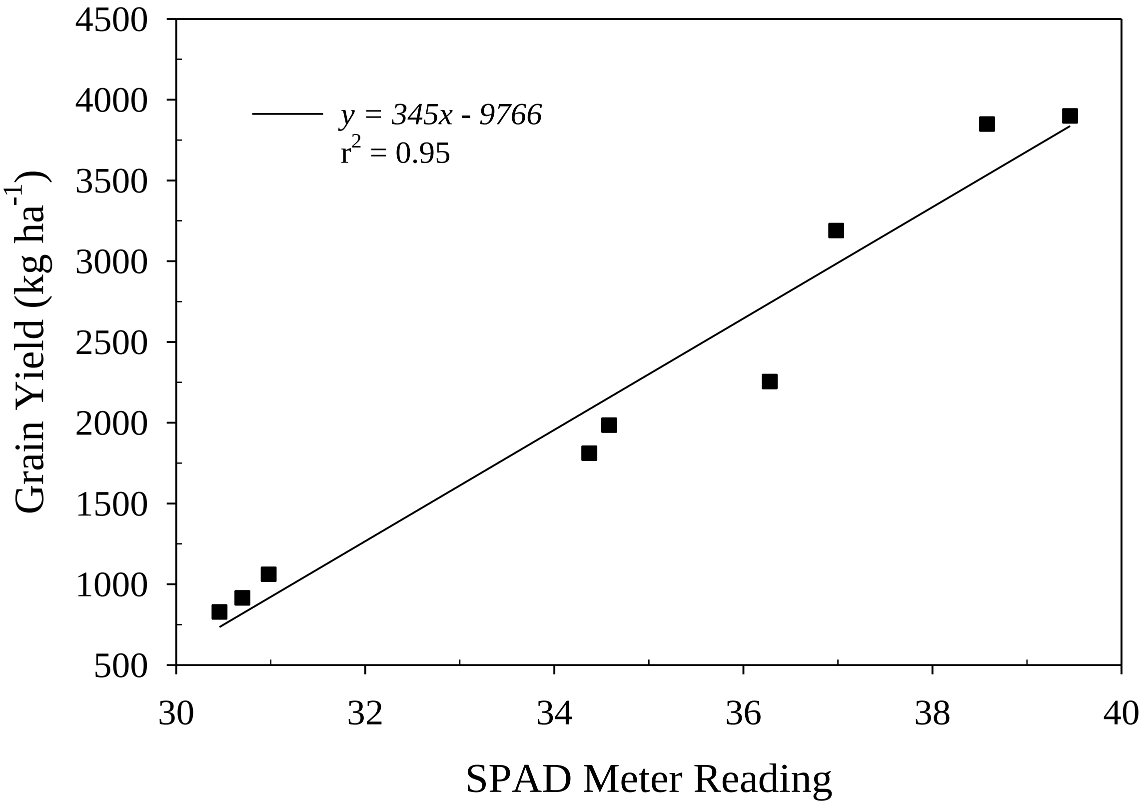

Figure 3.7. Comparison of mean SPAD meter readings with mean grain yields from Novelty 2009, Columbia 2010, and Mokane 2010. SPAD meter readings averaged for all growth stages (V6, V8, VT) and grain yields recorded at the end of the growing season. Treatments were volunteer corn densities ranging from 0 to 8 plants m^{-2}.

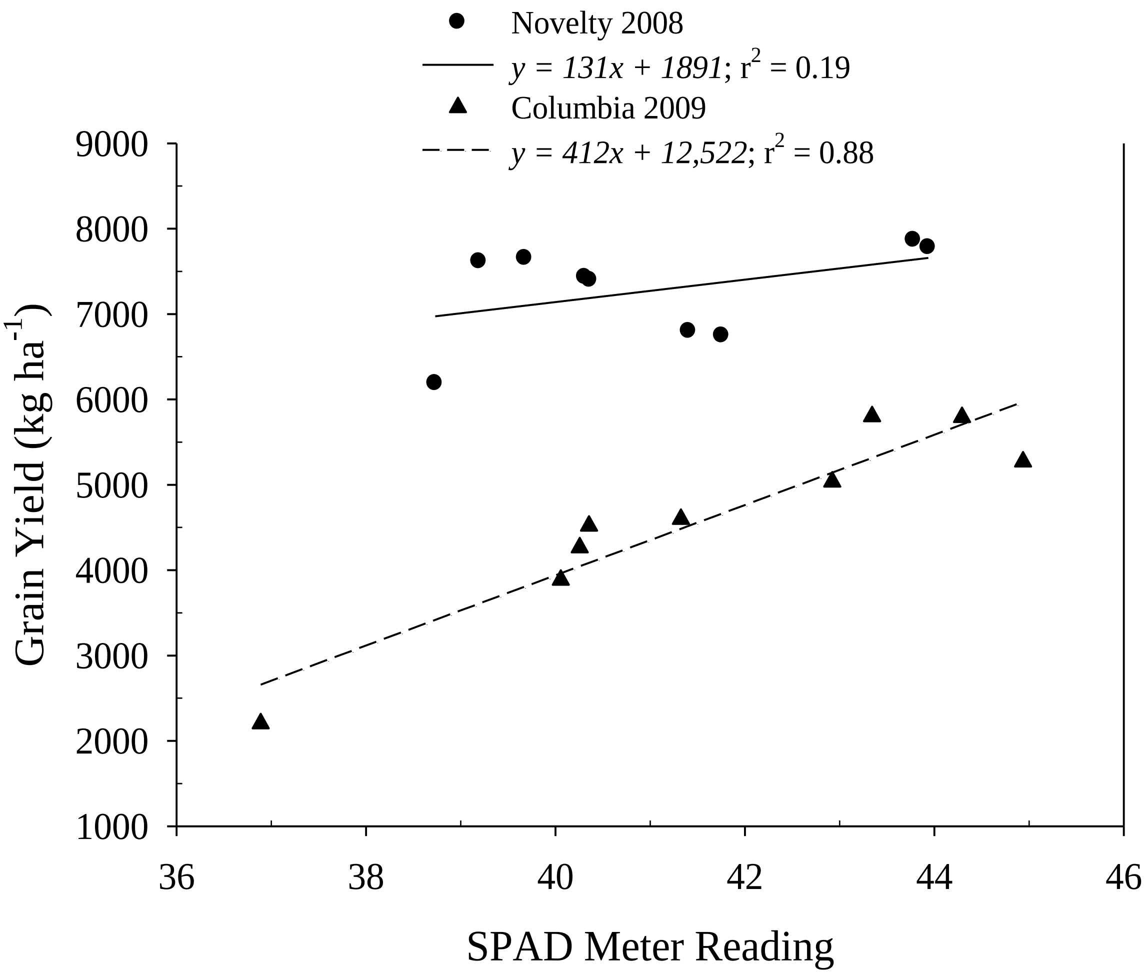

Figure 3.8. Comparison of mean SPAD meter readings with mean grain yields from Novelty 2008 and Columbia 2009. SPAD meter readings averaged for all growth stages (V6, V8, VT) and grain yields recorded at the end of the growing season. Treatments were volunteer corn densities ranging from 0 to 4 plants m^{-2} (●) and 0 to 3.4 plants m^{-2} (▲).

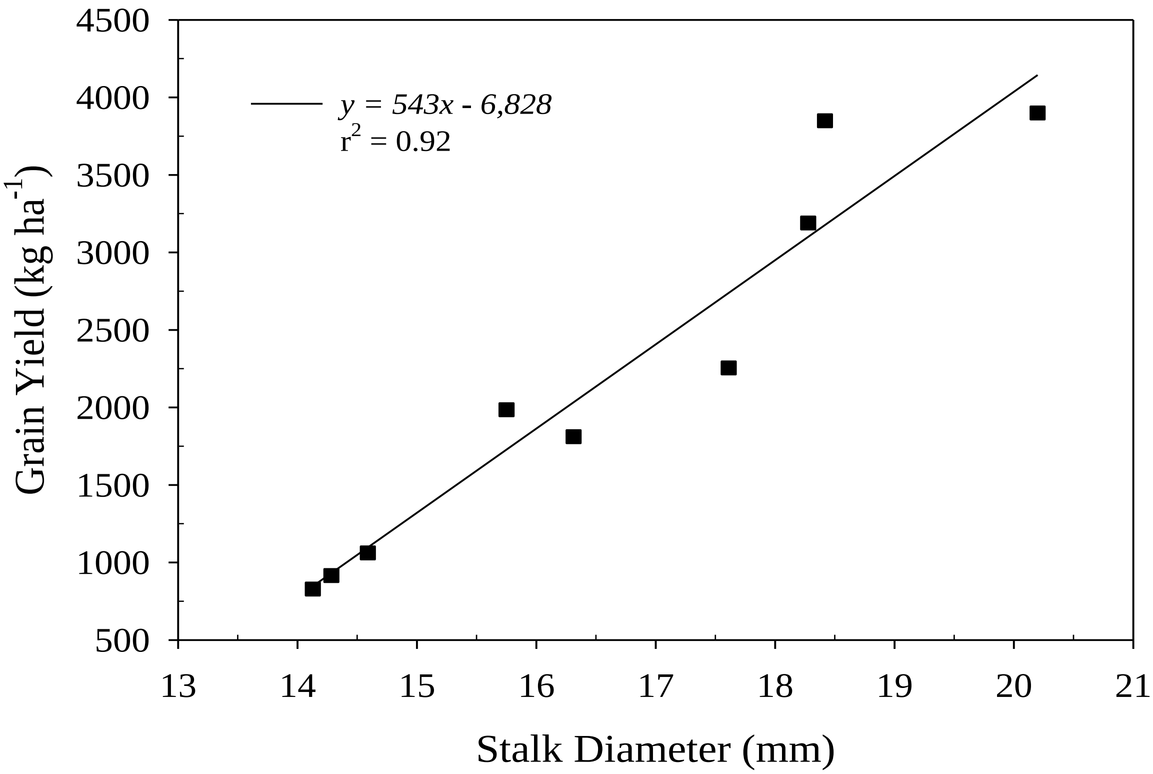

Figure 3.9. Comparison of mean stalk diameters with mean grain yields from Novelty 2009, Columbia 2010, and Mokane 2010. Stalk diameters recorded at the VT growth stage and grain yields recorded at the end of the growing season. Treatments included volunteer corn densities ranging from 0 to 8 plants m^{-2}.

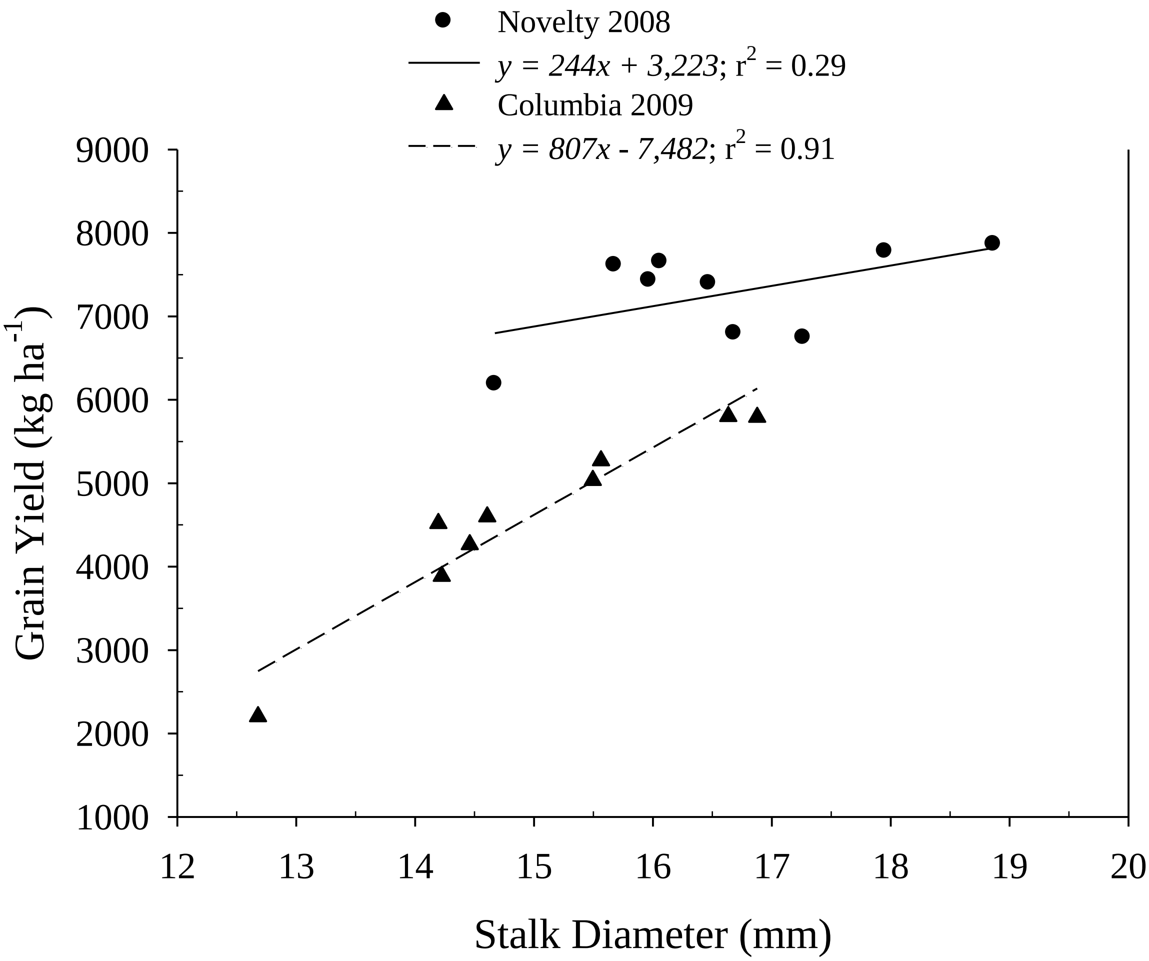

Figure 3.10. Comparison of mean stalk diameters with mean grain yields from Novelty 2008 and Columbia 2009. Stalk diameters recorded at the VT growth stage and grain yields recorded at the end of the growing season. Treatments were volunteer corn densities ranging from 0 to 4 plants m^{-2} (●) and 0 to 3.4 plants m^{-2} (▲).

Chapter IV

Management of Volunteer Corn *(Zea mays* L.*)* with Glufosinate or Imazethapyr + Imazapyr in Transgenic Corn

Tye C. Shauck and Reid J. Smeda*

Abstract. Volunteer corn (*Zea mays* L.) can compete with row corn for available resources, as well as vector pathogens and insects. Management of volunteer corn in a continuous corn system using a glyphosate-resistant (Gly-R) hybrid is difficult. No-till field trials were established in central and northeast Missouri in 2009 and 2010 to determine the efficacy of glufosinate or imazethapyr + imazapyr to control Gly-R volunteer corn. Separate blocks of glufosinate-resistant and imidazolinone-tolerant corn were planted in 76 cm rows, with Gly-R volunteer corn established between rows at densities of 1 (low) and 4 (high) plants m^{-2}. Herbicides were broadcasted at corn heights of 10, 20, and 40 cm. Visual control ratings 5 weeks after treatment were highest for the 20 cm application height, ranging from 89 to 100% and 74 to 89% with glufosinate and imazethapyr + imazapyr at 3 of 4 site years, respectively. Dry weights per plant indicated that applications at all heights reduced volunteer corn biomass by at least 89 and 70% with glufosinate and imazethapyr + imazapyr, respectively. At a high volunteer corn density, yield losses were prevented with glufosinate at all application heights and imazethapyr + imazapyr at 10 and 20 cm application heights. Rotating to a glufosinate-resistant or imidazolinone-tolerant hybrid was effective for control of Gly-R volunteer corn.

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Nomenclature: glufosinate; imazethapyr; imazapyr; volunteer corn, *Zea mays* L.; corn, *Zea mays* L.

Key Words: Glyphosate-resistant; Glufosinate-resistant; Imidazolinone-tolerant.

Introduction

Volunteer corn (*Zea mays* L.) can detrimentally impact row corn in a number of ways. Jeschke and Doerge (2008) reported grain yield losses of 1.5 to 13% when 0.5 to 4 volunteer corn plants m^{-2} competed with row corn. Alms et al. (2008) discovered grain yield losses of 9 and 40% at densities of 3.5 and 8.5 volunteer corn plants m^{-2}, respectively. Volunteer corn may also indirectly impact row corn by serving as a host for viruses and insect vectoring pathogens (Robertson et al. 2009). Summers et al. (2004) reported fall emerging volunteer corn was a critical overwintering host for the corn leafhopper (*Dalbulus maidis*), which is a vector for corn stunt spiroplasma (*Spiroplasma kunkelii*). Additionally, volunteer corn may aid in the selection of western corn rootworm (*Diabrotica virgifera*) resistance to *Bacillus thuringiensis* (Bt) (Wallheimer 2009). Wallheimer (2009) stated that hybrid corn with the Bt trait produced volunteer corn that expressed the Bt trait at low or sub-lethal concentrations. Rootworm larvae feeding on volunteer corn increases the potential for developing tolerance to the Bt trait (Wallheimer 2009).

The effectiveness of glyphosate on weed control in glyphosate-resistant (Gly-R) crops has led to widespread adoption. In 2010, Gly-R crops accounted for approximately 93% of soybean (*Glycine max* L.), 70% of corn, and 78% of cotton (*Gossypium hirsutum*) areas planted in the U.S. (Owen 2010). Glyphosate exhibits systemic activity on a broad spectrum of weed species and has low mammalian toxicity (Zimdahl 2007). However, volunteer corn from Gly-R corn has become a troublesome weed in subsequent crops (Thomas et al. 2007; Deen et al. 2006; Jeschke and Doerge 2008).

Management options for Gly-R volunteer corn in corn are limited. In continuous corn where the hybrid is Gly-R, there are no selective herbicides for removal of Gly-R volunteer corn. Tillage early in the fall following harvest may stimulate volunteer emergence prior to winter freezing which would reduce the potential for emergence the following spring (Anonymous 2010a; Anonymous 2010b). Spring tillage before planting and in-crop field cultivation after volunteer corn emergence may minimize the impact (Ferguson 2008). However, mechanical control is limited with widespread adoption of no-tillage production systems (Givens et al. 2009).

Selective herbicides applied on transgenic corn hybrids with resistance to non-glyphosate herbicides may provide adequate control of Gly-R volunteer corn. One control option includes: glufosinate (Ignite[1]), which can be applied to glufosinate-resistant (LibertyLink[2]) corn. Glufosinate inhibits glutamine synthetase and results in postemergence control of a broad spectrum of weed species; resistance in corn results from genetic modification of the target enzyme (Vasil 1996). Previous research has found that glufosinate applied on 8 to 20 cm tall Gly-R corn resulted in 70 to 100% control (Corbett et al. 2004; Bradley 2007; Steckel et al. 2009). The lack of systematic activity limits the size of volunteer corn sensitive to glufosinate, with a maximum labeled size of 30 cm (Anonymous 2008b).

Another control option for Gly-R volunteer corn is imazethapyr + imazapyr (Lightning[3]), which can be applied to imidazolinone-tolerant (Clearfield[4]) corn.

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[1] Ignite®: Bayer CropScience LP, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC, 27709

[2] LibertyLink®: Bayer CropScience LP, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC, 27709

[3] Lightning®: BASF Corporation, 26 Davis Drive, Research Triangle Park, NC, 27709

[4] Clearfield®: BASF Corporation, 26 Davis Drive, Research Triangle Park, NC, 27709

Imazethapyr and imazapyr are imidazolinones, a family of herbicides that target the plastid enzyme acetolactate synthase (ALS), also known as acetohydroxyacid synthase (AHAS) (Shaner et al. 1984). Imazethapyr and imazapyr are systemic postemergence herbicides that control many grass and broadleaf weeds (Alister and Kogan 2005). Johnson et al. (2001) reported 60 to 95% control of 10 to 15 cm tall Gly-R volunteer corn with imazethapyr + imazapyr at 0.063 kg ai ha^{-1}. However, precautions must be taken in regards to carryover effects on rotational crops.

Rapid growth of volunteer corn may preclude the timely use of glufosinate or imazethapyr + imazapyr. Additional research is necessary to assess the impact of these herbicides on a range of volunteer corn growth stages. The objectives of this research were to determine the efficacy and yield impacts of glufosinate and imazethapyr + imazapyr at three treatment timings on two densities of Gly-R volunteer corn in glufosinate-resistant and imidazolinone-tolerant hybrids, respectively.

Materials and Methods

Field trials were established in 2009 and 2010 at two locations in Missouri: central, at the Bradford Research and Extension Center near Columbia, and northeast, at the Greenley Research Center near Novelty. Soil at Columbia was a Mexico silt loam (Fine, smectitic, mesic Vertic Epiaqualfs) with 1.8 and 2.8% organic matter and pH of 6.3 and 6.3 in 2009 and 2010, respectively. Soil at Novelty was a Putnam silt loam (Fine, smectitic, mesic Vertic Albaqualfs) with 2.3 and 2.7% organic matter and pH of 6.1 and 5.8 in 2009 and 2010, respectively. Experimental areas were maintained under no-till conditions and the previous crops were soybeans at Columbia in 2008, corn at Columbia in 2009, and corn at Novelty in 2008 and 2009.

In distinct areas, LibertyLink corn (Dow '2G779-F80') or Clearfield corn (Garst '8488IT') was established in 76 cm rows at a depth of 3.8 cm and plant population of 69,190 seeds ha^{-1}. Each 3 m wide plot included four rows of corn for a length of 13.7 m. Planting dates were: May 21, 2009 and April 19, 2010 at Columbia and May 22, 2009 and June 18, 2010 at Novelty. Prior to or immediately after planting, glyphosate at 0.87 kg ae ha^{-1}, atrazine at 0.6 kg ai ha^{-1}, and s-metolachlor at 0.37 kg ai ha^{-1} were applied to the no-till plot areas to remove any weeds that were present. All herbicides were applied at a speed of 4.8 km h^{-1} with a CO_2 pressurized backpack sprayer equipped with XR8002 TeeJet[5] flat fan nozzle tips calibrated to deliver 140 L ha^{-1} at 138 kPa. Ammonium nitrate was broadcasted at 140 kg N ha^{-1} on April 22, 2009 and April 19, 2010 at Columbia, and May 22, 2009 and April 14, 2010 at Novelty. An additional 55 kg N ha^{-1} of ammonium nitrate was applied on June 18, 2010 at Novelty due to delayed planting (high rainfall) following initial application of ammonium nitrate.

Volunteer corn was planted at a depth of 2.5 to 3.8 cm randomly in each plot at the time of planting row corn using a jab planter. A glyphosate-resistant hybrid ['DKC 63-42 (VT3)'] was used to simulate F_2 (filial 2) Gly-R volunteer corn. Volunteer corn is typically an F_2 generation and exhibits less vigor than hybrid corn. Cross-pollination of hybrid corn creates genetic variability in the F_2 population, which could impact the uniformity of results in this experiment. Therefore, a hybrid (F_1) was used for consistent germination and growth.

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[5] TeeJet®: Spraying Systems Co. World Headquarters, P.O. Box 7900, Wheaton, IL, 60187-7900

Plot treatments included volunteer corn densities of 1 and 4 plants m^{-2}, and three herbicide application timings: 10, 20, and 40 cm volunteer corn. Volunteer corn establishment was low at Columbia 2009; therefore, densities were 0.5 and 1 plant m^{-2}. All treatments including glufosinate as the herbicide to remove volunteer corn were considered one unique experiment, and in a separate area, those treatments utilizing imazethapyr + imazapyr were considered a second experiment.

As volunteer corn reached the target size, glufosinate was applied at a rate of 0.49 kg ai ha^{-1} plus 3.36 kg ha^{-1} ammonium sulfate on glufosinate-resistant corn. For the second experiment, imazethapyr + imazapyr was applied at a rate of 0.047 + 0.016 kg ai ha^{-1} plus 2.8 kg ha^{-1} ammonium sulfate and 0.25% vol vol^{-1} non-ionic surfactant on target size imidazolinone-tolerant corn. Application equipment and conditions were as described above.

Data collected from each experiment included visual control and biomass of volunteer corn as well as yield of row corn. Visual control was estimated using a scale of 0 (no injury) to 100% (complete death) at 3 and 5 weeks after treatment (WAT). At the 5 WAT evaluation timing, 9 volunteer corn plants from each treated plot and 3 volunteer corn plants from each untreated plot were harvested at soil level. Plants were dried at 48 C for 5 days and dry weight recorded. Prior to grain harvest, volunteer corn was removed from each plot. Grain was harvested from the two center rows of each plot, with moisture levels adjusted to 15.5%. Grain production at Novelty 2010 was not collected because row corn establishment was inadequate to accurately assess grain yield.

Each experiment was designed as a randomized complete block with treatments arranged as a 2 (density) by 3 (plant height at application) factorial and replicated four times. Prior to analysis, Bartlett's test for equal variance was performed. Volunteer corn control ratings were subjected to an arc-sine square root transformation because of unequal variances due to proportions as presented by Snedecor and Cochran (1989). For plant dry weight, sub-samples were averaged to compute a mean for each plot. In SAS (2010), a MIXED procedure was used to determine effects on visual ratings and biomass of treated plants, and a GLM procedure distinguished effects on row corn grain yield. Due to a significant location by year interaction, all site years were analyzed separately. Mean differences were determined using Fisher's Protected LSD at P=0.05.

Results and Discussion

Application timing was an important variable influencing both glufosinate and imazethapyr + imazapyr activity on Gly-R volunteer corn at all site years (Table 4.1). Although the size of volunteer corn was an important influence on glufosinate and imazethapyr + imazapyr efficacy, density did not appear important at either timing of visual rating for both herbicides (Table 4.1). The lack of an interaction between application timing and density suggest that the response of volunteer corn to each herbicide was similar at all plant densities.

Visible control of volunteer corn with glufosinate was variable, with 80% or greater control only observed at both evaluation timings for 3 of 4 site years (Table 4.2). For 3 of 4 site years, volunteer corn control 5 WAT was 89 to 100% following applications on 20 cm plants; control was more inconsistent for 10 and 40 cm plants. If control of glufosinate was 80% or greater at 3 WAT, control at 5 WAT remained at or above that level.

Visible control of volunteer corn with imazethapyr + imazapyr was also variable, with 80% or greater control only observed at a single evaluation timing for 2 of 4 site years (Table 4.3). The onset of visual symptomology was slow, as control estimates were overall higher at the 5 than 3 WAT. For 3 of 4 site years, volunteer corn control 5 WAT was 74 to 89% following applications on 20 cm plants; control was more inconsistent for treated 10 and 40 cm plants.

Although visual control did vary with application timing on corn, it was not an important variable influencing the biomass of Gly-R volunteer corn (Table 4.4). Application timing of imazethapyr + imazapyr was only significant for 1 site year. The interaction between volunteer corn density and herbicide application timing also was not an important influence on plant biomass.

Volunteer corn was sensitive to glufosinate and imazethapyr + imazapyr at all treated sizes (Figure 4.1 and 4.2). At all site years, volunteer corn biomass following treatment with glufosinate was reduced 89 to 99% compared to the untreated control (Figure 4.1). Reductions in volunteer corn biomass were similar for each application timing at all site years, with reductions greatest for the 20 cm timing at 3 of 4 site years. Volunteer corn biomass following treatment with imazethapyr + imazapyr was reduced 70 to 97% compared to the untreated control (Figure 4.2). Reductions in volunteer corn biomass were similar for each application timing at all site years, with reductions greatest for the 20 cm timing at 2 of 4 site years.

The influence of application timing on grain yield was not consistent following glufosinate (2 of 3 site years) or imazethapyr + imazapyr (1 of 3 site years) treatments (Table 4.5). Similarly, volunteer corn density significantly influenced grain yield at only

1 of 3 site years for both glufosinate and imazethapyr + imazapyr. There was no interaction between application timing and density on grain yield.

Grain yield of glufosinate-resistant corn mostly reflected the efficacy of glufosinate (Figure 4.3). For Columbia 2009 (Figure 4.3 A), yields exceeded 5,000 kg ha^{-1} and all treatments resulted in similar yields. However, lower yields (< 4,000 kg ha^{-1}) at Novelty 2009 (Figure 4.3 B) and Columbia 2010 (Figure 4.3 C) resulted in yield differences between treatments. A density of 4 plants m^{-2} resulted in grain yield reductions up to 43% compared to a density of 1 plant m^{-2}. Application timing effects were more prevalent at a density of 4 plants m^{-2}, where all application timings increased grain yields by 72 to 183% compared to the untreated corn.

Grain yield of imidazolinone-tolerant corn was influenced by the efficacy of imazethapyr + imazapyr on volunteer corn (Figure 4.4). For Columbia 2009 (Figure 4.4 A), grain yield exceeded 4,500 kg ha^{-1} for all treatments; the similarity in grain yield among treatments suggest volunteer corn was not highly competitive at the 0.5 and 1 plant m^{-2} densities. However, in site years where overall grain yield was lower (< 4,500 kg ha^{-1}) competition by volunteer corn was noted at 4 plants m^{-2} for untreated versus treated corn. A density of 4 plants m^{-2} resulted in grain yield reductions by as much as 45% compared to a density of 1 plant m^{-2} at Columbia 2010. Application timing effects were more prevalent at a density of 4 plants m^{-2}, where 10 and 20 cm applications resulted in grain yields increasing by 102 to 105% and 126% compared to the untreated, respectively. In 3 of 4 treatments, the 40 cm application resulted in lower grain yields than untreated corn. An application at 10 and 20 cm resulted in grain yields increasing by 71 to 134% and 80% compared to an application at 40 cm, respectively.

Visual control of volunteer corn was not an effective method to predict the influence of glufosinate and imazethapyr + imazapyr (Table 4.2 and 4.3). Hager et al. (2005) found only 29% visual control of volunteer corn when glufosinate was applied at 23 cm corn heights, but 90 to 92% control on 33 to 61 cm tall plants. Currie et al. (2007) reported 45 and 41% control of Gly-R volunteer corn after glufosinate treatments at the 3 and 6 leaf stages, respectively. Corbett et al. (2004) and Bradley (2007) stated glufosinate applications on 8 to 15 cm Gly-R corn resulted in 85 to 100% control. Furthermore, Alms et al. (2008) stated volunteer corn treated with glufosinate at 0.48 kg ai ha^{-1} resulted in greatest control at application heights of 18 to 30 cm and inadequate control when applied at 13 to 15 and 46 to 91 cm. Johnson et al. (2001) found a wide range of volunteer corn control; 60 to 95% control of 10 to 15 cm Gly-R corn with imazethapyr + imazapyr at 0.063 kg ai ha^{-1}.

Plant biomass was an accurate method to determine glufosinate and imazethapyr + imazapyr activity. Labels for glufosinate and imazethapyr + imazapyr indicate the maximum application height for volunteer corn is 25 to 30 cm (Anonymous 2008a and Anonymous 2008b). However, all application timings reduced volunteer corn biomass from 70 to 99% with glufosinate or imazethapyr + imazapyr. Therefore, high levels of visual control may not be necessary to reduce the competitive potential of volunteer corn. Young and Hart (1997) reported 92 to 95% biomass reduction of sethoxydim-resistant volunteer corn at 8 WAT when treated at the two- to three-leaf stage with imazethapyr + imazaquin. Similar to our results, visible control was low, ranging from 68 to 83% even when biomass reductions were greater than 90% (Young and Hart 1997).

The definitive impact of glufosinate or imazethapyr + imazapyr on volunteer corn is protection of row corn yield (Figure 4.3 and 4.4). The relative similarity of grain yields among plots treated with glufosinate or imazethapyr + imazapyr versus untreated suggests that minimizing volunteer corn growth was more important than causing a high level of visual control. The benefits of controlling volunteer corn were more evident at site years with lower yields (Novelty 2009, Columbia 2010). When yields were lower, untreated volunteer corn at 4 plants m^{-2} significantly reduced row corn yield. Alms et al. (2008) found 0 and 23% yield losses at a densities of 3.5 and 7 plants m^{-2} following glufosinate treatments. In our experiment, at a high volunteer density, the application of glufosinate at all timings and imazethapyr + imazapyr at 10 or 20 cm prevented yield losses due to volunteer corn competition. Steckel et al. (2009) reported glufosinate at 0.59 kg ai ha^{-1} applied on 15 to 20 cm tall Gly-R volunteer corn did not prevent yield losses of row corn. However, glufosinate was applied before re-planting row corn; therefore, volunteer corn may have gained a competitive advantage over row corn.

At Novelty 2009 and Columbia 2010, the 40 cm application of imazethapyr + imazapyr resulted in numerically lower and significantly lower grain yields compared to applications at 10 and 20 cm (Figure 4.4). This may have resulted from herbicide injury on the row corn because it was larger than the recommended size on the label. Thompson et al. (2005) found 3 to 21% crop injury on two imidazolinone-tolerant hybrids when imazethapyr + imazapyr was applied at a rate of 0.063 kg ai ha^{-1} at the six- to eight-leaf stage. The Lightning label indicates that applications should only be made by drop nozzles in Clearfield corn if there are 6 or more leaf collars (Anonymous 2008a).

Crop injury was not assessed in this trial; therefore, reduced yields may also have been the result of early season competition prior to the 40 cm application.

In summary, visual ratings indicate 20 cm applications provided the best control, but dry weight reductions of volunteer corn were similar for all herbicide application timings. This suggests adequate control of volunteer corn is possible, even at volunteer corn heights up to 40 cm. Left untreated, Gly-R volunteer corn can compete with row corn and reduce grain yields.

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Table 4.1. ANOVA of visual control ratings taken at two timings (3 and 5 WAT) following herbicide application on glyphosate-resistant volunteer corn. Treatments were glufosinate or imazethapyr + imazapyr at three application timings (apptime) and two volunteer corn densities at two locations (Columbia, Novelty) in Missouri in 2009 and 2010.

		Pr > F							
		Glufosinate				Imazethapyr + Imazapyr			
Effect[a]	WAT[b]	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010
apptime	3	<0.0001	<0.0001	0.0067	<0.0001	0.0030	0.0069	<0.0001	0.1429
	5	<0.0001	<0.0001	0.0006	<0.0001	0.0148	<0.0001	<0.0001	<0.0001
density	3	0.2051	0.9453	0.0622	0.1214	0.0831	0.8208	0.0672	0.2189
	5	0.0077	0.9618	0.0557	0.1703	0.1603	0.7955	0.0109	0.1910
apptime*density	3	0.1487	0.7769	0.6692	0.2701	0.2662	0.1909	0.3670	0.6917
	5	0.0001	0.4646	0.5695	0.5576	0.0247	0.4021	0.8047	0.7129

[a] Effects: apptime = herbicide application timing: 10, 20, 40 cm volunteer corn; density was 0.5 and 1 (Columbia 2009) or 1 and 4 plants m^{-2} (all other site years).
[b] WAT = weeks after treatment.

Table 4.2. Visual control of glyphosate-resistant volunteer corn with glufosinate. Volunteer corn plants treated at three heights and two densities in LibertyLink® corn at two locations (Columbia, Novelty) in Missouri in 2009 and 2010.

		Columbia				Novelty			
		2009		2010		2009		2010	
Application Height (cm)	Density (plants m^{-2})	3 WAT[abc]	5 WAT	3 WAT	5 WAT	3 WAT	5 WAT	3 WAT	5 WAT
	0.5	18 c	11 b	--	--	--	--	--	--
10	1	19 c	14 b	100 a	100 a	24 b	8 b	76 b	46 c
	4	--[d]	--	96 ab	95 ab	24 b	6 b	53 c	36 c
	0.5	86 a	89 a	--	--	--	--	--	--
20	1	89 a	90 a	94 ab	94 b	79 a	83 a	99 a	100 a
	4	--	--	90 bc	90 b	73 a	78 a	98 a	100 a
	0.5	85 a	95 a	--	--	--	--	--	--
40	1	66 b	23 b	88 bc	88 bc	69 a	66 a	98 a	99 ab
	4	--	--	78 c	73 c	71 a	74 a	96 a	94 b

[a] Abbreviation: WAT, weeks after treatment.
[b] Ratings scale: 0 (no effect) to 100 (complete plant death).
[c] Means within each column followed by the same letter are not significantly different using Fisher's Protected LSD at P=0.05.
[d] Density not established at site year.

Table 4.3. Visual control of glyphosate-resistant volunteer corn with imazethapyr + imazapyr. Volunteer corn plants treated at three heights and two densities in Clearfield® corn at two locations (Columbia, Novelty) in Missouri in 2009 and 2010.

		Columbia				Novelty			
		2009		2010		2009		2010	
Application Height (cm)	Density (plants m^{-2})	3 WAT[abc]	5 WAT	3 WAT	5 WAT	3 WAT	5 WAT	3 WAT	5 WAT
	0.5	89 a	86 a	--	--	--	--	--	--
10	1	59 b	59 c	45 b	73 b	33 b	16 c	50 ab	45 b
	4	--[d]	--	43 b	48 c	46 ab	15 c	33 b	28 b
	0.5	48 b	68 bc	--	--	--	--	--	--
20	1	41 b	63 c	75 a	89 a	70 a	80 a	44 ab	81 a
	4	--	--	55 b	74 ab	64 a	78 ab	41 ab	79 a
	0.5	46 b	84 ab	--	--	--	--	--	--
40	1	40 b	85 ab	23 c	45 c	38 ab	55 b	64 a	93 a
	4	--	--	14 c	29 c	18 b	69 ab	54 ab	84 a

[a] Abbreviation: WAT, weeks after treatment.
[b] Ratings scale: 0 (no effect) to 100 (complete plant death).
[c] Means within each column followed by the same letter are not significantly different using Fisher's Protected LSD at P=0.05.
[d] Density not established at site year.

Table 4.4. ANOVA of glyphosate-resistant volunteer corn dry weights harvested five weeks after herbicide treatment. Treatments were glufosinate or imazethapyr + imazapyr at three application timings (apptime) and two volunteer corn densities at two locations (Columbia, Novelty) in Missouri in 2009 and 2010.

	Pr > F							
	Glufosinate				Imazethapyr + Imazapyr			
Effect[a]	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010
apptime	0.5527	0.9804	0.1304	0.1415	0.1431	0.9021	0.0279	0.4213
density	0.8353	0.4885	0.9504	0.6956	0.7313	0.9792	0.2833	0.4463
apptime*density	0.8264	0.7353	0.9415	0.7937	0.9709	0.7836	0.9885	0.8120

[a] Effects: apptime, 10, 20, 40 cm; density, 0.5 and 1 (Columbia 2009) or 1 and 4 plants m^{-2} (all other site years).

Table 4.5. ANOVA of row corn grain yield as influenced by glufosinate or imazethapyr + imazapyr activity on volunteer corn treated at different growth stages (apptime) and plant densities. Treatments were glufosinate and imazethapyr + imazapyr at four application timings and two volunteer corn densities at two locations (Columbia, Novelty) in Missouri in 2009 and 2010.

	Pr > F							
	Glufosinate				Imazethapyr + Imazapyr			
Effect[a]	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010	Columbia 2009	Novelty 2009	Columbia 2010	Novelty 2010
apptime	0.8093	0.0015	<0.0001	NA[b]	0.0528	0.0796	0.0003	NA
density	0.9135	0.0008	0.0874	NA	0.7882	0.7052	0.0043	NA
apptime*density	0.7827	0.1966	0.1225	NA	0.5053	0.2757	0.5440	NA

[a] Effects: apptime, untreated, 10, 20, 40 cm; density, 0.5 and 1 (Columbia 2009) or 1 and 4 plants m^{-2} (all other site years).
[b] NA, not available.

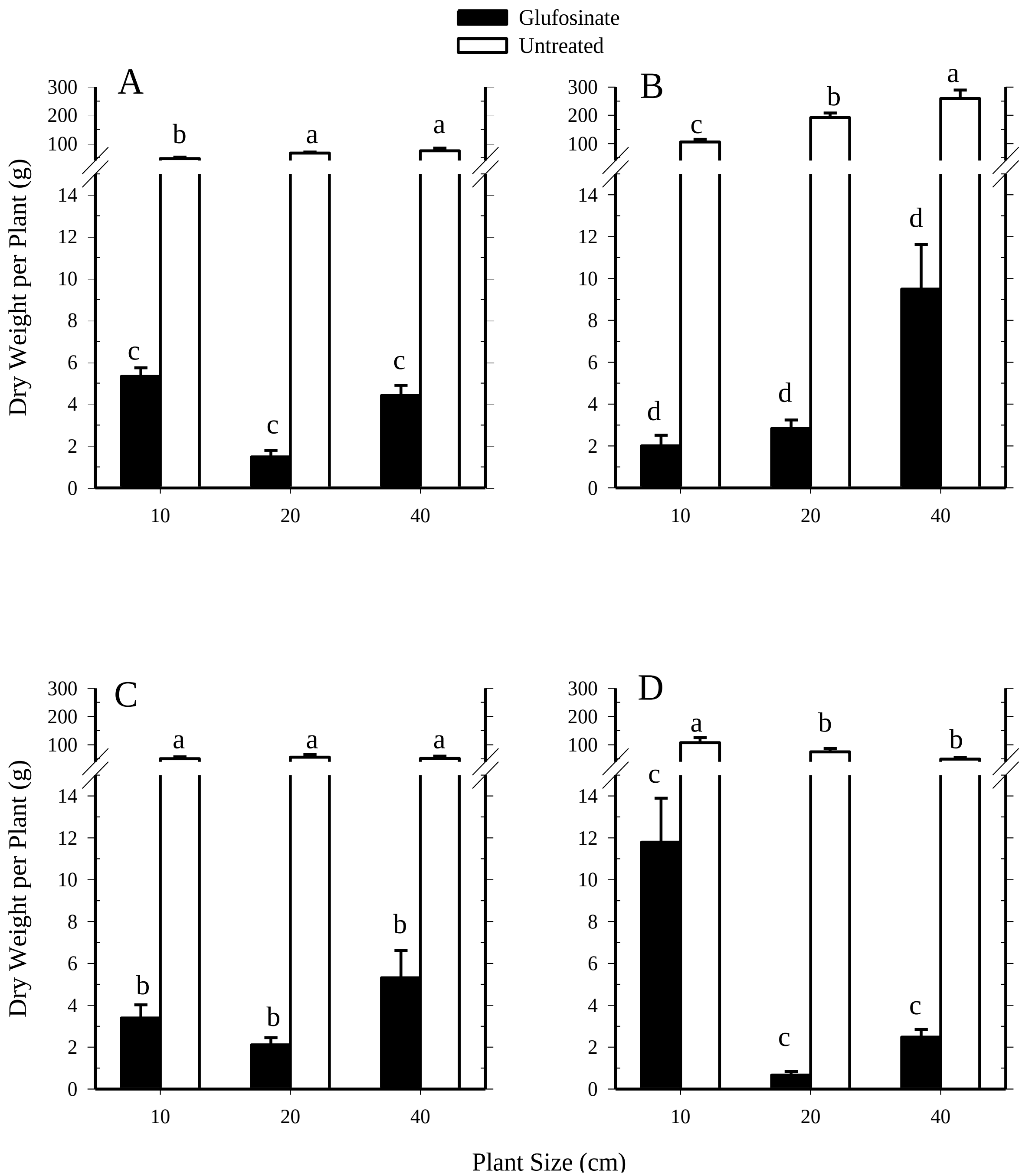

Figure 4.1. Dry weight of glyphosate-resistant volunteer corn at Columbia 2009 (A), Columbia 2010 (B), Novelty 2009 (C), and Novelty 2010 (D) following treatment with glufosinate. Glufosinate treatments made at three plant sizes (10, 20, 40 cm tall corn) and plants harvested 5 weeks after treatment. Vertical line bars above each bar indicate standard errors. Bars within each graph with the same letter are not significantly different using Fisher's Protected LSD at P=0.05.

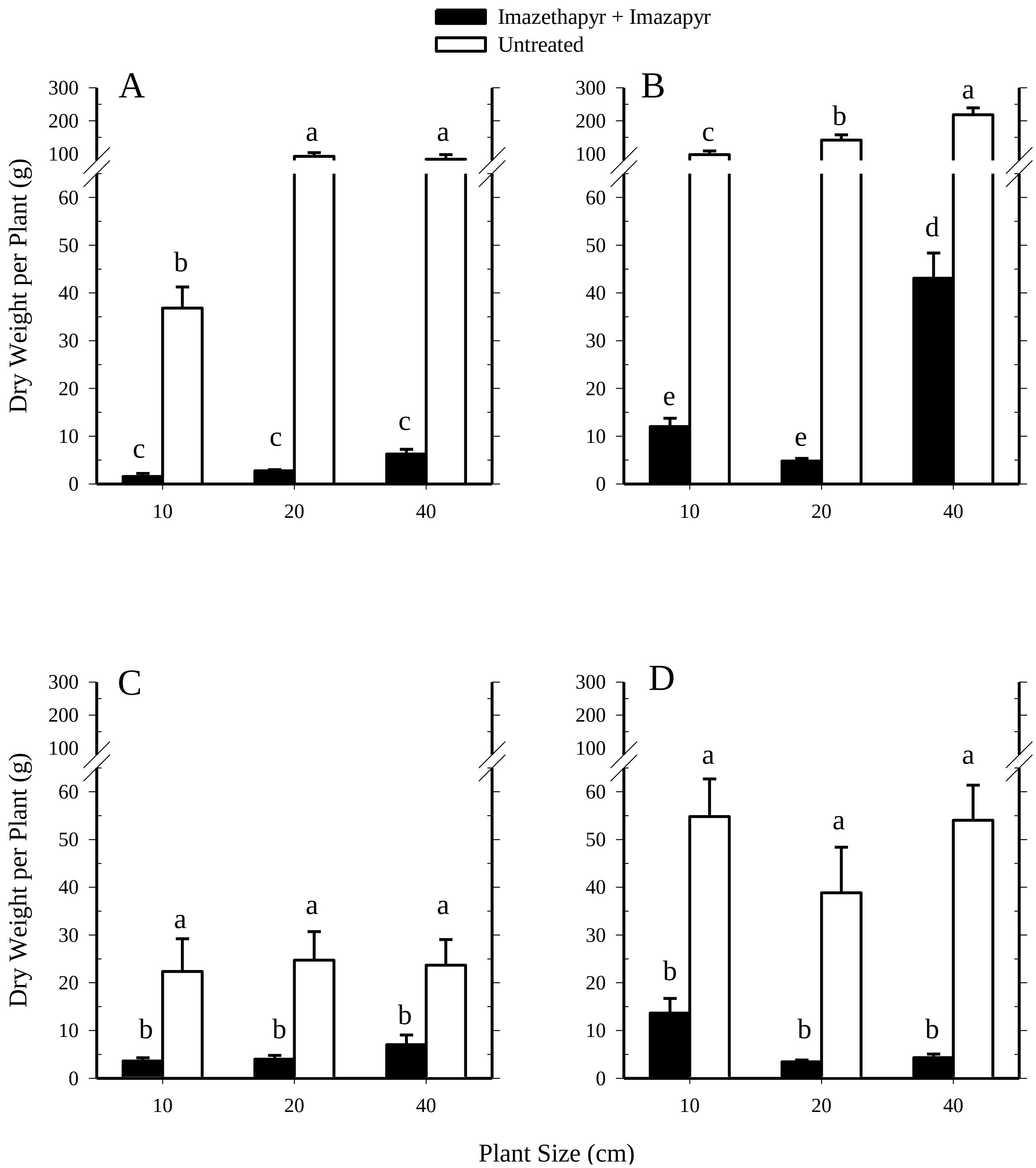

Figure 4.2. Dry weight of glyphosate-resistant volunteer corn at Columbia 2009 (A), Columbia 2010 (B), Novelty 2009 (C), and Novelty 2010 (D) following treatment with imazethapyr + imazapyr. Imazethapyr + imazapyr treatments made at three plant sizes (10, 20, 40 cm tall corn) and plants harvested 5 weeks after treatment. Vertical line bars above each bar indicate standard errors. Bars within each graph with the same letter are not significantly different using Fisher's Protected LSD at P=0.05.

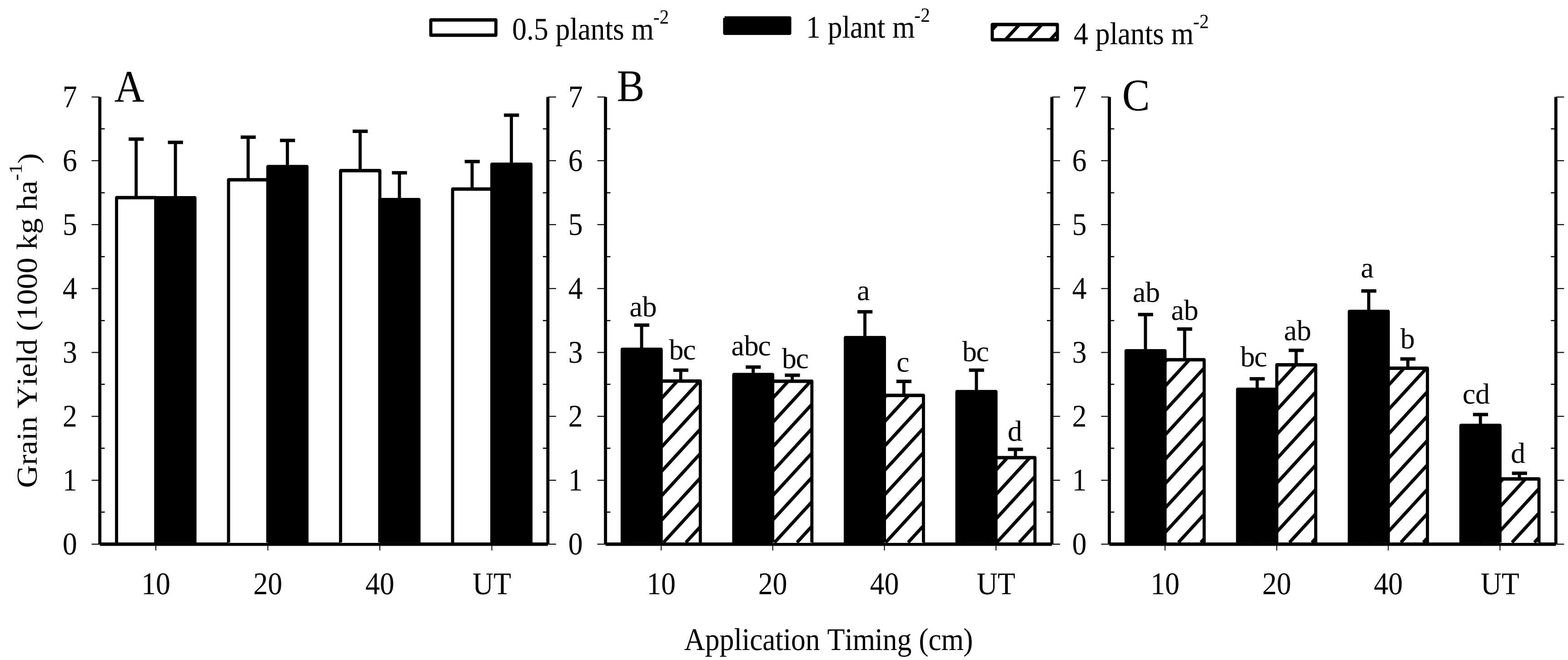

Figure 4.3. Row corn grain yield following competition with glufosinate-treated or untreated (UT) glyphosate-resistant volunteer corn at Columbia 2009 (A), Novelty 2009 (B), and Columbia 2010 (C). Glufosinate applications made at three plant sizes (10, 20, 40 cm tall corn) and two volunteer corn densities (0.5 and 1 plant m^{-2} [A], 1 and 4 plants m^{-2} [B, C]). Vertical line bars above each bar indicate standard errors. Bars within each graph with the same letter are not significantly different using Fisher's Protected LSD at P=0.05.

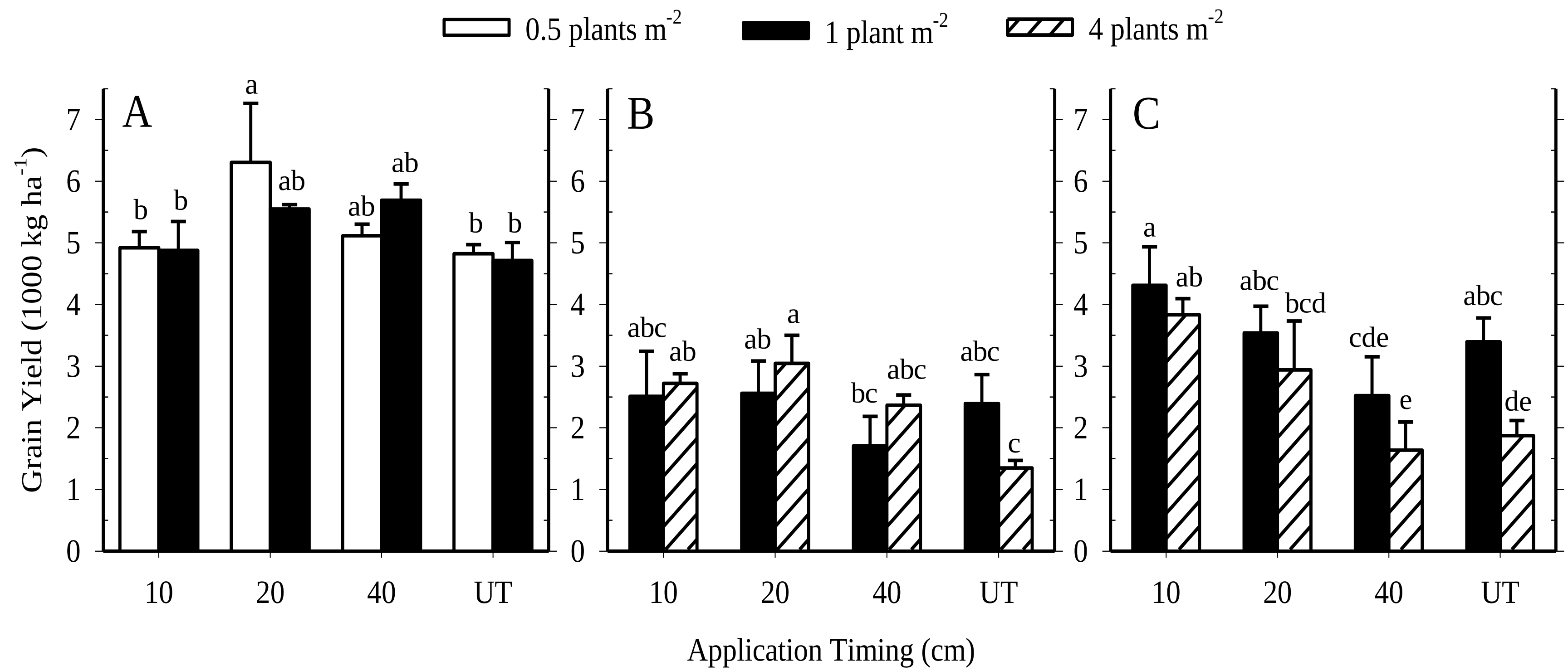

Figure 4.4. Row corn grain yield following competition with imazethapyr + imazapyr-treated or untreated (UT) glyphosate-resistant volunteer corn at Columbia 2009 (A), Novelty 2009 (B), and Columbia 2010 (C). Imazethapyr + imazapyr applications made at three plant sizes (10, 20, 40 cm tall corn) and two volunteer corn densities (0.5 and 1 plant m^{-2} [A], 1 and 4 plants m^{-2} [B, C]). Vertical line bars above each bar indicate standard errors. Bars within each graph with the same letter are not significantly different using Fisher's Protected LSD at P=0.05.

APPENDIX

Table A.1. Polynomial relationship between volunteer corn densities and SPAD meter readings taken at three corn growth stages. This analysis was used to determine the polynomial order for plotting regression lines. Chlorophyll levels were estimated at three locations: Novelty (NE MO; 2008, 2009), Columbia (central MO; 2009, 2010), and Mokane (central MO; 2010).

		Pr > F				
Polynomial Relationship[a]	Growth Stage	Novelty 2008	Columbia 2009	Novelty 2009	Columbia 2010	Mokane 2010
Linear	V6	0.7142	0.0061	0.0003	0.0105	<0.0001
	V8	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	VT	<0.0001	0.0021	<0.0001	<0.0001	<0.0001
Quadratic	V6	0.2368	0.1455	0.0816	0.4188	0.2388
	V8	0.9646	0.0849	0.0018	0.9209	0.0195
	VT	0.3197	0.1121	0.0069	0.2433	0.1867

[a] Polynomial relationship: if P value is significant for quadratic, then the relationship is quadratic and not linear.

Table A.2. Polynomial relationship between volunteer corn densities and stalk diameters measured at the VT growth stage. This analysis was used to determine the polynomial order for regression analysis. Stalk diameters were recorded at three locations: Novelty (NE MO; 2008, 2009), Columbia (central MO; 2009, 2010), and Mokane (central MO; 2010).

	Pr > F				
Polynomial Relationship[a]	Novelty 2008	Columbia 2009	Novelty 2009	Columbia 2010	Mokane 2010
Linear	<0.0001	0.0001	<0.0001	<0.0001	<0.0001
Quadratic	0.1791	0.1262	0.0127	0.1813	0.0002

[a] Polynomial relationship: if P value is significant for quadratic, then the relationship is quadratic and not linear.

Table A.3. Polynomial relationship between volunteer corn densities and grain yields estimated at the end of the growing season. This analysis was used to determine the polynomial order for regression analysis. Grain yields were estimated at three locations: Novelty (NE MO; 2008, 2009), Columbia (central MO; 2009, 2010), and Mokane (central MO; 2010).

	Pr > F				
Polynomial Relationship[a]	Novelty 2008	Columbia 2009	Novelty 2009	Columbia 2010	Mokane 2010
Linear	0.4574	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic	0.3931	0.2196	0.0027	0.1184	<0.0001

[a] Polynomial relationship: if P value is significant for quadratic, then the relationship is quadratic and not linear.

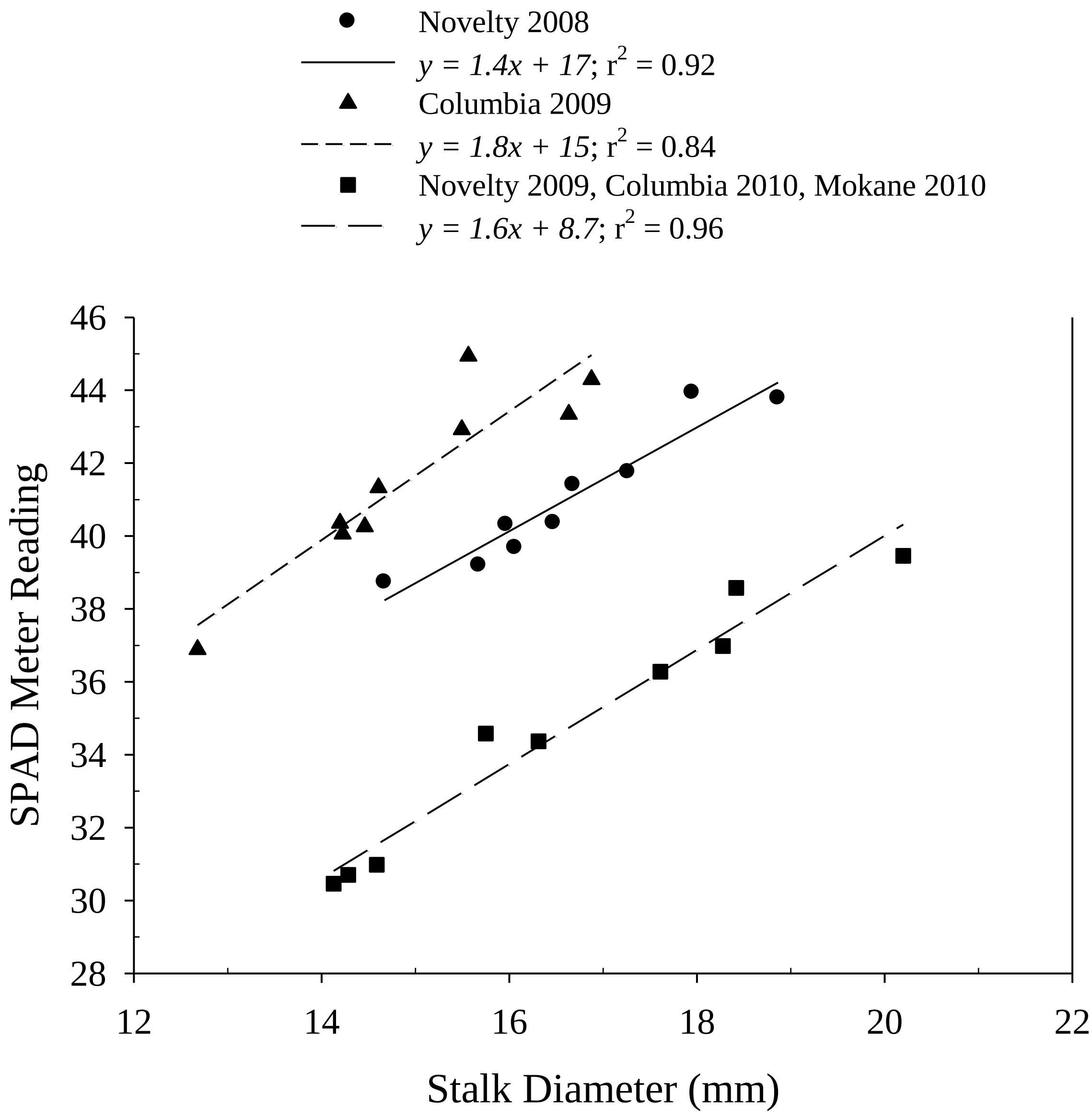

Figure A.1. Comparison of stalk diameters with SPAD meter readings from all site years. SPAD meter readings averaged for all growth stages (V6, V8, VT), and stalk diameters recorded at the end of the growing season. Treatments were volunteer corn densities ranging from 0 to 4 plants m^{-2} (●), 0 to 3.4 plants m^{-2} (▲), and 0 to 8 plants m^{-2} (■).