RELAY- AND DOUBLE-CROP PRODUCTION SYSTEMS FOR WHEAT

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The undersigned, appointed by the Dean of the Graduate School,

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And hereby certify that, in their opinion, it is worthy of acceptance.

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Introduction

Wheat is an important crop globally with 208 to 225 million ha producing 27 to 32 million Mg of grain in the past decade (FAOSTAT, 2012). The United States ranks 4th in global wheat production (Index Mundi, 2013) with 8.13% of total global wheat production (USDA ERS, 2014). The area of wheat production in Missouri has decreased from 1,114,000 ha in 1981 to 296,000 ha in 2009 (USDA NASS, 2010). Average yields have ranged from 2100 to 4100 kg ha^{-1} (USDA NASS, 2010). Wheat is produced as a single- and double-crop depending on the location in the U.S. and is an excellent cover crop for highly erodible soils typically found in upstate Missouri (Nelson et al., 2010; Nelson et al., 2011). Inter- and double-crop production systems provide farmers with opportunities to increase production and returns while providing cover to soils that are typically highly erodible. The utility of alternative grain and cover crops in wheat cropping systems may provide farmers with production, economic, and soil and conservation opportunities. Management systems need to be evaluated to determine the utility of alternative crops and wheat cropping systems in upstate Missouri.

Double-cropping

Double-cropping is a production system that includes the growth of two separate crops at different times in the same growing season. This system involves the harvesting of one species followed immediately by the planting of another. Compared with mono-cropping, double-cropping used climatic, land, labor, and equipment resources more efficiently and produced more total grain (Crabtree et al., 1990). Double-cropping increases the amount of time land is used for crop production and can increase potential profit (Pullins et al., 1997).

In Missouri as well as much of the Midwest and Southern United States, the most popular double-cropping system is winter wheat (*Triticum aestivum* L.) followed by soybean [*Glycine max* (L.) Merr]. Kyei-Boahen and Zhang (2006) found in Stoneville, Mississippi double-cropped soybean yields ranged from 2055 to 3767 kg ha^{-1}, which were 10-40% less than full-season soybean. With an average yield of 5170 kg ha^{-1}, the net return of the double-crop wheat-soybean system more than compensated for these differences, where wheat made up 60% of the net returns in the double-crop system. Crabtree et al. (1990) compared mono-crop and double-crop systems of wheat, soybean, and grain sorghum (*Sorghum bicolor* L.). Grain yields were less in double-cropped systems compared to mono-crop systems, 2500 kg ha^{-1} to 3050 kg ha^{-1}, 1930 kg ha^{-1} to 2470 kg ha^{-1}, and 4200 kg ha^{-1} to 5130 kg ha^{-1} for wheat, soybean and grain sorghum, respectively. However, the authors hypothesized yields of double-cropped wheat, soybean, and grain sorghum could be sustained over long periods and produce more total grain than mono-crops. Reporting on the quality of wheat and soybean in sole- and double-crop production systems in Balcarce, Argentina, Caviglia et al., (2011) found that double-cropped soybean achieved yields 85 to 100% of sole cropped soybean. Double-crop systems increased grain yield and glucose equivalent yield of soybean by 58 to 82% compared to sole crops. Regardless of whether soybean were relay-intercropped or sequentially planted with double-crops out yielded sole-crops 58 to 82% based on an

LER (Land Equivalent Ratio). An LER showed the efficiency of intercropping for using environmental resources compared with mono-cropping and comparable yields were obtained by growing two or more species together with the yields of growing each specific crop as a mono-crop (Malézieux et al., 2009; Lithourgidis et al., 2011b). LER = mixed yield^1/pure yield^1 + mixed yield^2/pure yield^2 (Malézieux et al., 2009). The resulting LER indicated the amount of land needed to grow both crops together compared with the amount of land needed to grow a mono-crop of each crop. An LER greater than 1.0 indicated inter-cropped systems were advantageous, whereas an LER less than 1.0 showed a yield disadvantage (Malézieux et al., 2009; Lithourgidis et al., 2011b).

One purpose of double-crop production systems is enhanced resource use. In a humid area of South America, Van Opstal et al., (2011) found that double-crop systems reached water productivity (0.85 compared to 0.43 g m^{-2} mm^{-1}) and radiation productivity (0.22 g MJ^{-1} to 0.11 g MJ^{-1}) values that were almost two times greater than the sole crop. Resource use was calculated as the product of the proportion of annual resources captured by crops to produce grain yield. They hypothesized that the increase in productivity was due to greater resource capture values. Sanford et al. (1973) found that winter wheat had a threefold greater yield following soybean than grain sorghum in a continuous double-crop system, which was attributed to the soil nitrogen fixing properties of soybean.

Brown (2006) evaluated phosphorus removal through cropping systems. He theorized this work as valuable to farmers who may be spreading manure with large amounts of P from concentrated animal feeding operation. Rationalizing that maximizing

P removal with cropping systems could allow for increased manure application rates, Brown evaluated whether double-crop corn (*Zea mays* L.) forage systems had the potential to increase crop P removal compared to mono-cropped corn. Phosphorus removal as well as cumulative forage production was greatest in the double-crop systems of winter barley (*Hordeum vulgare* L.) and winter and spring genotypes of wheat and triticale (*Triticale hexaploide* L.) followed by a double-crop of silage corn (Brown, 2006). Phosphorus removal increased 30 to 42% when corn was double-cropped with forages. Double-cropping winter forages and silage corn increased total forage production in most years, appreciably increased soil P removal, and reduced Olsen P (0.5 *M* $NaHCO_3$ extractable P) to the depth of 30 cm compared to mono-cropped corn (Brown, 2006).

Researchers have used resource productivity to evaluate double- and mono-cropped systems. Evaluating productivity of two resources, water and light, Caviglia et al. (2004) found on an annual basis that double-cropping dramatically increased the productivity of radiation use for both dry matter and yield. This was mainly related to an increased capture of total radiation. In addition, both water and RP (resource productivity defined by the ratio between the output and annual input of the resource) were greater in double-crops than in sole crops on an annual basis (i.e. from 1 May to 30 April). Double-crops used a larger fraction of annual rainfall compared to that of sole crops. The fraction increased for sole crops ranged from 0.26 to 0.51 while it increased 0.53 to 0.67 in double-crop systems (Caviglia et al., 2004).

Caviglia et al. (2004) reported that double-cropped wheat and soybean used between 54-70% of the annual rainfall; however, only 40% of the incident PAR (photosynthetically active radiation) was utilized. It was important that timing of crop cycles and rainfall cycles were a match. Water can be held in the soil thus offsetting the difference between water availability and demand; however, canopy size and structure at a given time determined the availability of PAR. Plant available water affected winter wheat grain production when researching the effects of tillage and nitrogen rates on wheat production (Halverson et al., 1999). No-till and minimal tillage yielded greater than conventional tillage, with grain yields of 2022 kg ha^{-1}, 1968 kg ha^{-1} and 1801 kg ha^{-1} respectively (Halverson et al., 1999).

Timing of planting is an integral part of a successful double-crop system. Planting time is critical in double-crop systems as maturity times and dates have greatly affected productivity (Sanford et al., 1973). Using crops that have alternative growth periods, such as winter wheat, are good options for double-cropping as they reach harvest during the summer and allow for sufficient time for a fast maturing crop, such as soybean, to reach maturity before a killing frost (Sanford et al., 1973; Kyei-Boahen and Zhang, 2006). Use of early maturing crops allows for earlier planting of the overwintering crop (Kyei-Boahen and Zhang, 2006). Establishing a second crop early was important because the rate of decline in yield with delayed sowing was about 1.3% per day for sole-crops and 0.5% per day for double-crops (Caviglia et al., 2011). Sanford et al. (1973) observed that no-till double-crop systems provided the least delay in establishing a second crop. Costs of no-till double-crop systems, grain sorghum or soybean were typically \$11 ha^{-1} less than conventional tillage (Sanford et al., 1973).

Double-crop systems need to be economically feasible. It is important to evaluate cropping systems economically as well as agronomically, since a cropping system may reduce yield of one component yet still increase returns of the entire system (Jacquest et al., 1997). Heatherly et al. (1996) studied mono-crop winter wheat systems and compared them to a wheat-soybean double-crop system in Stoneville, Mississippi. Combined net returns for double-cropped systems were greatest when compared against all treatments of mono-cropping for all years. Net returns for double-crop treatments were $55.21 per hectare in 1992-1993, and continued to be the greatest among all treatments across all years, showing that the income from soybean was an important component of the net returns. Previous research indicated economic returns of double-cropping were favorable when compared with sole, full season cropping of soybean (Jacquest et al., 1997). Agronomically, the double-crop system was more efficient than the relay-cropping system in the Southern US; however, both cropping systems were more efficient than single cropping system as indicated by the LER values. This led to greatest net returns in the double-cropping system.

Intercropping

Intercropping is the growth of two crops in the same field, where the component crops are not necessarily sown at the same time nor harvested at the same time, but they are grown simultaneously for a portion of their growing periods. Within an intercropping system, there is normally one main crop and one or more added crops often sown later in the season, with the main crop being of primary importance for economic or food production reasons (Lithourgidis et al., 2011a). Intercropping is still a common practice in developing countries, with small farms finding greater productivity in terms of harvestable products per unit area by 20 to 60% over mono-cropping (Lithourgidis et al., 2011a). This was largely attributed to more efficient resource use, which was the primary benefit of intercropping.

The most common advantage of intercropping is the production of greater yields on a given piece of land by making more efficient use of the available growth resources. This could be due to different rooting characteristics, canopy structure, height, and nutrient requirements or resource use at different times (Fujita et al., 1992; Midmore, 1993; Thiessen Martens et al., 2001; Echarte et al., 2011; Eskandari, 2011; Lithourgidis et al., 2011a; Eskandari and Ghanbari, 2012). Intercrop systems can be planted simultaneously or staggered taking advantage of cool and warm season adapted species. By staggering planting dates, the relative periods of complimentarity and competition are modified and can influence the component crop's yield potential (Midmore, 1993). In general, the crop planted first has a competitive advantage over the intercrop as it has previous access to limiting factors.

Defining complimentarity and competition is important for a successful intercropping system. The point at which complimentarity becomes competition among crops can be manipulated through management practices and depends largely on each crop's response to limiting factors such as light, soil moisture, and nutrients (Midmore, 1993). Resource complementarity minimizes niche overlap and competition between crop species, and permits crops to capture a greater range and quantity of resources compared to a single crop. Thus, selecting crops that differ in competitive ability over time or space is essential for an efficient intercropping system as well as decisions on planting date, plant arrangement, and density (Lithourgidis et al., 2011a). Increased use of resources, through niche differentiation must outweigh interspecific competition in an intercrop (Schröder and Köpke, 2012). Intercropping success can be affected by factors such as relative density of component crops, amount of limiting resources, and crop row spacing (Eskandari and Ghanbari, 2012). If the intercrops are complimentary, they often will use resources more efficiently than if mono-cropped.

Zhang and Li (2003) developed the 'competition-recovery production principle' to determine the impact of intercrops on one another. Interspecific interaction increases growth, nutrient uptake, and yield of the dominant species, but it hinders the growth and nutrient uptake of the subordinate crop (intercrop) during the co-existence of both crops. However, after harvest of the earlier-maturing species, there was recovery of nutrient uptake and growth, which allowed for the later-maturing species to compensate for impaired growth during the intercrop period once the early-maturing species was harvested (Zhang and Li, 2003). Several types of intercrop systems use mixtures of spatial and temporal arrangements. These include mixed intercropping, alternate-row intercropping, within-row intercropping, strip intercropping, and relay-intercropping (Lithourgidis et al., 2011a). Jensen et al., (2006) found that competition and complementarity between species enhanced productivity, increased resource use, and improved plant health among pea (*Pisum sativum* L.)-barley intercrops. Eskandari (2011) found that intercropping systems with wheat and faba bean (*Vicia faba* L.) had increased environmental resource consumption, with more light interception, water, and nutrient uptake compared with sole crops. They used competitive ratios, values that show the degree of competition by determining the number of times that the dominant species is more competitive than the recessive species, to show that bean was 1.2 times more competitive than wheat for Mg uptake and 1.17 times more competitive for Ca uptake. However, wheat was 1.16 and 1.35 times more competitive for K and P than faba bean, respectively. Relative yield total (RYT= $(Y_{ij}/Y_{ii}) + (Y_{ji}/Y_{jj})$ where Y is yield per unit area, Y_{ii} and Y_{jj} are sole crop yield of the component crops i and j, respectively, and Y_{ij} and Y_{ji} are intercrop yield) was used to determine that Ca, K, P, and Mg use efficiency in an intercrop system with wheat and faba bean were 62, 50, 45, and 42% more efficient than sole crops, respectively (Eskandari, 2011).

Relay- and double-cropping represent options for incorporating legume crops into annual cropping systems without sacrificing grain production (Thiessen Martens et al., 2001). Cereal-legume intercrops are a common practice, possibly increasing dry matter production and grain yield when compared with monocultures (Fujita et al., 1992; Thiessen Martens et al., 2001; Lithourgidis et al., 2011b). This was due to N transfer from the biological N fixation of the legume to the cereal that can increase the cropping system's N use efficiency and thus its yield (Danso et al., 1987; Fujita et al., 1992; Akhtar et at., 2010; Naudin et al., 2010; Lithourgidis et al., 2011a; Mariotti et al., 2011; Pelzer et al., 2012; Tosti and Guiducci, 2012). When a legume is grown in association with another crop (intercropping), such as a cereal, the N nutrition of the associated crop may be increased by direct N transfer from the legume to the cereal crop (Giller and Wilson, 1991). This system can be important for farmers in developing countries where low input systems are employed or as a way to reduce fertilizer inputs to decrease cost and environmental concerns from fertilizer runoff and chemical degradation (Fujita et al., 1992; Akhtar et al., 2010). According to Fujita et al. (1992), indeterminate legumes fixed more N than determinate legumes in intercropping systems. Cowpea (*Vigna unguiculata* L.) received 53-69% of its N from biological fixation which was not affected by intercropping. The way leguminous roots release nitrogen is not very well understood; however, crop densities affecting the distance between plant roots were important for cereal crops to take up released nitrogen (Fujita et al., 1992).

In wheat-pea cropping systems, Lithourgidis et al. (2011b) found that pea and wheat, rye (*Secale cereale* L.), or triticale mixtures had yield advantages for using the available resources when compared to their monocultures. The pea-wheat 80:20 seeding ratio had the greatest wheat crude protein yield and nitrogen uptake over all other cropping systems. When using intercrops and sole crops of durum wheat (*Triticum durum* L.) and field bean with different N fertilizer amounts and row ratios in Northern Italy, Mariotti et al. (2011) decreased added N fertilizer and improved forage yield and quality with an intercrop system over sole crops. On average, the crude protein for durum wheat was only 68 g kg $^{-1}$ for sole crop which rose to 82 g kg^{-1} for intercrops across row ratio and N fertilizer. LER values indicated that the intercropping systems used N resources in the environment more effectively than sole crops. Naudin et al. (2010) found that regardless of the crop stage in pea-wheat intercrop, added N increased wheat growth and decreased pea growth. The added N made wheat more competitive in the intercrop system for a longer period of time. Wheat grain yields were not significantly affected, yields of 637 g m^{-2} for fertilized plots and 594 g m^{-2} for unfertilized plots were observed and growth patterns among intercrops remained similar across fertilizer rates (Naudin et al., 2010). In a wheat-pea intercrop, Ghaley et al. (2005) observed similar results in

Denmark. Increased N fertilizer improved the competitiveness of wheat in the intercrop and decreased the proportion of pea, but did not influence total grain yield of the intercrop. The average recovery of urea fertilizer nitrogen in the pea-wheat intercrop was 32%, which was more than pea alone (15%) but less than wheat alone (45%). The authors found that intercropping increased total plant and grain dry matter and N yield, as well as grain N concentration and the proportion of N derived from symbiotic N_2 fixation (Ghaley et al., 2005). Ghaley et al. (2005) stated that intercropped pea and wheat complemented each other in the use of N sources at the smallest soil N level which was emphasized by final LER values of 1.34 in the no nitrogen fertilizer treatment compared to 0.85 when N was applied at 8 g N m^{-2}. Pea-wheat intercropping seemed to be an optimal cropping strategy in relation to the use of N resources, because wheat efficiently exploits soil mineral N sources while at the same time scavaging fixed N_2 from pea in the cropping system.

Evaluating sole and intercrops of wheat and chickpea (*Cicer arietinum* L.), Akhtar et al. (2010) determined that cumulative grain values were twice as large for intercrops compared to sole wheat crops. Intercrops accumulated larger N in their biomass with a maximum of 87 kg N ha^{-1}, while the maximum for sole crops was 58 kg N ha^{-1}. Intercrops also increased phosphorous uptake compared to sole crops. In terms of productivity and farm profitability, intercropped fields of wheat and chickpea were superior compared to sole cropped fields. Similarly, the LER based on grain dry matter yields in five different European countries showed that the intercropping yield advantage of barley-wheat was on average 21%, with both soil N and N_2 fixation being 20-30% more efficient (Jensen et al., 2006). LER values showed a 12% advantage for faba bean intercropped with safflower and an 18% advantage for faba bean intercropped with white mustard (*Brassica hirta* L.) compared with a faba bean sole crop (Schröder and Köpke, 2012). Generally, large amounts of nitrogen in the shoots reflected greater utilization of soil mineral nitrogen. In cropping systems with legumes, efficient symbiosis with *Rhizobia* bacteria was demonstrated (Schröder and Köpke, 2012). Light transmittance to the legume was a critical factor limiting legume establishment as the intercrop was directly influenced by canopy development (Blaser et al., 2007).

Using eight different locations in France, Pelzer et al. (2012) found that pea intercropped in wheat, regardless of amount of applied fertilizer (4.5 Mg ha^{-1} with nitrogen and 4.4 Mg ha^{-1} without), had greater yields than sole pea crops (3.8 Mg ha^{-1}) and close to sole wheat yields (5.4 Mg ha^{-1}). Yields were attained with the intercrop using 1.8 times less nitrogen fertilizer than wheat alone (Pelzer et al. 2012). The average gross margin of the pea-wheat intercrop with or without nitrogen fertilization was greater than the average gross margins of the pea (317 versus 298 € ha^{-1}) and wheat (292 versus 245 € ha^{-1}) sole crops with or without nitrogen fertilizer (Pelzer et al., 2012). Similarly, results from Bulson et al. (1997) in Pangbourne, England showed that as long as the density of wheat was greater than 25% within the field, the gross margin of intercropped wheat-soybeans was greater than the optimal density of either crop planted alone. In addition, intercropping wheat with soybean increased weed suppression along with yield, economic returns, and LER compared with optimum seeding rates of individual crops (Bulson et al., 1997). There were monetary advantages of all intercropping systems in a wheat-chickpea intercrop indicating yield advantages with a significantly greater gross return of 647 € ha^{-1} under 30 cm intercrop weeded twice (Banik et al., 2006). Increased returns were due to greater productivity with fewer input costs (Banik et al., 2006).

Intercropping may affect other nutrients in the soil besides nitrogen. In neutral and alkaline soils, increased inorganic P availability by rhizosphere acidification due to N_2 fixation was a benefit to the intercropped cereal (Betencourt et al., 2012). In the presence or absence of phosphorus fertilizer, Betencourt et al. (2012) found that P availability increased in the rhizosphere of both wheat and chickpea, especially when intercropped in the absence of P. Gooding et al. (2007) determined that intercropping wheat with grain legumes (faba bean and pea) increased grain N concentration up to 8% and S up to 4%. In corn-soybean intercrop, corn alone had the greatest resource productivity; however, corn-soybean intercrops resulted in greater radiation and water productivities than sole soybean crops, which was due to an increase in water capture efficiency (Coll et al., 2012). Similarly, intercrops used more water, with increases in evapotranspiration of 27% for sunflower (*Helianthus annus* L.)-soybean intercrop and 21% for a corn-soybean intercrop compared to those crops grown alone (Coll et al., 2011).

Root systems play an important role in the success of intercrops. When growing faba beans with oilseed crops, intercropping resulted in more horizontal root distribution compared with a single crop. Root length density (RLD) was enhanced as well as a more regular root distribution that corresponded with the specific species when the faba beans were intercropped (Schröder and Köpke, 2012). Looking at wheat-corn and faba bean-corn intercrops, roots of the intercropped wheat spread under corn plants, and had much greater root length density at all soil depths than sole wheat (Li et al., 2006). On the other hand, roots of corn intercropped with wheat were limited laterally, but had a greater RLD than sole-cropped corn. The spatial distribution of roots and their density in the soil may affect the ability of a crop to acquire nutrients and water necessary to sustain plant growth. The greater soil exploration and apparent root compatibility helped explain yield increases in spite of potential root competition for nutrients (Li et al., 2006). Other research has reported that not only root interference for water and nutrients was important but also shoot interference (Hiltbrunner et al., 2007).

There are many different indices available to calculate and determine possible advantages and disadvantages of intercrops as well as the efficacy of each cropping system. Using the right tool can be crucial for interpreting data. Several indices that have been used include aggressivity (AG), cumulative relative efficiency index (REIc), land equivalent ratio (LER), comparative absolute growth rate (CRG), change in contribution (CC), and interspecific and intraspecific index (IE and IA) (Bedoussac and Justes, 2011). Research found that AG indices rarely provided information on whether a crop was dominant or dominated in the cropping system, unlike results that research literature was claiming, while LER was more relevant and useful for showing the pattern of outcomes of competition in intercropping (Bedoussac and Justes, 2011). These indices can express various competition attributes in plant communities and cropping systems, including competition intensity, competitive effects, and the outcome of competition (Lithourgidis et al., 2011b). LER was probably the most popular index used to measure intercrop systems since crops could be added to make a combined yield, and calculate a relative yield advantage, which allowed individual LERs to be compared against each other

(Lithourgidis et al., 2011b). For instance, a study showed that pea and wheat, rye, or triticale mixtures had yield advantages for using available resources when compared to their monocultures. The pea-wheat 80:20 seeding ratio had the largest crude protein yield and nitrogen uptake in wheat over all other cropping systems (Lithourgidis et al., 2011b). LER values indicated that intercrop treatments used resources that already existed in the environment more effectively than the individual crops and also indicated better utilization of soil N sources. In addition, forage yields from intercropped fields were greater than that of the sole crops even with optimal mixtures (Mariotti et al., 2011).

Alternative crops

Working with alternative cropping systems such a double-cropping, intercropping, and even cover cropping, the selection of crops is equally important as timing, spacing, inputs, and other considerations. For instance, winter wheat and winter canola were often the first crop in a double-cropping system (Pullins et al., 1997). The best varieties of these crops were those that matured early enough allowing for quick planting and adequate growth of the second crop (Pullins et al., 1997). Other factors that affect the selection of alternative crops include weed suppression, resource use, and markets. Morris and Parrish (1992) showed that sunflower residue in a double-crop system was not harmful to early planted wheat growth as long as the residue was not incorporated. Aqueous extracts of sunflowers did not affect germination of wheat, but did affect seedling growth showing a possible allelochemical effect; however, incorporation of the sunflower residue reduced weed species, especially broadleaves (Morris and Parrish, 1992).

Resource use is another factor that affects alternative crop selection. Much research has been conducted looking at the effects of a legume on nitrogen supply to intercrops (Danso et al., 1987; Fujita et al., 1992; Akhtar et at., 2010; Naudin et al., 2010; Lithourgidis et al., 2011a; Mariotti et al., 2011; Pelzer et al., 2012; Tosti and Guiducci, 2012). Relay- and double-cropping represented an option for incorporating legume crops into annual cropping systems without sacrificing grain production (Thiessen Martens et al., 2001). Success of the relay-intercrop was dependent on the establishment of the second crop under the canopy of the first (Thiessen Martens et al., 2001). Jensen et al. (2012) stated that among the cool season grain legumes, faba bean relied most on nitrogen fixation, which benefited subsequent crops with substantial N and saved up to 100-200 kg N ha. In Senegal, Sarr et al. (2008) determined the impact of applied nitrogen and nitrogen uptake of pearl millet (*Pennisetum glaucum* L.) and cowpea using ^{15}N labeled urea. The cropping system with the largest nitrogen use efficiency (NUE) was intercropped cowpea at 46%. When looking at grain yield and biomass accumulation, LER values (1.68 to 1.71) for millet-cowpea intercropping had significant advantages over a sole crop of either species (Sarr et al., 2008). Often buckwheat (*Fagopryum sagittatum* L.) was grown as a soil cover and green manure, and produced modest amounts of biomass, but P was more available to the component crop (Myers and Meinke, 1994). Thus in Missouri there are good opportunities for buckwheat as a double-crop following wheat.

Rapid growth of buckwheat may allow it to be planted as a double-crop reducing risk associated with early frost and add economic value (Nelson et al., 2000). Research has showed that in southern Missouri buckwheat and sunflower had the most competitive returns. In Northeast Missouri, gross margins were \$217.10 ha^{-1}, with buckwheat and sunflower was \$287.60 ha^{-1}, compared to \$2.70 ha^{-1} for soybean (Nelson et al., 2000). Finally, the economics and market opportunities have to be taken into account when choosing alternative crops. One of the largest challenges that farmers face with alternative crops is marketing.

Research in Wisconsin demonstrated that red-clover (4200 kg ha^{-1} aboveground biomass) was the most productive and reliable legume choice as a green manure crop when it was interseeded into winter wheat in early spring compared to hairy vetch (3385 kg ha^{-1}) and crimson clover (2050 kg ha^{-1}) (Stute and Shelley, 2008). In Michigan, red clover produced significantly more above and below ground biomass than fallow (0.97-2.14 kg ha^{-1}). Corn N biomass (109.1-148.1 kg ha^{-1}) and grain yield (5800-7200 kg ha^{-1}) were increased by including red clover when compared to fallow (Gentry et al., 2013). Nitrogen credit from red clover was similar across management type (30-48 kg N ha^{-1}) with the first year of introduction to the conventional system providing an apparent 55 kg N ha^{-1} (Gentry et al., 2013). Relay-intercropping increased the average return to N investment across the N fertility gradient when estimating N and forage values of red clover biomass (265-1380 kg ha^{-1}) compared to sole wheat (Gaudin et al., 2014). However, N application at maximum economic rate (MERN) for wheat decreased economic benefits as well as possible system benefits of red clover. Red clover contribution to the total intercrop yield decreased with N rates greater than 40 kg N ha^{-1}, thus the authors argue that reduction of N rates from the largest N recommendations can maximize economic returns for both wheat and red clover and increase profits for both species (Gaudin et al., 2014).

Frost seeded crops, especially legumes, can add forage and provide nitrogen for subsequent crops (Blaser et al., 2007), making it attractive to growers looking for more cost-effective production systems (Mutch et al., 2003). Nitrogen accumulation was 107, 110, and 196 kg N ha^{-1} at three locations in East Lansing, Michigan for frost-seeded red clover (*Trifolium pretense* L.) into winter wheat (Hesterman et al., 1992). As measured by the fertilizer replacement value (FRV), red clover frost-seeded into wheat was worth over 111 kg N ha^{-1}. The amount of N contribution was affected by N accumulated by the legume, which was influenced by the length of time between legume seeding date and the end of growth (Hesterman et al., 1992). In Ohio, Ngalla and Eckert (1987) reported a contribution equivalent of 56 to 67 kg N ha^{-1} from frost-seeded red clover into wheat for the subsequent corn (*Zea mays* L.) crop.

Various factors such as crop species, growth stage, duration of freezing temperature, soil moisture, type, hardening, and freezing and thawing sequences contributed to a complex pattern that determines frost tolerance of a particular species (Badaruddin et al., 2001). For instance, winter annual legumes that reached flowering stages exhibited poor frost resistance (Brandsæter et al., 2000). Hardening is a physiological change of a plant with cold temperature treatment (commonly termed as vernalization). Hardening increased seedling survival of forage legumes [alfalfa (*Medicago sativa* L.), red clover, sweetclover (*Melilotus officinalis* Lam.), alsike clover (*Trifolium. hybridium* L.), white clover (*Trifolium repens* L.), and sainfoin (*Onobrichis viciifolia* Scop),] and soybean and field pea (*Pisum sativum* L.) up to 40% compared to unhardened seedlings (2-40% less survival at -4 to -8 ^{o}C) (Badaruddin et al., 2001). Experiments showed hairy vetch (*Vicia villosa* Roth.) possessed the greatest winter hardiness ranking compared to black medic (*Medicago lupulina* L.), crimson clover (*Trifolium incarnatum* L.), and subclover (*Trifolium subterranteum* L.) (Brandsæter and Netland, 1999). Hairy vetch provided the largest biomass production in both fall (287 kg ha^{-1}) and spring (3,118 kg ha^{-1}), greater soil cover (95-100%), and reduced weed biomass compared to other cover crops (Brandsæter and Netland, 1999). The authors stated that hairy vetch had similar winter fitness compared to red clover, another winter hardy crop (Brandsæter and Netland, 1999). Results of a winter annual legume experiment showed that hairy vetch cultivars, especially cv. Hungvillosa, exhibited the best frost resistance compare to yellow sweet clover [*Melilotus officinalis* (L.) Pall.] (Brandsæter et al., 2000). At the lowest temperature (-9 ^{o}C), 'Hungvillosa' hairy vetch had the highest relative biomass (75% of the control of 0 ^{o}C) (Brandsæter et al., 2000)

Row spacing

Optimal row spacing is important to improve crop productivity since plants growing in too wide of a row may not efficiently utilize light, water and nutrient resources. However, crops grown in too narrow rows may result in severe inter-row competition. Row spacing may also modify plant architecture, photosynthetic competence of leaves and dry matter partitioning in several field crops (Hussain et al., 2012). Successful crop mixtures extend the sharing of available resources over time and space which exploit variation between component crops such as rates of canopy development, final canopy width and height, photosynthetic adaption of canopies to irradiance conditions and rooting depth (Midmore, 1993). Thus, deciding on crop geometry and row orientation manipulated crop competiveness and sharing of natural resources (Midmore, 1993). Plant arrangement was key for large grain yield potential of wheat and other row crops (Pandey et al., 2013). Different types of intercropping systems used several mixtures of spatial and temporal planting arrangements (Lithourgidis et al., 2011a). The idea was to increase the competitive ability of the crop through spacing, orientation, elevated seeding rates and more uniform spatial planting patterns (Kolb et al., 2012). For greater yields, a larger proportion of incident radiation at the soil surface must be intercepted by the crop canopy. If the distance between the rows is too wide, solar radiation that penetrates between crop rows is unutilized. On the other hand, plants may become crowded and suffer from mutual shading if the row width is too narrow (Pandey et al., 2013). All of these factors focused on resource use and light interception, thus making crop tillering, height and weed competition important.

Light interception was important in intercrop systems and was affected by the crop architecture and canopy structure. Generally, cereals were taller and shaded the component leguminous crop, which was why row spacing and plant arrangement influenced the success of the systems (Fujita et al., 1992). A single crop each year used only a small proportion of potentially available resources. Calculations for the southeast Pampas area indicated that sole crops of wheat, corn, or soybean captured only 20-36% of the annual incident photosynthetically active radiation (Coll et al., 2012). Borger et al. (2012) found that light interception by crops increased in narrow spacing 63% to 70% of wide rows; however, there was only a significant difference in wheat at one site-year. However, Champion et al. (1998) reported that light interception measurements taken throughout the growth cycle showed significance at 10 cm above ground level when measured parallel to the direction of sowing on one date for different row spacings.

Optimum row spacing can help optimize tillering capacity and may ensure increased wheat yields (Hussain et al., 2012). Wheat sown under narrow row spacing (15 cm) produced greater wheat yields due to a significant increase in productive tillers (Hussain et al., 2012). Narrow-row spacing increased inter-row competition at this location. Wider row spacing (30 cm) increased the number of grains per spike and 1000-grain weight, but could not compensate for the drastic decrease in productive tillers thus resulting in decreased grain yields (Hussain et al., 2012). Similarly, Zhou et al. (2011) found that wheat yields were greatest for 14 cm spacing with yields ranked 14>7>24.5>49 cm. Grain yields and total dry matter accumulation for 49 cm row spacing had yields that were lower than the other row spacings. However, Pandey et al. (2013) reported that wheat cultivated at 20 cm row spacing produced significantly more effective tillers as compared to 15 and 25 cm row spacings. However, wheat row spacing did not affect tillering capacity or crop biomass (Champion et al., 1998).

Plant spacing and row direction can affect weed suppression. During early growth stages, interference between crop and weed plants is commonly affected by the quality of reflected light. The reflection of far-red photons by the stem of one plant lowered the red to far-red photon ratio of light experienced by the stems of neighboring plants. This modified the light environment in the plant stem tissue, which resulted in increased stem elongation. As plants aged, the crop canopy closed and mutual shading further increased competition for photosynthetic light (Borger et al., 2010). The best results were obtained in an east-west row direction with 20 cm rows and two hand weedings. Compared to a control, there was a 44% increase in crop growth and 21% increase in crop yield (Hozayn et al., 2012). Weed biomass was smaller in narrow rows (93 g m^{-2}) compared to wide rows (107 g m^{-2}) (Borger et al., 2010). In a wheat-frost seeded legume intercrop system, red clover (*Trifolium pretense* L.) and alfalfa (*Medicago sativa* L.) were frost-seeded into winter wheat and triticale and the legume intercrop did not affect grain yield but did reduce weed density and dry matter up to 40 days after harvest (Blaser et al., 2007). Champion et al. (1998) reported that manipulation of the crop for weed suppression by reducing row width was less successful than increasing plant density. The authors reported that narrow rows did not enhance shading and suppression of weed biomass; however, research included only wheat and not intercrops.

Wheat rows in relay-intercropping are often wider than conventionally planted wheat in order to allow light for the subsequent intercrop. When intercropping clover into wheat, Thorsted et al. (2006) found that interspecific competition during vegetative growth was reduced by increasing width of the rototilled strips from 7 to 14 cm, which resulted in greater grain yields and increased grain N uptake. However, when not intercropping, and thus using wider rows for the intercrop, wider rows were not necessarily beneficial. Over two years, four different wheat planting patterns were employed including conventional seeding (Porter and Khalilian, 1995). This research indicated that there was no significant difference among treatments for total above ground dry matter, number of grains per area, grain weight, or grain yield. These findings indicated that there were no negative effects of wide-row planting on wheat yields (Porter and Khalilian, 1995). However, row spacing affected yields with narrow rows yielding more grain than wide rows, suggesting that closeness of planting enabled more efficient utilization of resources (Champion et al., 1998; Drew et al., 2009).

Orientation of the rows has affected photosynthetic efficiency and canopy temperature (Pandey et al., 2013). A uniform distribution and proper orientation of plants over a cropped area were needed for greater light interception throughout the crop profile and maximize photosynthetic efficiency by all the leaves of a plant (Pandey et al., 2013). The effect of row orientation varied with latitude and seasonal tilt of the earth. Near the equator, north-south row orientation as opposed to east-west orientation provided crops larger levels of light absorption for most of the year (Borger et al., 2010). At higher latitudes (up to 55^{o}), absorption of light was greatest in north-south planted crops in the summer and east-west crops during the rest of the year. From 65^{o} upwards, east-west orientation provided the greatest light absorption all year (Borger et al., 2010). For example, wheat crops planted east-west in Western Australia had 24% greater yields than those oriented north-south and lesser weed biomass by 51% (Borger et al., 2010). Wheat intercepted 28% more light across all crop types (wheat, barley, canola, lupine (*Lupinus angustifolius* L.), and field pea) and light interception was greater in east-west orientation (72%) than north-south (61%) (Borger et al., 2010).

Cover crops

A cover crop refers to a plant which was grown in rotation during periods when main crops were not grown (Mohammadi, 2013). There were many benefits of cover crops, with the most direct positive being increased yield of the marketable crop. Other benefits included greater yield stability, reduced fertilizer inputs, weed suppression, breakage of disease or pest cycles, increased soil and water quality, and nutrient cycling efficiency (Hoffbeck et al., 2008; Snapp et al., 2005; Thiessen Martens et al., 2001).

There were also several benefits that specifically dealt with soil conservation and the reduction of soil erosion, nitrate leaching, and chemical runoff (Snapp et al., 2005). Other soil benefits included improved water infiltration, soil moisture retention, improved soil tilth, and nutrient enhancement (Teasdale, 1996). Finally, planting a cover crop may replace an unmanageable weed population such as common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and some annual grasses with a manageable crop or mulch (Teasdale, 1996). Determining the seeding timing, type, and desired benefits from the cover crop are important for adoption and utilization. For winter cover crops, a cash crop does not have to be sacrificed, and planting normally occurs in the fall after harvest of an annual cash crop (Snapp et al., 2005).

Several measures have evaluated the use of cover crops for weed control (Hiltbrunner et al., 2007; Teasdale, 1996). Before considering legume cover crops as a viable alternative for integrated weed management, management strategies needed to be identified that maximized the weed control benefits as well as minimized the negative impact on growth and yield of winter wheat (Hiltbrunner et al., 2007). For example, three leguminous living mulches, white clover (*Trifolium repens* L.), subclover (*Trifolium subterraneum* L.), and birdsfoot trefoil (*Lotus corniculatus* L.), reduced the density of monocot, dicot, spring germinating and annual weeds. However, winter wheat grown in cover crops experienced a 60% reduction in grain yields. Hiltbrunner et el. (2007) observed that legume cover-crops or presence of weed densities reduced tillering of wheat plants compared to the cover only and weed free treatments. A reduction in tillering was considered the primary cause of reduced wheat yields. Shoot interference caused lesser dry matter production and consequently smaller grain yield of the main crop (Hiltbrunner et al., 2007). Sattell et al. (1999) stated that field trials in Oregon showed that properly managed cover crops reduced the amount of nitrate leached from the soil to aquifer below.

In addition to several benefits from the cover crops, it is important that they do not negatively impact the main crop at the same time be successful in terms of dry matter accumulation. Red clover had the greatest dry matter accumulation (1800 kg ha^{-1}). Drill-seeding did not have an effect on grain yield, indicating that relay-intercropped legumes did not negatively impact the main crop of wheat (Thiessen Martens et al., 2001). The researchers determined production of legume dry matter in the relay-intercrop system was related to light interception through the canopy of the cereal crop (Thiessen Martens et al., 2001). This was due to cereal canopy traits which affected legume shoot size during the overlap growth period (Blaser et al., 2007). Cereals with a larger leaf area index (LAI), which were greater than 5.6, were effective and transmitted less light due to larger PAR absorption rates which subsequently decreased legume intercrop growth (Blaser et al., 2007).

In addition to weed suppression, cover crops contributed towards nutrient recycling in the soil or prevented leaching. Karmberger et al. (2009) compared non-leguminous cover crops, Italian ryegrass (*Lolium multiflorum* L.), winter rape (*Brassica napus* L.), and leguminous cover crops, subclover and crimson clover (*Trifolium incarnatum* L.). The non-leguminous cover crops decreased soil mineral nitrogen in the winter across all experiments and soil depths from 0-90 cm. In a meta-analysis of experiments, cover crops reduced nitrate leaching, while non-legume cover crops showed a 70% leaching reduction (Tonitto et al., 2006). The authors reported that post-harvest N uptake of non-leguminous cover crops averaged between 20 and 60 kg N ha^{-1} and reduced nitrate leaching by 40-70% (Tonitto et al., 2006). Greater yields were observed in corn grown after clover, which was most likely due to added nitrogen from the cover crops, but nitrogen content of corn following the non-leguminous cover crops was similar to the fallow control (Karmberger et al., 2009). Similarly, the meta-analysis by Tonitto et al. (2006) compared conventional and diversified systems using both leguminous and non-leguminous winter cover crops, and found that yields of cash crops following non-leguminous cover crops did not differ from yields following fallow.

Radish cover crop

According to the Maryland Cooperative Extension, the precise classification of oilseed, forage radishes, and other type of radishes is not well established (Weil et al., Fact Sheet 824). This was due to their ability to readily cross-pollinate and therefore distinctions among subspecies are often blurred. Thus much of the research concluded with slightly different radish species may be applicable across subgroups.

The radish (*Raphanus sativus* L.) in particular has been growing in popularity as a cover crop. Its cultivation results in several possible benefits from improved soil aeration, weed suppression, nutrient capture, and possible yield increases to the following grain crops. Sojka et al. (1991) noted that in addition to weed suppression, radish could offer typical cover crop benefits such as reduced soil erosion, increased soil moisture and soil organic matter. Lawley et al. (2011) planted forage radishes along with ryegrass and no cover crop treatments in Maryland before 1 September and produced 3.9 to 6.6 Mg ha^{-1}

shoot dry matter and 1.3 to 3.2 Mg ha^{-1} tuber dry matter. There was no difference in the subsequent corn crop yield among cover crops; however, there was reduced population of corn at several site years after ryegrass treatments. This was attributed to residue interference on corn seed placement and emergence. However, radishes had a small C:N ratio and winter killed leaving a low residue environment for spring crop planting. Cover crops that do not overwinter, such as forage radish provided less residue which simplified spring seeding, provided warmer soils, and allowed for more timely planting of subsequent crops compared to a cover crop that overwintered such as ryegrass (Lawley et al., 2011).

Stivers-Young (1998) used Brassica cover crops [oilseed radish, white senf mustard (*Brassica hirta*), kale (*Brassica oleracea*), canola (*Brassica napus* L.), turnip (*Brassica rapa* L.), and yellow mustard] planted in late August in Western New York and produced aboveground biomass yields between 3000-4000 kg ha^{-1}, took up 100-120 kg ha^{-1} of soil N, and reduced soil inorganic N compared to bare soil. After winter kill, very little biomass residue was detectable with Brassica species only having 40% of detectable ground cover. Brassica species had short growth periods, as short as 70 days, and thus can fit well into crop rotations following a winter annual crop such as wheat. They produced enough biomass to reduce erosion, reduce nutrient leaching, and added organic matter to the soil which benefited the subsequent spring crop (Khatib et al., 1997).

Nutrients

One of the benefits that cover crops have offered is increased nutrient uptake and the subsequent release of nutrients as well as reduced nutrient leaching. The recent effects of cover crops on the environmental fate of nutrients are summarized in Table 1. There has been nutrient research with forage radishes as well as other varieties. Perhaps the most important nutrient for plant production, nitrogen, has received a lot of attention in the literature. Management of nitrogen flows received special attention because it is often the primary limiting factor of growth and thus motivates farmers to use fertilizers, as well as losses to the environment can occur in several different forms while most of these forms (except for N_2) affect the environment (Vos and van der Putten, 1997). The N retained by a cover crop is mainly returned to the surface soil layer when it is killed, either during winter freeze or by spring tillage. In this way, the cover crop acts as fertilizer for the next crop in the rotation (Sapkota et al., 2012). Constantin et al. (2010), with three, 13-17 year long locations in Northern France, determined that establishing catch crops appeared to be an efficient way to decrease nitrate leaching even in the long term. Cover crops decreased N leaching 9 to 32 kg N ha^{-1} yr^{-1} across the three sites and in the fall catch crops decreased soil mineral nitrogen by approximately 50% with 30 to 35 kg N $ha^{-1}$and 5 to 26 kg N ha^{-1} in the winter across all three locations (Constantin et al., 2010).

Root growth and biomass yield of fodder radish, perennial ryegrass, and chicory (*Cichorium intybus* L.), indicated that fodder radish developed the deepest root system and depleted deeper soil layers of N than the other two cover crops, with 6-7 times lesser mineral N than the non-catch crop systems (Sapkota et al., 2012). Thus, the least amount of N was leached 2 m deep with fodder radish. Fodder radish reduced leaching by 79% compared to non-catch cover crop controls. Kristensen and Thorup-Kristensen (2004) observed that fodder radish had a root system that grew deeper into the soil profile than winter rye and ryegrass, leaving only 18 kg N ha^{-1} residual soil NO_3 in comparison to winter rye (59 kg N ha^{-1}) and ryegrass (87 kg N ha^{-1}). The NO_3 level in the fodder radish plots stayed at a significantly lesser level than winter rye and ryegrass of 0.2 to 0.3 mg N kg at 0.5 to 2.5 m in the soil. Calculated N inflow rates using N uptake and root length densities showed fodder radish had inflow rates of 3 to 5 pmol m^{-1} s^{-1} at a 1-2 m depth and even smaller rates at 2.5 m (Kristensen and Thorup-Kristensen, 2004). These results led to fodder radish having the greatest values for plant biomass N of the cover crops that were evaluated.

Similarly, Munkholm and Hansen (2012) noted that fodder radish had the largest N uptake in the above ground biomass with a value of 55 kg N ha^{-1}, compared to dyer's woad (31 kg N ha^{-1}) and ryegrass (37 kg N ha^{-1}) in Denmark. In a study comparing forage radish, oilseed radish, and rape to rye, a common cover crop in the mid-Atlantic coastal plain, Brassica species had significantly greater rates of nitrogen uptake in shoots than rye, with forage radish and rape producing 41% more shoot dry biomass and 46% more N uptake than rye (Dean and Weil, 2009). Nitrogen root uptake was more than three times as great in forage radish as in rape. In the fall, radish plants took up more N and removed nitrate more efficiently than either rape or rye (Dean and Weil, 2009). A radish cover crop planted in eastern France decreased soil mineral N, and consequently reduced nitrate leaching as well as nitrate concentration in percolating water throughout the winter and spring with values of 45 mg NO_3 L^{-1} for the radish cover crop compared to bare soil (91 mg NO_3 L^{-1}). This indicated that 29 kg N ha^{-1} leached in the radish treatments compared to 60 kg N ha^{-1} for the control (Justes et al., 1999). At incorporation in January, total N uptake by roots and shoots was 47 kg N ha^{-1} for radish (Justes et al., 1999).

Another nutrient that is important for cover crops is carbon, especially when it comes to adding carbon to the soil and increasing organic matter. Researching fodder radish in conventional and no-tilled fields, Mutegi et al. (2012) determined that the fall to winter growth period of radish there was below ground input of 1.0 Mg C ha^{-1} in conventional till and 1.2 Mg C ha^{-1} in no-till at 0-45 cm. Above ground biomass at termination of radishes was 200 and 219 g m^{-1} for no-till and conventional till, respectively. With the inclusion of C available in above ground biomass, estimated total system C contribution at incorporation was 162.4 g C m^{-1} in no-till and 169.1 g C m^{-1} in conventional till (Mutegi et al., 2011).

Other nutrients researched with radish included phosphorous and sulfur. Forage radish was unique in terms of P cycling due to its large tissue P concentrations, rapid growth in the fall, and subsequent rapid decomposition in winter and spring after being winter killed (White and Weil, 2011). Radish shoots had greater P concentrations than a winter rye cover crop in a study in Maryland. After three years, forage radish increased soil P concentration at a depth of 0-2.5 cm resulting in values of 101 mg P kg^{-1} compared to rye (82 mg P kg^{-1}) (White and Weil, 2011). In addition, soil within 3 cm of the forage radish tuber had greater P concentration. The authors hypothesized that when radishes winter kill and the residue begins to decompose, P held in the tuber was released back into the soil (White and Weil, 2011). Sulfate retention potential in the soil depends on many factors including pH and concentration of sulfate as well as other ions in the soil. However, soil retention can be weak as sulfate moves easily with water movement through the soil causing large amounts of S leaching (Eriksen and Thorup-Kristensen, 2002). Across all cover crops, fodder radish (36 kg S ha^{-1}) had the greatest aboveground

S uptake, compared to ryegrass (8 kg S ha^{-1}) and winter rape (22 kg S ha^{-1}) as well as the highest soil S removal. At a 0.5-0.75 m depth, where fodder radishes were planted, sulfate concentration was only 19% of the control. Large concentrations of S were found in the top 0.5 m of soil implying that fodder radish was able to trap sulfate in the fall and mineralize S the following spring in the top layers of the soil, thus preventing leaching and providing S to the subsequent crop. Soil S availability was subsequently increased to barley following fodder radish compared to winter rye (Eriksen and Thorup-Kristensen, 2002).

Roots

An important factor determining the effectiveness of cover crops is the ability of roots to grow and explore the soil for water and nutrients. As roots grow, they experience impedance and decreased growth rates due to the force necessary to displace soil particles as they elongate through the soil. Root elongation rate decreased due to the increased resistance of soil particles to displacement from soil compaction (Clark et al., 2003). Soil compaction, especially in subsurface layers, may restrict deep root growth and adversely affect plant access to subsoil water as well as nutrients from the middle to late part of the growing season when rainfall is usually sparse and evapotranspiration is great. The resulting increase in drought stress may limit plant growth and yield (Chen and Weil, 2011).

There has been some research that shows that particular types of roots penetrate soils better and reduce subsoil compaction. Species with thicker roots had better penetration of the subsurface, and research has suggested that this may have occurred because thicker roots were more resistant to buckling and could thus penetrate deeper in the soil profile (Materechera et al., 1992). Chen and Weil (2010) noted that species such as the forage radish and rapeseed with greater root diameters had greater root densities than those with small root diameters in compacted soil due to larger diameter roots needing to overcome less friction pressure of the soil and less cell wall tension in comparison to small diameter roots. Tap rooted species may penetrate compacted soil better than fibrous-rooted species thus making them better adapted for use in 'biological tillage' (Chen and Weil, 2010). Evaluating compaction alleviation of forage radish, rapeseed, and winter rye; forage radish had more roots than winter rye at a 10-50 m depth and more than rapeseed at 20-45 cm under high compaction (Chen and Weil, 2010). Forage radish root number increased with penetration resistance, while rye roots decreased by a power function. Looking at 15-50 cm depth, forage radish had 2.7, 1.9, and 0.8 times as many roots as rye under high, medium and no compaction, respectively (Chen and Weil, 2010).

The forage radish taproots not only reduced soil compaction, but also provided channels for the following crop. Channels produced by cover crop roots in fall and winter when soils are relatively moist may facilitate the penetration of compacted soils by subsequent crop roots in summer when soils are relatively hard and dry (Chen and Weil, 2011, Creswell and Kirkegaard, 1995). Kirkegaard et al. (1993) hypothesized that tap-rooted Brassica crops produce channels in the dense subsoil, which were utilized by the subsequent wheat crop to access water and nutrients and increase yield. In their review, the authors found that in seasons with adequate rainfall, the yield advantage of wheat grown after the Brassica crop was in the range of 15-25% greater compared with a wheat mono-crop. William and Weil (2004), using a minirhizotron camera, observed the path of soybean roots and the channels they followed from previous plantings of three Brassica species (canola, oilseed radish, and forage radish) and winter rye. Their observations suggested that roots of summer crops grew following channels created by preceding cover crops. Forage radish increased soybean yields 200 kg ha^{-1} and the impacts of preceding cover crops were greatest during severe drought and high compaction. This was related to the ability of forage radish to provide low resistance channels for soybean roots to search for water in the subsoil late in the season during drought (Williams and Weil, 2004). Evaluating forage radish, rapeseed and winter rye as cover crops followed by corn, forage radish and rapeseed were the most effective in reducing the effects of soil compaction on corn with corn having more roots at a 45 cm depth in the forage radish treatments (Chen and Weil, 2011).

Channel creation is important for soil compaction alleviation, as well as nutrient uptake which is affected by density and depth of roots. Kristensen and Thorup-Kristensen (2004) looked at Italian ryegrass, winter rye, and fodder radish catch cover crops, with the root depth of each species reaching 0.6, 1.1, and 2.4+ m, respectively. Root frequency for the fodder radish stayed large at 7 to 92% all the way down to 1.5 m, which was 48% greater than the other two species. Vos and van der Putten (1997) stated that one of the properties that determines if a crop species is suitable to be a nutrient catch crop is rapid penetration to depth of roots.

Finally, roots must obtain nutrients from the soil. In order to capture inorganic N in the soil, the root system of the cover crop must come into contact with available N, thus the growth of the root system is important (Sapkota et al., 2012). Fast and deep growing roots, such as fodder radish was effective at mineral N uptake which reduced nitrate-N leaching (Munkholm and Hansen, 2012). Root depth was greater for fodder radish (175 cm) compared with dyer's woad (155 cm) and perennial ryegrass (74 cm), while fodder radish had a greater root frequency than the other cover crops (Munkholm and Hansen, 2012).

Weed Suppression

There are two primary ways that cover crops can suppress weeds: competition and allelopathy. Different research studies have come to different conclusions regarding the impact of a cover crop on weed suppression. Teasdale (1996) reviewed cover crop research and determined that control of weeds increased with greater amounts of cover crop residue biomass; however, weed suppression was species specific in terms of both the cover crop and weed. A more recent review stated that studies have revealed alternative methods such as the use of allelopathy, cover crops, and living mulches which were low cost, effective and eco-friendly practices for sustainable weed management in cropping systems (Mohammadi, 2013). Weed control was related to cover crop residue in many cases and there were many factors related to radiation interception that affected weed suppression. Residues affected the quality and wavelength of light hitting weed seeds which influenced germination and emergence (Altieri et al., 2011), but also impacted soil temperature and evaporative soil water loss. Lawley et al. (2012) argued that the main mechanism of weed suppression by forage radishes was rapid canopy development and fall cover crop competition. The authors observed early spring weed suppression of common chickweed (*Stellaria media* L.) and henbit (*Lamium amplexicaule* L.) where forage radishes were grown regardless of the amount of biomass incorporated into the soil. Forage radishes showed almost complete weed control in early spring and control declined throughout the growing season as summer annual weeds became prominent, although suppression was still greater than weedy checks.

Weed suppression is a desirable trait from cover crops and in general, cover cropping systems have large potentials for weed management in agroecosystems (Mohammadi, 2013). There has been research done showing weed suppression by a variety of Brassica species cover crops including forage radishes. Al-Khatib et al. (1997) found that weed populations of winter annual weeds such as common chickweed, henbit, and common lambsquarters were smallest following rapeseed and white mustard compared to wheat in green pea fields. Averaging over Brassica species, cover crops reduced weed emergence of common lambsquarters and redroot pigweed 24-31% compared with fallow land. Preceding Brassica cover crops reduced weed biomass of kochia (*Kochia scoparia* L.), sheperd's-purse (*Capsella bursa-pastoris* L.), and green foxtail (*Setaria viridis* L.) in green pea, potato, and soybean (Haramoto and Gallandt, 2005). Research in Southern Brazil included a mixture of rye, black oats (*Avena strigosa* L.), ryegrass, vetch (*Vicia sativa* L.), and fodder radish grown as cover crops. All treatments decreased weed biomass 0.26-1.19 kg ha^{-1} compared with fallow ground (Altieri et al., 2011). In Western New York, Brassica cover crops (oilseed radish, white senf mustard, kale, canola, turnip, and yellow mustard) were planted and cover crop residues significantly suppressed weeds, with earlier planted crops (25 August) having particular greater winter annual weed [common chickweed, henbit, and malva (*Malva moschata* L.)] suppression than later planting dates (Stivers-Young, 1998).

In Maryland, Lawley et al. (2011) planted forage radishes before September 1 and produced 3.9 to 6.6 Mg ha^{-1} shoot dry matter and 1.3 to 3.2 Mg ha^{-1} tuber dry matter, along with ryegrass (4.1 Mg ha^{-1} dry matter) and no cover crop treatments. Forage radish provided complete weed suppression in early fall through winter and into early March when weed cover was only 0-3%; however, weed suppression from radishes did not extend to the next growing season and a post emergence herbicide was needed to be applied to avoid yield reduction in corn due to weed interference (Lawley et al., 2011). Malik et al. (2008) looked at radish and winter rye cover crops with varying rates of herbicide application in South Carolina and Georgia. Wild radish reduced weed biomass of Florida pusley (*Richardia scabra* L.), large crabgrass (*Digitaria sanguinalis* L.), and ivy-leaf morning-glory (*Ipomoea hederacea* L.) 52% when compared to weedy cover. Sweet corn with wild radish or rye cover crops as well as half or full rates of atrazine (2-Chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) plus S-metolachlor (2-chloro-N-(2-ethyl-6- methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide) produced 18,000 to 19,000 more ears ha^{-1} than a non-cover crop control which showed the importance of reducing weed competition.

Light competition early in the season has affected weed germination and growth. The competitiveness of fodder radish, oilseed radish, rape, and winter rye crops that had the strongest competitive ability in the fall for weed control was strongly correlated to light interception early in the season (Kruidhof et al., 2008). Lawley et al. (2012)

hypothesized that rapid canopy development may have shifted or changed the phytochrome state of weed seeds leaving them dormant or affecting germination rates. In several experiments, fodder radish had the shortest T_{50} (time to reach 50% soil cover) value as well as the largest biomass production; leading to their conclusions that light interception correlated with weed suppression (Kruidhof et al., 2008). Both fodder radish and winter rye were successful at fall weed suppression; however, like Lawley et al. (2011), they reported that weed suppression decreased as spring progressed. In his review, Teasdale (1996) wrote that winter cover crops provided good weed suppression in early spring, but did not maintain season long weed control. This early suppression of weeds may permit the spring planted crop to emergence and establish before significant summer annual weed emergence occurs.

Some research has shown weed suppression was attributed to allelopathy. Allelopathy is an important term when discussing agricultural weed control. It was defined as the direct or indirect harmful or beneficial effects of one plant on another through chemical compounds that escape into the environment (Rice, 1974). While Molish coined the term in 1937 (Choesin and Boerner, 1991) to include both harmful and beneficial biochemical interaction among plants as well as microorganisms, scholars such as Pliny and Theophrastus recognized the existence of interference between plants as early as 285 BC (Rice, 1974; Velicka et a.l, 2012). Allelochemicals typically reached the environment through exudation from roots, leaching from stems and leaves, and decomposing of plant material (Xuan et al., 2005). It is hard to completely quantify allelopathic effects due to the difficulty in distinguishing plant-allelochemical interactions and distinguishing those interactions from basic competition among plants

(Choesin and Boerner, 1991). In order for allelopathy to occur and be an important process in the agricultural community, the allelochemical must be released into the environment in measurable amounts, reside for a significant amount of time in the environment it is released, and be transported to the target plant (Choesin and Boerner, 1991).

Among Brassica cover crops, radish is of particular interest as there has not been a lot of research done using it as an allelopathic plant. Wild radish is a prominent weed in the southeastern United States, and it could be used as an allelopathic weedy cover crop within cropping systems if it was found to suppress weed emergence or growth without adversely affecting crops (Norsworthy, 2003). Norsworthy (2003) showed that germination and radicle growth of all weed species [sickle pod (*Senna obtusifolia* L.), prickly sida (*Sida spinosa* L.), and yellow nutsedge (*Cyperus esculentus* L.)] evaluated were reduced by extract of forage radish in comparison to the controls. Emergence and shoot fresh weight were reduced by wild radish residue incorporated into soil, with the level of suppression dependent on the quantity of residue incorporated (Norsworthy, 2003). Uremis et al. (2009) found similar results for johnsongrass (*Sorghum halepense* L.) suppression, and the amount of isothiocyanates showed that allelopathy played a role in johnsongrass suppression by brassica species (round white, garden, black, and little radish, rapeseed, and turnip) (Uremis et al., 2009). However, a greater level of johnsongrass suppression by black radish might have resulted from larger contents of isothiocyanates, especially isothiocyanate allyl because amount of isothiocyanate benzyl was similar among all extracts studied (Uremis et al., 2009).

Living plants do not actively release large amounts of isothiocyanates (ITCs), an important active compound derived from glucosinolates, because glucosinolates are located in the vacuole and myrosinase is bound in the cell wall (Petersen et al., 2001). Thus, in intact plant tissues, glucosinolates are separated from the endogenous enzyme myrosinase which catalyzes their hydrolysis (Sarwar et al., 1998; Gimsing and Kirkegaard, 2006,). It is not until the tissue was broken down and the myrosinase interacted with and hydrolyzed the glucosinolates allowing them to become active. Large amounts of ITC were released during the breakdown of cells and it is for this reason that it is possible to control weeds in the following crop if Brassica plant tissue was incorporated into the soil (Brown and Morra, 1995; Petersen et al, 2001; Morra and Kirkegaard, 2002; Xuan et al., 2005; Matthiessen and Kirkegaard, 2006). On their own, glucosinolates had limited biological activity (Bialy et al., 1990, Brown et al., 1991), but they are important because of the wide variety of active products that derive from them as a result of myrosinase action (Matthiessen and Kirkegaard, 2006).

TABLE 1.1. Summary of major cover crop, nutrient uptake, and environmental impacts.

Cover crop	Nutrient	Environmental Impacts	Reference
Ryegrass, mustard, radish	Nitrogen	- Decreased N leaching 9, 32, and 19 kg N ha^{-1} yr^{-1}, respectively - All catch crops decreased soil mineral nitrogen 50% with different locations ranging from 30 - 35 kg N ha^{-1} 5 - 26 kg N ha^{-1} decreased soil N	Constantin et al., 2010
Forage radish, oilseed radish, rape, winter rye	Nitrogen	- Shoot dry biomass of forage radish was 41% greater than winter rye - N uptake of forage radish was 46% greater than winter rye - Forage radish N uptake was 3x greater than rape	Dean and Weil, 2009
Fodder radish	Sulfur	- Greatest aboveground S uptake was 36 kg S ha^{-1} compared to ryegrass with 8 kg S ha^{-1} and winter rape (22 kg S ha^{-1}) - Sulfate concentration was only 19% of the control at 0.5-0.75 m	Eriksen and Thorup-Kristensen, 2002
Oil radish	Nitrogen	- Reduced nitrate leaching and nitrate concentration in percolating water 45 mg NO3 L^{-1} compared to bare soil (91 mg NO3 L^{-1}) - Less residual soil N (29 kg N ha^{-1}) compared to 60 kg N ha^{-1} for bare soil, total uptake was 47 kg N ha^{-1}	Justes et al., 1999

TABLE 1.1. (con't).

Italian ryegrass, winter rape, subclover, crimson clover	Nitrogen	- Decreased soil mineral nitrogen in the winter from 0-90 cm soil depths	Karmberger et al., 2009
Fodder radish	Nitrogen	- 18 kg N ha^{-1} residual soil NO3 - Less than winter rye (59 kg N ha^{-1}) as well as ryegrass (87 kg N ha^{-1})	Kristensen and Thorup-Kristensen, 2004
Fodder radish	Nitrogen	-Uptake was 55 kg N ha^{-1} - Greater than dyer's woad (31 kg N ha^{-1}) - Equal to ryegrass (37 kg N ha^{-1})	Munkholm and Hansen, 2012
Fodder radish	Carbon	- Below ground input was 1.0 Mg C ha^{-1} for conventional till and 1.2 Mg C ha^{-1} for no-till at 0-45 cm - Dry matter above ground biomass was 200 g m^{-1} for no-till and 219 g m^{-1} conventional till - Total system contribution for no-till was 162.4 g C m^{-1} and 169.1 g C m^{-1} for conventional till	Mutegi et al., 2012
Fodder radish	Nitrogen	- Depleted deeper soil layers of N 6-7 times - Lower mineral N with perennial ryegrass and chicory, at a 2 m depth - Reduced leaching by 79%	Sapkota et al., 2012

TABLE 1.1. (con't).

Cereal rye	Nitrogen	- 33% reduction of N leaching for zero urea fertilizer - 32% of medium rate of urea - 42% of recommended rate of urea	Sattell et al., 1999
Hairy vetch, clover, field pea, alfalfa, cereal rye, annual rye, oat	Nitrogen	- 40-70% nitrate leaching reduction - Post-harvest N uptake averaged 20- 60 kg N ha^{-1}	Tonitto et al.,2006
Forage radish	Phosphorous	- Increased P concentration 101 mg P kg^{-1} compared to 82 mg P kg^{-1} for rye at 0-2.5 cm	White and Weil, 2011

TABLE 1.2. Summary of recent research on the impact of selected cover crops on weed suppression.

Cover crop	Weeds evaluated	Suppression/utility	Reference
Rapeseed, white mustard	Common chickweed, henbit, common lambsquarter	-Reduced weed emergence 30% -Reduced 50-96% weed biomass in potato	Al-Khatib et al., 1997
Fodder radish, rye, black oats, ryegrass, vetch	Signal grass, Ipomoea grandifolia, beggar's-tick, milkweed	- Decreased weed biomass 0.26-1.19 kg ha-1	Altieri et al., 2011
Yellow mustard, spring canola, winter rapeseed	Common lambsquarter, redroot pigweed	- Reduced weeds 24-31%	Haramoto and Gallandt, 2005
White clover, subclover, birdsfeet trefoil	monocot, dicot, spring germinating and annual	- Reduced the density of weeds	Hiltbrunner et al., 2007
Fodder radish, winter oilseed rape, winter rye	Common lambsquarter	- > 70% weed biomass reduction	Kruidhof et al., 2008
White lupin	Common lambsquarter	- 40% weed biomass reduction	Kruidhof et al., 2008
Forage radish	Common chickweed, henbit, speedwell, shepherd's-purse	- Complete weed suppression early fall-early March	Lawley et al., 2011
Forage radish	Common chickweed, henbit	- Almost complete control - 14 to 71% ground cover in control plots	Lawley et al., 2012

TABLE 1.2. (con't).

Wild radish, rye	Florida pusley, large crabgrass, ivy-leaf morning-glory	- Reduced weed biomass 52%	Malik et al., 2008
Forage radish	sickle pod, prickly sida, yellow nutsedge, pitted morningglory	- >95% weed fresh weight reduction	Norsworthy, 2003
Turnip, rape	Spiny sowthistle, scentless mayweed, smooth pigweed, barnyardgrass, blackgrass	- Reduced germination by 84% (spiny sowthistle) to 16% (blackgrass) at 5 mg L^{-1} methyl-isothiocyanate concentration	Petersen et al., 2001
Oilseed radish	Common chickweed, henbit, malva	- Reduced weed biomass 81-100%	Stivers-Young, 1998
White senf, mustard, kale, canola, turnip, yellow mustard	Common chickweed, henbit, malva	- Reduced weeds by 113.4-514.7 kg ha^{-1}	Stivers-Young, 1998
White, garden, black, and little radish, turnip, rapeseed	Johnsongrass	- Black radish and rapeseed had 90% weed suppression	Uremis et al., 2009
Alfalfa, kava	Barnyardgrass, monochoria	- 80–100 % weed control inhibiting growth up to 10 days	Xuan et al., 2005

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CHAPTER 2- WINTER WHEAT ROW SPACING AND ALTERNATIVE CROP EFFECTS ON RELAY-INTERCROP, DOUBLE-CROP, AND WHEAT YIELDS

ABSTRACT

In Missouri as well as much of the Midwest and Southern United States, the most popular double-cropping system was winter wheat (*Triticum aestivum* L.) followed by soybean [*Glycine max* (L.) Merr]. These two crops can also be used in an intercrop system, but selecting an optimal row spacing was important to increase crop productivity. Research was conducted to evaluate 1) winter wheat inter- and double-crop production systems using a variety of alternative crops, and 2) the impact of different wheat row spacings on intercrop establishment and yields within the various cropping systems. Field research was conducted during droughts in 2012 and 2013. Spacing of wheat rows impacted wheat yields by 150 kg ha^{-1}, as well as yields of the alternative crops. Narrower row spacings (150 kg ha^{-1}) and the double-crop system (575 kg ha^{-1}) increased yield due to the lack of interference for resources with wheat in 2013. Land equivalent ratio (LER) values determining productivity of intercrop systems of 19 and 38 cm row, and showed an advantage for alternative crops in 2013, but not in 2012. This signified that farmers in Northeast Missouri could potentially boost yield potential for a given field and produce additional forage or green manure yields in a year with a less severe drought.

INTRODUCTION

Double-cropping is a production system that includes the growth of two separate crops at different times in the same growing season. This typically involves harvesting one species followed immediately by planting another. Compared with mono-cropping systems, double-cropping has used climatic, land, labor, and equipment resources more efficiently and produced more total grain in some situations (Crabtree et al., 1990). Double-cropping increased the amount of time land was used for crop production and has increased potential profit (Pullins et al., 1997).

In Missouri as well as much of the Midwest and Southern United States, the most popular double-cropping system was winter wheat (*Triticum aestivum* L.) followed by soybean [*Glycine max* (L.) Merr] (Kyei-Boahen and Zhang, 2006). Research comparing mono-crop and double-crop wheat systems using a variety of other crops such as soybean and grain sorghum (*Sorghum bicolor* L.), showed double-crop systems increased grain yield and net returns of the overall system (Crabtree et al., 1990; Kyei-Boahen and Zhang, 2006; Caviglia et al., 2011). These increases were attributed to greater resource utilization. In humid areas of South America, Van Opstal et al., (2011) found that double-crop systems reached water productivity (0.85 compared to 0.43 g m^{-2} mm^{-1}) and radiation productivity (0.22 g MJ^{-1} to 0.11 g MJ^{-1}) values that were almost two times greater than the sole crop. Resource use was calculated as the product of the proportion of annual resources captured by crops to produce grain yield. Evaluating productivity of water and light, Caviglia et al. (2004) found that double-cropping dramatically increased the productivity of radiation for both dry matter and yield on an annual basis.

Intercropping is the growth of two crops in the same field where the component crops were not necessarily sown at the same time nor harvested at the same time, but were grown simultaneously for a majority of their growing periods. Within an intercropping system, there was normally one main crop and one or more added crops often sown later in the season with the main crop being of primary importance for economic or food production reasons (Lithourgidis et al., 2011a). The most common advantage of intercropping was the production of greater yield on a given piece of land by making more efficient use of available resources. This could have been due to different rooting characteristics, canopy structure, height, and nutrient requirements or resource use at different times (Fujita et al., 1992; Midmore, 1993; Thiessen Martens et al., 2001; Eskandari and Ghanbari, 2010; Echarte et al., 2011; Eskandari, 2011; Lithourgidis et al., 2011a). The point at which complimentarity became competition among crops could be manipulated through management practices (Midmore, 1993). Row spacing could be critical in determining success of an intercrop as it impacted the crop's response to limiting factors such as light, soil moisture and nutrients as well as the availability of resources.

Selecting an optimal row spacing was important to improve crop productivity as plants growing in too wide of a row may not efficiently utilize light, water and nutrient resources. However, crops grown in too narrow rows may result in severe inter-row competition. Row spacing also modified plant architecture, photosynthetic competence of leaves, and dry matter partitioning in several field crops (Hussain et al., 2012). Successful crop mixtures extended the sharing of available resources over time and space and exploited variation between component crops such as rates of canopy development, final canopy width and height, photosynthetic adaption of canopies to irradiance conditions, and rooting depth (Midmore, 1993; Lithourgidis et al., 2011a).

Light interception was important in intercrop systems and was affected by the crop architecture and canopy structure. Generally, cereals were taller and shaded the component leguminous crop, which is why row spacing and plant arrangement influenced the success of the systems (Fujita et al., 1992). A single crop each year used only a small proportion of potentially available resources and calculations for the southeast Pampas area in Argentina which indicated that sole crops of wheat, corn, or soybean captured only 20-36% of the annual incident photosynthetically active radiation (Coll et al., 2012).

Optimum row spacing helped optimize tillering and ensured increased wheat yields (Hussain et al., 2012). Wheat sown under narrow-row spacing (15 cm) produced greater wheat yields due to a significant increase in productive tillers (Hussain et al., 2012). Narrow-row spacing increased inter-row competition while a wider row spacing (30 cm) increased the number of grains per spike and 1000-grain weight, but did not compensate for the drastic decrease in productive tillers which resulted in decreased grain yields (Hussain et al., 2012). Similarly, Zhou et al. (2011) found that wheat yields were highest for 14 cm row spacing with yields ranked 14>7>24.5>49 cm. However, Pandey et al. (2013) reported that wheat cultivated in 20 cm rows produced significantly more effective tillers compared to 15 and 25 cm rows.

Plant spacing and row direction can also affect total weed suppression. During early growth stages, interference between crop and weed plants was commonly affected by the quality of reflected light. The reflection of far-red photons by the stem of one plant lowered the red to far-red photon ratio of light experienced by the stems of neighboring plants (Borger et al., 2010). This modified the light environment in the plant stem tissue, which resulted in increased stem elongation. As plants aged, the crop canopy closed and mutual shading further increased the competition for photosynthetic light (Borger et al., 2010). The best results were obtained in an east-west row orientation with 20 cm rows and two hand weedings. For that management regime, there was a 44% increase in crop growth and 21% increase in crop yield compared to a control (Hozayn et al., 2012). Weed biomass was lower (93 g m^{-2}) in narrow row spacing (18 cm) compared to wide row (36 cm) weed biomass (107 g m^{-2}) (Borger et al., 2010). In a wheat-frost seeded legume intercrop system, red clover (*Trifolium pretense* L.) and alfalfa (*Medicago sativa* L.) were frost-seeded into winter wheat and triticale, and the legume intercrop did not affect grain yield, but did reduce weed density and dry matter up to 40 days after harvest (Blaser et al., 2007). Champion et al. (1998) reported that manipulation of the crop for weed suppression by reducing row width was less successful than increasing plant density in wheat only fields. The authors reported that narrow rows did not enhance shading and suppression of weed biomass; however, the research included wheat only and no intercrops.

Wheat rows in relay-intercropping are often wider than conventionally planted wheat in order to allow light for the subsequent intercrop. When intercropping clover into wheat, Thorsted et al. (2006) found that interspecific competition during vegetative growth was reduced by increasing width of the rototilled strips from 7 to 14 cm, which resulted in greater grain yields and increased grain N uptake. However, when using wider rows without an intercrop, wider rows did not necessarily benefit yields. Over two years, four different wheat planting patterns were employed including conventional seeding (Porter and Khalilian, 1995). There were no significant differences among treatments for total above ground dry matter, number of grains per area, grain weight, or grain yield. These findings indicated that there were no negative effects of wide-row planting on wheat yields (Porter and Khalilian, 1995). However, other research showed that row spacing affected yields; narrow rows yielded more grain compared to wide rows. This suggested that closeness of planting enabled more efficient utilization of resources (Champion et al., 1998; Drew et al., 2009).

The most common intercropping system is wheat and a legume such as soybean or red clover, as the nitrogen fixing properties of legumes work well with wheat and a subsequent rotational crop (Danso et al., 1987; Fujita et al., 1992; Lithourgidis et al., 2011a; Mariotti et al., 2011; Akhtar et al., 2010; Naudin et al., 2010; Pelzer et al., 2012; Tosti and Guiducci, 2012). Research in Wisconsin demonstrated that red-clover (4200 kg ha^{-1} aboveground biomass) was the most productive and reliable legume choice as a green manure crop when it was interseeded into winter wheat in early spring compared to hairy vetch (3385 kg ha^{-1}) and crimson clover (2050 kg ha^{-1}) (Stute and Shelley, 2008). In Michigan, red clover produced significantly more above and belowground biomass (0.97-2.14 kg ha^{-1}) than fallow. Corn N biomass (109.1-148.1 kg ha^{-1}) and grain yield (5800-7200 kg ha^{-1}) were increased by including red clover when compared to fallow (Gentry et al., 2013). Nitrogen credit from red clover (30-48 kg N ha^{-1}) was similar across management type with the first year of introduction to the conventional system providing an apparent 55 kg N ha^{-1} (Gentry et al., 2013). Relay-cropping increased the average return to N investments across the N fertility gradient when estimating N and forage values of red clover biomass (265-1380 kg ha^{-1}) compared to sole wheat (Gaudin et al., 2014).

Nitrogen application at maximum economic rate (MERN) for wheat decreased economic benefits as well as possible system benefits of red clover. Red clover contribution to the total intercrop yield decreased with N applications greater than 40 kg N ha^{-1}, thus the authors argue that reduction of N rates can maximize economic returns for both wheat and red clover increase profits for both species (Gaudin et al., 2014). Results of a winter annual legume experiment showed that hairy vetch cultivars, especially cv. Hungvillosa, exhibited the best frost resistance compare to yellow sweet clover [*Melilotus officinalis* (L.) Pall.]. At the lowest temperature (-9^{o}C), hairy vetch Hungvillosa had the largest relative biomass (75% of the control of 0^{o}C) (Brandsæter et al., 2000). The objectives of this research were to evaluate 1) winter wheat inter- and double-crop production systems using a variety of alternative crops, and 2) the impact of different wheat row spacings on intercrop establishment and yields within the various cropping systems.

MATERIALS AND METHODS

A field trial was initiated in the fall of 2011 and continued through 2013 at the University of Missouri Greenley Research Center near Novelty, Missouri (40°1'17" N 92°11'24.9" W). Soft red winter wheat, 'MFA 2525', was planted in a split-plot design. The main plot was row spacing and cropping system, and sub-plot was alternative crop species. Four replications were planted in plots that were 3 by 9 m. On 3 October 2011, wheat was no-till drill seeded at 112 kg ha^{-1} in 19 cm rows using a Great Plains no-till drill (Great Plains Ag., Salina, KS). In plots that would contain wheat in 38 cm rows but had been planted in 19 cm rows, every other row was sprayed out using a hand held sprayer containing glyphosate at 1.06 kg ai ha^{-1} and nonionic surfactants at 0.25% vol./vol. The soil was a Kilwinning silt loam (fine, montmorillonitic, mesic, Vertic Ochraqualfs). Wheat planted on October 2011 over wintered and then was relay-intercropped (4 April) and double-cropped (16 June) in the spring of 2012 and harvested (15 June) in the summer of 2012. The second year of wheat was no-till drill seeded at 112 kg ha^{-1} in 19 cm and 38 cm rows using a Great Plains no-till drill (Great Plains Ag, Salina, KS) on 11 October 2012. The soil was a Putnam silt loam (fine, montmorillonitic, mesic Vertic Albaqualfs). Wheat over-wintered and was relay-intercropped (29 April) and double-cropped (3 July) in the spring of 2013 and harvested on 3 July 2013.

Diammonium phosphate and potassium chloride were broadcast at 35 kg N ha^{-1}, 89 kg P_2O_5 ha^{-1} and 134 kg K_2O ha^{-1} on 3 October 2012. Ammonium nitrate was broadcast spread on all plots at an amount of 111 kg N ha^{-1} on 27 March 2012 and 22 March 2013, using a hand held fertilizer spreader. On 4 April 2012 and 2 February 2013, cowpea (*Vigna unguiculata* L.) at 56 kg ha^{-1}, soybean at 440,000 seeds ha^{-1}, pea (*Pisum sativum* L.) at 34 kg ha^{-1}, hairy vetch (*Vicia villosa* L.) at 39 kg ha^{-1}, red clover (*Trifolium pretense* L.) at 11 kg ha^{-1}, grain amaranth (*Amaranthus hypochondriacus* L.) at 11 kg ha^{-1}, grain sorghum (*Sorghum vulgare* L.) at 11 kg ha^{-1}, and pearl millet (*Pennisetum glaucum* L.) at 17 kg ha^{-1} were broadcast seeded into the standing winter wheat. The alternative crops were chosen for a variety of reasons. Pea, cowpea, hairy vetch, and red clover are legume species and could add nitrogen to the soil (Lithourgidis et al., 2011a). Other crops including grain sorghum and grain amaranth have drought tolerance and could be harvested for grain to create additional income as there are potential markets for these crops in Missouri (Nelson et al., 2000).

On 4 April 2012 and 29 April 2013, eight alternative crops were no-till seeded in 38 cm rows using a split-row planter (John Deere 7200, Moline, IL) into standing wheat with 19 and 38 cm rows. Finally, following wheat harvest all sub-plot crops were no-till, double-crop seeded using a split-row planter (John Deere 7200, Moline, IL) on 16 June 2012 and 3 July 2013. Emergence of the alternative crops and stand counts were evaluated on 17 May 2012 and 5 June 2013. Heights were recorded on 9 July 2013. There was no height data recorded in 2012 for alternative crops due to the lack of plant growth from dry conditions. Following the double-crop planting, emergence of the double-cropped alternative crops were recorded on 11 July 2012 and 11 July 2013.

Leaf Area Index (LAI) and light interception (LI) was recorded on 12 June 2012 and 29 May 2013 at wheat flag leaf. Data were recorded using a SunScan canopy analysis system (Delta-T, Burwell, Cambridge, UK). Light interception was calculated by measuring both incident and transmitted light through the canopy simultaneously. Intercepted light is the amount of the incident that was not transmitted. Wheat was harvested on 15 June 2012 and 3 July 2013 using a 1.5 m head on a Wintersteiger plot combine (Wintersteiger Delta, 4910 Ried, Austria, Dimmelstrasse 9) and yields were determined per plot. Alternative crops were hand weeded three times throughout the growing season following the harvest of the wheat. Alternative crops were hand harvested from a 0.3 by 0.75 m quadrat on 9 October 2012 and 2013.Yields were separated into grain and total plant dry matter. Land equivalent ratio (LER) values were calculated using wheat and alternative crop data and the calculation LER = mixed yield^1/pure yield^1 + mixed yield^2/pure yield^2 (Malézieux et al., 2009). The resulting value indicated the amount of land needed to grow both crops together compared with the amount of land needed to grow a mono-crop of each crop.

Data were subjected to ANOVA (SAS, 2010), and means separated using Fisher's Protected LSD (P = 0.1). LAI and LI data were analyzed comparing 19 and 38 cm row spacing. Wheat yields were combined over site-year in the absence of significant interactions, adjusted to 130 g kg^{-1} grain moisture prior to anaylsis, and evaluated across row spacing within alternative crops. Emergence, grain and biomass yields of alternative crops were presented separately across row spacing and site years. LER values were presented separately for years due to an interaction and were evaluated for each alternative crop. Years were presented separately due to significant difference between years especially when yields were significantly impacted by drought in 2012, and compared among cropping systems.

RESULTS AND DISCUSSION

Environmental Conditions

Annual precipitation for 2011-2012 was below average and was average for 2012-2013 compared to precipitation data from the last 10 years (Figure 1). During the wheat growing season in 2011-2012 from planting in October through winter total rainfall was 252 mm (Figure 1a). Total precipitation for 2012 was 722 mm; however, there was only 215 mm of rainfall from May through August, 60 mm of which occurred on the last day of August. Total precipitation in 2012 was 262 mm below the 10 year average for the alternative crops (Figure 1a). In 2013, total precipitation was 1003 mm and again from June through August there was only 140 mm of rainfall with no rain in August for the alternative crops (Figure 1b).

During the summer of 2012, temperatures were abnormally high with an average temperature of 23.7°C from May through August and 30.7°C was the average high temperature (data not presented). In comparison, 2013 was a relatively cool summer with an average temperature through the summer of 21.2°C and an average high temperature of 27.3°C. Due to below average rainfall as well high average temperatures in 2012, research completed in the growing years of 2011-2012 and 2012-2013 was conducted under dry summer conditions, and extreme drought conditions for 2011-2012.

Light interception

Light interception was 3% greater in 19 cm wide wheat rows than 38 cm rows in 2011-2012 and similar in 2012-2013 (Table 1). With narrower row spacing, there were probably more wheat plants in the field allowing for greater interception of light. For the 2011-2012 growing season, 19 cm wide rows also had a greater leaf area index compared with 38 cm rows. Leaf area index was not different in 2013.

Research has shown that light interception was important in intercrop systems and was affected by the crop architecture and canopy structure (Fujita et al., 1992; Borger et al., 2012; Coll et al., 2012). Similarly, Borger et al. (2012) found that light interception by crops increased in narrow row spacing 63% to 70% of wide rows, while and

Champion et al. (1998) reported that light interception measurements taken throughout the growth cycle 10 cm above ground level varied for different row spacings.

Wheat yields

There were no year interactions for wheat yields across both years (2011-2012 and 2013-2013), but the main effect of row spacing affected yield (*P*=0.06) (Table 2). Wheat yields were 100 kg ha^{-1} to 980 kg ha^{-1} above average wheat yields for Missouri (USDA NASS, 2010). Wheat yields were 4375 to 4725 kg ha^{-1} in 2012 and 2013 for the double-crop system and were greater when compared with relay-intercropping at either row spacing for pearl millet, soybean, red clover, hairy vetch, and pea. Wheat yields for double-cropped soybeans were 535 kg ha^{-1} greater than wheat that was relay-intercropped in 19 cm rows and 715 kg ha^{-1} greater than wheat that was relay-intercropped in 38 cm rows. Double-cropped red clover wheat yields were 555 and 605 kg ha^{-1} greater compared to relay-intercropping at 38 cm and 19 cm, respectively. Similarly, when pea was used as a double-crop wheat yields were greater than the 38 cm row (715 kg ha^{-1}) and the 19 cm intercrop system (740 kg ha^{-1}). Finally, intercropping hairy vetch decreased yields 575 kg ha^{-1} in 19 cm wheat and 890 kg ha^{-1} in 38 cm wheat compared to double-crop hairy vetch. Relay-intercropping cowpea into 38 cm wheat reduced yields compared to 19 cm relay-intercrop and double-crop systems 655 and 940 kg ha^{-1}, respectively (Table 2). There were no differences in wheat yields for grain sorghum or grain amaranth. Double-cropping may have resulted in greater wheat yields due to physical damage from intercropping. Ngalla and Eckert (1987) reported a 4% reduction to wheat due to physical damage to wheat. Double-cropping may have also produced greater wheat yields due to the lack of competition for resources from intercrops (Midmore, 1993, Thorsted et al., 2006). For soybean, 38 cm row spacing decreased wheat yields 180 kg ha^{-1} compared to 19 cm rows in either cropping system. This may have been due to competiveness of soybean preventing tillering of wheat that was associated with wider row spacings (Pandey et al., 2013). Hairy vetch had greater wheat yields in double-cropped systems (4680 kg ha^{-1}) than either row spacing in the intercrop system (4330 kg ha^{-1} for 19 cm rows and 4150 kg ha^{-1} for 38 cm rows) which was probably due to crop interference.

Research has shown that row spacing can help optimize wheat yields; however, results have differed depending on the selection of narrow or wide row spacing. (Champion et al., 1998; Hussain et al., 2012; Pandey et al., 2013). Wheat sown under narrow row spacing (15 cm) produced greater wheat yields due to a significant increase in productive tillers (Hussain et al., 2012). Wider row spacing (30 cm) increased the number of grains per spike and 1000-grain weight, but could not compensate for the drastic decrease in productive tillers which decreased grain yields (Hussain et al., 2012). Similarly, Zhou et al. (2011) found that wheat yields were greatest for 14 cm spacing with yields ranked 14>7>24.5>49 cm row spacing. However, Pandey et al. (2013) reported that wheat cultivated at 20 cm row spacing produced significantly more effective tillers as compared to 15 cm row spacings. Thorsted et al. (2006) found that interspecific competition during vegetative growth was reduced by increasing width of the rototilled strips from 7 to 14 cm, and research completed by Porter and Khalilian (1995) indicated that there were no negative effects of wide-row planting on wheat yields. Conversely, narrow rows yielded more grain than wide rows, suggesting that closeness of planting enabled more efficient utilization of resources (Champion et al., 1998; Drew et al., 2009). Finally, wheat yields may have been affected by row orientation due to impacts on light interception and photosynthetic efficiency (Borger et al., 2010; Pandey et al., 2013). The effect of row orientation varied with latitude and seasonal tilt of the earth. (Borger et al., 2010). For example, wheat crops planted east-west in Western Australia had 24% greater yields than those oriented north-south and 51% lower weed biomass (Borger et al., 2010).

Alternative crop yields

Due to the severe drought in 2012, alternative crops in the intercrop system died due to plant interference. While the intercrops emerged (Table 3) prior to wheat harvest on 15 June, all of the intercrops eventually died. There was a severe drought during the summer of 2012 and the intercrop system was burdened by too much competition for water with wheat (Midmore, 1993; Coll et al., 2012). The intercrops died after emergence probably due to lack of water and extreme heat, which was exacerbated by interference with wheat. The double-crop planting produced greater biomass yields ranging from 145 kg ha^{-1} for red clover to 20,295 kg ha^{-1} for sorghum (Table 4). Across all alternative crops, the double-cropping system yielded significantly greater than the intercrops. With a later planting date, crops received water at important establishment and maturation points that was not available to intercrops earlier in the season. In addition, temperatures started to decrease at the end of the summer, meaning that growth occurred during slightly cooler temperatures (an average temperature of 22.4°C from planting to harvest). Finally, the alternative crops planted in the double-crop system did not have to compete with wheat for water and other resources.

Alternative crops yielded greater in 2013 for relay-intercrops compared to 2012 with the exception of pearl millet, amaranth, and pea in some spacings. In 2012, there was no yield for intercrops, but in 2013 total biomass reached 17,155 kg ha^{-1} for sorghum. Early rainfalls in May and June and cooler summer temperatures allowed for greater intercrop growth before a "flash drought" occurred late in the summer. There were trends that occurred across alternative crops. With the exception of hairy vetch, alternative crops generally yielded greater either in the double-crop system (cowpea, amaranth, and pea) or in the no wheat (grain sorghum and clover) or 38 cm intercrop system (pearl millet) (Table 4). This most likely occurred because of reduced competition for resources due to either no wheat being present or greater distance between the wheat rows for the alternative crop.

Hairy vetch was the exception with greater biomass yields of 1020 kg ha^{-1} for 19 cm row spacing intercrop and 1080 kg ha^{-1} for no wheat compared to 19 cm double-crops. As a vining plant, hairy vetch probably benefitted in the 19 cm rows from having wheat stalks closer which provided it with physical support. Since hairy vetch is often a frost seeded species (Brandsæter and Netland, 1999) and it can withstand colder temperatures. However, double-crop planting on 9 July may have caused average temperatures to be too high for good growth of hairy vetch. Visual observations noted that hairy vetch performed very well in Northeast Missouri as an intercrop, often forming ground cover and good biomass production that suppressed weeds such as common waterhemp (*Amaranthus rudis* Saur.) (visual observation).

There were only four alternative crops that produced grain yield in the double-crop system in 2012 including pearl millet (125 kg ha^{-1}), grain sorghum (470 kg ha^{-1}), amaranth (410 kg ha^{-1}), and soybean (560 kg ha^{-1}) (Table 5). Cropping system affected alternative crop grain yields in 2013 (Table 5). For pearl millet and amaranth, grain yields were 175 to 412 kg ha^{-1} greater in the double-crop system compared to either row spacing in the intercrop system. Similarly, grain yields were greatest for sorghum and soybean in the mono-crop system with no wheat. In both the mono-crop, no wheat system and the double-crop system the alternative crop did not have to compete with wheat for resources.

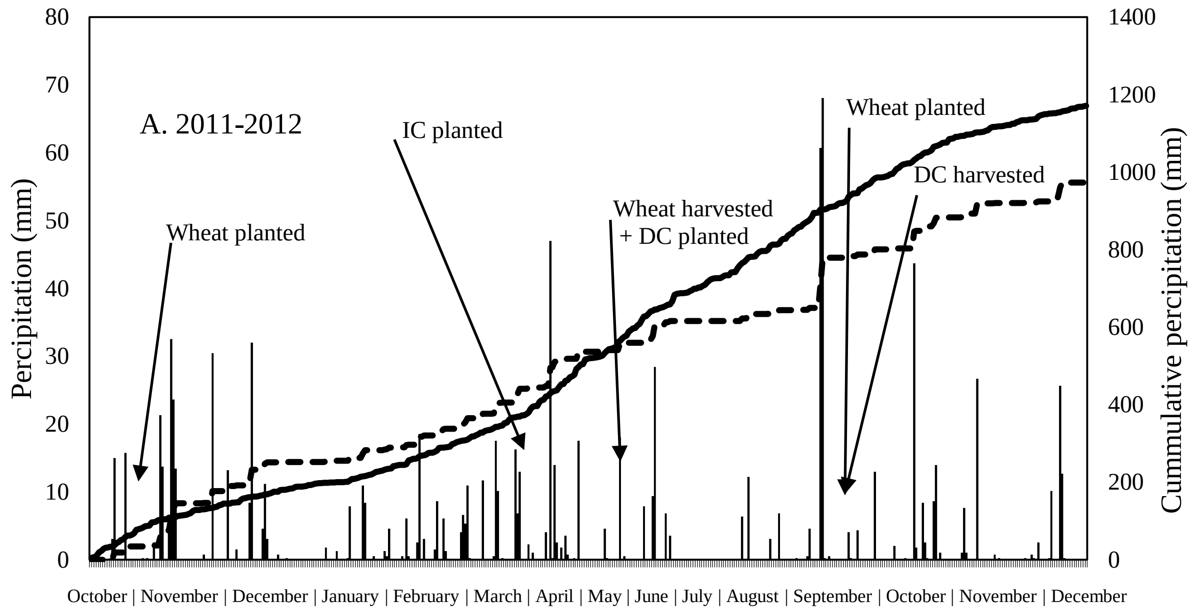
Land Equivalent Ratio

A LER shows the efficiency of intercropping for using the environmental resources compared with mono-cropping and compares yields obtained by growing two or more species together with the yields of growing the same crops as a mono-crop (Malézieux et al., 2009; Lithourgidis et al., 2011b). A LER greater than 1.0 indicated inter-cropped systems were advantageous, whereas a LER less than 1.0 showed a yield disadvantage (Malézieux et al., 2009; Lithourgidis et al., 2011b). Drought greatly impacted LER values in 2012. Due to no intercrop production after wheat harvest (by mid-summer), with the exception of grain sorghum and clover in 38 cm rows, all LER values were below 1.0 (Table 6). This was reasonable since the relay-intercrop system failed leaving only wheat yields as the marketable product. However, the double-crop system did provide some yield, perhaps increasing the value of the field by producing two yields in one growing season when compared with the mono-crop system.

Interestingly, there was successful alternative crop production in the relay-intercropping system in 2013 and LER values across all alternative crops, with the exception of pearl millet, were above 1.0 (Table 6). Hairy vetch had the greatest LER value across row spacing with 1.2 to 2.15 greater LER values compared with all intercrops. This corresponded with visual observations of large amounts of hairy vetch biomass production. In addition, 19 cm spacing LER was significantly greater than 38 cm row spacing. By producing positive LER values representing yield advantages of the intercropping system, using intercrops as forages or green manures, may potentially benefit farmers' production systems in years with low rainfall and temperatures (2013) but not in years with low rainfall and high temperatures (2012).

CONCLUSION

This research was conducted during extreme drought conditions in 2011-2012 and flash drought in 2012-2013. Winter wheat yields were not impacted as the majority of its lifecycle was completed during traditionally wetter periods of the year; however, alternative crop yields were decreased with the lowest establishment and survival in 2012. Spacing of wheat rows impacted wheat yields, as well as the type of cropping system for some alternative crops. In 2012, there were no alternative crop yields for the relay-intercrop or mono-crop system due to extreme drought conditions; however, wider row spacings or the double-crop system increased yield due to interference for resources with wheat in 2013. Land equivalent ratio values determining productivity of intercrop systems of 19 and 38 cm row spacing compared with sole-cropping systems showed that, with the exception of grain sorghum and 38 cm row spacing clover, there was no yield advantage for the intercropping system for any alternative crops in 2012. In 2013, LER values showed an advantage for all alternative crops with the exception of pearl millet in 19 cm spacing. This signified that farmers in Northeast Missouri could potentially boost their yield potential for a given field and perhaps produce additional forage or green manure yields in a year with a less severe drought.



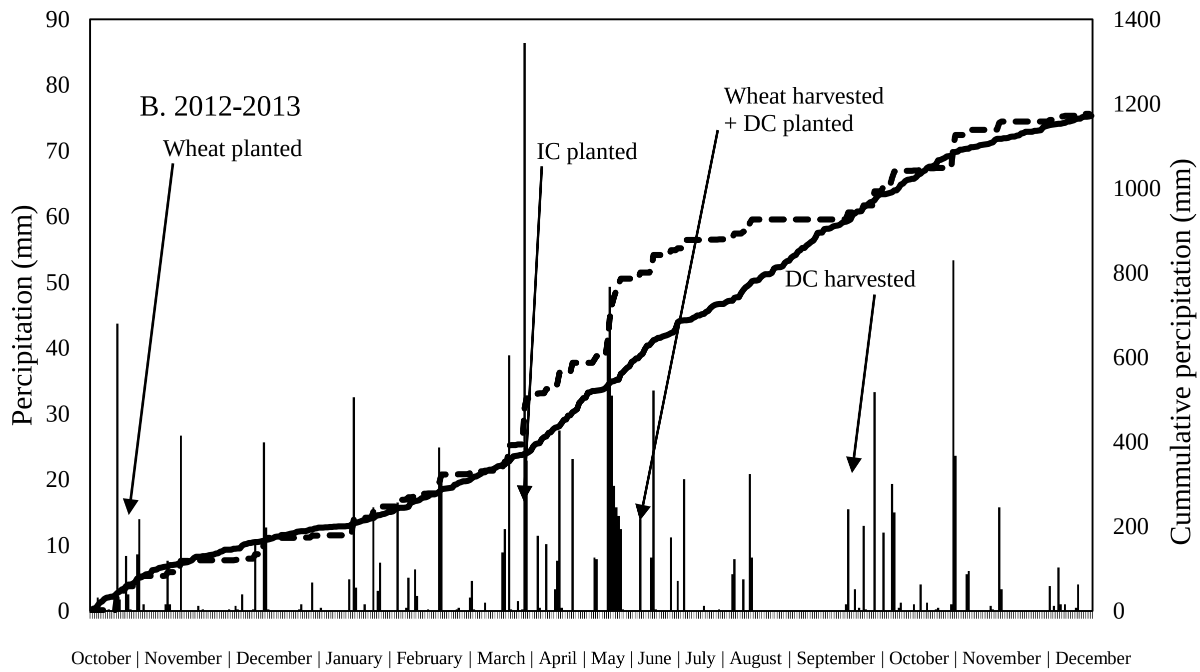


Figure 2.1. Daily (bar) and cumulative precipitation data for individual years (dash line) and 10-year average (solid line) for experiment form 2011-2012 (A) and 2012-2013 (B). Double-crop (DC), relay-intercrop (IC) planting and harvest dates for wheat and alternative crops were labeled with arrows.

Table 2.1. Light interception (LI) and leaf area index (LAI) of wheat planted in 19 and 38 cm wide rows.

	2012		2013	
Wheat row spacing	LI	LAI	LI	LAI
	------------	%	------------	
19 cm row	77	2.7	89	3.6
38 cm row	74	2.4	85	4.0
LSD (*P*=0.1)	2	0.2	NS	NS

Table 2.2. Wheat yield response to relay-intercrops planted into 19 and 38 cm row spacings and following 19 cm wheat with no mechanical damage that was subsequently double-crop seeded in 2012 and 2013.

	Cropping system		
	Relay-intercrop		Double-crop
Crop	19 cm	38 cm	19 cm
	------------	kg ha^{-1}	------------
Cowpea	4425	3775	4715
Pearl Millet	4120	4070	4665
Sorghum	4340	4195	4625
Amaranth	4105	4035	4375
Soybean	4105	3925	4640
Red Clover	4055	4105	4660
Hairy Vetch	3935	3960	4675
Pea	4150	3835	4725
LSD (*P*=0.1)	------------ 435 ------------		

Table 2.3. Alternative crop emergence in intercrop and double-crop systems for 2012 and 2013.

	2012					2013				
	Relay-intercrop			Double-crop		Relay-intercrop			Double-crop	
Crop	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)
	1000 plants ha^{-1}									
Cowpea	0	0	0	1429	299	267	0	0	1725	67
Pearl Millet	27	0	0	1456	459	0	0	0	458	88
Sorghum	0	0	0	3181	1080	81	54	647	1051	333
Amaranth	0	0	0	9167	406	0	0	0	512	358
Soybean	81	108	1132	1833	297	1402	1510	2076	1375	524
Red Clover	566	1456	27	593	1190	3396	4259	9111	4178	2290
Hairy Vetch	350	997	1402	2156	604	3909	4259	10432	2615	1670
Pea	674	593	1563	917	242	122	1267	1856	943	490

Table 2.4. Dry biomass yields of alternative crops for 2012 and 2013.

	2012					2013				
	Relay-intercrop			Double-crop		Relay-intercrop			Double-crop	
Crop	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)
	kg ha^{-1}									
Cowpea	0	0	0	2370	740	770	1065	440	2715	1190
Pearl Millet	0	0	0	3310	345	0	805	0	1315	735
Sorghum	0	0	0	20295	19835	3470	2930	17155	5395	2755
Amaranth	0	0	0	1590	470	40	265	0	930	335
Soybean	0	0	0	3250	470	715	820	2670	2520	1660
Red Clover	0	0	0	145	125	375	930	1120	250	400
Hairy Vetch	0	0	0	1110	285	1790	1165	1850	770	690
Pea	0	0	0	565	225	35	465	0	695	640

Table 2.5. Alternative crop grain yields for wheat row spacing in 2012 and 2013.

	2012					2013				
	Relay-intercrop			Double-crop		Relay-intercrop			Double-crop	
Crop	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)	19 cm	38 cm	No wheat	19 cm	LSD (*P*=0.1)
	kg ha^{-1}									
Cowpea	0	0	0	0	0	0	39	16	4	52
Pearl Millet	0	0	0	125	45	0	82	0	257	106
Sorghum	0	0	0	470	235	450	675	2059	337	698
Amaranth	0	0	0	410	275	22	50	0	462	70
Soybean	0	0	0	560	365	32	163	859	172	505
Red Clover	0	0	0	0	0	0	0	18	0	23
Hairy Vetch	0	0	0	0	0	0	0	0	0	0
Pea	0	0	0	0	0	0	0	0	36	47

Table 2.6. Land equivalent ratios (LER) for intercropping of wheat and all alternative crops for 19 and 38 cm row spacing.

	2012			2013		
Crop	19 cm	38 cm	LSD (*P*=0.1)	19 cm	38 cm	LSD (*P*=0.1)
Cowpea	0.94	0.74	0.38	1.34	1.21	0.71
Pearl millet	0.8	0.87	0.41	0.97	1.40	0.77
Grain sorghum	1.01	1.00	0.26	1.26	1.28	0.42
Amaranth	0.97	0.96	0.14	1.01	1.25	0.55
Soybean	0.87	0.90	0.28	1.23	1.19	0.16
Clover	0.91	1.03	0.22	1.32	1.76	0.24
Hairy Vetch	0.78	0.81	0.26	3.12	2.39	1.09
Pea	0.83	0.77	0.16	1.02	1.51	1.23

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CHAPTER 3-EFFECT OF ALTERNATIVE CROP PLANTING DATE ON INTER- AND DOUBLE-CROP YIELDS

ABSTRACT

Planting date is an integral part of a successful double-crop system. In addition, planting time of an intercrop is important and can greatly affect crop yields. Cool adapted species that can be frost-seeded take advantage of unused light and space between rows of slow-growing spring or fall such as winter wheat, thus making an earlier planting date more beneficial. The objective of this research was to evaluate the difference between early broadcast frost-seeding, mid-season relay-intercropping, and double-cropping planting dates of alternative crops on wheat and alternative crop yields. Field research was conducted in 2012 and 2013 near Novelty, MO. Cropping system and alternative crop selection affected wheat yields by 15 to 455 kg ha^{-1}. Although emergence occurred in 2012, there were no alternative crop yields for the frost-seeded and relay-intercrop system due to drought. However, planting date and cropping system affected alternative crops differently in 2013. Land equivalent ratio (LER) values determined there was an advantage for alternative crops when alternative crops survived past emergence. Frost-seeding provided yield advantages in both years with the exception of radish and hairy vetch in 2012 and faba bean in 2013. This signified that farmers in Northeast Missouri could potentially boost their yield potential for a given field and perhaps produce additional forage or green manure yields in a year with a less severe drought by using several alternative crops. The effectiveness will depend on the cropping system that was employed.

INTRODUCTION

A double-crop production system includes the growth of two separate crops at different times in the same growing season. This typically involves harvesting one species followed by planting of another. Compared with mono-cropping, double-cropping used climatic, land, labor, and equipment resources more efficiently and produced more total grain (Crabtree et al., 1990). Double-cropping increased the amount of time land was used for crop production and has increased profit potential (Pullins et al., 1997). In Missouri as well as much of the Midwest and Southern United States, the most popular double-cropping system is winter wheat (*Triticum aestivum* L.) followed by soybean [*Glycine max* (L.) Merr].

Planting date is an integral part of a successful double-crop system since crop maturity date can greatly affect productivity (Sanford et al., 1973). Using crops that have alternative growth periods, such as winter wheat with a short season crop, was a good option for double-cropping since wheat reached harvest during the summer and allowed sufficient time for a fast maturing crop such as soybean to reach maturity before a killing frost (Sanford et al., 1973; Kyei-Boahen and Zhang, 2006). By using early maturing crops, this allowed for earlier planting of the overwintering crop (Kyei-Boahen and Zhang, 2006). Sanford et al. (1973) observed that no tillage, double-crop systems provided the least delay in establishing a second crop. When evaluating costs of no-till double-crop systems, either with grain sorghum or soybean, inputs were $11 ha^{-1} less than conventional tillage. After 1 December, the rate of decline in yield with delayed sowing was about 1.3% per day for sole-crops and 0.5% per day for double-crops, emphasizing the importance of early establishment of the second crop (Caviglia et al., 2011). A later planting date can be used to decrease competition for resources among plants, but also make them more complimentary. Planting date is important when considering water and light availability as well as favorable temperature conditions for plant development (Midmore, 1993). Caviglia et al. (2004) reported that double-cropped wheat and soybeans used between 54-70% of the annual rainfall; however, only 40% of the incident photosynthetically active radiation (PAR). It was important that timing of crop cycles and rainfall cycles were a match in a double-crop production system. Water can be held in the soil thus offsetting the difference between water availability and demand; however, canopy size and structure at a given time determined the availability of PAR. Plant available water affected winter wheat grain production when researching the effects of tillage and nitrogen rates on wheat production (Halverson et al., 1999). No-till and minimal tillage yielded greater than conventional tillage, with grain yields of 2022 kg ha^{-1}, 1968 kg ha^{-1} and 1801 kg ha^{-1}, respectively (Halverson et al., 1999).

Intercropping is the growth of two crops in the same field, where the component crops are not necessarily sown at the same time nor harvested at the same time, but they are grown simultaneously for a portion of their growing periods. Within an intercropping system, there is normally one main crop and one or more additional crop often sown later in the season. The main crop was of primary importance for economic or food production reasons (Lithourgidis et al., 2011a). Intercropping is still a common practice in developing areas, with small farms finding 20 to 60% greater productivity in terms of harvestable products per unit area compared to mono-cropping (Lithourgidis et al., 2011a). This was largely attributed to more efficient resource use, which is the primary benefit of intercropping. The most common advantage of intercropping was the production of greater yields on a given piece of land through more efficient use of the available resources. Intercrop systems can be planted simultaneously or staggered which can take advantage of cool and warm season species. By staggering planting dates, the relative periods of complimentarity and competition were modified and influenced the component crop’s yield potential (Midmore, 1993). In general, the crop planted first had a competitive advantage over the intercrop as it had previous access to limiting factors. Several types of intercrop systems used mixtures of spatial and temporal arrangements. These include mixed intercropping, alternate-row intercropping, within-row intercropping, strip intercropping, and relay-intercropping (Lithourgidis et al., 2011a). Planting time of an intercrop is important and can greatly affect crop yields. Within a week, relative growth, canopy height, and canopy width of a standing crop can change affecting the intercrop positively or negatively (Midmore, 1993). Thus, the competition for resources can be managed through careful planting times of the second crop (Midmore, 1993). Traditionally, intercropping cereal grains such as wheat was done through a broadcast over-seeding or through inter-row planting using planting machinery.

The practice of broadcasting a small-seeded legume into an established stand of winter wheat during late winter is known as “frost seeding”, which established a cover crop understory in the wheat crop at no expense to the wheat crop (Hesterman et al., 1992; Mutch et al., 2003). Frost seeding was a common and cost-effective method of broadcasting seed as an intercrop (Singer et al., 2006). Frost-seeding or ‘cracked soil surface’ seeding, consisted of sending seed into cracks in the field caused by freezing (Stute and Shelley, 2008). Frost seeded crops, especially legumes, can add forage and provide nitrogen for subsequent crops (Blaser et al., 2007), making intercropping attractive to growers looking for more cost-effective production systems (Mutch et al., 2003). Nitrogen accumulation was 107 to 196 kg N ha^{-1} at three locations in East Lansing, Michigan for frost-seeded red clover (*Trifolium pretense* L.) into winter wheat (Hesterman et al., 1992). As measured by the fertilizer replacement value (FRV), red clover frost-seeded into wheat was worth over 111 kg N ha^{-1}. The amount of N contribution was affected by the N accumulated by the legume, which was influenced by the length of time between legume seeding date and the end of growth (Hesterman et al., 1992). In Ohio, Ngalla and Eckert (1987) reported a contribution equivalent of 56 to 67 kg N ha^{-1} from frost-seeded red clover into wheat for the subsequent corn (*Zea mays* L.) crop.

Various factors such as crop species, growth stage, duration of freezing temperature, soil moisture, type, and compaction, and freezing and thawing sequences contributed to a complex pattern that determines frost tolerance of a particular species (Badaruddin et al., 2001). For instance, winter annual legumes that reached early flowering stages exhibited poor frost resistance (Brandsæter et al., 2000). Hardening is a physiological change of a plant with cold temperature treatment (commonly termed as vernalization). Hardening increased seedling survival of forage legumes [alfalfa (*Medicago sativa* L.), red clover, sweetclover (*Melilotus officinalis* Lam.), alsike clover (*Trifolium. hybridium* L.), white clover (*Trifolium repens* L.), and sainfoin (*Onobrichis viciifolia* Scop),] and soybean and field pea (*Pisum sativum* L.) by up to 40% when compared to unhardened seedlings (2-40% less survival at -4 to -8 ^{o}C) (Badaruddin et al., 2001). Experiments showed hairy vetch (*Vicia villosa* Roth.) possessed the greatest winter hardiness compared to black medic (*Medicago lupulina* L.), crimson clover (*Trifolium incarnatum* L.), and subclover (*Trifolium subterranteum* L.) (Brandsæter and Netland, 1999). Hairy vetch had the greatest biomass production in both fall (287,000 Mg ha^{-1}) and spring (3,118,000 Mg ha^{-1}), greater soil cover (95-100%), and reduced total weed biomass compared to other cover crops (Brandsæter and Netland, 1999). In addition, hairy vetch had similar winter fitness compared to red clover, another winter hardy crop (Brandsæter and Netland, 1999).

Cool adapted species that can be frost seeded take advantage of unused light and space between rows of slow-growing spring or fall such as winter wheat, thus making an earlier planting date more beneficial (Midmore, 1993). In Wisconsin, interseeded red clover captured 90 days of sunlight which was wasted in a sole crop rotation (Stute and Shelley, 2008). Seeding clover or other forage legumes after wheat harvest was more risky due to potential for dry conditions and a shorter growing season which made interseeding or frost seeding attractive (Stute and Shelley, 2008). However, delayed planting of warm-season dry beans (*Phaseolus vulgaris* L.) reduced risk of spring frost, a hazard for spring-seeded grains and forage legumes which may occur from early April through the first part of June in the northern Great Plains (Badaruddin et al., 2001). Conversely, the risk of a killing fall frost was increased by delayed planting in short growing season environments (Badaruddin et al., 2001). In Ohio, there was no benefit from double-cropped red clover following wheat because of insufficient biomass accumulation (Ngalla and Eckert, 1987). However, relay-cropping red clover into winter wheat in Ontario provided a longer period for red clover establishment (Gaudin et al., 2014). Additionally, properly managed interseeded red clover did not reduce wheat yield or interfere with harvest (Stute and Shelley, 2008). In Southern Ontario across 10 locations, economic returns of wheat-red clover relay-intercropping were optimized by reducing N rates by 10-12% which reduced wheat yields only 1-4% and did not negatively affect grain N concentration. Yield losses were offset by increased returns associated with strong red clover production (Gaudin et al., 2014). Finally, wheat yields were not affected by the presence of clover, and common ragweed was reduced (1100-2100 kg ha^{-1}) when red clover was frost seeded into winter wheat in Southwest Michigan (Mutch et al., 2003).

The most common intercropping system was wheat and a legume such as soybean as the nitrogen fixing properties of legumes work well with wheat and a subsequent rotational crop (Danso et al., 1987; Fujita et al., 1992; Lithourgidis et al., 2011a; Mariotti et al., 2011; Akhtar et al., 2010; Naudin et al., 2010; Pelzer et al., 2012; Tosti and Guiducci, 2012). Other crops such as sunflower have drought tolerance and could be harvested for grain to create additional income as there are potential markets for these crops in Missouri (Nelson et al., 2000). Research has shown that sunflowers may also reduce weeds in these cropping systems (Morris and Parrish, 1992). Buckwheat has often been grown as a soil cover and green manure, and produced modest amounts of biomass (Myers and Meinke, 1994). Phosphorus was more available with buckwheat to component crops (Myers and Meinke, 1994). Rapid growth of buckwheat may allow it to be planted as a double-crop and reduce risk associated with early frost and add economic value (Nelson et al., 2000). Research has shown that in northern Missouri buckwheat and sunflower had the most competitive returns (Nelson et al., 2000). In Northeast Missouri gross margins were \$217.10 ha^{-1} and sunflower was \$287.60 ha^{-1}, compared to \$2.70 ha^{-1}

for soybean (Nelson et al., 2000). Results of a winter annual legume experiment showed that hairy vetch cultivars, especially cv. ‘Hungvillosa’, exhibited the best frost resistance compare to yellow sweet clover [*Melilotus officinalis* (L.) Pall.] (Brandsæter et al., 2000). At the lowest evaluated temperature (-9 ºC), hairy vetch Hungvillosa had the largest relative biomass (75% of the control of 0 ºC) (Brandsæter et al., 2000). Finally, forage radish boasts a myriad of possible benefits from improved soil aeration, weed suppression, nutrient capture, and possible yield increases to the rotational grain crops (Sojka et al., 1991; Constantin et al., 2010; Lawley et al., 2011; Sapkota et al., 2012). Limited research has evaluated the intersection of various alternative crops for cover and grain production in wheat cropping systems in the Midwest U.S. The objective of this research was to evaluate the difference between early frost-seeding broadcast, mid-season relay-intercropping, and late double-cropping planting dates of alternative crops on wheat yields as well as alternative crop yields.

MATERIALS AND METHODS

A field trial was conducted in the fall of 2011 and repeated in the fall of 2012 at the University of Missouri Greenley Research Center near Novelty (40°1'17" N 92°11'24.9" W). The experiments were arranged in a split-plot design with four replications. The main plot was planting time/cropping system, and sub-plot was the alternative crop species. Plots were 3 by 12 m. ‘MFA2525’ wheat was no-till drill seeded at 112 kg ha^{-1} in 19 cm rows using a Great Plains no-till drill (Great Plains Ag., Salina, KS). The soil type was a Kilwinning silt loam (fine, montmorillonitic, mesic, Vertic Ochraqualfs). Wheat planted on 3 October 2011 over wintered and alternative crops were frost-seeded (4 April), relay-intercropped (4 April), and double-cropped (16 June) in the spring of 2012 and wheat was harvested (15 June) in the summer of 2012 (Figure 1a). The soil in the second year of the experiment was a Putnam silt loam (fine, montmorillonitic, mesic Vertic Albaqualfs). Wheat over-wintered and alternative crops were frost-seeded on 21 February, relay-intercropped on 29 April, and double-cropped on 3 July in the spring of 2013 and wheat was harvested on 3 July 2013 (Figure 1b).

Diammonium phosphate and potassium chloride were broadcast at 35 kg N ha^{-1}, 89 kg P_2O_5 ha^{-1}, and 134 kg K_2O ha^{-1} on 3 October 2012. Ammonium nitrate was broadcast applied on all plots at 111 kg N ha^{-1} 27 March 2012 and 22 March 2013 using hand held fertilizer spreaders. On 4 April 2012 and 21 February 2013, buckwheat (*Fagopyrum esculentum* L.) at 62 kg ha^{-1}, tillage radishes (*Raphanus sativus* L.) at 6.7 kg ha^{-1}, sunflowers (*Helianthus annuus* L.) at 5.6 kg ha^{-1}, hairy vetch (*Vicia villosa* L.) at 39 kg ha^{-1}, and faba beans (*Vicia faba* L.) at 225 kg ha^{-1} were broadcast seeded into the standing winter wheat. The five alternative crops were drill seeded using a split row planter (John Deere 7200, Moline, IL) on 4 April 2012 and 29 April 2013 in 38 cm rows into standing wheat. Finally, following wheat harvest all five alternative crops were drill seeded using a split row planter (John Deere 7200, Moline, IL) on 16 June 2012 and 3 July 2013. Emergence of the alternative crops and stand counts were evaluated on 17 May 2012 and 5 June 2013. Heights were recorded on 9 July 2013. There was no height data recorded in 2012 for alternative crops due to no plant growth from the dry conditions. Following the double-crop planting, emergence of the double-cropped alternative crops was recorded on 11 July 2012 and 2013. Plots were left untouched with only wheat to serve as a control to the broadcasted and intercropped treatments. The alternative crops were chosen for a variety of reasons. Faba bean and hairy vetch are legume species and could add nitrogen to the soil (Lithourgidis et al., 2011a). Other crops including sunflowers have drought tolerance and could be harvested for grain to create additional income as there are potential markets for these crops in Missouri (Nelson et al., 2000).

Wheat was harvested on 15 June 2012 and 3 July 2013 using a 1.5 m head on a Wintersteiger plot combine (Wintersteiger Delta, 4910 Ried, Austria, Dimmelstrasse 9) and yield was adjusted to 130 g kg^{-1} prior to analysis. Alternative crops were hand weeded three times throughout the growing season following harvest of wheat. Alternative crops were hand harvested from a 0.3 by 0.75 m quadrat on 9 October 2012 and 2013 and dried prior to collecting weights. Yields were separated into grain and total plant dry matter. Land equivalent ratio (LER) values were calculated using wheat and alternative crop data as: LER = mixed $yield^1$/pure $yield^1$ + mixed $yield^2$/pure $yield^2$ (Malézieux et al., 2009). The resulting value indicated the amount of land needed to grow both crops together compared with the amount of land needed to grow a mono-crop of each crop.

Data were subjected to ANOVA (SAS, 2010) and means were separated using Fisher’s Protected LSD ($P = 0.1$). Wheat yields were combined over site-year in the absence of significant interactions, and an analysis evaluated cropping systems within alternative crops. For alternative crops, yields were presented separately for each year due to a significant interaction between years, especially when 2012 yields were significantly impacted by drought and data were compared for different planting dates.

RESULTS AND DISCUSSION

Environmental Conditions

Annual precipitation in 2012 was 267 mm below average compared to the last 10 years (Figure 1a). During the wheat growing season, total rainfall was 252 mm in 2011-2012; however, from May through August there was only 215 mm of rainfall. On the last day of August, 60 mm of precipitation occurred from the storms following Hurricane Isaac adding some needed precipitation that helped with grain fill of plants that had survived the summer. In 2013, total precipitation was 1003 mm, but there was only 140 mm of precipitation from June through August and there was no rain in August (Figure 1b). Although total precipitation in 2013 was similar to the 10 year average (984 mm), the lack of rain in August produced a ‘flash drought’ during grain fill which affected most summer annuals.

During the summer of 2012, temperatures were abnormally high with an average temperature of 23.7^{o}C from May through August and 30.7^{o}C average high temperature during this period (data not presented). In comparison, 2013 was relatively cool with an average summer temperature of 21.2^{o}C and an average high temperature of 27.3^{o}C (data not presented). Due to below average rainfall as well high average temperatures, the results of this research during 2012-2013 were representative of drought conditions that can occur in this region and extreme drought conditions for 2011-2012.

Wheat yields

Wheat yields were 105 kg ha^{-1} below to 730 kg ha^{-1} above average wheat yields for Missouri (USDA NASS, 2010). Wheat with relay-intercropped alternative crops yielded 480 to 570 kg ha^{-1} less than wheat where the alternative crop was double-cropped or frost-seeded (Table 1). This was partially due to physical injury to the wheat crop from planting machinery (Figure 2), but no significant reduction was observed where no crop was interseeded in wheat (4010 kg ha^{-1}). For buckwheat, sunflower, radish and hairy vetch both double-crop planting and frost-seeding produced greater yields that relay-intercropping by 430-640 kg ha^{-1}, 395-445 kg ha^{-1}, 360-475 kg ha^{-1}, 455-730 kg ha^{-1}, respectively (Table1).

Hairy vetch had the greatest difference (730 kg ha^{-1}) in grain yields for double-cropping (no injury or competition) compared to intercropping. Hairy vetch performed well in Northeast Missouri as an intercrop in dry conditions and often had complete ground cover and biomass that greatly suppressed weeds such as common waterhemp (*Amaranthus rudis* Saur.) (visual observation). Because hairy vetch was the most productive crop, it may have provided greater resource competition with wheat in frost-seeding and intercropping systems which decreased wheat yields. However, in a double cropping system where both species do not exist in the field at the same time, wheat had greater yields (275-730 kg ha^{-1}).

Research has shown that frost-seeding cover crops into standing wheat normally does not reduce wheat yields. Janke et al. (1987) observed no effect on wheat yields when hairy vetch was broadcast or drill-seeded into standing wheat. In Michigan, frost-seeding and interseeding alfalfa and red clover had no effect on small grain yield wheat yields that ranged from 2535 to 4335 kg ha^{-1} (Hesterman et al., 1992). Ngalla and Eckert (1987) reported a slight reduction (4%) in wheat yields from frost seeding clover, which was attributed to physical damage from machinery associated with frost seeding not from red clover interference. Similar experiences were observed during this research. There was some mechanical damage to the already standing wheat from the drill seeding of alternative crops (Figure 2); therefore, wider wheat row spacings may be needed.

Alternative crop yields

Due to the severe drought in 2012, alternative crops in the frost-seeded and intercrop system died due to plant interference. While the intercrops emerged (Table 2) prior to wheat harvest on 15 June, all of the intercrops died. Since there was a severe drought during the summer of 2012, the intercrop system was probably burdened by too much competition for water with wheat (Midmore, 1993; Coll et al., 2012). The intercrops died after emergence which was probably due to lack of water and extreme heat, which was exacerbated by interference with wheat. The double-crop planting system produced greater biomass yields ranging from 10 kg ha^{-1} for faba bean to 2995 kg ha^{-1} for radish (Table 3). Thus, across all alternative crops the double-cropping system yielded significantly greater than the early frost-seeded or intercrop planted systems.

The greater yields achieved in the double-cropping system compared to frost seeding and intercropping may have occurred due to a later planting date. Crops received water at important establishment and maturation points that was not available to intercrops earlier in the season. In addition, temperatures started to decrease at the end of the summer, meaning that growth occurred during slightly cooler temperatures (an average temperature of 22.4°C from planting to harvest). Finally, the alternative crops did not have to compete with wheat for water and other resources as a double-crop.

Alternative crops generally yielded greater in 2013 compared to 2012 except double-cropped buckwheat radish, faba beans, and hairy vetch (Table 3). There was no yield for frost-seeded or relay-planted intercrops in 2012, but total biomass reached up to 515 kg ha^{-1} for hairy vetch in the frost-seeding system and 840 kg ha^{-1} in the relay-intercropped system in 2013. Early rainfalls in May and June allowed for increased intercrop growth before drought set in later in the summer (Figure 1). Several alternative crops were unsuccessful in the frost-seeding and relay-intercropping systems (buckwheat and sunflower), but were able to produce some biomass in the double-crop system (Table 3). Radish biomass was 575 to 1005 kg ha^{-1} greater in intercrop and double-crop systems compared with frost-seeding. Research has shown that radish growth and production was sensitive to planting date and temperature (Pandey et al., 2009; Alam et al., 2010; Lawley et al., 2011; Ebrahimi et al., 2013). The frost-seeding system may have been less successful for radishes due to cooler temperatures and time of season when radish seed was broadcast seeded.

Biomass yields of hairy vetch were greatest in a relay-intercropping system (840 kg ha^{-1}) compared to frost-seeding (515 kg ha^{-1}). This was probably due to better seed-to-soil contact in establishment (visual observation). As a vining plant, hairy vetch worked well in the intercropping system. Wheat plants provided structure for continued growth of hairy vetch which allowed for greater yields. Hairy vetch has been utilized in a frost-seeding system and can withstand colder temperatures (Brandsæter and Netland, 1999). The double-crop planting date, 9 July, may have been late enough in the season that average temperatures were too high for good growth and development. Faba bean, also did not follow the patterns of the other alternative crops. In the relay-intercrop system faba bean produced 340 kg ha^{-1} while it did not produce any biomass in the frost-seeded or double-cropped system (Table 3).

Alternative crops produced very little grain yield in the cropping systems that were evaluated during drought conditions (Table 4). There were no grain yields from frost-seeded crops or intercrops in 2012 due to the dying of alternative crops after establishment. Buckwheat (65 kg ha^{-1}) was the only alternative crop that produced grain yield in the double-crop system. This may have been due to dormant seeds that emerged when conditions were favorable since buckwheat grows quickly in the fall (Myers and Meinke, 1994). Similarly, double-cropping was the only system to produce alternative crop grain yields in 2013 (Table 4). In the double-crop system, the alternative crops did not have to compete with wheat and had greater vegetative growth which produced grain yields.

Land equivalent ratio

A land equivalent ratio (LER) shows the efficiency of intercropping for using the environmental resources compared with mono-cropping and compares yields obtained by growing two or more species together with the yields of growing the same crops as a mono-crop (Malézieux et al., 2009; Lithourgidis et al., 2011b). A LER greater than 1.0 indicated inter-cropped systems were advantageous, whereas a LER less than 1.0 showed a yield disadvantage (Malézieux et al., 2009; Lithourgidis et al., 2011b). Drought greatly impacted LER values in 2012. All LER values were below 1.0 for the intercrop system across alternative crops due to no alternative crop production in the relay-intercrop system (Table 5). This was reasonable since the intercrop system failed and under drought conditions wheat yields were the marketable product. Interestingly, buckwheat (1.12), sunflower (1.01), and faba bean (1.01) had LER values greater than 1.0 in the frost-seeding system. Frost-seeded alternative crops emerged except for sunflower (Table 2), but all frost-seeded alternative crops died and did not produce biomass or grain yields for the system. LER values above 1.0 may have occurred due to less establishment of alternative crops in the frost-seeded system when compared relay-intercrop due to less soil-to-seed contact. If emergence of alternative crops was reduced, competition with wheat may have been low enough to allow for strong enough wheat yields to produce LER values at or above 1.0.

There was successful alternative crop production in the relay-intercropping system in 2013 except for buckwheat and sunflower (Table 3 and 4). Across all alternative crops, with the exception of relay-intercropping buckwheat or faba bean, all LER values were above 1.0 (Table 5). For the frost-seeded system, all alternative crops had values above 1.0, again with the exception of faba bean. Hairy vetch had the greatest LER value (2.19). This corresponded with other visual observations of high levels of hairy vetch production. By producing positive LER values representing yield advantages of the intercropping system, using intercrops as forages or green manures may potentially benefit farmers' production systems during years with low rainfall and low temperatures.

CONCLUSION

This research was conducted during drought conditions in the summers of 2012 and 2013. Winter wheat yields were not impacted as the majority of its lifecycle was completed during traditionally wetter periods of the year; however, alternative crop yields were poor in 2012. Cropping system and alternative crop selection impacted wheat yields. In 2012, although emergence occurred, there were no alternative crop yields for the frost-seeded and relay-intercrop system due to drought. However, planting date and cropping system affected alternative crops differently in 2013. Relay-intercrop and double-crop system increased yields for radish while relay-intercropping had greater yields for hairy vetch and faba bean. Land equivalent ratio values determining productivity of crop systems showed there was no yield advantage for the relay-intercropping system for any alternative crops in 2012. In 2013, LER values showed an advantage for all alternative crops with the exception of intercropped buckwheat and faba bean. Frost-seeding provided yield advantages in both years with the exception of radish and hairy vetch in 2012 and faba bean in 2013. This signified that farmers in Northeast Missouri could potentially boost their yield potential for a given field and perhaps produce additional forage or green manure yields in a year with a less severe drought by using several alternative crops, but the effectiveness will depend on the cropping system that was employed.

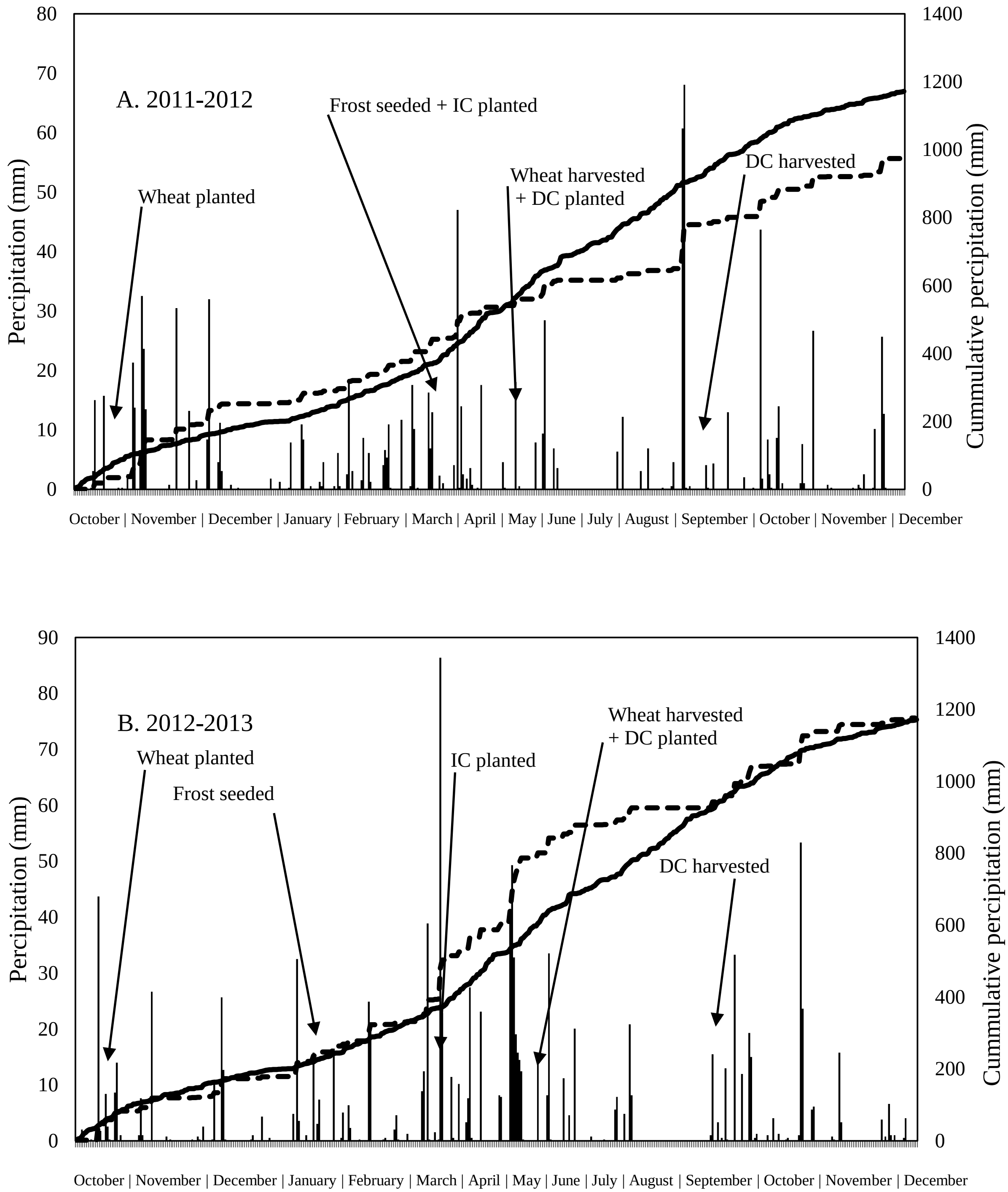

Figure 3.1. Daily (bar) and cumulative precipitation data for individual years (dash line) and 10-year average (solid line) for experiment form 2011-2012 (A) and 2012-2013 (B). Double-crop (DC), relay-intercrop (IC) planting and harvest dates for wheat and alternative crops were labeled with arrows.

Figure 3.2. Damage to wheat from machinery during relay-intercrop planting in 2012.

Table 3.1. Wheat yields for frost-seeded (FS), relay-inter (IC) and double-cropping (DC) systems in 2012 and 2013 for various alternative crops in upstate Missouri. Date were combined over years.

	Planting date		
Crops	FS	IC	DC
	---------	kg ha^{-1}	-------
Buckwheat	4465	3825	4255
Sunflower	4335	3890	4285
Radish	4255	3895	4370
Faba bean	4385	3630	4090
Hairy Vetch	4100	3645	4375
Wheat	4190	4010	4260
LSD (*P*=0.1)	---------	290	---------

Table 3.2. Alternative crop emergence across frost-seeded (FS), relay-inter (IC) and double-cropping (DC) systems for 2012 and 2013.

	2012				2013			
Alternative Crop	FS	IC	DC	LSD (*P*=0.1)	FS	IC	DC	LSD (*P*=0.1)
	------------------------------------- 1000 plants ha^{-1} -------------------------------							
Buckwheat	108	1914	4771	1460	0	404	5391	372
Sunflower	0	0	620	415	0	81	3720	740
Radish	782	1887	782	1570	0	728	2291	325
Faba bean	917	997	0	393	0	674	0	338
Hairy Vetch	485	2318	1779	1140	0	2830	2561	1860

Table 3.3. Dry biomass yields of alternative crops across frost-seeded (FS), relay-intercropped (IC) and double-cropped (DC) systems for both years.

	2012				2013			
Alternative crop	FS	IC	DC	LSD (*P*=0.1)	FS	IC	DC	LSD (*P*=0.1)
	kg ha^{-1}							
Buckwheat	0	0	425	385	0	0	425	115
Sunflower	0	0	1030	590	0	0	2405	550
Radish	0	0	2995	650	195	770	1200	450
Faba bean	0	0	10	9	0	340	0	455
Hairy vetch	0	0	930	275	515	840	680	210

Table 3.4. Grain yields of alternative crops across frost-seeded (FS), intercropped (IC), and double-cropped (DC) systems for 2012 and 2013.

	2012				2013			
Alternative crop	FS	IC	DC	LSD (*P*=0.1)	FS	IC	DC	LSD (*P*=0.1)
	------------------------------------ kg ha^{-1} ------------------------------------							
Buckwheat	0	0	64.4	45.8	0	0	51.4	27.5
Sunflower	0	0	0	0	0	0	494.6	241.2
Radish	0	0	0	0	0	0	0	0
Faba bean	0	0	0	0	0	0	0	0
Hairy vetch	0	0	0	0	0	0	0	0

Table 3.5. Land equivalent ratios (LER) for frost-seeded (FS) and relay-intercropping (IC) systems of wheat and alternative crops in 2012 and 2013.

	2012			2013		
	FS	IC	LSD (*P*=0.1)	FS	IC	LSD (*P*=0.1)
Buckwheat	1.12	0.96	0.21	1.01	0.92	0.05
Sunflower	1.01	0.83	0.26	1.01	1.02	0.08
Radish	0.99	0.88	0.16	1.15	1.53	0.55
Faba bean	1.07	0.92	0.53	N/A[+]	N/A	N/A
Hairy Vetch	0.96	0.82	0.33	1.56	2.19	0.93

[+] N/A= Not available. There were no faba bean yields in 2013 to calculate an LER value.

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CHAPTER 4 - EFFECT OF GRAZING, TILLAGE, PLANTING DATE ON FORAGE RADISH PRODUCTION

ABSTRACT

There are many benefits of cover crops including increased yield of a marketable crop, greater yield stability, reduced fertilizer inputs, weed suppression, and interruption of disease or pest cycles. Radish (*Raphanus sativus* L.) has been increasing in popularity as a cover crop since it may increase soil aeration, weed suppression, nutrient capture, and yield to the following grain crop. Brassica species could be used as a forage crop. The objective of this research was to evaluate the effect of grazing, tillage and planting date (early and late September) on forage radish establishment and production, winter annual weed suppression, and the impact on subsequent corn growth and yields. Radish planting date significantly impacted biomass production, with the earlier planting date producing greater total biomass for tops (4910 kg ha^{-1}) and tubers (3080 kg ha^{-1}) prior to a killing frost. Winter annual weed control often followed radish production patterns. Weed plant density and total weights were reduced by the early compared to the late radish planting date. There were no differences among treatments and factors for any corn production measurements except for a 665 kg ha^{-1} yield reduction for early planted radishes in 2013. Results showed that if planted early enough in the fall, a farmer in upstate Missouri could effectively produce forage radishes and may achieve winter annual weed suppression following the radishes, but did not increase corn yield in drought years.

INTRODUCTION

A cover crop refers to a plant which was grown in rotation during periods when main crops are not grown (Mohammadi, 2013). There were many benefits of cover crops, but the most direct positive being increased yield of a marketable crop. Other benefits included greater yield stability, reduced fertilizer inputs, weed suppression, interruption of disease or pest cycles, increased soil and water quality, and increased nutrient cycling efficiency (Thiessen Martens et al., 2001; Snapp et al., 2005; Hoffbeck et al., 2008). There were also several farm benefits that specifically dealt with soil conservation and the reduction of soil erosion, nitrate leaching, and chemical runoff (Snapp et al., 2005). Other soil benefits included improved water infiltration, soil moisture retention, improved soil tilth, and nutrient efficiency (Teasdale, 1996). Finally, planting a cover crop replaced an unmanageable weed population such as common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retrofelxus* L.), and some annual grasses with a manageable crop or mulch population (Teasdale, 1996). Determining the seeding timing, type, and desired benefits from the cover crop was important for adoption and utilization. For winter cover crops, a cash crop does not have to be sacrificed, and planting normally occurs in the fall after harvest of an annual cash crop (Snapp et al., 2005).

Radish (*Raphanus sativus* L.) has been increasing in popularity as a cover crop. It boasts a myriad of possible benefits including improved soil aeration, weed suppression, nutrient capture, and possible yield increases to the following grain crops. Sojka et al (1991) noted that in addition to weed suppression, radish offered typical cover crop benefits such as reduced soil erosion, increased soil moisture infiltration and increased soil organic matter. In Maryland, forage radishes planted before September 1 produced 3.9 to 6.6 Mg ha^{-1} shoot dry matter and 1.3 to 3.2 Mg ha^{-1} tuber dry matter (Lawley et al., 2011). There was no difference in the subsequent corn (*Zea mays* L.) crop yield among cover crops; however, there was reduced corn populations in the several site years following annual ryegrass (*Lolium perenne* L.). Radishes had a small C:N ratio and winter killed leaving a low residue environment for spring crop planting. Cover crops that did not overwinter, such as forage radish, left less residue which simplified spring seeding, provided warmer soils, and allowed for more timely planting of subsequent crops compared to a cover crop that overwintered such as ryegrass (Lawley et al., 2011).

Planting date of radishes was found to influence radish production (Pell at al., 1993; Pandey et al., 2009; Alam et al., 2010; Ebrahimi et al., 2013). Sowing date influenced vegetative and reproductive growth period as well as the balance between those stages and ultimately affected yield (Ebrahimi et al., 2013). An appropriate radish sowing date helped reduce damage caused by cold or heat as well as pests, diseases, and weeds. Also, a favorable planting date coincided with favorable climatic factors that affected production such as coincidence of flowering time with suitable temperature were found important for good establishment (Ebrahimi et al., 2013). Proper radish sowing time depended on the existing environment and variety selection. Growers tended to manipulate sowing dates to obtain better growth and larger yields (Alam et al., 2010). Timing of planting may be significant due to light available and temperature. In addition to the amount of light available, the season may impact radish production (Pell at al.1993). In growth chambers, radishes exhibited a more adverse response to soil moisture deficits in the spring than fall. It was important that timing of crop cycles and rainfall cycles were a match (Caviglia et al., 2004).

Due to the importance of planting date, establishing radish after wheat may provide greater opportunities for successful growth and cover crop benefits. Sanford et al. (1973) observed that no-till double-crop systems provided the least delay in establishing a second crop. Research examing the effects of fodder radish in conventional and no-tilled fields, determined that during the fall to winter growth period there was a below ground input of 1.0 Mg C ha^{-1} in conventional till and 1.2 Mg C ha^{-1} in no-till at 0-45 cm (Mutegi et al., 2012). Dry matter above ground biomass at termination of radishes was 200 and 219 g m^{-1} for no-till and conventional till, respectively. With inclusion of C available in above ground biomass, estimated total system C contribution at incorporation was 162.4 g C m^{-1} in no-till and 169.1 g C m^{-1} in conventional till (Mutegi et al., 2011).

Weed suppression is a desirable trait from cover crops (Haramoto and Gallandt, 2005; Altieri et al., 2011; Lawley at al., 2011, 2012; Mohammadi, 2013). Research has shown weed suppression by a variety of Brassica species cover crops including forage radishes. Al-Khatib et al. (1997) found that weed populations of winter annual weeds such as common chickweed (*Stellaria media* L.), henbit (*Lamium amplexicaule* L.), and common lambsquarter were lowest following rapeseed and white mustard when compared to wheat in green pea (*Pisum sativum* L.) fields. Averaging over Brassica species, weed emergence of common lambsquarters and redroot pigweed was reduced by 24-31% compared with fallow land (Al-Khatib et al., 1997). Similarly, weed biomass of kochia (*Kochia scoparia* L.), sheperd's-purse (*Capsella bursa-pastoris* L.), and green foxtail (*Setaria viridis* L.) was reduced 20% in green pea, potato (*Solanum tuberosum* L.) and soybean (Haramoto and Gallandt, 2005). In Southern Brazil, fodder radish decreased weed biomass 0.26-1.19 kg ha^{-1} compared with fallow ground (Altieri et al., 2011). In Western New York, Brassica cover crops [oilseed radish, white senf mustard (*Sinapis alba* L.), kale (*Brassica oleracea* L,), canola (*Brassica campestris* L), turnip (*Brassica rapa* L.), and yellow mustard (*Brasicca compestriss* L.)] were planted and cover crop residues had greater winter annual weed suppression [common chickweed, henbit, and malva (*Malva moschata* L.)] when cover crops were planted earlier (25 August) than later planting dates (Stivers-Young, 1998). Winter annual weed suppression with radish in late March was 21-96% and 38-76% at the time of corn planting (Lawley et al., 2011)

An important factor determining the efficacy of cover crops is the ability of roots to grow and explore the soil for water and nutrients. As roots grew, they experienced impedance and decreased growth rates due to the force necessary to displace soil particles for elongation through the soil and root elongation rate decreased due to the increased resistance of soil particles to displacement from soil compaction (Clark et al., 2003). Soil compaction, especially in subsurface layers, may restrict deep root growth and adversely affect plant access to subsoil water as well as nutrients from the middle to late part of the growing season when rainfall is usually sparse and evapotranspiration is high. The resulting increase in drought stress may limit plant growth and yield (Chen and Weil, 2011).

Limited research has evaluated the effect of radish cover crops for grazing cattle. However, research has been completed examing grazing of other Brassica species.

Brassica species can be used as a supplemental or alternative forage (Guillard and Allinson, 1988; Wiedenhoeft and Barton, 1994; McCartney et al., 2009). Comparing summer and fall grown Bassica species, larger light intensities and temperatures in the summer increased dry matter production and structural components of the crops compared to fall grown crops (Guillard and Allinson, 1988). Digestible energy (DE) of roots and shoots of all Brassica crops was 37 to 70 MJ ha^{-1} greater in the summer than fall (Guillard and Allinson, 1988). Oilseed radish produced pasture yields of over 6200 kg ha^{-1} of dry matter (Berkenkamp and Meeres, 1988), while forage rape, turnip, and forage radish provided 4350 to 5690 kg ha^{-1} of dry matter with yield increasing from September harvest date a October and November harvest date (Kunelius and Sanderson, 1989). The objectives of this research were to evaluate the effects of grazing, tillage and planting date on forage radish establishment and production and to determine the impact of these practices on subsequent corn growth and yields.

MATERIALS AND METHODS

Field research was conducted in the fall of 2011 to 2012 and an additional site was established in 2012 to 2013 at the University of Missouri Greenley Research Center near Novelty (40°01'N, 92°11'W). Treatments were arranged in a split-split plot design with four replications. The main plot was the presence or absence of grazing, sub-plot was conventional tillage or no-till, and the sub-sub plots were 3 by 15 m radish planting dates (early and late September).

The fields had previously been brown mid-rib sorghum (*Sorghum bicolor* L.) to allow for early and late planting dates. A burndown application of paraquat at 0.4 kg ai ha^{-1} and crop oil concentrate at 1.4 kg a.i. ha^{-1} was applied on 29 August 2011 or glyphosate at 1.3 kg ai ha^{-1} and hydroxyl carboxylic acid at 0.3 L ae ha^{-1} on 31 August 2012. Strips in the field (22 by 15 m) were tilled two times using an 8756 Tilloll (Landoll, Marysville, Kansas) prior to planting (Figure 1). 'Tillage Radish' ((*Raphanus sativus L.*) Cover Crop Solutions LLC, Lititz, PA) were no-till drilled into the tillage sub-plots with a Great Plains no-till drill (Great Plains Ag, Salina, KS) at 10 kg ha^{-1} on 1 September 2011 and 31 Aug 2012 (early planting date) or 26 September 2011 and 1 October 2012. The late planting date corresponded with the first corn harvested in the region. The soil was a Kilwinning silt loam (fine, montmorillonitic, mesic, Vertic Ochraqualfs). On 11 October 2011 and 28 September 2012, main plots were grazed with black-angus beef cattle (*Bos Tauurus* Aberdeen angus) or were not grazed and fenced out using electrical fencing (Figure 1).

Radish tissue samples of tops and tubers from a 0.3 by 0.3 m quadrat were collected from all plots on 5 December 2011 and 10 December 2012. Samples were weighed for fresh weights, dried, and then weighed again for a dry weight. The number of plants were counted from the 0.3 by 0.3 quadrat.

Weed suppression of common chickweed (*Stellaria media* L.) and henbit (*Lamium amplexicaule* L.) in 2012 as well Carolina foxtail (*Alopecurus carolinianus* L.) and downy brome (*Bromus tectorum* L.) in 2013 was visually rated on a scale of 0 (no control) to 100% (complete weed suppression). Ratings were recorded on 13 and 22 March 2012 and 22 and 25 April 2013. In addition to visual control, tissue samples of common chickweed and henbit were collected within a 0.3 by 0.3 m quadrat in each plot.

The wet and dry weight of the total weed biomass was recorded as well as the density of individual weed species.

The following spring, corn (*Zea mays* L.) (DK 62-97) was no-till planted on 10 April 2012 and 4 May 2013 (John Deere 7000, Moline, IL) in the same field following radish cover crop treatments in 76 cm rows (Figure 1). Corn management information is reported in Table 1. On 23 and 30 May 2012 as well as 30 May and 6 June 2013, corn height and corn development stages were recorded. Ear leaf chlorophyll measurements (SPAD, Aurora, IL) and plant number were determined at 27 June 2012 and 1 August 2013 (VT, tasseling). Corn was harvested on 20 August 2012 and 1 October 2013 using a Wintersteiger plot combine (Wintersteiger, 4910 Ried, Austria, Dimmelstrasse 9). Grain samples were collected from each plot and were analyzed with a near infrared grain analysis machine (1241 Foss Infratec, Eden Prairie, MN) for oil, protein, starch, extractable starch, and grain density.

Data were subjected to ANOVA (SAS, 2010), and means separated using Fisher's Protected LSD (P=0.1). Radish production and weed control were reported separately for year, tillage, and planting date due to interactions. Downy brome and henbit were also reported separately by grazing, and corn grain data were presented separately by year and planting date only.

RESULTS AND DISCUSSION

Environmental conditions

Annual precipitation for 2011-2012 and 2012-2013 was below average compared to precipitation data from the last 10 years (Figure 2). During the radish growing season in 2011 from planting in September through winter, total rainfall was 267 mm (Figure 2a) which was similar to the 10-year average of 268 mm. Total precipitation for 2012 was 722 mm; however, there was only 215 mm of rainfall from May through August. This was 210 mm below the 10 year average when the majority of corn growth occurred. On the last day of August, 60 mm of precipitation occurred from the storms following Hurricane Isaac (Figure 2a). In 2013, total precipitation was 1003 mm but there was only 140 mm of rainfall from June through August with no rain in August (Figure 2b).

During the summer of 2012, temperatures were abnormally high with an average temperature of 23.7^{0}C from May through August and 30.7^{0}C average high temperature during this period (Figure 3a). In comparison, 2013 was relatively cool with an average temperature of 21.2^{0}C and an average high temperature of 27.3^{0}C through the summer (Figure 3b). Due to below average rainfall as well high average temperatures, specifically in 2012, the results of this research during 2011-2012 were achieved under drought conditions and in 2012-2013 under “flash drought” conditions.

Radish production

Radish planting date significantly impacted radish production, with a tillage*planting date interaction (*P*=0.005) for top biomass thus data were presented separately for year, tillage type, and planting date (Table 3). Tuber production (P<0.001) and number of plants (P=0.02) were significantly different across planting date. The earlier planting date (1 September 2011, 31 August 2012) produced 2534 to 4781 kg ha^{-1} more total biomass for tops and 2236 to 2732 kg ha^{-1} for tubers (P=0.0001, 0.0002) compared to the late planting date (Table 3). With the exception of number of plants ha^{-1} in 2012, all radish production data were greater from the earlier planting date compared with the later date across both years.

Research has evaluated the effect of planting date on radish production which has reported similar findings to those shown here. In Bangladesh, sowing time significantly affected growth and yield of radishes with the 1 November planting date producing the greatest tuber yield (81.8 Mg ha^{-1}) compared to the lowest yield on December 1 (68.7 Mg ha^{-1}) (Alam et al., 2010). In addition, 1 November produced the greatest root length per plant (25.6 cm root^{-1}) compared with the shortest on 1 December (23.5cm root^{-1}) and the maximum number of leaves (16.3 plant^{-1}) and leaf length (59.6 cm leaf^{-1}) were produced by plants sown on 1 November (Alam et al., 2010). All parameters showed decreased values as sowing date was delayed. Thus, these results correspond with previous research showing earlier planted radishes producing greater yields than later planted radishes.

Results were similar when radishes were planted every ten days beginning on 9 November in India. The second planting date (19 November) produced the maximum radish yield (28.4 Mg ha^{-1}), root length (24.45 cm root^{-1}) and root weight (0.097 kg root^{-1}), and the last planting date (9 December) produced the least yield (23.2 Mg ha^{-1}), root length (22.31 cm root^{-1}) and root weight (0.008 kg root^{-1}) (Pandey et al., 2009). The authors concluded that a delay in planting significantly reduced radish yield (Pandey et al., 2009). Similarly, black radishes (*Raphanus sativus* var. *niger*) were planted on 10, 20, and 30 September and 10 September radish yields were 21.9 Mg ha^{-1} but had decreased to 9.8 Mg ha^{-1} by 30 September in Iran (Ebrahimi et al., 2013). A delay in planting date meant shorter days and thus a decreased levels of light interception as well as fewer degree days required for crop growth (Ebrahimi et al., 2013).

Weed control

Winter annual weed control often followed radish production patterns. Weed suppression, plant density, and total weight were all significantly impacted by planting date of radishes (Table 4). Downy brome was present only in 2013. There was a year*tillage*planting date interaction for chickweed (P=0.001) and henbit (P=0.0006) (Table 4). Planting date was significant for chickweed and henbit control across years, and the earlier radish planting date had 20-55% greater chickweed and 34-72% henbit control compared to a later radish planting date and non-seeded controls. Earlier planted radish had greater weed suppression; however, radish planted in tilled areas had greater weed control than those in no-till areas across planting date. Across year and planting date conventionally tilled areas had 0-33% greater chickweed, 0-35% greater henbit, and 0-14% greater downy brome control than no-till radish. This was probably due to the effect of tillage on establishment of radish.

Conventional tillage may not be as important for species with tap roots such as radishes. Tap rooted species such as the forage radish and rapeseed (*Brassica napus* L.) penetrated compacted soil better than fibrous-rooted species thus making them better adapted for use in ‘biological tillage’ (Chen and Weil, 2010). Forage radish had more roots than winter rye (*Secale cereale* L.) at a 10-50 m depth and more than rapeseed at 20-45 cm under high compaction (Chen and Weil, 2010). In conventional and no-tilled fields, fodder radish had below ground input of 1.0 Mg C ha^{-1} in conventional till and 1.2 Mg C ha^{-1} in no-till at 0-45 cm (Mutegi et al., 2011). Dry matter above ground biomass at radish termination was 200 and 219 g m^{-1} for no-till and conventional till, respectively, which led to an estimated total system C contribution at incorporation of 162.4 g C m^{-1} in no-till and 169.1 g C m^{-1} in conventional till with the inclusion of C available in above ground biomass (Mutegi et al., 2011). This result supports the conclusion that better establishment of radish occurs in conventional tillage compared to no-till.

Total weed biomass had a year*planting date interaction (P=0.027). Early planted radishes had 538 to 1529 kg ha^{-1} less total weed biomass than later planted radishes and 720 to 3487 kg ha^{-1} less total weed biomass than non-seeded controls (Table 3). Total weed biomass was greater in 2013 than 2012, with the greatest weed biomasses in non-seeded controls of 3910 kg ha^{-1} in 2013 compared to 2340 kg ha^{-1} in 2012 which was probably due to the biomass contribution of downy brome.

There are two primary ways that forage radish can induce weed suppression: competition and allelopathy. Teasdale (1996) reviewed cover crop research and determined that weed suppression was species specific in terms of both the cover crop and weed. Lawley et al. (2012) argued that the main mechanism of weed suppression by forage radishes was rapid canopy development and fall cover crop competition. Kruidhof et al. (2008) stated that the competitiveness of fodder and oilseed radish was strongly correlated to light interception early in the season. Fodder radish had the shortest T_{50} (time to reach 50% soil cover) value as well as the largest biomass production; leading to conclusions that light interception correlated with greater weed suppression (Kruidhof et al., 2008). Lawley et al. (2012) hypothesized that rapid canopy development may have shifted or changed the phytochrome state of weed seeds leaving them dormant or affecting germination rates. Forage radish provided complete weed suppression in early fall through the winter and into early March when weed cover was only 0-3%; however, weed suppression from radishes did not extend to the next growing season and a post emergence herbicide was needed to be applied to avoid yield reduction in corn due to weed interference in Maryland (Lawley et al., 2011). However, wild radish reduced weed biomass of Florida pusley (*Richardia scabra* L.), large crabgrass (*Digitaria sanguinalis* L.), and ivy-leaf morning-glory (*Ipomoea hederacea* L.) 52% compared to weedy cover (Malik et al., 2008).

Some research has shown weed suppression was attributed to allelopathy. Allelochemicals typically reach the environment through exudation from the roots, leaching from stems and leaves, and decomposing of plant material (Xuan et al, 2005). Among Brassica cover crops, radish is of particular interest as there has not been a lot of research done using it as an allelopathic plant. Norsworthy (2003) showed that germination, emergence, radicle growth, and shoot fresh weight of all weed species [sickle pod (*Senna obtusifolia* L.), prickly sida (*Sida spinosa* L.), and yellow nutsedge (*Cyperus esculentus* L.)] evaluated were reduced by extract of forage radish in comparison to the controls. Johnsongrass (*Sorghum halepense* L.) suppression by Brassica species (round white, garden, black, and little radish, rapeseed, and turnip) was observed, and the amount of isothiocyanates showed that allelopathy played a role in johnsongrass suppression (Uremis et al., 2009). Isothiocyanate production and allelopathy were not measured in this experiment. However, results showed that highest weed control occurred with an earlier planting date (Table 3) where there was also the greatest radish production (Table 3). This may have occurred from greater canopy development and competition for light which affected winter annual weed establishment and emergence.

The presence or absence of grazing on radishes did have significant impact on downy brome (P=0.044) and henbit (P=0.004) (Table 5). This may have been due to soil compaction from cattle while they grazed, consumption of the winter annual weeds by cattle, or perhaps disturbance of weed seed beds. Limited research has evaluated the effect of radish cover crops for grazing cattle. Animal grazing can influence weeds either directly by eating or damaging the weeds, or indirectly by conditioning and making land more competitive and resistant to subsequent weed populations (Johnston and Peake, 1960; Popay and Field, 1996). Johnston and Peake (1960) showed that over a five year-period in Alberta, Canada, basal area of leafy spurge (*Euphorbia esula* L.) was reduced 98% from grazing of sheep. High intensity low-frequency (HILF) grazing by cattle significantly reduced Canadian thistle (*Cirsium arvense* L.) by 81,000 plants ha^{-1} over three years (De Bruijn and Bork, 2006). Finally, Popay and Field (1996) noted that grazing animals can reduce seed numbers of species that could become weeds in the cropping phase. In this system, the pasture phase was the forage radish followed by the cropping stage which was corn. Perhaps by grazing radishes weed suppression of winter annual weeds could be increased as well as adding additional forage for cattle production.

Corn production

Corn was no-till planted following radish seeding dates, grazing, and tillage treatments. There was no effect of tillage radish on ear leaf chlorophyll content and final plant population (data not presented). There were no differences among treatments for any corn production measurements in 2012 except for oil and protein concentration (Table 6). Drought conditions led to low overall corn yields (2435 to 2580 kg ha^{-1}) in 2012. There was a year*planting date interaction for grain yield in 2013 (P=0.04). Corn following later planted radishes had 665 kg ha^{-1} greater yields compared to early planted radishes and 550 kg ha^{-1} compared to non-seeded controls. Research has shown that a radish cover crop may increase drought tolerance of the subsequent crop due to root characteristics (Williams and Weil, 2004; Chen and Weil, 2011), but our research on claypan soils does not support this claim. The burndown herbicide application may have helped suppress weeds at the later planting date and reduced the impact of winter annual weeds on yields compared to the non-seeded control. Channels produced by cover crop roots in fall and winter when soils are relatively moist may facilitate the penetration of compacted soils by subsequent crop roots in summer months when soils are relatively hard and dry (Creswell and Kirkegaard, 1995; Williams and Weil, 2004; Chen and Weil, 2011). Forage radish increased soybean yields 200 kg ha^{-1} and the impact of the preceding cover crop was greatest during severe drought and high compaction (Williams and Weil, 2004). Forage radish and rapeseed were most effective in reducing the effects of soil compaction on corn, and corn had more roots at a 45 cm depth in the forage radish treatments (Chen and Weil, 2011). However, results from this research did not show greater drought tolerance for corn following early planted radishes.

Grain quality (percent oil and grain density) had year*planting date interactions and planting date interactions (percent protein and extractable starch) (Table 6). There were no significant differences in grain composition in 2012, possibly from the poor growing conditions and yield. Later radish planting date had greater protein concentration and grain density compared to the earlier planting and non-seeded control in 2013. However, the earlier planting date and non-seeded control had greater oil and extractable starch concentrations than the later planting date.

Research on forage radish nutrient uptake and the subsequent release of nutrients as well as reduced nutrient leaching has shown significant N uptake and reduced leaching (Justes et al., 1999; Kristensen and Thorup-Kristensen, 2004; Dean and Weil, 2009; Constantin et al., 2010; Munkholm and Hansen, 2012; Sapkota et al., 2012). Fodder radish reduced leaching by 79% compared to non-catch cover crop controls (Sapkota et al., 2012). Kristensen and Thorup-Kristensen (2004) observed that the fodder radish had a root system that grew deeper into the soil profile than winter rye and ryegrass, leaving only 18 kg N ha^{-1} residual soil NO_3 in comparison to winter rye (59 kg N ha^{-1}) and ryegrass (87 kg N ha^{-1}). Similarly, Munkholm and Hansen (2012) noted that fodder radish had the greatest N uptake in the above ground biomass with a value of 55 kg N ha^{-1}, compared to dyer's woad (31 kg N ha^{-1}) and ryegrass (37 kg N ha^{-1}) in Denmark. Radish plants took up more N and removed nitrate more efficiently than either rape or rye (Dean and Weil, 2009). In eastern France, 29 kg N ha^{-1} leached in the radish treatments compared to 60 kg N ha^{-1} for the control (Justes et al., 1999). At incorporation in January, total N uptake by roots and shoots was 47 kg N ha^{-1} for the radish (Justes et al., 1999).

Future research should expand upon N rates applied for corn and the impact on crop growth following radishes.

Research has also shown that forage radish was unique in terms of P cycling (White and Weil, 2011). After three years, forage radish increased P concentration in the soil at a depth of 0-2.5 cm resulting in values of 101 mg P kg^{-1} compared to rye (82 mg P kg^{-1}) (White and Weil, 2011). Across all cover crops, fodder radish (36 kg S ha^{-1}) had the greatest aboveground S uptake, compared to ryegrass (8 kg S ha^{-1}) and winter rape (22 kg S ha^{-1}) as well as the highest soil S removal (Eriksen and Thorup-Kristensen, 2002). High concentrations of S were found in the top 0.5 m implying that fodder radish was able to trap sulfate in the fall and mineralize the S in the following spring in the top layers of the soil, thus preventing leaching and providing S to the subsequent crop (Eriksen and Thorup-Kristensen, 2002).

CONCLUSION

Annual precipitation for 2012 and 2013 was below average as compared to the precipitation data from the last 10 years. Due to below average rainfall and high average temperatures, specifically in 2012, the research completed in the growing years of 2011-2012 and 2012-2013 were done under drought conditions, and extreme drought conditions for 2011-2012. Time of planting of radishes significantly impacted radish production, with the earlier planting date (1 September 2011, 31 August 2012) producing greater total biomass for tops and tubers at both sampling dates. Winter annual weed control often followed radish production patterns. Weed suppression, plant density, and total weed weight were all significantly impacted by planting date of radishes with earlier planting dates having greater weed control. There were no differences among treatments and factors for any corn production measurements in 2012, and in 2013 there was no effect of tillage radish on chlorophyll content and final plant population. In 2013, corn following later planted radishes had greater yields compared to early planted radishes and non-seeded controls. These results showed that if planted early enough in the fall, a farmer in upstate Missouri could produce forage radishes and may achieve winter annual weed suppression following the radishes, but use of radishes did not increase corn yield in drought years.

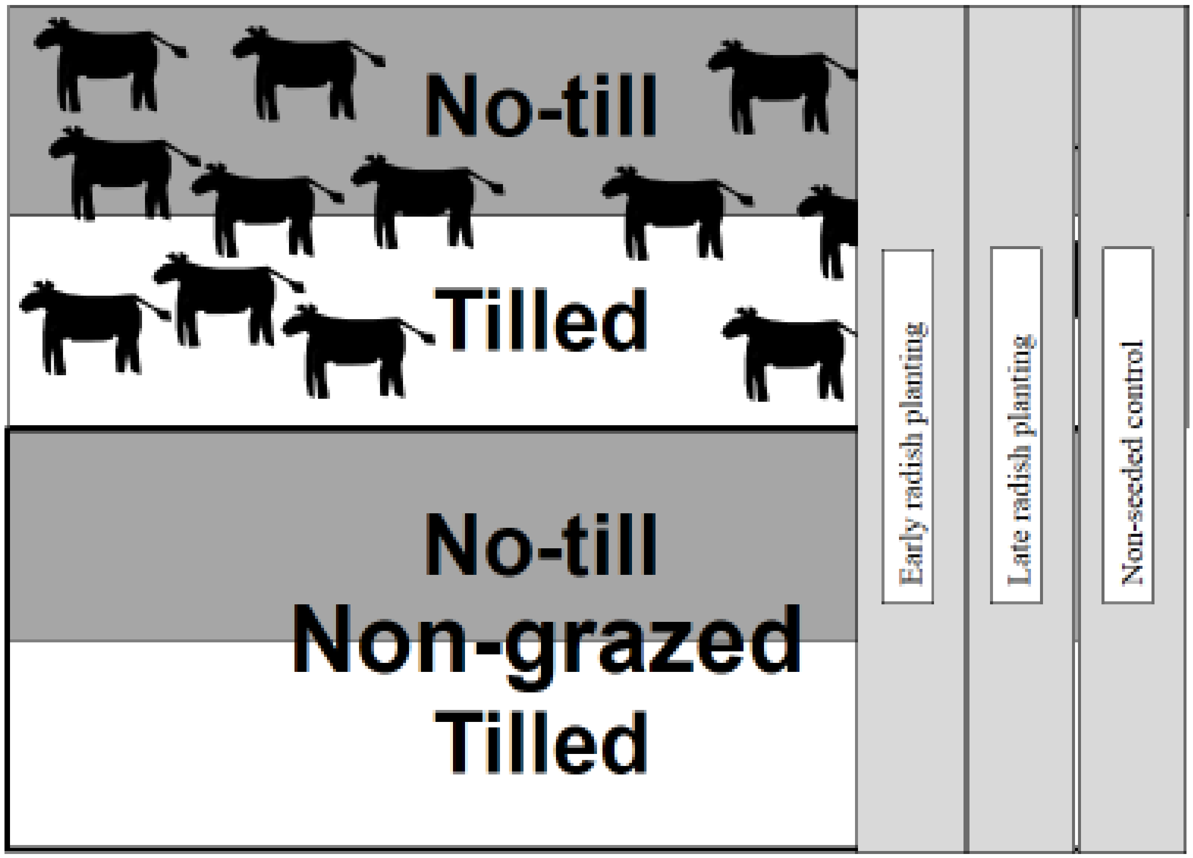

Figure 4.1. Diagram of a single field repetition of the experiment with main plot (grazing), sub-plot (tillage), and sub-sub-plot (planting date).

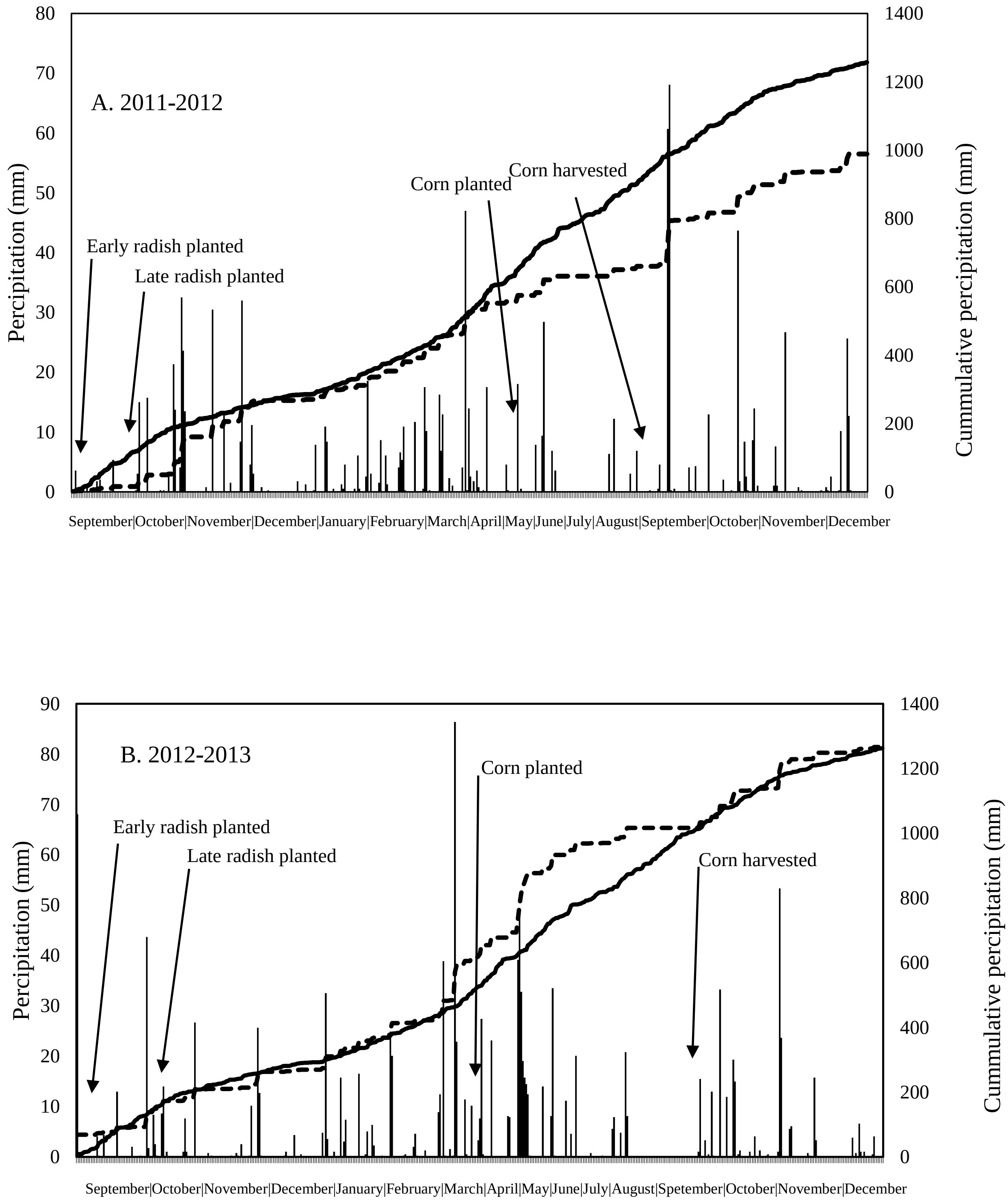

Figure 4.2. Daily (bar) and cumulative precipitation data for individual years (dash line) and 10-year average (solid line) for experiments from 2011-2012 (A) and 2012-2013 (B).

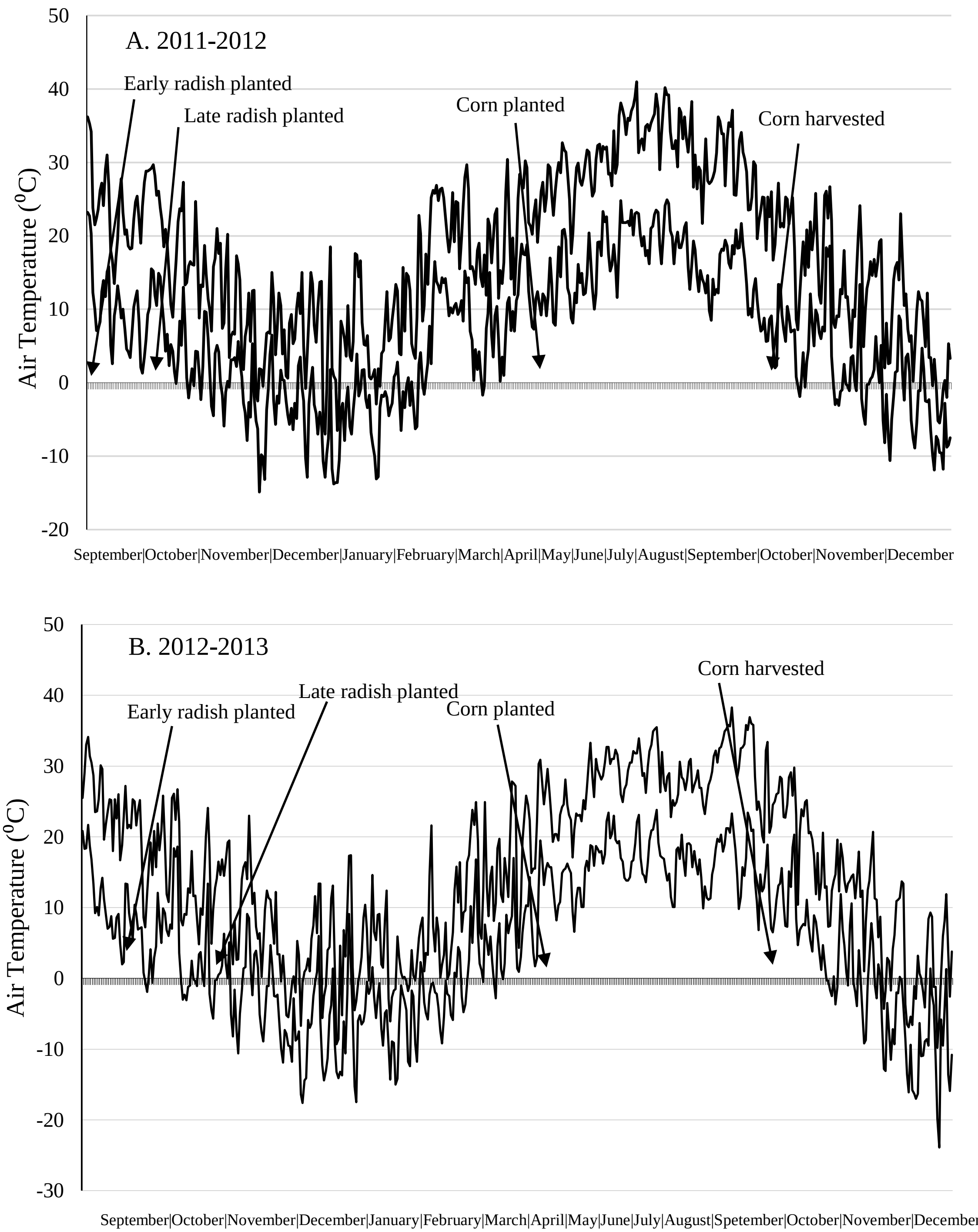

Figure 4.3. Daily maximum and minimum air temperature data for experiments from 2011-2012 (A) and 2012-2013 (B).

Table 4.1. Corn management information in 2012 and 2013 following radish plots planted the previous year.

Management information	2012	2013
Planting Date	9 April	4 May
Hybrid	DKC 62-97	DKC 62-97
Population (seeds ha^{-1})	81,400	81,400
Fertilizer	9 April Anhydrous ammonia at 167 kg N ha^{-1} 12 April N-P-K at 19-80-133	1 May Anhydrous ammonia at 167 kg N ha^{-1}
Weed management	2 April Saflufenacil at 0.03 kg ai ha^{-1} + glyphosate at 0.9 kg ai ha^{-1} + NIS at 0.25% v/v + 32% UAN at 2.35 L ha^{-1}	26 April Glyphosate at 1.3 kg ai ha^{-1} + saflufenacil at 0.25 kg ai ha^{-1} + MSO at 1% v/v + AMS at 22.7 g L^{-1}
	13 May Acetochlor at 2.6 kg ai ha^{-1} + glyphosate at 1.3 kg ai ha^{-1}	21 May Acetochlor at 2.6 kg ai ha^{-1} + glyphosate at 1.3 kg ai ha^{-1} + NIS at 0.25% v/v + 32% UAN at 2.35 L ha^{-1}
	4 June Glyphosate at 1.3 kg ai ha^{-1} + mesotrione at 0.11 kg ai ha^{-1} + AMS at 22.7 g L^{-1} + COC at 2.3 L ha^{-1}	

†Acetochlor, 2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide; anhydrous ammonia, NH_3; ammonium sulfate, Liase $(NH_4)_2$ SO_4; crop oil concentrate, alkylphenoxy polyethoxy ethanols; glyphosate, N-(phosphonomethyl)glycine; mesotrione, 2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione; methylated seed oil, methyl ester; non-ionic surfactant, 3-oxapentane-1,5-diol, propane-1,2,3-triol, alklphenol ethoxylate, polydimethylsiloxane.

‡Abbreviations; AMS, ammonium sulfate; COC, crop oil concentrate; NIS, non-ionic surfactant; MSO, methylated seed oil; UAN, urea ammonium sulfate

Table 4.2. Initial selected soil characteristics for 2012 and 2013.

Year	pH	OM	NA	CEC	Ca	Mg	K
	(0.01 $CaCl_2$)	%	cmol kg^{-1}		-------	kg ha^{-1}	--------
2012	5.3	4.4	4.7	13.8	3482	329	209
2013	5.3	4.0	5.0	14.0	3477	327	208

†NA = neutralizable acidity; OM = organic matter; CEC = cation exchange capacity.

Table 4.3. Radish plant number, top and tuber dry weight biomass in 2012 and 2013 by planting date and tillage type. Data were averaged over grazing system.

	2012						2013					
	Tilled			No-till			Tilled			No-till		
Radish production	Early	Late	LSD (*P*=0.1)	Early	Late	LSD (*P*=0.1)	Early	Late	LSD (*P*=0.1)	Early	Late	LSD (*P*=0.1)
Plant number (1000 plant ha^{-1})	834	619	NS	646	619	NS	377	296	63	484	242	63
Tuber biomass (kg ha^{-1})	3081	349	541	2742	506	1021	2561	6	702	2680	2	736
Top biomass (kg ha^{-1})	4274	1402	1349	3960	1426	1608	4909	128	667	4225	45	1645

Table 4.4. Weed suppression data by tillage treatment and radish planting date (early, late, and none) in 2012 and 2013.

	2012								2013							
	Conventional till				No-till				Conventional till				No-till			
Weed species	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)
	Control (%)															
Chickweed	57	3	0	17	24	4	2	12	84	44	0	33	81	26	0	32
Henbit	77	5	0	10	42	8	2	18	89	49	0	33	82	38	0	34
Downy brome	Ø †	Ø	Ø	Ø	Ø	Ø	Ø		90	61	0	34	76	54	0	31
	Density (1000 plants ha^{-1})															
Chickweed	0	0	0	0	0	0	2000	2000	0	360	360	530	0	360	2700	840
Henbit	0	0	0	0	0	0	1400	7800	0	6500	9200	4400	240	14000	1100	4000
Downy brome	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	610	480	12000	4900	2700	850	14000	4600
	Total dry weight (kg ha^{-1})															
All weeds	283	1812	2340	548	1163	1701	1883	566	101	1207	3134	987	423	1663	3910	1322

† Weed suppression was not present. Downy brome was not present in 2012.

Table 4.5. Downy brome and henbit density in grazed and non-grazed areas in 2012 and 2013.

	2012								2013							
	Grazed				Non-grazed				Grazed				Non-grazed			
Weed species	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)
	---------- 1000 plants ha^{-1} ----------															
Downy brome	Ø †	Ø	Ø	Ø	Ø	Ø	Ø	Ø	2700	970	9700	4100	610	360	16000	4300
Henbit	0	0	14000	7800	0	0	0	0	0	11000	6800	6100	240	10000	3500	5500

† Downy brome was not present in 2012.

Table 4.6. Corn grain yield and quality response to radish planting date (early, late, and none) in 2012 and 2013.

	2012				2013			
Corn production	Early	Late	None	LSD (*P*=0.1)	Early	Late	None	LSD (*P*=0.1)
Yield (kg ha^{-1})	2435	2580	2560	NS†	9800	10465	9915	355
Oil (%)	2.6	2.5	2.6	0.1	3.2	3.1	3.3	0.1
Protein (%)	10.1	10.2	10	0.1	9	9.5	8.8	0.2
Starch (%)	74.6	74.6	74.5	NS	74.1	73.9	74	0.2
Extractable starch (%)	65.3	65.2	65.2	NS	67.6	66.7	70	0.4
Grain Density (%)	1.2	1.2	1.2	NS	1.3	1.3	1.3	NS

†NS = non-significant

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CHAPTER 5 – EFFECT OF PLANTING DATE AND NITROGEN RATES ON FORAGE RADISH BIOMASS PRODUCTION IN UPSTATE MISSOURI

ABSTRACT

There are many benefits of cover crops including increased yield of a marketable crop, greater yield stability, reduced fertilizer inputs, weed suppression, and interruption of disease or pest cycles. Radish (*Raphanus sativus* L.) has been increasing in popularity as a cover crop. Planting date of radishes has been found to influence radish production. It is a standard practice in Missouri agriculture to add nitrogen fertilizer to non-leguminous crops such as wheat and corn regardless of the nitrogen form; however, there is limited research on the effects on nitrogen rates on radish production or if nitrogen is needed since radish is used to trap N. The objective of this research was to evaluate radish biomass production as impacted by radish planting date and nitrogen fertilizer amount following wheat. Across planting date and year, the non-fertilized controls had shorter radishes than any nitrogen rate. Chlorophyll content of radish tops differed across year, planting date, and nitrogen rates. As nitrogen rates increased chlorophyll content increased. Although the greatest chlorophyll levels were achieved at 67 kg N ha^{-1}, chlorophyll levels did not significantly increase after 33 kg N ha^{-1}. Radish top dry biomass production was greatest (30 to 2945 kg ha^{-1}) at the first planting date in 2012 and 2013 compared to the other planting dates. This research demonstrated that radishes should be planted in late summer prior to 1 September for optimum radish biomass production and to achieve maximum yields for farmers in upstate Missouri.

INTRODUCTION

A cover crop refers to a plant that was grown in rotation during periods when main crops are not grown (Mohammadi, 2013). Many benefits of cover crops have been identified, but the most direct positive being increased yield of a marketable crop. Other benefits of cover crops included greater yield stability, reduced fertilizer inputs, weed suppression, breakage of disease or pest cycles, increased soil and water quality, and increased nutrient cycling efficiency (Thiessen Martens et al., 2001; Snapp et al., 2005; Hoffbeck et al., 2008). There were also several benefits that specifically dealt with soil conservation and the reduction of soil erosion, nitrate leaching, and chemical runoff (Snapp et al., 2005). Other soil benefits included increased water infiltration, soil moisture retention, improved soil tilth, and nutrient efficiency (Teasdale, 1996). Finally, planting a cover crop replaced an unmanageable weed population such as common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retrofelxus* L.), and some annual grasses with a manageable crop or mulch population (Teasdale, 1996). Determining the seeding timing, type, and desired benefits from the cover crop are important for adoption and utilization. For winter cover crops, a cash crop does not have to be sacrificed, and planting normally occurs in the fall after harvest of an annual cash crop (Snapp et al., 2005).

Radish (*Raphanus sativus* L.) has been growing in popularity as a cover crop. It boasts a myriad of possible benefits including improved soil aeration, weed suppression, nutrient capture, and possible yield increases to the following grain crops. Sojka et al (1991) noted that in addition to weed suppression, radish offered typical cover crop benefits such as reduced soil erosion, increased soil moisture infiltration and soil organic matter. In Maryland, forage radishes planted before September 1 produced 3.9 to 6.6 Mg ha^{-1} shoot dry matter and 1.3 to 3.2 Mg ha^{-1} tuber dry matter (Lawley et al., 2011). There was no difference in the subsequent corn (*Zea mays* L.) crop yield among cover crops; however, there was reduced corn populations in the several site years following annual ryegrass (*Lolium perenne* L.). Radishes had a small C:N ratio and winter killed leaving a low residue environment for spring crop planting. Cover crops that did not overwinter, such as forage radish, left less residue which simplified spring seeding, provided warmer soils, and allowed for more timely planting of subsequent crops compared to a cover crop that overwintered such as ryegrass (Lawley et al., 2011).

Planting date of radishes was found to influence production (Pell at al., 1993; Pandey et al., 2009; Alam et al., 2010; Ebrahimi et al., 2013). Sowing date influenced vegetative and reproductive growth period as well as the balance between them and ultimately affected yield (Ebrahimi et al., 2013). An appropriate sowing date helped reduce damage caused by cold or heat as well as pests, diseases, and weeds. Also a favorable planting date coincided with climatic factors that affected production such as coincidence of flowering with suitable temperature were found important for good establishment (Ebrahimi et al., 2013). Proper radish sowing time depended on the existing environment as well as variety selection. Growers tended to manipulate these sowing times to obtain better growth and greater yields (Alam et al., 2010). Timing of planting may be significant due to light available and temperature. Light treatments affected radish growth and yield (Schmitt et al., 1986; Pell et al., 1993). In a pot experiment, radish growth rates and mass decreased with decreasing light (Schmitt et al., 1986) and photoperiod influenced biomass partitioning (Pell et al., 1993). In addition to the amount of light available, the season may impact radish production (Pell at al.1993). In growth chambers, radishes exhibited a more adverse response to soil moisture deficits in the spring than fall. Soil moisture induced reductions in CO_2 fixation and thus subsequent biomass accumulation (Pell et al., 1993). The authors hypothesized spring conditions led to a large relative growth rate and more rapid water loss by the shoot thus favoring a negative impact of reduced soil moisture which was more evident in the spring. It was important that timing of crop cycles and rainfall cycles were a match (Caviglia et al., 2004).

Due to the importance of planting date, establishing radish after wheat may provide greater opportunities for successful growth and cover crop benefits. Establishing a second crop early was important because after 1 December the rate of decline in yield with delayed sowing was about 1.3% per day for sole-crops and 0.5% per day for double-crops (Caviglia et al., 2011). Sanford et al. (1973) observed that no-till double-crop systems provided the least delay in establishing a second crop. Plant available water affected winter wheat grain production when researching the effects of tillage and nitrogen rates on wheat production (Halverson et al., 1999). No-till and minimal tillage yielded higher than conventional tillage, with grain yields of 2022 kg ha^{-1}, 1968 kg ha^{-1} and 1801 kg ha^{-1}, respectively (Halverson et al., 1999).

It is standard practice in Missouri agriculture to add nitrogen fertilizer to non-leguminous crops such as wheat and corn regardless of the nitrogen form. However, there is limited research on the effects on nitrogen rates on radish production (Sanchez et al., 1991; Hochmuth et al., 1996) or if nitrogen is needed since radish is used to trap N. Nitrogen fertilizer increased seed yield of radish by 1.4 q ha^{-1}, but yields increased to 2.3

q ha^{-1} when 30 kg ha^{-1} of phosphorus was added (Sharma, 2000). Research in Pakistan showed that the addition of nitrogen fertilizer significantly increased radish biomass and yield compared to no-fertilized controls (Asghar et al., 2006). However, research in Florida reported that no response was observed with nitrogen fertilizer and thus it was not recommended for radish production (Hochmuth et al., 1996). Other research determined that radishes used soil mineral N, and that N fertilization did not increase radish yields in that system (Sanchez et al., 1991). The objective of this research was to evaluate radish biomass production as impacted by radish planting date and nitrogen fertilizer rate.

MATERIALS AND METHODS

Field research was conducted at the University of Missouri Greenley Research Center near Novelty (40°01'N, 92°11'W) in 2012 and 2013. The experiment was arranged in split-plot design. The main plot was planting date and sub-plot was nitrogen fertilizer rate. Four replications were planted in 3 by 10.5 m plots on a Kilwinning silt loam (fine, montmorillonitic, mesic, Vertic Ochraqualfs). In a field that had previously been winter wheat (*Triticum aestivum* L.), ‘Tillage radishes’ (*Raphanus sativus* L.) (Cover Crop Solutions LLC, Lititz, PA) were no-till drilled (Great Plains Ag, Salina, KS) at 10 kg ha^{-1} every two weeks. These dates were 1 August, 17 August, 30 August, 12 September, and 28 September in 2012 and 11 July, 1 August, 14 August, 28 August, and 11 September in 2013. Nitrogen in the form of ammonium nitrate (34-0-0) at 0, 17, 33 and 67 kg N ha^{-1} was applied across all radish planting dates on 5 October 2012 and 12 September 2013 using a hand spreader. Radish heights were recorded at 0, 6, 13, 16, 23, 27, 34, 40, 48, 55, 62, 68 days after fertilizer treatment (DAT). Height of radishes were taken 6, 12, 18, 25, 33, and 39 DAT. Clethodim at 0.07 kg ai ha^{-1} and crop oil concentrate at 2.4 L ha^{-1}

were applied on 29 October 2012 to reuce interference with wheat. On 12 November 2012 and 22 October 2013 chlorophyll measurements of the radish tops were recorded by a hand SPAD meter (SPAD, Aurora, IL). Radish top biomass was collected from a 0.3 by 0.3 m quadrat on 13 November 2012 and 12 November 2013. Wet weights were recorded immediately after collection, samples were dried, and dry weights were recorded.

Data were subjected to ANOVA (SAS, 2010), and means separated using Fisher's Protected LSD (P=0.1). Radish heights and chlorophyll content were reported separately for year, planting date, and nitrogen rate due to interactions. Radish biomass production was separated by year and planting date, but analyzed across nitrogen rates. Dry weights were used instead of fresh weights as both weights represented the same amount of biomass produced, except fresh weights included the water weight as well.

RESULTS AND DISCUSSION

Environmental conditions

Annual precipitation for 2012-2013 was similar to the 10 year average (Figure 1). During the radish growing season in 2012 from planting in August to a killing frost in winter total rainfall was 339 mm (Figure 1a) which was similar to the 10-year average of 381 mm. Total precipitation for 2012 was 722 mm; however, there was only 215 mm of rainfall from May through August, 210 mm below the 10 year average, meaning that the radishes were planted following drought conditions. On the last day of August, 60 mm of precipitation occurred from the storms following Hurricane Isaac (Figure 1a). In 2013, total precipitation was 1003 mm but there was only 140 mm of rainfall from June through August and absolutely no rain in August (Figure 1a). In addition, rainfall in September and October was only 123 mm, 58 mm below the 10 year average, before the last two days of October when there were 77 mm of rainfall. Thus for the second year, radishes grew under dry conditions (Figure 2b).

During the summer of 2012, temperatures were abnormally high with an average temperature of 23.7^{0}C from May through August and 30.7^{0}C average high temperature during this period (Figure 2a). During the radish growth period of August through October there was an average temperature of 17.4^{0}C. In comparison, 2013 was relatively cool with an average temperature of 21.2^{0}C and an average high temperature of 27.3^{0}C through the summer (Figure 2b). From July through October the average temperature was 19.9^{0}C. Due to below average rainfall as well high average temperatures, specifically in 2012, the results of this research during 2012 were achieved under drought conditions and in 2013 under “flash drought” conditions.

Radish height

Radish heights were impacted by planting date and nitrogen amount (Table 1). Across planting dates radish height reached a maximum at 23 DAT in 2012 and 40 DAT in 2013 (Figure 3). In general, earlier planting dates had taller radishes than later plantings for all measurement dates across nitrogen rates (Table 1). The first planting date was taller than the rest in 2012 with the exception of 34 DAT for 17 and 67 kg N ha^{-1}, when the first and second planting dates were taller than the other 3 planting dates. In 2013, the first or the first two planting dates had greater heights than the other planting dates with the exception of 13 and 40 DAT at 67 kg N ha^{-1} when the first three planting dates were taller than the last two (Table 1).

Nitrogen rates also impacted radish height. Across planting date and year, the non-fertilized controls had shorter radishes than any nitrogen amount. The amount with the greatest radish heights across planting date in 2012 was 33 kg N ha^{-1}. After that rate, at 67 kg N ha^{-1}, heights did not increase with more added nitrogen (Figure 1). Results were different in 2013. With the exception of 13 DAT at the 2nd planting date, 6, 13, and 40 DAT at the 3rd planting, 13 and 40 DAT at the 4th planting, 6 DAT at the 5th planting, there were no differences among radish heights due to nitrogen rates which was probably due to limited rainfall during this period.

There is limited research on radish heights as influenced by planting date. Research on planting time of radish supports the results that earlier planted radishes having greater growth. Research has shown that earlier planted radishes had greater yields than later planted radishes (Pandey et al., 2009; Alam et al., 2010; Ebrahimi et al., 2013). However, crop growth rates are impacted by available light (Liu et al., 2013; Zhang et al., 2014). The exclusion of both ultra-violet radiation (UV-B and UV-A) caused elongated internodes on soybean plants resulting in 198 to 237% increase in plant height (Zhang et al., 2014). Similarly, Liu et al. (2013) reported 16 to 44% decreased plant height when soybean was exposed to enhanced UV-B. According to research completed in Davis, California, a 16 hour photoperiod was optimal for flowering of radish (Suge and Rappaport, 1968). It is probable that radishes planted earliest had the best light as well as temperature conditions for optimal growth and height (Figure 3). Greatest radish heights were reached at 23 DAT across planting dates in 2012 due to optimal growth conditions and height did not increase after that due to the plant's physiological changes to reproductive growth (Table 3). Finally, research completed in India reported that radish height increased with nitrogen rate by 8.6 to 22 cm compared to the non-fertilized control (Sharma, 2000). The authors attributed this to possible increased cell division and elongation (Sharma, 2000). Similar patterns were observed with increased radish height as N rates increased.

Radish chlorophyll content

Radish chlorophyll content was variable and was impacted by year, planting date, and nitrogen rate, with a year*planting date*nitrogen rate interaction (P=0.09) (Table 3). In 2012, the first planting date (17 August) had the greatest chlorophyll concentration than the other planting dates regardless of nitrogen application rate. However, the third and fourth planting dates (14 and 28 August) had significantly greater chlorophyll content than the other planting dates in 2013.

Nitrogen rates also impacted chlorophyll content. In general across planting dates, increased rates of N led to increased chlorophyll content of radishes in 2012 (Figure 4). With the exception of the 28 September 2012 planting date, 67 kg ha^{-1} had the greatest chlorophyll levels by 2.9 to 8.5 SPAD units. Interestingly, chlorophyll increases were not significant above 33 kg ha^{-1} as measured by LSD values. In 2013, chlorophyll content in radishes did not follow nitrogen rates as closely which was probably due to drier conditions. At the last two planting dates (28 August and 11 September) the greatest chlorophyll content recorded was at the greatest N level (67 kg ha^{-1}); however, the previous three planting dates reached their largest chlorophyll levels at only 17 kg ha^{-1} by 2.1 to 3.5 SPAD units (Figure 4).

Radish biomass

Planting date significantly impacted radish top biomass production (Figure 5). A year*planting date interaction (P=0.0003) implicated that across nitrogen rates, planting date affected radish growth. Across years, the first planting date produced the greatest biomass yields with 1 August 2012 producing 920 to 2945 kg ha^{-1} more biomass compared with 30 August and 28 September respectively, and 11 July 2013 producing 1700 kg ha^{-1} more biomass compared to 11 September (Figure 5). Across all planting dates, there was greater radish production in 2013 compared to 2012. This may have resulted from cooler conditions in 2013 providing better growth conditions for radishes regardless of planting date.

Research evaluating the effect of planting date on radish production has reported similar findings to those shown here. In Bangladesh, sowing time significantly affected growth and yield of radishes with the 1 November planting date producing the highest root yield (81.8 Mg ha^{-1}) compared to the lowest yield on December 1 (68.7 Mg ha^{-1}) (Alam et al., 2010). In addition, 1 November produced the greatest root length per plant (25.6 cm $root^{-1}$) when compared with the shortest on 1 December (23.5cm $root^{-1}$) and the maximum number of leaves (16.3 $plant^{-1}$) and leaf length (59.6 cm $leaf^{-1}$) were produced by plants sown on 1 November (Alam et al., 2010). All parameters showed decreasing trend as sowing date was delayed.

Results were similar when radishes were planted every ten days beginning on 9 November in India. The second planting date (19 November) produced the maximum radish yield (28.4 Mg ha^{-1}), root length (24.45 cm $root^{-1}$) and root weight (0.097 kg $root^{-1}$), and the last planting date (9 December) produced the least yield (23.2 Mg ha^{-1}), root length (22.31 cm $root^{-1}$) and root weight (0.008 kg $root^{-1}$) (Pandey et al., 2009). The authors thus concluded that delay in planting significantly reduced radish yield (Pandey et al., 2009) In Iran, black radishes (*Raphanus sativus* var. *niger*) were planted on 10, 20, and 30 September and 10 September radish yields were 21.9 Mg ha^{-1} but had decreased to 9.8 Mg ha^{-1} by 30 September (Ebrahimi et al., 2013). Delay in planting meant shorter days and thus a decreased level of light interception as well as fewer degree days required for crop growth (Ebrahimi et al., 2013).

Although research concludes that nitrogen fertilizer can improve crop yields (Vos and van der Putten, 1997; Kristensen and Thorup-Kristensen, 2004; Dean and Weil, 2009; Constantin et al., 2010; Sapkota et al., 2012) there is limited research about the impact of nitrogen fertilizer on radish in particular. Nitrogen fertilization did not impact radish yield in 7 of 8 experiments conducted in Florida (Sanchez et al., 1991). The total amount of fertilizer-derived N from the marketable radishes averaged only between 2 to 8 kg N ha^{-1}, prompting the authors to determine that the radishes used soil mineral N, and that N fertilization did not increase radish yields in that system (Sanchez et al., 1991). The recommended nitrogen fertilizer amount in Pakistan was 60 kg N ha^{-1} and increased fresh radish biomass by 73% and yield by 14%, with an increase of 0.19 kg plant^{-1} and 32 Mg ha^{-1} when compared to a non-fertilized control (Asghar et al., 2006). Results revealed that enriched compost with 50% recommended nitrogen fertilizer had similar yields compared to 100% N fertilizer alone, and the authors stated that this could possible half of the nitrogen fertilizer (Asghar et al., 2006).

CONCLUSION

This research was conducted during drought conditions in 2012 and 2013. There was limited precipitation in the summer of 2012 preceding the planting of radishes and 2013 experienced a flash drought with no precipitation in August and little rainfall September through October. Radish heights were impacted by planting date and nitrogen rate. In general, earlier planting dates had taller radishes than later planted for all measurement dates across nitrogen rates. Across planting date and year, the non-fertilized controls had shorter radishes than any nitrogen rate. The greatest radish heights were produced at 33 kg N ha^{-1}, and after that, increasing N up to 67 kg N ha^{-1}, heights did not significantly increase. Chlorophyll content of radish tops differed across year, planting date, and nitrogen rates. Nitrogen rates impacted chlorophyll content while the greatest chlorophyll levels were achieved at 67 kg N ha^{-1}; however, chlorophyll levels did not significantly increase after 33 kg N ha^{-1}. Radish top dry biomass production was greatest at the first planting date across years. When compared to the other planting dates, biomass was greater by 30 to 2945 kg ha^{-1}. These results corresponded with other research that evaluated the effect of planting date on radish production, finding that earlier planted radishes produced greater yields. This research demonstrates that planting date was important for radish biomass production and to achieve maximum yields farmers in upstate Missouri should plant radishes in late summer to early fall.

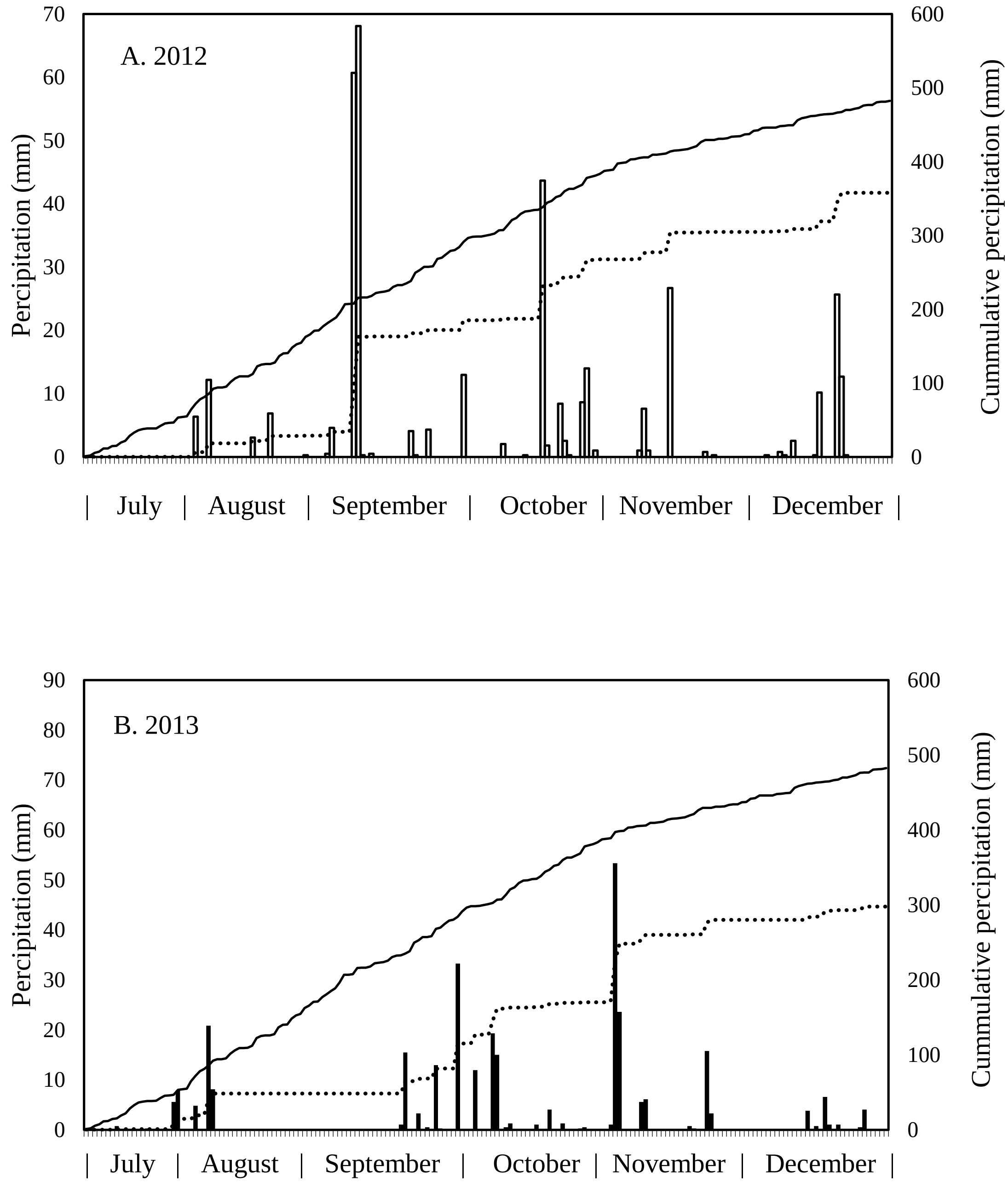

Figure 5.1. Daily (bar) and cumulative precipitation data for individual years (dash line) and 10-year average (solid line) for experiments in 2012 (A) and 2013 (B).

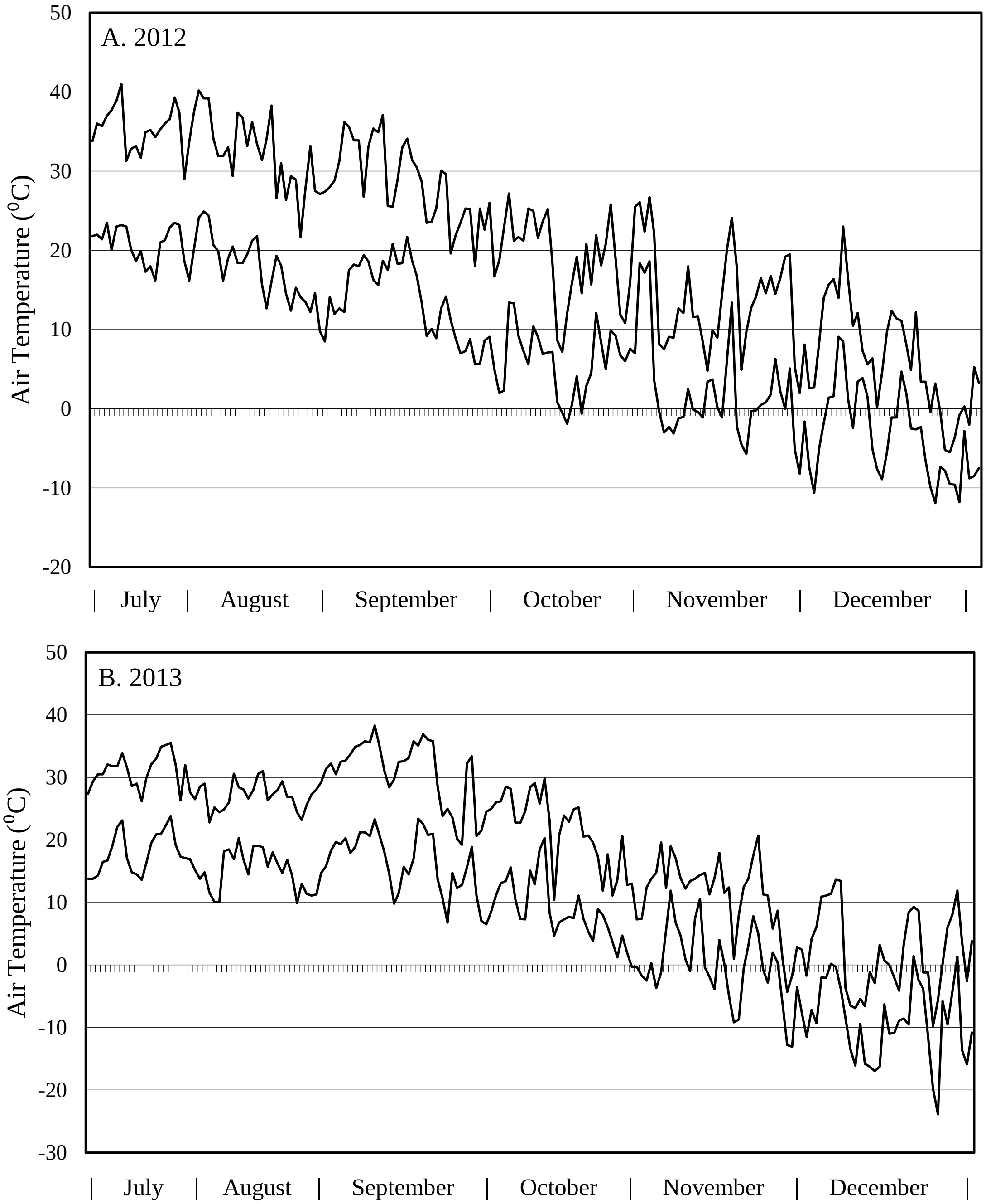

Figure 5.2. Daily maximum and minimum air temperature data for experiments in 2012 (A) and 2013 (B).

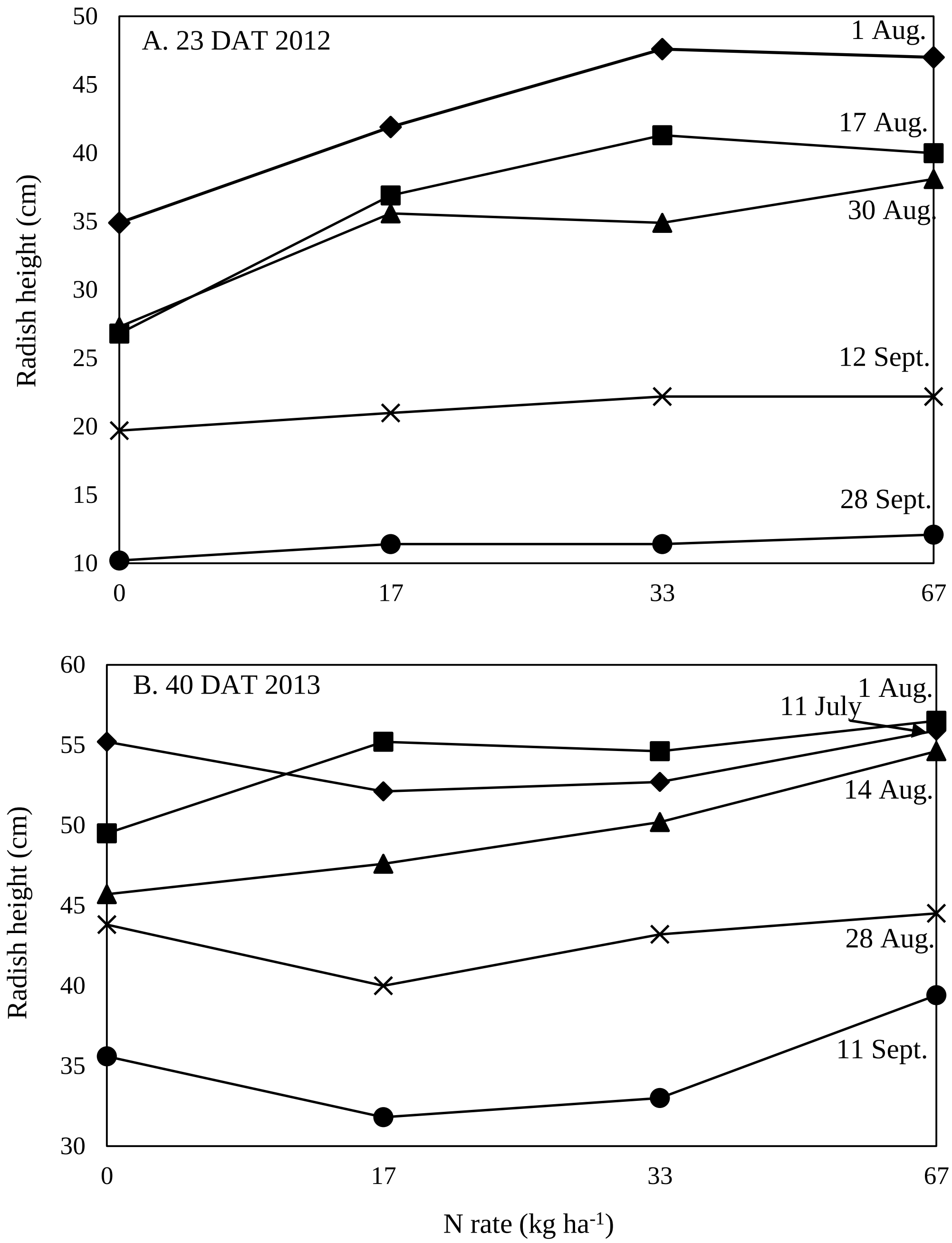

Figure 5.3. Radish heights for different planting dates at maximum heights [23 days after treatment (DAT)] in 2012 (A) and 2013 (40 DAT) (B) separated by nitrogen rates (kg ha^{-1}).

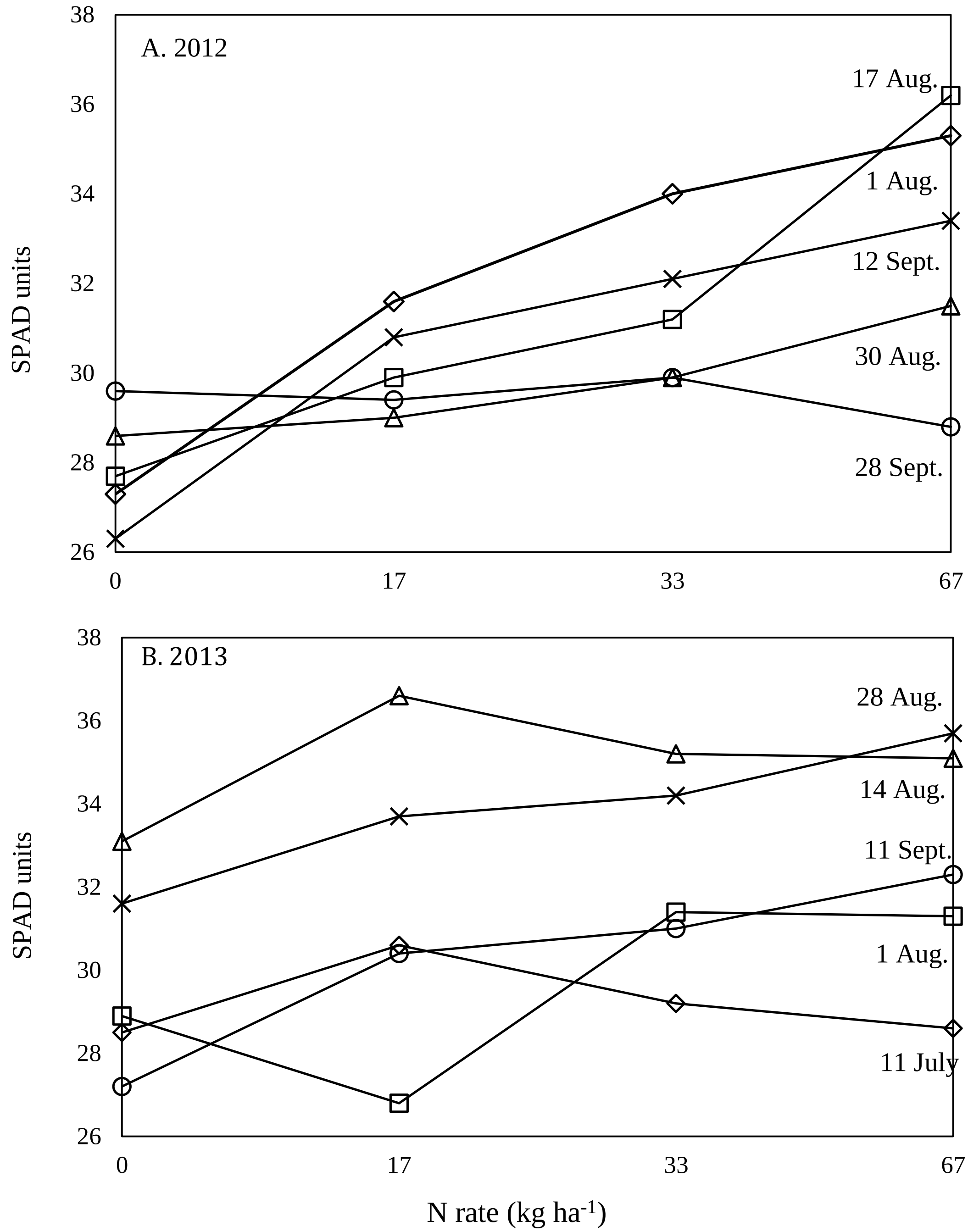

Figure 5.4. Chlorophyll content, as measured by SPAD meters, of radish tops separated by planting date and nitrogen fertilizer rate in (0, 17, 33, and 67 kg N ha^{-1}) in 2012 and 2013.

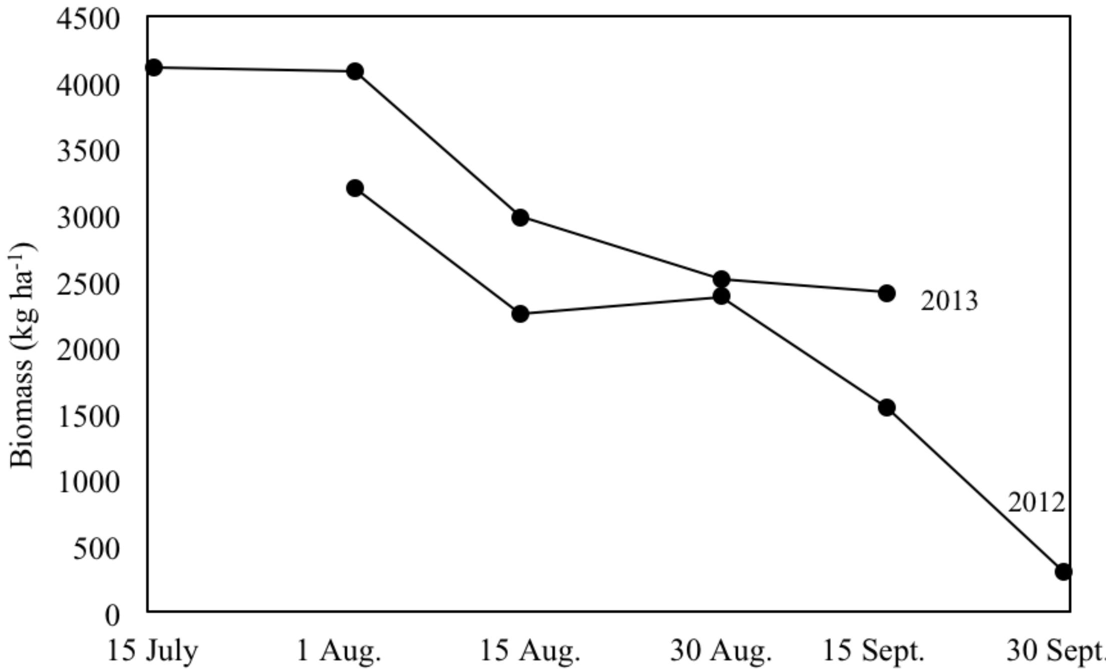

Figure 5.5. Radish top dry biomass with different planting dates averaged over nitrogen rates in 2012 [LSD (*P*=0.1) = 340] and 2013 [LSD (*P*=0.1) = 635

Table 5.1. Radish heights at all five planting dates 6, 13, 16, 23, 34, 40 days after treatment (DAT) and separated by nitrogen rates (kg ha^{-1}) for 2012 and 2013.

		2012					2013				
Days after treatment		0	17	33	67	LSD (*P*=0.1)	0	17	33	67	LSD (*P*=0.1)
		---------------				cm	---------------				
6 DAT	1st planting	31.1	33	34.9	32.4	3.8	30.5	36.8	33.7	27.9	5.6
	2nd planting	25.4	25.4	25.4	25.4	0	27.9	27.3	30.5	26	6.1
	3rd planting	20.3	20.3	20.3	20.3	0	15.2	16.5	19.7	17.8	1.8
	4th planting	10.2	10.2	10.2	10.2	0	6.4	8.9	7.6	7.6	0.8
	5th planting	2.5	2.5	2.5	2.5	0	2.5	2.5	3.2	2.5	4.1
	LSD (*P*=0.1)	1.8	1.7	0.7	1.4		3.3	3.3	6.1	4.5	
13 DAT	1st planting	32.4	36.2	38.1	36.2	2.8	39.4	38.7	37.5	37.5	6.4
	2nd planting	27.3	28.6	29.8	28.6	2.8	38.7	38.1	34.9	36.2	10.4
	3rd planting	26	27.9	27.9	27.3	2.3	21	22.9	26	34.3	2.5
	4th planting	12.7	12.7	12.7	12.7	0	9.5	14	10.8	11.4	1.0
	5th planting	5.1	5.1	5.1	5.1	0	7	7.6	8.3	7.6	4.6
	LSD (*P*=0.1)	1.7	2.2	1.4	3.3		6.7	4.9	7.5	5.6	
16 DAT	1st planting	35.6	40.7	42.5	40.6	3.3	48.9	49.5	52.1	48.3	4.1
	2nd planting	29.2	32.4	34.9	33.7	3.6	43.2	44.5	44.5	42.5	7.1
	3rd planting	27.3	30.5	29.8	28.6	2.8	36.9	66.7	36.2	39.4	3.8
	4th planting	17.1	17.1	16.5	17.1	1.3	20.3	21.6	21	22.2	1.3
	5th planting	5.1	5.1	5.1	5.1	0	14	13.3	14	14	6.4
	LSD (*P*=0.1)	3.6	4.1	2.7	2.9		7.5	4.8	7.2	4.8	
23 DAT	1st planting	34.9	41.9	47.6	47	4.6	52.7	59.3	54.6	57.2	9.1
	2nd planting	26.8	36.9	41.3	40	3.3	49.5	45.7	52.7	49.5	7.6
	3rd planting	27.3	35.6	34.9	38.1	5.3	38.7	37.5	42.5	45.1	6.6
	4th planting	19.7	21	22.2	22.2	2.5	31.8	39.8	27.9	33.7	2.8
	5th planting	10.2	11.4	11.4	12.1	2.0	22.2	22.2	22.9	23.5	11.9
	LSD (*P*=0.1)	3.7	4.8	4	3.1		13.3	6.3	8.3	5.7	
34 DAT	1st planting	36.2	34.9	41.3	40	6.1	48.9	54	52.1	54	7.6
	2nd planting	29.2	34.9	37.5	36.2	4.6	50.8	49.5	49.5	48.9	7.6
	3rd planting	26	33	31.7	31.1	3.6	44.5	41.3	46.4	44.5	4.8
	4th planting	18.4	18.4	18.4	17.8	0.8	34.9	38.1	37.5	40	4.1
	5th planting	7.6	7.6	7.6	7.6	0	31.1	29.8	31.8	31.1	8.1
	LSD (*P*=0.1)	4.2	3.1	3.6	4.3		8	7.6	9	6	
40 DAT	1st planting	34.3	36.8	40.6	38.7	4.1	49.5	55.2	54.6	56.5	6.4
	2nd planting	27.9	30.5	33	34.3	5.8	55.2	52.1	52.7	55.9	11.2
	3rd planting	26.7	29.2	31.1	30.5	3.8	45.7	47.6	50.2	54.6	8.6
	4th planting	19.1	19.1	19.1	19.1	0	43.8	40	43.2	44.5	4.1
	5th planting	10.2	10.2	10.2	10.2	0	35.6	31.8	33	39.4	7.6
	LSD (*P*=0.1)	5.3	5.1	2.8	3.7		9.4	8.2	7.3	5.8	

† Radish planing dates in 2012 were 1 Aug., 17 Aug., 30 Aug., 12 Sept., and 28 Sept. for the 1st through 5th planting dates, respectively. Radish planting dates in 2013 were 11 July, 1 Aug., 14 Aug., 28 Aug., and 11 Sept. for the 1st through 5th planting dates, respectively.

Table 5.2. Chlorophyll content, as measured by a SPAD meter, of radish tops separated by planting date and nitrogen fertilizer rate (0, 17, 33, and 67 kg N ha^{-1}) for 2012 and 2013.

	2012					2013				
Planting date	0	17	33	67	LSD (*P*=0.1)	0	17	33	67	LSD (*P*=0.1)
1st planting	27.3	31.6	34	35.3	4.1	28.5	30.6	29.2	28.6	5.1
2nd planting	27.7	29.9	31.2	36.2	5.9	28.9	26.8	31.4	31.3	3.9
3rd planting	28.6	29.0	29.9	31.5	3.2	33.1	36.6	35.2	35.1	3.8
4th planting	26.3	30.8	32.1	33.4	3.5	31.6	33.7	34.2	35.7	2.2
5th planting	29.6	29.4	29.9	28.8	4.2	27.2	30.4	31.0	32.3	3.5
LSD (*P*=0.1)	4.9	4.3	3.5	4.7		3.6	4.3	3.1	3.7	

Table 5.3. Radish top dry weight biomass response to planting dates. Data were averaged across nitrogen rate for 2012 and 2013.

Planting date	2012		2013	
		------ kg ha^{-1} ------		
1st planting	1 Aug.	3201.0	11 July	4103.1
2nd planting	17 Aug.	2249.5	1 Aug.	4077.4
3rd planting	30 Aug.	2380.0	14 Aug.	2982.2
4th planting	12 Sept.	1544.3	28 Aug.	2511.4
5th planting	28 Sept.	303.3	11 Sept.	2404.3
LSD (*P*=0.1)		341.8		638.4

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CHAPTER 6 – EFFECTS OF INTERCROP PLANTING DATE AND NITROGEN APPLICATION ON FORAGE RADISH PRODUCTION AND SOYBEAN YIELD

ABSTRACT

Complimentarity and competition is important for a successful intercropping system. Forage radish may compete with soybean when it is incorporated into an intercrop system; however, there is limited research in this area. The objective of this research was to evaluate radish overseeding planting date with or without N on soybean grain yield and radish biomass production in relay-intercropping compared to double-cropping system. Soybean yields were not impacted by radish planting dates but there was an increase in yield at one date for nitrogen applied with radishes. Due to flash drought conditions in 2013, radish biomass yields were low. Radish production showed that earlier planting dates (prior to September 1) with adequate rainfall produced greater top and tuber biomass in 2012. This corresponded with research that has evaluated the effect of planting date on radish production. This research demonstrates that planting date was important for radish biomass production and to achieve maximum yields farmers in upstate Missouri should overseed radishes into soybean prior to September 1 when experiencing drought conditions.

INTRODUCTION

Intercropping is the growth of two crops in the same field, where the component crops are not necessarily sown at the same time nor harvested at the same time, but they are grown simultaneously for a portion of their growing periods. Within an intercropping system, there is normally one main crop and one or more added crops often sown later in the season, with the main crop being of primary importance for economic or food production reasons (Lithourgidis et al., 2011a). Intercropping is still a common practice in developing countries, with small farms finding larger productivity in terms of harvestable products per unit area by 20 to 60% over mono-cropping (Lithourgidis et al., 2011a). This is largely attributed to more efficient resource use, which is the primary benefit of intercropping. The most common advantage of intercropping is the production of greater yield on a given piece of land by making more efficient use of the available growth resources. This could be due to different rooting characteristics, canopy structure, height, and nutrient requirements or resource use at different times (Fujita et al., 1992; Midmore, 1993; Thiessen Martens et al., 2001; Echarte et al., 2011; Eskandari, 2011; Lithourgidis et al., 2011a; Eskandari and Ghanbari, 2010). Intercrop systems can be planted simultaneously or staggered taking advantage of cool and warm season adapted species. By staggering planting dates, the relative periods of complimentarity and competition are modified and can influence the component crop's yield potential (Midmore, 1993). In general, the crop planted first has a competitive advantage over the intercrop as it has previous access to limiting factors.

Defining complimentarity and competition is important for a successful intercropping system. The point at which complimentarity becomes competition among crops can be manipulated through management practices and depends largely on each crop's response to limiting factors such as light, soil moisture, and nutrients (Midmore, 1993). Resource complementarity minimizes niche overlap and competition between crop species, and permits crops to capture a greater range and quantity of resources compared to a single crop. Thus, selecting crops that differ in competitive ability over time or space is essential for an efficient intercropping system as well as decisions on planting date, plant arrangement, and density (Lithourgidis et al., 2011a). Increased use of resources, through niche differentiation must outweigh interspecific competition in an intercrop (Schröder and Köpke, 2012). Intercropping success can be affected by factors such as relative density of component crops, amount of limiting resources, and crop row spacing (Eskandari and Ghanbari, 2010). If intercrops are complimentary, they often will use resources more efficiently than if mono-cropped.

Zhang and Li (2003) developed the ‘competition-recovery production principle’ to determine the impact of intercrops on one another. Interspecific interaction increases growth, nutrient uptake, and yield of the dominant species, but it hinders the growth and nutrient uptake of the subordinate crop (intercrop) during the co-existence of both crops. However, after harvest of the earlier-maturing species there was recovery of nutrient uptake and growth, which allowed for the later-maturing species to compensate for impaired growth during the intercrop period once the early-maturing species was harvested (Zhang and Li, 2003). Several types of intercrop systems use mixtures of spatial and temporal arrangements (Jensen et al., 2006; Eskandari, 2011).

Relay- and double-cropping has represented an option for incorporating legume cover crops into annual cropping systems without sacrificing grain production (Thiessen Martens et al., 2001; Ghaley et al., 2005; Naudin et al., 2010; Lithourgidis et al., 2011b; Mariotti et al., 2011; Pelzer et al., 2012). Intercropping has also been reported to increase soil P availability and grain S concentration (Gooding et al., 2007; Betencourt et al., 2012). This system can be important for farmers in developing countries where low input systems are employed or as a way to reduce fertilizer inputs to decrease cost and environmental concerns from fertilizer runoff and chemical degradation (Fujita et al., 1992; Akhtar et al., 2010). Brassica species, like the forage radish, may impact nutrients available in the intercrop system; however, there is limited research in this area. In addition, there is limited research on the use of nitrogen fertilizer for radish production (Sanchez et al., 1991; Hochmuth et al., 1996) which may be utilized as a cover crop for grazing livestock. Nitrogen fertilizer increased seed yield of radish by 1.4 t ha^{-1} but yields increased to 2.3 t ha^{-1} when 30 kg ha^{-1} of phosphorus was added. Research in Pakistan showed that the addition of nitrogen fertilizer significantly increased radish biomass and yield compared to no-fertilized controls (Asghar et al., 2006). However, research in Florida reported that no response was observed with nitrogen fertilizer and thus it was not recommended for radish production (Hochmuth et al., 1996). Other research determined that radishes used soil mineral N, and that N fertilization did not increase radish yields in that system (Sanchez et al., 1991) which allows for immobilization of N with a radish cover crop. The objective of this research was to evaluate radish overseeding planting date with or without N on soybean grain yield and radish biomass production in relay-intercropping compared to a double-cropping system.

MATERIALS AND METHODS

Field research was conducted at the University of Missouri Greenley Research Center near Novelty (40°01'N, 92°11'W) in 2012 and 2013. Soybean (*Glycine max* Merr.), ‘Ag3730’, (Asgrow, Monsanto, St. Louis, MO) was no-till planted with Great Plains no-till drill (Great Plains Ag, Salina, KS) on 30 May 2012 while ‘Ag3432’ was planted on 8 June 2013 at 445,000 seeds ha^{-1}. Soybean management is reported in Table

1. ‘Tillage radish’ Cover Crop Solutions LLC, Lititz, PA was broadcast overseeded in 3 by 15 m plots into standing soybean at 10 kg ha^{-1} using a hand spreader in presence or absence of 34 kg ha^{-1} of ammonium nitrate on 31 August, 12 September, and 28 September 2012 as well as 29 August, 11 September, and 30 September 2013. The trial was arranged as a randomized complete block design with four replications. The amount of applied N was based off of previous research that reported 34 kg N ha^{-1} to be optimum for forage use (Chapter 5). On 4 October 2012 and 18 October 2013, soybean were harvested (Wintersteiger Delta, Salt Lake City, UT) and radishes were no-till drill-seeded (Great Plains, Salina, KS) at 10 kg ha^{-1} on 8 October 2012 and 18 October 2013. In addition, on 8 October 2012 and 18 October 2013, all remaining plots that had not received nitrogen across the various planting dates received 34 kg N ha^{-1} of hand broadcast ammonium nitrate.

There were two separate fertilizer application dates to mimic a practical application for farmers. As a broadcast over-seeded intercrop, farmers in upstate Missouri may apply radishes via airplane to minimize damage to an existing crop such as soybeans. When the radishes are flown on, there is also an opportunity to add N fertilizer to the batch thus optimizing plane use and providing N for the radishes and soybean from emergence of the radishes and during soybean grain fill (R6). The second nitrogen application date mimicked a broadcast spreader of N to radish after soybean was harvested. Nitrogen fertilizer is heavy and would increase aerial application costs, thus a farmer may wait until after harvest of the main crop to avoid damage to it and then broadcast N onto emerged radishes.

Data were subjected to ANOVA (SAS, 2010) and means were separated using Fisher's Protected LSD (P=0.1). Soybean yields were combined over years and main effects for planting date and nitrogen application timing were presented. Radish tops and tuber production was reported separately for year and planting date due to a significant interaction.

RESULTS AND DISCUSSION

Environmental conditions

During the radish growing season in 2012 from planting in August through the winter, total rainfall was 339 mm (Figure 1a) which was similar to the 10-year average of 381 mm. Total precipitation for 2012 was 722 mm; however, there was only 215 mm of rainfall from May through August which was 210 mm below the 10 year average, meaning that radishes were planted following drought conditions. On the last day of August, 60 mm of precipitation occurred from storms following Hurricane Isaac (Figure 1a). In 2013, total precipitation was 1003 mm, but only 140 mm of percipitation from June through August and no rain was recorded in August (Figure 1a). In addition, rainfall in September and October was only 123 mm, 58 mm below the 10 year average, before the last two days of October when there was 77 mm of rainfall. Thus radishes grew under extremely dry conditions in the autumn months of 2013 (Figure 1b).

During the summer of 2012, temperatures were abnormally high with an average temperature of 23.7^{0}C from May through August and 30.7^{0}C average high temperature during this period (Figure 2a). In comparison, 2013 was relatively cool with an average temperature of 21.2^{0}C and an average high temperature of 27.3^{0}C through the summer (Figure 2b). Due to below average rainfall as well high average temperatures, specifically in 2012, the results of this research during 2012 were achieved under drought conditions and in 2013 under “flash drought” conditions.

Soybean production

Soybean yields had a planting date*nitrogen application timing interaction (P=0.09) (Figure 3). Soybean yields differed up to 150 kg ha^{-1} among radish planting dates and nitrogen application timings, while differences in yields were up to 175 kg ha^{-1} different between nitrogen timings across radish planting dates. Interestingly, a specific nitrogen timing did not increase soybean yields over another except for the 15 Sept. Nitrogen application at radish seeding which had greater soybean yields compared to the non-seeded control and the second planting date (12 September 2012, 11 September 2013). In other intercropping systems, research found that competition and complementarity between species enhanced productivity (Jensen et al., 2006; Eskandari, 2011). Possibly due to dry conditions, those results were not observed in this research. The added N may have increased soybean yields; however, the timing of the N application did not impact soybean production except for the second planting date (12 Sept.).

Radish production

There was significantly less radish biomass of both tops and tubers in 2013 than in 2012 (Figure 4). This may have been due to several reasons. Environmental conditions were different for the radish growing period in 2012 than 2013. In 2012, although there had been extreme drought in the summer, by the time most of the radish planting and growth occurred, there was some precipitation (234 mm) from September through October. However, there was a flash drought in August 2013 and only 123 mm of precipitation during September and October with the majority of the rainfall occurring on only three dates (Figure 1). Thus, radishes growing in 2013 received significantly less precipitation which may have impacted growth. Secondly, early soybean growth was greater in 2013 than 2012 (visual observation). Due to drought conditions, soybean stand and growth was reduced in 2012. More nutrients and light may have been available to radishes for a longer period of time due to a more open canopy and smaller soybean root systems (Jensen et al., 2006). In 2012, competition with soybean may have negatively impacted radish production. Interspecific interactions increase growth, nutrient uptake, and yield of the dominant species, but it hinders the growth and nutrient uptake of the subordinate crop (intercrop) during the co-existence of both crops (Zhang and Li, 2003). Due to limited water, radishes may never have recovered growth after soybean harvest. And thus the point at which complimentarity became competition among crops occurred due to limiting factors such as light, soil moisture, and nutrients (Midmore, 1993).

There was a year*planting date interaction for radish tops and tuber biomass (P<0.0001) due to the difference in biomass production in each year (Figure 4). Across years, the first planting date had greater production in terms of tops and tuber biomass production. In 2012, the first planting date (31 August 2012) had the greatest top (1026 to 1401 kg ha^{-1}) and tuber (2837 to 2962 kg ha^{-1}) biomass than all other planting dates. The first planting date in 2013 (29 August) had the greatest top biomass and 17.7 kg ha^{-1} greater top biomass growth compared with the second planting date (12 September) and subsequent planting dates. Tuber biomass was not different across planting dates in 2013.

Research looking at the effect of planting date on radish production has reported similar findings (Pandey et al., 2009; Alam et al., 2010). In Bangladesh, sowing time significantly affected growth and yield of radishes with the 1 November planting date producing the greatest root yield (81.8 Mg ha^{-1}) compared to the lowest yield on December 1 (68.7 Mg ha^{-1}) (Alam et al., 2010). In addition, 1 November produced the greatest root length per plant (25.6 cm $root^{-1}$) when compared with the shortest on 1 December (23.5 cm $root^{-1}$) and the maximum number of leaves (16.3 $plant^{-1}$) and leaf length (59.6 cm $leaf^{-1}$) were produced by plants sown on 1 November (Alam et al., 2010). All parameters showed decreasing production as sowing date was delayed.

Results were similar when radishes were planted every ten days beginning on 9 November in India. The second planting date (19 November) produced the maximum radish yield (28.4 Mg ha^{-1}), root length (24.45 cm $root^{-1}$) and root weight (0.097 kg $root^{-1}$), and the last planting date (9 December) produced the least yield (23.2 Mg ha^{-1}), root length (22.31 cm $root^{-1}$) and root weight (0.008 kg $root^{-1}$) (Pandey et al., 2009). The authors concluded that a delay in planting reduced radish yield (Pandey et al., 2009). In Iran, black radishes (*Raphanus sativus* var. *niger*) were planted on 10, 20, and 30 September and 10 September with radish yields that were 21.9 Mg ha^{-1}, but decreased to 9.8 Mg ha^{-1} by 30 September (Ebrahimi et al., 2013). Delay in planting meant shorter days and thus a decreased level of light interception as well as fewer degree days required for crop growth (Ebrahimi et al., 2013). In addition, delayed planting decreased temperatures during crop growth (Figure 2).

Nitrogen application timing did not impact radish biomass production (data not presented). Similarly, radish yield in 7 of 8 experiments conducted in Florida were not impacted by nitrogen fertilizer (Sanchez et al., 1991). The total amount of fertilizer-derived N from the marketable radishes averaged only between 2 to 8 kg N ha^{-1}, prompting the authors to determine that the radishes used soil mineral N, and that N fertilization did not increase radish yields in that system (Sanchez et al., 1991). This would be beneficial following wheat and could trap N in the soil profile. Similarly, no response was observed with nitrogen fertilizer by Hochmuth et al., (1996), and thus was not recommended for radish production.

CONCLUSION

Soybean were grown during drought conditions in 2012 and 2013. There was limited precipitation in the summer of 2012 preceding radish overseeding planted dates, but late rainfall helped in the establishment of broadcast seeded radish. In 2013, there was a “flash drought” with no precipitation in August and little rainfall in September through October. Soybean yields were not impacted by radish planting dates; however, there was an increase in soybean yield during the mid September planting date when N was applied with the overseeding of radishes. Due to flash drought conditions in 2013, biomass yields were small. Radish production showed that earlier planting dates (prior to September 1) produced greater top and tuber biomass across years. This corresponded with research that has evaluated the effect of planting date on radish production. This research demonstrates that planting date was important for radish biomass production and to achieve maximum yields farmers in upstate Missouri should overseed radishes into soybean prior to September 1.

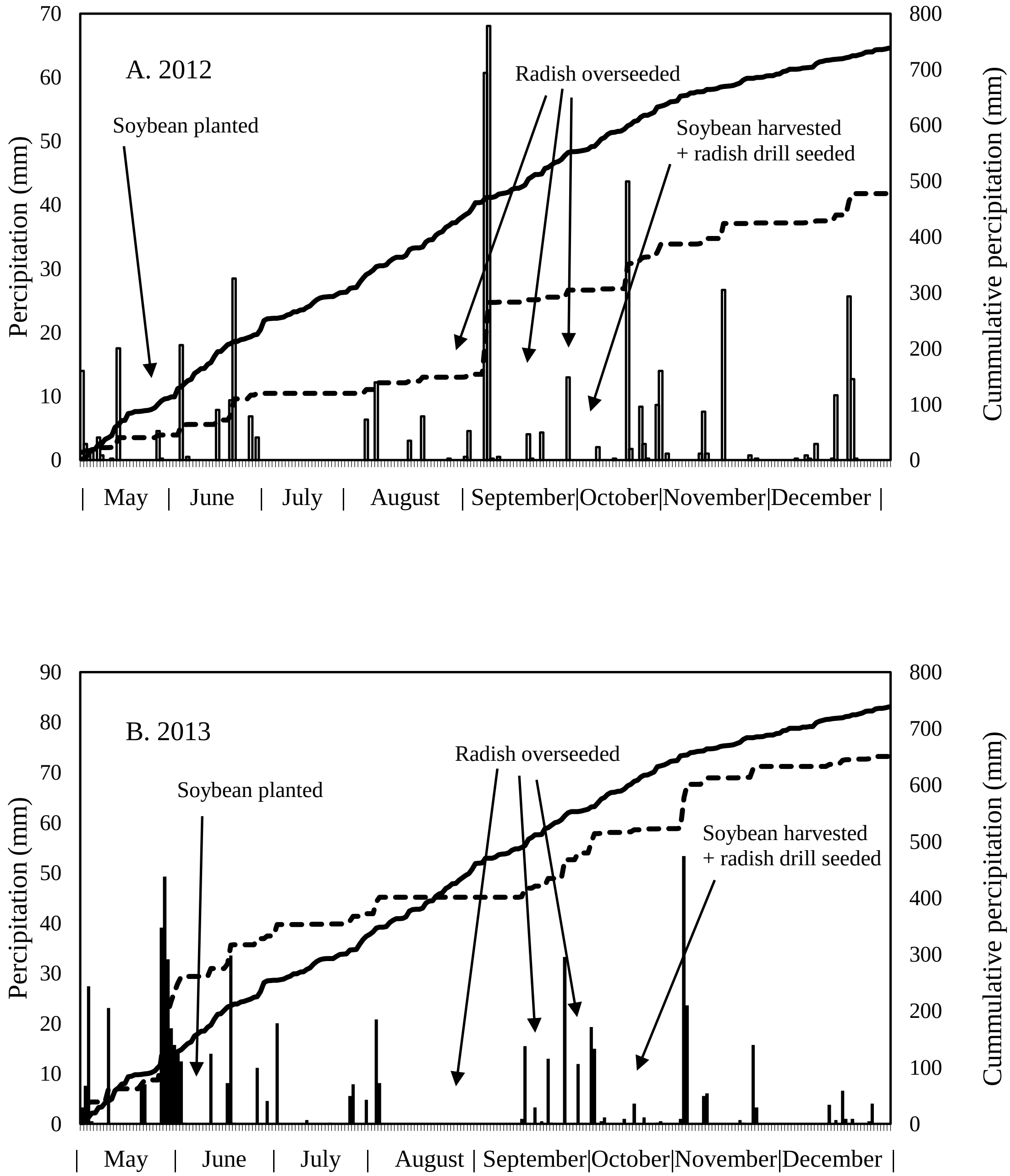


Figure 6.1. Daily (bar) and cumulative precipitation data for individual years (dash line), and 10-year average cumulative precipitation (solid line) for experiments in 2012 (A) and 2013 (B).

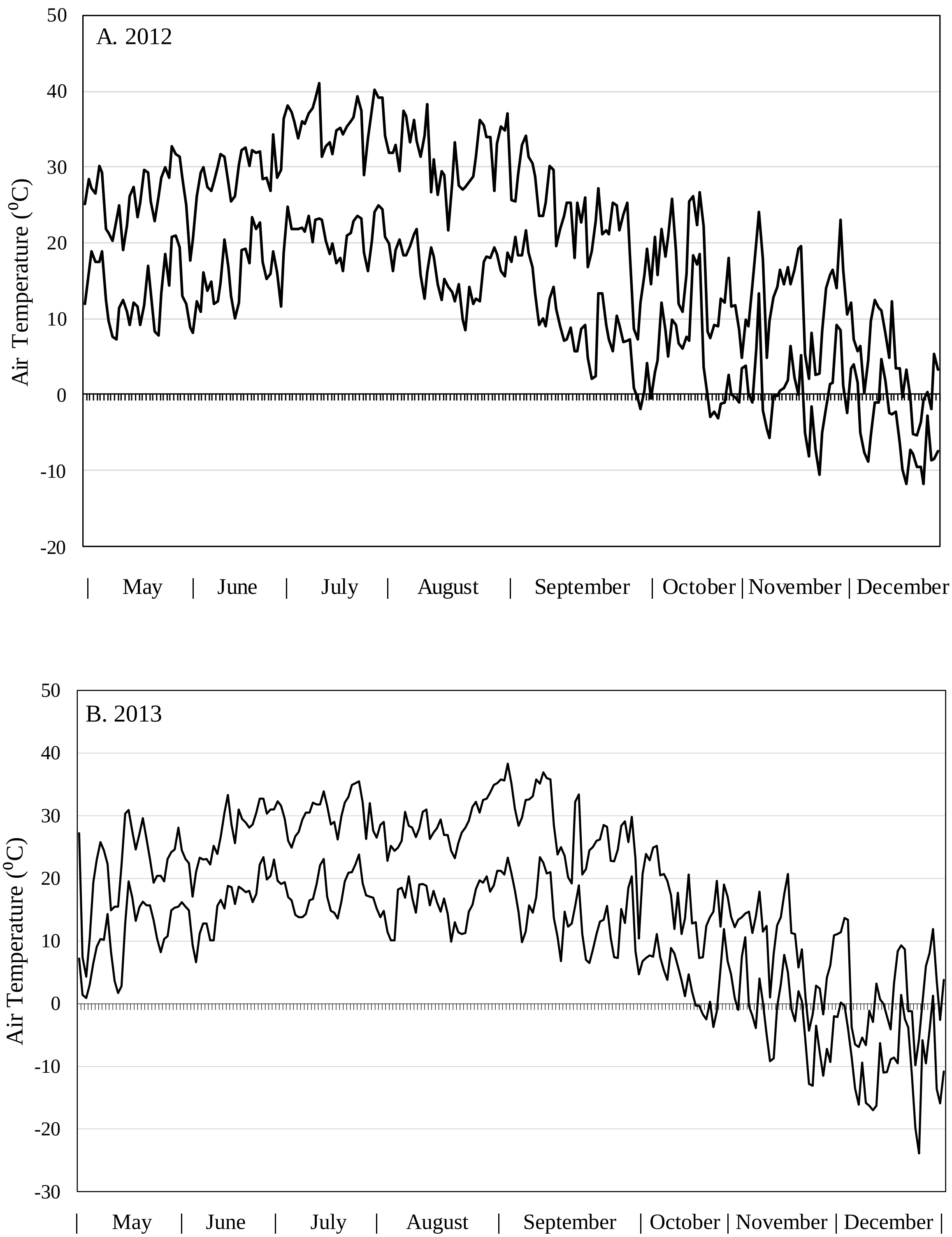


Figure 6.2. Daily maximum and minimum air temperature data in 2012 (A) and 2013 (B).

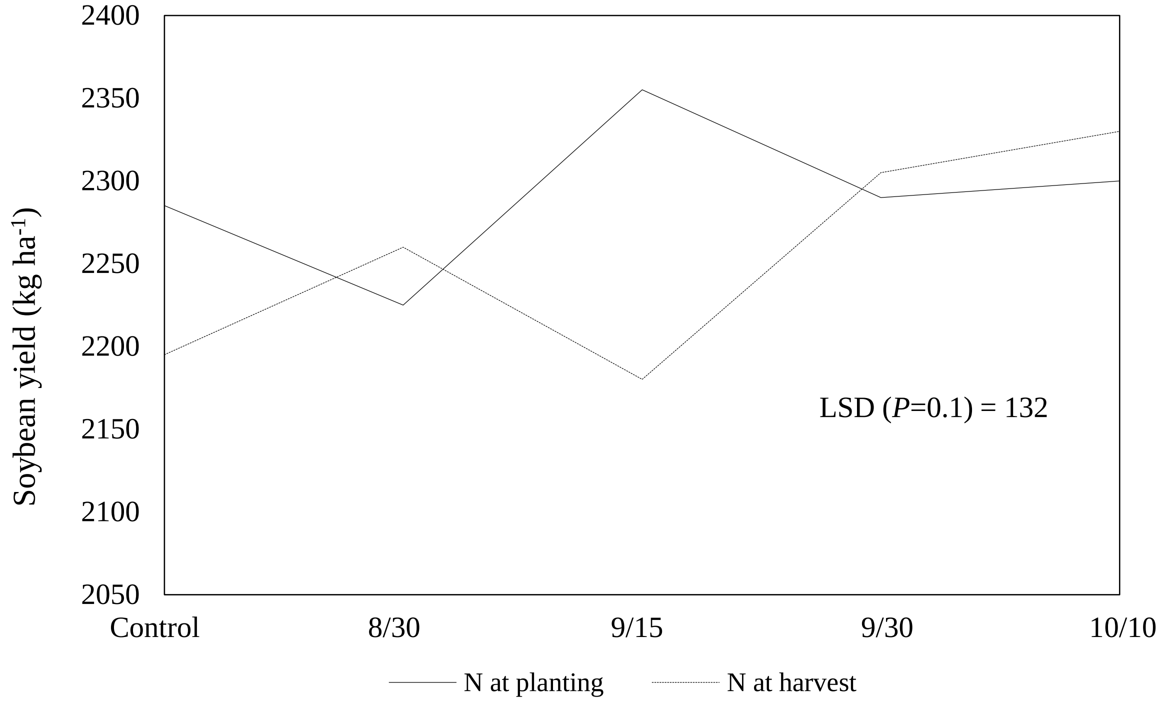
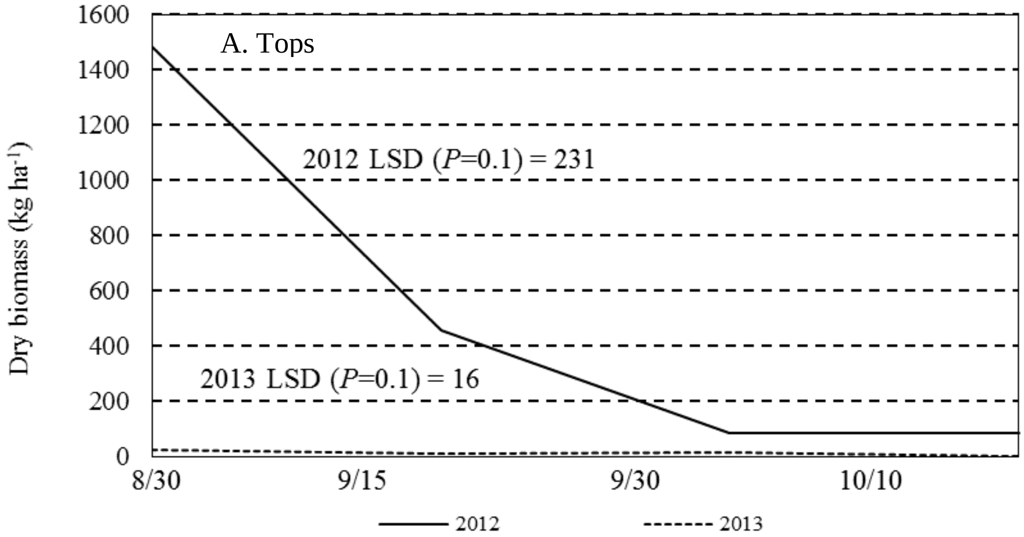


Figure 6.3. Soybean yields as impacted by radish planting date and nitrogen application timing (at planting or harvest) across years. Data were averaged over years (2012 and 2013). Planting dates were an average of 2013 and 2013.



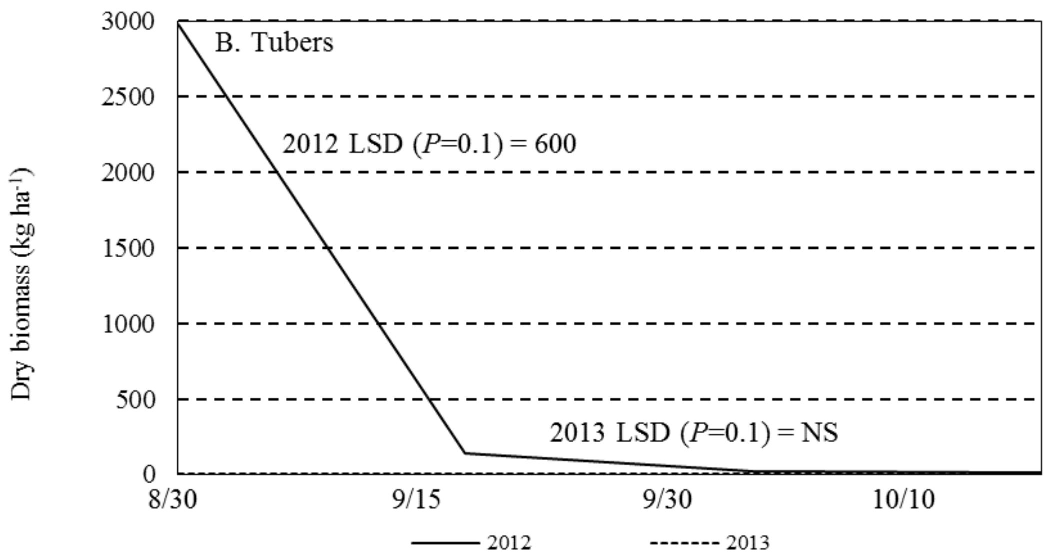


Figure 6.4. The effect of radish planting date on dry weight biomass yields of tops and tubers. Data were averaged over years (2012 and 2013) and N application timing (at planting or after soybean harvest).

Table 6.1. Soybean management information for 2012 and 2013.

Management information	2012	2013
Planting Date	30 May	8 June
Cultivar	Asgrow 3730	Asgrow 3432
Population (seeds ha^{-1})	445,000	445,000
Pest management	2 April Saflufenacil at 0.03 kg ai ha^{-1} + glyphosate at 0.9 kg ai ha^{-1} + NIS at 0.25% v/v + 32% UAN at 2.35 L ha^{-1}	24 May Glyphosate at 0.9 kg ai ha^{-1} + sulfentrazone at 0.01 kg ai ha^{-1} + COC at 2.3 L ha^{-1} + 32% UAN at 2.35 L ha^{-1}
	5 June Saflufenacil at 0.03 kg ai ha^{-1} + glyphosate at 1.3 kg ai ha^{-1} + NIS at 0.25% v/v + 32% UAN at 2.35 L ha^{-1}	18 June Glyphosate at 0.9 kg ai ha^{-1} + fomesafen at 0.45 kg ai ha^{-1} + cloransulam at 0.003 kg ai ha^{-1} + NIS at 0.25% v/v + AMS at 22.7 g L^{-1}
	22 June Fomesafen at 0.35 kg ai ha^{-1} + glyphosate at 0.9 kg ai ha^{-1} + AMS at 22.7 g L^{-1} + NIS at 0.25% v/v	

†Cloransulam-methyl, N-(2-carbomethoxy-6-chlorophenyl)-5-ethoxy-7-fluoro(1,2,4)triazolo-[1,5-c]pyrimidine-2-sulfonamide; fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxyl]-N-(methylsulfonyl)-2-nitrobenzamide; glyphosate, N-(phosphonomethyl)glycine; non-ionic surfactant, 3-oxapentane-1,5-diol, propane-1,2,3-triol, alklphenol ethoxylate, polydimethylsiloxane; sulfentrazone, 2,4-dichloro-5-(4-difluoromethyl-4,5-dihydro-3-methylu-5-oxo-1H-1,2,4-triazol-1-yl)methanesulfonanilide.

‡Abbreviations; AMS, ammonium sulfate; NIS, non-ionic surfactant; MSO, methylated seed oil; UAN, urea ammonium sulfate.

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