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A Study of Short-Season Winter Cover Crops for Organic High Tunnel Production Systems

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A Study of Short-Season Winter Cover Crops for Organic High Tunnel Production Systems

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of the requirements for the degree of
Master of Science in Horticulture

by

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Bachelor of Science in Agriculture, 2011

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This thesis is approved for recommendation to the Graduate Council.

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ABSTRACT

This two-year study investigated short-season winter cover crops to improve soil quality and growth of subsequent vegetable crops in an organic high tunnel production system. Five winter cover crop treatments including a nontreated control, Austrian winter peas (*Pisum arvense*), bell beans (*Vicia faba*), mustard (*Brassica juncea* cv. Kodiak), and Daikon radish (*Raphanus sativus* var. longipinnatus) were grown in a high tunnel in a randomized complete block design from mid-November to mid-March, mowed and incorporated into the soil, and followed by a succession of vegetable crops including tomato (*Lycopersicon lycopersicum*, cv. ‘Plum Dandy’) and broccoli (*Brassica oleracea var. italica*, cv. ‘Bay Meadows’). In 2014 winter peas yielded the greatest above-ground biomass (284 g/m^2), though in 2015 mustard and radish cover crops yielded greater above-ground biomass (424 g/m^2 and 395 g/m^2, respectively). Across both years winter peas contained the highest foliar N concentration (3.8%) and resulted in the greatest biomass N contribution, at an average of 10.2 g N/m^2. The N contribution from winter pea resulted in a significantly lower soil C:N ratio 30 days after incorporation. Cover crop treatments did not result in significant changes to soil quality variables including soil organic matter, pH, and EC, though changes were observed over time across all treatments. The winter pea cover crop resulted in greater tomato leaf chlorophyll estimates than the nontreated control across both years, greater tomato foliar N concentration than all other treatments in 2015, and greater tomato plant biomass compared to the control. Though statistical differences were not detected due to high background variation, the winter pea cover crop resulted in a 48% increase in mean tomato yield compared to the control. Broccoli plant biomass was significantly greater following winter pea and radish cover crop treatments compared to the control (808 g/plant and 726 g/plant, respectively, compared to 600 g/plant), however cover crop treatments were not found to significantly affect broccoli harvest variables. Overall findings point to a cumulative effect of cover cropping on soil quality and vegetable crop production in a high tunnel, though the two-year timeline of this project limited the ability to understand long-term effects.

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INTRODUCTION & LITERATURE REVIEW

Introduction

Although cover crops have been well studied for field production systems, their application in high tunnel vegetable production has had limited study. Available information on the subject was limited to Extension bulletins, newsletters, conference presentations, and production manuals (Baldwin, 2010; Blomgren and Frisch, 2007; Evans et al., 2011; Melendez and Rabin, 2012; Rivard, 2013). Despite negative and dismissive reports on high tunnel cover crops from Extension agents and farmers in the Northeast (Blomgren and Frisch, 2007), preliminary studies in New Jersey and Mississippi have shown opportunity for winter cover crops to provide benefits to high tunnel vegetable production, including the uptake of leachable excess nutrients, weed suppression, and spring nitrogen release (Evans et al., 2011; Melendez and Rabin, 2012).

The reported and potential benefits of high tunnel cover crops justify further research on the subject. To begin with, the timing of cover cropping in a high tunnel can minimize the negative aspects of the practice. Local growers have said that the period between mid-November and mid-February was the least productive season for high tunnel vegetable growers in the South due to cold temperatures and low light (Dr. C. Rom, personal communication). During this period, tunnels are commonly idle. By selecting this period to grow a winter cover crop that can tolerate such environmental conditions, the lost revenue stream for the grower is minimized. The modified environment of a high tunnel, with increased soil and air temperatures (Wien, 2009), could also speed the growth of winter cover crops during the proposed period in winter, producing more green biomass than would be produced during the same period in the field. It is thought that if a green manure crop was able to improve soil quality and decrease the requirement for purchased organic matter and fertilizer inputs, the cost savings for the grower could justify the additional management input.

Intensive vegetable production in a high tunnel requires inputs of organic materials to maintain soil organic matter, preserve soil quality, and ensure long-term productivity (Coleman, 1999; Lamont et al., 2003; Milner et al., 2009). Green manure cover crops have been shown to increase soil organic matter and nutrient cycling (Pieters, 1927; Powlson et al., 1987), and could replace purchased organic inputs in high tunnel production. Winter legumes have shown the potential to contribute significant amounts of nitrogen to subsequent vegetable crops in a field setting (Burket et al., 1997; Gaskell and Smith, 2007), which would reduce purchased fertilizer costs for high tunnel growers if similar rates of nitrogen contribution occurred in the high tunnel system. The deterioration of soil quality and the formation of hard pans due to frequent tillage is a documented problem in high tunnel production, which could be ameliorated by the ability of green manure cover crops to improve soil structure and aggregate formation (Hermawan and Bomke, 1997; Roberson et al., 1991; Tisdall and Oades, 1982) and improve the rooting depth of vegetable crops due to the “bio-drilling” effect of certain cover crops (Weil and Kremen, 2007). The ability of legume and brassica winter green manures to suppress soil-borne pathogens in vegetable crops (Monfort et al., 2007; Zhou and Everts, 2007) is another important benefit that winter cover crops could provide to high tunnel systems.

The ability of winter cover crops to affect the yield and performance of vegetable crops in field production systems have been well-documented in the scientific literature. It is the assertion of this study that short-season winter cover crops grown in a high tunnel, then mowed and incorporated, will improve the growth and yield of subsequent vegetable crops.

Objectives

The objectives of the following experiments were:

1. To evaluate the performance of winter cover crops grown in a high tunnel environment and their effect on soil variables
2. To evaluate the effect of winter cover crops on the growth and yield of subsequent vegetable crops tomato and broccoli in a high tunnel production system

Hypotheses

From these objectives, the following hypotheses (Ho: null hypotheses) have been developed:

1. Ho: There will be no differences between tested cover crop treatments on physical or chemical characteristics of the soil as compared to the control.
2. Ho: The tested cover crop treatments will have no effect on the growth and yield of tomato and broccoli as compared to the control.

Literature Review

High Tunnel Production

High tunnel use for specialty crop production has been increasing in the United States and throughout the world (Carey et al., 2009; Lamont, 2009). This is due to the benefits that high tunnel structures provide for specialty crops, including a protected environment from insect pest and weather stresses, the ability to extend the harvest and production season, increased yield, improved crop quality, and more effective pest management (Carey et al., 2009). Increased marketable production in addition to an early or extended harvest season has demonstrated high tunnels to be both practical and economically viable for high-value specialty crop production (Lamont et al., 2003).

High tunnels, also called hoop houses, are single-span to multi-span structures typically covered in a single layer of polyethylene greenhouse film (Carey et al., 2009). They can be semi-permanent, movable, or temporary, and most often do not require any electrical infrastructure (Carey et al., 2009). Due to the lack of electrical utilities, high tunnels are passively heated and cooled, relying on solar radiation for heating and passive ventilation for cooling (Carey et al., 2009). Crops in high tunnels are usually grown in the ground, but sometimes grown in artificial media, requiring irrigation due to rainfall exclusion (Carey et al., 2009). Drip or trickle irrigation is most commonly used in high tunnels due to the efficient delivery of moisture to the rhizosphere and lack of foliar wetting (Lamont, 2009).

The first documented high tunnel, a wooden structure covered in a single layer of greenhouse polyethylene, was invented in 1953 by Dr. Emery Emmert of the University of Kentucky (Orzolek, 2013). Despite the fact that high tunnels were invented in the U.S. in the 1950s, it was not until the 1990s that the technology was adopted, through the promotion and research of extension professionals in the Northeast including Lamont (Carey et al., 2009). Since then, the work of innovative growers (Blomgren and Frisch, 2007; Byczynski, 2003; Coleman, 1998, 1999; Wiediger and Wiediger, 2003) has contributed to the increasing awareness and popularity of high tunnels for fruit, flower, and vegetable production throughout the United States (Carey et al., 2009).

Common practices and best management practices for high tunnel production have been detailed (Lamont, 2009) despite the fact that high tunnel technology has been applied to a broad range of environments and geographical locations. Annual crops in high tunnels are most often grown in native soil on raised beds made with a tractor bedder or mounded by hand. The raised beds are often covered in plastic mulch to increase the soil temperature and decrease weed pressure. Due to the use of plastic mulch, drip irrigation has been commonly used to deliver water and fertilizer via drip tape placed under the layer of mulch. Multiple vegetable crops are commonly grown during the same season, planted at high density, to maximize the productivity of the high tunnel space and to capitalize on the ability of the high tunnel to extend the production season through environmental modification (Lamont, 2009). Because of the intensive cropping of annual high tunnel systems, high inputs of organic matter and fertilizer have been required to sustain optimal yields (Coleman, 1999; Lamont et al., 2003). For organic vegetable growers, certified through the National Organic Program (USDA, 2000), the use of large amounts of compost and organic fertilizers has been a practice to sustain yields and maintain soil organic matter in high tunnel systems (Milner et al., 2009). Because of the high cost of organic fertilizers and compost, fertilization is the most expensive cultural practice in organic vegetable production, with nitrogen being the most important and costly nutrient to manage in organic systems (Gaskell and Smith, 2007).

The harvest of multiple crops annually from a high tunnel system, coupled with the tillage used to prepare beds and incorporate fertilizers, has been shown to lead to the depletion of soil organic matter unless regular supplementation of organic matter is done (Blomgren and Frisch, 2007). Others reported that frequent tillage in a high tunnel system can also create hard pans that can restrict water movement through the soil profile and lead to the destruction of soil aggregation and reduce soil pore space needed to hold air and water (Blomgren and Frisch, 2007). High-tunnel growers minimize the negative effect of tillage on soil quality by reducing tillage frequency, maintaining permanent beds, and utilizing less destructive methods of soil preparation, such as using the broadfork (Coleman, 1999). Intensive production in a limited space with compromised soil quality can also lead to the build-up of high populations of soilborne plant pathogens and ~~severe~~ root disease problems for vegetable crops (Abawi and Widmer, 2000).

Cover Crops in Vegetable Production

Cover crops grown in rotation in field vegetable production systems have well-documented benefits (Burket et al., 1997; Gaskell and Smith, 2007; Robacer et al., 2016; Snapp et al., 2005). These benefits indicate the potential for solving the previously described problems associated with intensive vegetable production in high tunnels, though the research to date on the application of cover crops in high tunnels has been limited.

The practice of growing crops for the specific purpose of protecting or improving agricultural soils was first documented during the Chou dynasty in China more than 3,000 years ago, and later documented by the Greeks during the First Century B.C.E. (Pieters, 1927; Burket et al., 1997). The term “cover crop” was first used by Professor L.H. Bailey near the turn of the 20th century to designate a crop specifically planted to cover an orchard floor throughout the winter and protect tree roots (Pieters, 1927), though it has grown into a broader term for crops grown for soil conservation and soil improvement in a variety of agricultural systems. Cover crops can be green manures, catch crops, living mulches, and forage crops, but in all cases a primary purpose of the crop is for soil improvement, rather than for marketable harvest (Clark ed., 2007). The wide array of benefits from cover crops include supplementing fertilizer requirements, suppressing weeds, decreasing populations of soil-borne pathogens, improving soil quality, increasing water infiltration, relieving soil compaction and building soil structure, adding organic matter, encouraging beneficial microbial populations, enhancing nutrient cycling, preventing soil erosion, conserving soil moisture, and protecting water quality (Clark ed., 2007; Snapp et al., 2005).

Cover crops can be divided into categories based on whether the species are legumes or non-legumes, and based on their season of use (e.g. winter, spring, summer, fall). According to Clark (2007), common summer cover crops for the South include the following legumes: cowpea (*Vigna unguiculata* (L.) Walp), sunn hemp (*Crotalaria juncea* L.); and the following non-legumes: sorghum-sudangrass (*Sorghum bicolor* (L.) Moench x *S. sudanense* (P.) Stapf.), pearl millet (*Pennisetum glaucum* L.), buckwheat (*Fagopyrum esculentum* Moench), and mustard (*Brassica juncea* L.). Common winter cover crops include the following legumes: hairy vetch (*Vicia villosa* Roth), crimson clover (*Trifolium incarnatum* L.), Austrian winter pea (*Pisum sativum* L. subsp. *arvense*); and the following non-legumes: cereal rye (*Secale cereale* L.), annual ryegrass (*Lolium multiflorum* Guss.), oats (*Avena sativa* L.), mustard (*B. juncea*), forage turnip (*B. rapa* L. ssp. *rapa),* and oilseed radish (*Raphanus sativus* L.) (Clark ed., 2007).

Cover crops can also be divided into functional groups, including green manure crops, catch crops, disease suppressive cover crops, smother crops, living mulches, and insectary cover crops. Green manure cover crops are grown for the purpose of incorporating green crop biomass into the soil. As Dr. Adrian Pieters writes in *Green Manuring: Principles and Practice,* a definitive book on the subject published in 1927,

> “the value of green manuring lies in the fact that organic matter is worked into the soil and the organic matter in soil is recognized as being one of its most valuable constituents. The soil nitrogen is associated with the organic matter and the decay of this organic matter influences the availability of the soil minerals."

Legumes are often grown as green manure crops due to their ability to fix atmospheric nitrogen and contribute significant amounts of nitrogen to the following cash crop (Ladd et al., 1981; Snapp et. al., 2005). Grass (*Poaceae spp.*) and brassica (*Brassicaceae spp.*) cover crops are also used as green manures, but they have lower nitrogen content due to their inability to fix atmospheric nitrogen (Clark ed., 2007). Research has shown that crop productivity has been maintained in the absence of nitrogen fertilizer through the incorporation of legume crop residue (Fauci and Dick, 1994), with leguminous cover crops providing as much as 100-200 pounds of nitrogen per acre to vegetable cropping systems (Gaskell and Smith, 2007). Burket et al. (1997) found that nitrogen fertilizer could be applied at one-half the recommended rate for broccoli and one-third the recommended rate for sweet corn when legume green manures were incorporated to achieve the same yield as a control fertilized at the full rate with no green manure. Though there are limitations to the ability of green manures to supply all of a cash crop’s nitrogen requirement. Gaskell et al. (2006) found that green manures can be a valuable source of short-term nitrogen, but long-season vegetable crops grown after a green manure will require additional sources of nitrogen later in the season. Also, only a fraction of the total nitrogen made available by a green manure crop will be utilized by the following cash crop due to the timing of mineralization versus the crop’s nitrogen uptake rate. Hadas et al. (2004) found that nitrogen recovery rates for a crop grown after a green manure crop range from 10-50% of the total green manure nitrogen.

Catch crops are grown after a primary or economic crop to scavenge plant-available nitrogen and prevent nitrogen loss from the soil system. It has been reported that vegetable crop residues can release large amounts of N through mineralization after the incorporation of crop residues into the soil (Wehrmann and Scharpf, 1987; Rahn et al., 1992), with a risk of these residues contributing to N losses by leaching (Neeteson, 1995). Non-leguminous cover crops can deplete nitrate and water from the surface layer of soil after the harvest of a cash crop, decreasing the leaching of nitrate from the soil system and preventing the pollution of ground water supplies (Martinez and Guiraud, 1990; Meisinger et al., 1991; Powlson, 1988). Wyland et al. (1996) found that the winter cover crops phacelia (*Phacelia tanacetifolia* Benth. cv. Phaci) and Merced rye (*Secale cereale* L. cv. Merced) have the ability to reduce winter nitrate leaching after broccoli production by 65-70% compared to a fallow control. The nitrogen taken up by the winter cover crop treatments was then made available to the following broccoli crop through mineralization after incorporation, leading to increased yields of broccoli in the phacelia treatment.

Cover crops have been used for disease suppression in vegetable production systems. *Brassica* cover crops have been shown to provide control of an array of soil-borne pathogens in a variety of cropping systems. Brown mustard (*B. juncea*) was effective in suppressing root rot (*Rhizoctonia solani* Kühn) in sugar beet production (Motisi et al., 2009); Indian mustard (*Brassica juncea* cv. Nemfix and BQ mulch™) green manures proved effective in the suppression of root knot nematode (*Meloidogyne javanica* Treub) in soil and roots, and the improved productivity of wine grapes (*Vitis vinifera* L. cv Sémillon) (Rahman et al., 2011); and in Georgia a variety of *Brassica* spp. cover crops were shown to suppress root-knot nematode in plasticulture vegetable production (Monfort et al., 2007). Other cover crops outside of the *Brassica* genus have also exhibited the ability to control soil-borne diseases. Hairy vetch (*V. villosa*) green manures have been shown to suppress Fusarium wilt (*Fusarium oxysporum* Schldtl.) in watermelon (*Citrullus lanatus* Thunb.) (Zhou and Everts, 2007). A cover crop of marigold (*Tagetes patula* cv. 'Ground Control') grown for seven months and then incorporated is a very effective control of plant-parasitic nematodes and fungal pathogens (*Verticillium dahliae* Kleb.), more effective than the chemical alternative (Korthals et al., 2014). And the tropical grass cover crop, Sudangrass cv. Trudan 8 (*Sorghum sudanense* x. *S. sudanense* Stapf) showed the ability to reduce egg production and root gall severity of *Meloidogyne hapla* Chitwood nematode in lettuce production (Abawi and Widmer, 2000).

Smother crops are cover crops or green manures grown for the purpose of weed suppression. These cover crops are able to put on vigorous vegetative growth and out-compete weeds for light, water, and nutrient resources; and high seeding rates are important for ensuring thick stands (Grubinger, 1999). Sorghum-sudangrass (*Sorghum bicolor* (L.) Moench x *S. sudanense* (P.) Stapf.) and cowpea (*Vigna unguiculata* L.) have been demonstrated to be effective in suppressing weeds in southern agricultural systems (Creamer et al., 1997; Ngouajio et al., 2003). Smother crops can provide additional benefits when incorporated into the soil as green manures. The efficient suppression of weed growth in addition to nitrogen recycling was demonstrated by a winter cover of cereal rye (*Secale cereale*) and a mixture of rye and bell bean (*Vicia faba*) in California coastal cabbage (*Brassica oleracea*) production (Putnam and Holt, 1983).

Cover crops can also be grown as living mulches. For this purpose, the cover crop is interplanted with an annual or perennial cash crop and grown to suppress weeds, reduce soil erosion, improve soil fertility, and improve water infiltration (Sullivan, 2003). Cover crops can also provide habitat for beneficial insect predators that control populations of insect pests (Bugg et al., 1990).

Cover Crops in High Tunnel Vegetable Production

Although cover crops have been well studied for field production systems, their application in high tunnel vegetable production has had limited study. Available information on the subject was limited to Extension bulletins, newsletters, conference presentations, and production manuals (Baldwin, 2010; Blomgren and Frisch, 2007; Evans et al., 2011; Melendez and Rabin, 2012; Rivard, 2013). Despite negative and dismissive reports on high tunnel cover crops from Extension agents and farmers in the Northeast (Blomgren and Frisch, 2007), preliminary studies in New Jersey and Mississippi have shown opportunity for winter cover crops to provide benefits to high tunnel vegetable production, including the uptake of leachable excess nutrients, weed suppression, and spring nitrogen release (Evans et al., 2011; Melendez and Rabin, 2012).

Arguments have been made to dismiss the applicability of cover crops in high tunnel systems (Blomgren and Frisch, 2007; Melendez and Rabin, 2012). The risk of soil erosion is minimized in a high tunnel, so cover crops are not specifically required to prevent soil loss. Cover crops grown throughout the winter in a warm high tunnel could provide habitat for overwintering pests. Season extension in a high tunnel minimizes the windows of time between crops, which eliminates niches that cover crops usually fill. And lastly, the capital investment in a high tunnel makes growers reluctant to use valuable high tunnel ground to grow a crop that does not provide immediate economic return.

Despite these issues, the reported and potential benefits of high tunnel cover crops justify further research on the subject. To begin with, the timing of cover cropping in a high tunnel can minimize the negative aspects of the practice. Local growers have said that the period between mid-November and mid-February was he least productive season for high tunnel vegetable growers in the South due to cold temperatures and low light (Dr. C. Rom, personal communication). During this period, tunnels are idle. By selecting this period to grow a winter cover crop that can tolerate such environmental conditions, the lost revenue stream for the grower is minimized. The modified environment of a high tunnel, with increased soil and air temperatures (Wien, 2009), could also speed the growth of winter cover crops during the stated 90-day period in mid-winter, producing more green biomass than would be produced during the same period in the field. It is thought that if a green manure crop was able to improve soil quality and decrease the requirement for purchased organic matter and fertilizer inputs, the cost savings for the grower could justify the additional management input.

Intensive vegetable production in a high tunnel requires inputs of organic materials to maintain soil organic matter, preserve soil quality, and ensure long-term productivity (Coleman, 1999; Lamont et al., 2003; Milner et al., 2009). Green manure cover crops have been shown to increase soil organic matter and nutrient cycling (Pieters, 1927; Powlson et al., 1987), and could replace purchased organic inputs in high tunnel production. Winter legumes have shown the potential to contribute significant amounts of nitrogen to subsequent vegetable crops in a field setting (Burket et al., 1997; Gaskell and Smith, 2007), which would reduce purchased fertilizer costs for high tunnel growers if similar rates of nitrogen contribution occurred in the high tunnel system. The deterioration of soil quality and the formation of hard pans due to frequent tillage is a documented problem in high tunnel production, which could be ameliorated by the ability of green manure cover crops to improve soil structure and aggregate formation (Hermawan and Bomke, 1997; Roberson et al., 1991; Tisdall and Oades, 1982) and improve the rooting depth of vegetable crops due to the "bio-drilling" effect of certain cover crops (Weil and Kremen, 2007). The ability of legume and brassica winter green manures to suppress soil-borne pathogens in vegetable crops (Monfort et al., 2007; Zhou and Everts, 2007) is another important benefit that winter cover crops could provide to high tunnel systems.

The ability of winter cover crops to improve the yield and performance of vegetable crops in field production systems have been well-documented in the scientific literature. It is the assertion of this study that short-season winter cover crops grown in a high tunnel, then mowed and incorporated, will improve the growth and yield of subsequent vegetable crops.

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CHAPTER 1. PERFORMANCE OF FIVE WINTER COVER CROP TREATMENTS IN HIGH TUNNEL AND SOIL QUALITY EFFECTS.

Abstract

Four different winter cover crop species, Austrian winter peas (*Pisum arvense*), bell beans (*Vicia faba*), mustard (*Brassica juncea* cv. Kodiak), and Daikon radish (*Raphanus sativus var. longipinnatus*), plus an untreated control were evaluated for their effects soil quality and supplement fertilizer requirement when grown as a green manure from mid-November to mid-March, before a succession of two vegetable crops in a high tunnel system in a two year trial. Soil tests before and after the cover crop treatments, in addition to biomass measurements and foliar nutrient tests, determined the organic matter and nutrient contribution of the winter cover crops. Winter peas resulted in the greatest biomass production in year 1 with mustard and radish producing the greatest biomass in year 2. Winter peas, however resulted in the greatest amount of biomass N contribution to the soil system in both years 1 and 2, with a significant reduction in the soil C/N ratio detected in both years measured 30 days after incorporation. Mustard, radish, and winter pea cover crops all resulted in significant weed suppression in the second year, with mustard resulting in virtually no weedy biomass. Soil bulk density (BD) decreased over the course of the study, but the BD under cover crop treatments were not significantly different than the BD measured under the untreated control. Soil pH decreased over the course of the study, though the bell bean, mustard, and radish cover crops resulted in pH values greater than the final pH measured under the control treatment. Soil electrical conductivity (EC) increased over the course of the study, with winter pea leading to increased measured EC at 30 days after cover crop incorporation and radish resulting in a final soil EC that was greater than the control.

Introduction

The benefits of cover crops grown in rotation in field vegetable production systems have been well-documented in the scientific literature (Burket et al., 1997; Gaskell and Smith, 2007; Snapp et al., 2005). These benefits demonstrate the potential for improving soils quality issues associated with intensive vegetable production in high tunnels, though the research to date on the application of cover crops in high tunnels is limited.

Green manure cover crops are grown for the purpose of incorporating green crop biomass into the soil. As Dr. Adrian Pieters writes in *Green Manuring: Principles and Practice*, a definitive book on the subject published in 1927, "the value of green manuring lies in the fact that organic matter is worked into the soil and the organic matter in soil is recognized as being one of its most valuable constituents. The soil nitrogen is associated with the organic matter and the decay of this organic matter influences the availability of the soil minerals." Legumes are often grown as green manure crops due to their ability to fix atmospheric nitrogen and contribute significant amounts of nitrogen to the following cash crop (Ladd et al., 1981; Snapp et. al., 2005). Grass (*Poaceae spp.*) and brassica (*Brassicaceae spp.*) cover crops are also used as green manures, but they have lower nitrogen content due to their inability to fix atmospheric nitrogen (Clark ed., 2007).

Research has shown that crop productivity can be maintained in the absence of nitrogen fertilizer through the incorporation of legume crop residue (Fauci and Dick, 1994), with leguminous cover crops providing as much as 100-200 pounds of nitrogen per acre to vegetable cropping systems (Gaskell and Smith, 2007). Burket et al. (1997) found that nitrogen fertilizer could be applied at one-half the recommended rate for broccoli and one-third the recommended rate for sweet corn when legume green manures were incorporated to achieve the same yield as a control fertilized at the full rate with no green manure. Though there are limitations to the ability of green manures to supply all of a cash crop's nitrogen requirement. Gaskell et al. (2006) found that green manures can be a valuable source of short-term nitrogen, but long-season vegetable crops grown after a green manure will require additional sources of nitrogen later in the season. Also, only a fraction of the total nitrogen made available by a green manure crop will be utilized by the following cash crop due to the timing of mineralization versus the crop's nitrogen uptake rate. Hadas et al. (2004) found that nitrogen recovery rates for a crop grown after a green manure crop range from 10-50% of the total green manure nitrogen.

Smother crops are cover crops or green manures grown for the purpose of weed suppression. These cover crops are able to put on vigorous vegetative growth and out-compete weeds for light, water, and nutrient resources; and high seeding rates are important for ensuring thick stands (Grubinger, 1999). Sorghum-sudangrass (*Sorghum bicolor* (L.) Moench x *S. sudanense* (P.) Stapf.) and cowpea (*Vigna unguiculata* L.) have been demonstrated to be effective in suppressing weeds in southern agricultural systems (Creamer et al., 1997; Ngouajio et al., 2003). Smother crops can provide additional benefits when incorporated into the soil as green manures. The efficient suppression of weed growth in addition to nitrogen recycling was demonstrated by a winter cover of cereal rye (*Secale cereale*) and a mixture of rye and bell bean (*Vicia faba*) in California coastal cabbage (*Brassica oleracea*) production (Putnam and Holt, 1983).

There has been very limited research conducted on the use of cover crops in high tunnel vegetable production. Available information on the subject is limited to Extension bulletins, newsletters, conference presentations, and production manuals (Baldwin, 2010; Blomgren and Frisch, 2007; Evans et al., 2011; Melendez and Rabin, 2012; Rivard, 2013). Despite negative and dismissive reports on high tunnel cover crops from extension agents and farmers in the Northeast (Blomgren and Frisch, 2007), preliminary studies in New Jersey and Mississippi have shown opportunity for winter cover crops to provide benefits to high tunnel vegetable production, including the uptake of leachable excess nutrients, weed suppression, and spring nitrogen release (Evans et al., 2011; Melendez and Rabin, 2012).

Intensive vegetable production in a high tunnel requires inputs of organic materials to maintain soil organic matter, preserve soil quality, and ensure long-term productivity (Coleman, 1999; Lamont et al., 2003; Milner et al., 2009). Green manure cover crops have been shown to increase soil organic matter and nutrient cycling (Pieters, 1927; Powlson et al., 1987), and could replace purchased organic inputs in high tunnel production. Winter legumes have shown the potential to contribute significant amounts of nitrogen to subsequent vegetable crops in a field setting (Burket et al., 1997; Gaskell and Smith, 2007), which would reduce purchased fertilizer costs for high tunnel growers if similar rates of nitrogen contribution occurred in the high tunnel system. The deterioration of soil quality and the formation of hard pans due to frequent tillage is a documented problem in high tunnel production, which could be ameliorated by the ability of green manure cover crops to improve soil structure and aggregate formation (Hermawan and Bomke, 1997; Roberson et al., 1991; Tisdall and Oades, 1982) and improve the rooting depth of vegetable crops due to the “bio-drilling” effect of certain cover crops (Weil and Kremen, 2007). The ability of legume and brassica winter green manures to suppress soil-borne pathogens in vegetable crops (Monfort et al., 2007; Zhou and Everts, 2007) is another important benefit that winter cover crops could provide to high tunnel systems.

The ability of winter cover crops to improve the yield and performance of vegetable crops in field production systems have been well-documented in the scientific literature. It is the hypothesis of this study that short-season winter cover crops grown in a high tunnel, then mowed and incorporated, will improve the growth and yield of subsequent vegetable crops.

Research Objective

To evaluate the growth and performance of winter cover crop treatments grown in a high tunnel environment and their effects on soil variables.

Materials and Methods

Experimental Parameters:

This study was conducted at the University of Arkansas Agriculture Research and Extension Center in Fayetteville, Arkansas (Latitude: 36.1N; Longitude: 94.1W; Altitude: 427m/1400ft; USDA Cold Hardiness Zone 6b; AHS Heat Zone 7), within the organic horticulture research block. The site had Captina silt loam soil with a pH between 6.5 and 6.7. Crops were grown inside a ClearSpan™ Quonset-style high tunnel (FarmTek, Dyersville, Iowa) with dimensions of 6 m by 41.5 m, covered in a single layer of 6 mil polyethylene plastic glazing (with UV protection). Passive ventilation was provided by rolling down sidewall curtains and opening roll-up endwall doors. The high tunnel (HT) was opened for ventilation when the outside temperature exceeded 10 °C in sunny conditions or exceeded 16 °C in overcast conditions, to prevent the temperature inside the high tunnel from exceeding 32 °C. All components of this study were managed in compliance with the USDA National Organic Program (USDA, 2000) requirements for certification, and the site had previously received organic management for 5 years.

Prior to the commencement of this study a summer cover crop of sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. sudanense*) and cowpeas (*Vigna unguiculata* cv. Iron and

Clay) were grown in the HT as a catch crop in order to create consistent soil conditions throughout the HT. In early November 2013, the cover cops were cut with a string-trimmer and the biomass was removed from the HT to create low-fertility conditions. The remaining stubble was mowed and the ground was irrigated with impact sprinklers to provide soil moisture for tillage. On November 14, the soil within HT was tilled to a depth of 8 cm with a Toro® Dingo tiller. The remaining cover crop surface stubble was removed from the tunnel on Nov. 15 and the ground was tilled again to a depth of 8 cm to prepare for planting of cover crop treatments.

Treatments

This study evaluated five winter cover crop treatments: 1) nontreated control, 2) Austrian winter peas (*Pisum arvense*), 3) bell beans (*Vicia faba*), 4) mustard (*Brassica juncea* cv. Kodiak), and 5) Daikon radish (*Raphanus sativus var. longipinnatus*), for their performance in a high tunnel system and their effects on soil quality characteristics when grown as a green manure from mid-November to mid-March, before a succession of two vegetable crops in a HT system.

Cover Crop Planting and Management:

Cover crop seeds were planted on 16 November, 2013, two weeks following the mowing and removal of summer cover crop biomass from the high tunnel. In 2014, cover crop treatments were planted on 20 November, using the same planting methods with the same treatments planted to each plot in both years of the study. The cover crop treatments were arranged in a randomized complete block design (Figure A.1) with three blocks of each treatment. Each block (measuring 6 m by 12.2 m) was divided into five plots measuring 6 m by 2.4 m. Treatment plots were assigned at random throughout each block using an online random number generator. Treatment 1 was the control, with no cover crops planted. Treatment 2 was planted with Austrian winter peas at 1.46 kg per 100 m^2 (Cogger, 1997) or 0.22 kg per plot. Treatment 3 was planted with bell beans at 1.46 kg per 100 m^2 (Cogger,1997) or 0.22 kg per plot. Treatment 4 was planted with ‘Kodiak’ mustard (Mighty Mustard®, Davidson Commodities, Spokane, WA) at 0.25 kg per 100 m^2 or 0.04 kg per plot. Treatment 5 was planted with Daikon radish at 23 kg per ha (Clark, 2007) or 0.33 kg per plot.

Cover crop seed was broadcast by hand, with each plot divided into quarters and broadcast in sections to create an even distribution. Mustard and radish seed were raked in to a depth of approximately 1.2 cm with a bow rake. Winter pea and bell bean seed were tilled in to the soil at a depth of approximately 5 cm with a small, front-tine tiller. The day after planting, the high tunnel was irrigated with overhead impact sprinklers to provide 31 mL of water per m^2. Sprinklers were situated 1.7 m high on PVC risers, each sprinkler 3.7 m apart. Irrigation was provided as needed throughout the growth of the cover crops.

The cover crops were covered with floating row cover (Agribon AG-19) to protect from winter kill when the ambient temperature reached -6.6 °C or below. An additional layer of 6 mm greenhouse plastic was used when temperatures were forecast to reach -12.2 °C or below.

The cover crop treatments were mowed on 8 April 2014 and 7 April 2015, or approximately 143 and 138 days after planting, respectively. A string-trimmer was used to mow the cover crops with a board used as a shield to prevent the spread of biomass from the plot being mowed into adjacent plots. Following mowing, cover crop residue was incorporated with a rotary tiller mounted on a two-wheel tractor (BCS America, Portland, OR). Each plot was tilled individually with tiller tines cleaned between plots to prevent cross-plot contamination. The high tunnel was irrigated with 25 L of water per m^2 using impact sprinklers and closed for 21 days before planting of tomatoes to encourage breakdown of cover crop residues. Soil samples were taken from each treatment plot at the end of the three-week period to measure cover crop effect on soil quality.

Experimental Design:

The experiment was designed as a split-plot within a randomized complete block design, with cover crop treatments serving as the main plot and year serving as the subplot. The high tunnel was blocked by location with three blocks of the five cover crop treatments (Figure A.1), providing three replications of each treatment within each year. Statistical analyses were performed with SAS 9.2 software (SAS Institute, Cary, NC) using PROC MIXED and PROC GLM for analysis of variance and PROC CORR for correlation analyses. Significant was determined at an alpha of 0.05.

High Tunnel Environmental Parameters:

High tunnel ambient air temperature was recorded throughout the duration of the study and is presented in the Appendix.

Experimental Variables:

Experiment 1. Cover crop biomass and nutrient content. Height and shoot biomass of cover crops were measured on 28 March 2014, and 27 March 2015, one week prior to mowing. Three height measurements per plot were taken of the standing cover crop to determine mean height per plot. Biomass samples were then collected from three randomly placed 0.5 m^2 quadrats in each plot, dried in a forced-air oven at 50°C for one week, and weighed to determine dry weight biomass. A 100 gram sub-sample from each biomass sample was ground for shoot fraction nutrient analysis. Cover crop tissue nutrient concentrations were determined by inductively coupled plasma atomic emission spectrometry (SPECTRO ARCOS ICP, SPECTRO

Analytical Instruments Inc, Mahwah, NJ) after HNO_3 digestion at the University of Arkansas Division of Agriculture Soil Testing and Research Laboratory, in Fayetteville, AR. Carbon and nitrogen concentration (percent dry weight basis) of the biomass samples were measured using an Elementar vario EL cube (Elementar Americas, Inc., Philadelphia, PA). The total biomass N contribution for each treatment was calculated by multiplying the shoot tissue N concentration by the dry weight biomass (g/m^2) to arrive at units of g/m^2. Estimates of cover crop biomass N (kg) per hectare were calculated using the equation:

$$N\ g/m^2 = 10 \times N\ kg/ha.$$

Experiment 2. Effect of winter cover crops on high tunnel soil quality. Soil samples were collected from treatment plots at one week before cover crop incorporation (28 March 2014 and 28 March 2015) and three weeks after incorporation (26 April 2014 and 28 April 2015), with six 2.0 cm (dia.) by 15 cm (depth) cores collected from each treatment plot and combined for each sample. Soil samples were analyzed for organic matter content, pH, electrical conductivity, bulk density, and soil C and N concentration. Soil organic matter was determined by weight loss on ignition (LOI) using the procedures described by Maguire and Heckendorn (2011). Bulk density measurements were collected on the same soil sample dates using metal cylinder rings measuring 600 mm tall and 550 mm in diameter, with three samples collected per plot and analyzed as sub-samples. Soil bulk density samples were dried in a forced-air oven at 55°C for one week and then weighed to determine bulk density values. Soil pH and EC were analyzed at the University of Arkansas Division of Agriculture Soil Testing and Research Laboratory using a 2:1 soil/water ratio. Carbon and nitrogen concentration (percent dry weight basis) of the soil samples were measured using an Elementar vario EL cube.

Results

Experiment 1. Cover crop biomass and nutrient content.

The cover crop species studied exhibited significant differences for many of the variables measured. The cover crop species varied in height, with a significant two-way interaction between year and cover crop species over the course of the study. In 2014 winter peas, bell beans, and mustard had similar height measurements, while in 2015 bell beans, mustard, and radish cover crops were significantly taller than winter peas. The radish cover crop was the tallest in both 2014 and 2015, due to stem elongation during flowering, which occurred before measurement (Figure 1). Bell beans, mustard, and radish cover crops were significantly taller in 2015 than in 2014.

This trend also occurred in dry weight biomass measurements, where bell beans, mustards, and radishes produced more biomass in 2015 than in 2014 (Figure 2). Meanwhile, winter pea produced similar amount of biomass across two years. In 2014 winter peas produced significantly greater dry biomass compared to the other cover crop species, but in 2015 both mustard and radish yielded greater biomass than winter pea. Correlation analysis among cover crop variables are summarized in Table 1. A positive correlation coefficient (0.58) between cover crop height and cover crop shoot biomass was observed (Figure 3). Taller cover crop species produced greater shoot dry biomass. This is logical as a crop with a taller canopy will have a greater volume of space for leaf area and thus biomass production.

By harvesting the weedy biomass from each plot separately from the cover crop biomass, the effect of cover crop species on weed growth was measured (Figure 4). The control treatment had the greatest weedy biomass, while the mustard cover crop resulted in no weedy biomass. Winter pea and radish resulted in some weedy biomass dry weights that were greater than zero, but similar to mustard. Bell beans resulted in a significantly greater weedy biomass than the other cover crop species, showing that it was less effective in suppressing the growth of weeds. A greater cover crop biomass lead to decreases in weedy biomass, as indicated by the negative correlation coefficient (-0.61) between cover crop biomass and weedy biomass (Figure 5). This relationship can be explained by the competition for light between a cover crop and understory weeds. A cover crop species with a greater biomass production per unit area will likely have a denser crop canopy that can shade out understory weeds.

Cover crop above-ground biomass was sampled and analyzed for nutrient content before termination. Table 2 shows the results for 2014 and 2014 for macronutrients P, K, Ca, Mg, and S in addition to micronutrients Na, Fe, Mn, Zn, Cu, and B. The following elements showed a significant two-way interaction between year and cover crop species: K, Ca, Fe, Mn, and B. The concentration of the remaining analyzed elements was affected by cover crop species as the main effect.

Shoot tissue N concentration varied from 1.37% to 3.78% among the cover crop treatments (Table 3). The winter pea cover crop contained the greatest N concentration (3.75%), followed by bell beans with an N concentration of 3.14% (Figure 6). Mustard and radish had the lowest shoot tissue N concentration, at 1.53% and 1.37% respectively. While the cover crop species did not have significant differentiation for shoot tissue C concentration, there were differences between 2014 and 2015 values within treatments, with 2015 resulting in a greater C% for winter pea, bell bean, mustard, and radish compared to their respective values in 2014 (Figure 7). The tissue C concentration of weeds from the weedy control remained similar in both years. In 2015 all cover crop species had higher C concentration in shoot biomass than the weedy control.

A significant two-way interaction between year and cover crop treatment was observed for total cover crop biomass N (Figure 8). While the total biomass N (g/m^2) of winter pea was similar in 2014 and 2015, the other cover crop species had greater shoot biomass N in 2015 than in 2014. Winter pea contained the greatest shoot biomass N among all treatments in 2014. In 2015, winter pea and bell beans contained similar shoot biomass N, which was greater than that in all other cover crop treatments. In both years, mustard and radish had similar shoot biomass N as the weedy control.

When evaluating all cover crop variables we observed correlations between cover crop N and height; cover crop C and biomass; cover crop height and biomass; and cover crop biomass and weedy biomass (Table 1). A negative correlation (-0.43) existed between cover crop N concentration and cover crop height (Figure 9), indicating that as cover gets taller, shoot tissue N concentration gets higher. This is most likely a dilution effect as similar amount of N is distributed across a larger volume of shoot tissues. . Since it appears that the N concentration of cover crop tissue was affected by the height of the cover crop, we would expect for a calculation of total cover crop N (N concentration multiplied by cover crop biomass) to be a more accurate metric for comparing the quantity of N contributed by the cover crop species.

A positive correlation coefficient (0.68) existed between cover crop C concentration and cover crop biomass (Figure 10), suggesting that as the dry weight of above-ground biomass increased, the concentration of C within the above-ground cover crop tissue also increased. From this relationship we would expect that cover crops species with high-carbon tissue will result in much greater carbon returns to the soil than cover crop species that have a lower tissue C concentration.

Experiment 2. Effect of winter cover crops on high tunnel soil quality.

The effects of cover crops on the HT soils were not as apparent as the differences in growth and development of the cover crops. However, some results and trends are worth noting. The year of study was a main effect for both soil organic matter (SOM) and bulk density (BD) while cover crop treatment was not a significant effect across years (Table 4). SOM decreased from 2014 to 2015, from a mean of 3.02% to a mean of 1.64%, which is possibly due to differences in sampling procedure between the two years. Soil BD decreased approximately 12% from 2014 to 2015, with mean values at 1.61 and 1.43 g/cm^3, respectively. The change in BD over time without a cover crop effect may be due to management practices in the tunnel including tillage and bed preparation. Or it is possible that the incorporation of the weedy biomass in the non-treated control plots had a similar effect on BD as the incorporation of cover crop biomass.

Soil N concentration was not affected by sampling date or cover crop treatment (Table 5). Soil C concentration, on the other hand, was affected by the sampling date as a main effect. Mean soil C concentration was highest when sampled before cover crop incorporation, with values at 1.31% and 1.33% in March 2014 and 2015, respectively. The post-incorporation soil C was significantly lower, at 1.22% and 1.15% measured in April 2014 and 2015, respectively. This indicates an accumulation of soil C while winter cover crops were growing in the ground and then a net loss of soil C after cover crop tissue had been incorporated.

The soil C/N ratio was affected by an interaction between sampling date and cover crop treatment (Table 5). While soil C/N under the various cover crop treatments was not significantly different on the 28 March 2014 sampling date, differences were detected between cover crop treatments when soil was sampled 30 days after cover crops were incorporated

(Figure 11). The winter pea and bell beans cover crop resulted in a significant decrease in soil C/N after incorporation (9.6, 11.0, respectively) when compared to the pre-incorporation value (10.5, 10.2 respectively), indicating an increase of N availability in the soil system. For the winter pea cover crop there was an increase in soil N concentration measured from March to April 2014 (1,166 mg/kg to 1,200 mg/kg) coupled with a decrease in soil C from 1.22% to 1.17%, which explains the decrease in soil C/N ratio. For the bell bean cover crop there was a decrease in soil N from March to April 2014 (1,233 mg/kg to 1,144 mg/kg) in addition to an even greater decrease in soil C from 2.37% to 2.00%, which was enough to decrease the C/N ratio. The post-incorporation C/N for winter pea was lower than the soil C/N for mustard (10.7) or radish (11.0), which were not different from pre-incorporation concentration.

By 28 March 2015 when pre-incorporation soil samples were collected again, the soil C/N had increased significantly after 2 seasons for winter pea, bell bean, and radish compared to their Mar 2014 values. The soil C/N did not change under the weedy control and mustard treatments, however. When soil C/N was measured 30 days after incorporation on 28 April 2015, winter pea, bell bean, and radish resulted in significantly lower values compared to their pre-incorporation C/N. Winter pea soil C/N decreased from 11.6 to 9.6, bell bean decreased from 12.0 to 9.9 and radish decreased from 12.4 to 10.1 from 28 March to 28 April 2015, respectively. Of these three treatments that resulted in a significant decrease in soil C/N after incorporation, winter pea was the only cover crop that resulted in a final soil C/N that was significantly less than the control (10.6).

A negative correlation was observed between cover crop biomass N and soil C/N ratio when data were analyzed across years (PCC = -0.56, p-value = 0.001) (Figure 12 and Table 6).

This relationship supports the observation that high N cover crop species in the study resulted in lower soil C/N after incorporation.

Soil pH decreased over the timeline of the study, from 6.63 (28 Mar. 2014) to 6.20 (12 Nov. 2015) (Figure 13). Incorporating cover crop residue did not appear to significantly affect soil pH, with no differences detected between the pH of samples pre-incorporation compared to samples post-incorporation. Winter pea resulted in a soil pH (6.45) similar to the control treatment (6.48), whereas bell bean, mustard, and radish resulted in mean soil pH values that were significantly greater than the control (6.60, 6.60, and 6.59, respectively).

There was a two-way interaction of sampling date and cover crop on soil EC (Table 7). Soil EC was similar on most sampling dates, ranging from 130 to 150 dS/m. However, on the post-incorporation sampling date of 25 April 2014 the winter pea treatment resulted in a greater soil EC (184 dS/m) than all other treatment, which ranged from 128 to 143 dS/m (Figure 14). On the final sampling date of 12 Nov. 2015, soil EC values were greater than all other date-treatment combinations with the exception of the April 2014 winter pea measurement. For the Nov 2015 sampling date, soil EC values ranged from 208 to 263 with radish having a greater EC than all other treatments on that sampling date.

Discussion

In horticultural cropping systems, the long-term productivity of the soil is determined in part by soil quality characteristics including soil C and SOM, BD, pH and EC (Bonanomi, et al., 2014; Colla, et al., 2000; Song, et al., 2011; Tian et al., 2011). The presence and availability of soil N is also an important factor in the productivity of horticultural crops (Cogger, et al., 2016). It has been reported that the intensive cultivation of crops within high tunnel systems may lead to soil quality decline, with decreases in SOM and increases in BD (Blomgren and Frisch, 2007; Bonanomi, et al., 2014). Winter cover crops were tested for their growth and production within a high tunnel system and for their effect on soil quality and soil fertility.

In the present study, some changes in soil characteristics were observed during the 2 year study consistent with previous reports on the decrease of soil C, SOM, and soil pH and the increase in soil EC in intensively-cropped vegetable production systems (Table 4, Table 5, Figure 13, Figure 14). However, some cover crop treatments may reduce or slow soil acidification within this production system (Figure 13). In addition, we found that soil BD decreased across all treatments over time under this management system (Table 4).

Within this study, four winter cover crop species were assessed for their growth and biomass production in a high tunnel production system. Differences were observed for cover crop height and dry biomass production (Figure 1, Figure 2) between years 2014 and 2015 of the study, which can be attributed to a change in soil N status. Across all treatments there was an increase in mean soil N by 402 mg/kg from the beginning of the vegetable crop production cycle (March) to the end of the production cycle (Nov.) in 2014, resulting in a higher soil N available to the cover crop treatments grown in the second year of the study. While the mustard and radish cover crops showed an increase in both height and biomass from 2014 to 2015 due to elevated soil N, Austrian winter pea produced a similar dry biomass between the two years (Figure 1, Figure 2). The consistency in winter pea biomass production despite changes in soil N status can be attributed to the legume cover crop’s ability to fix atmospheric N (Ladd et al., 1981; Snapp et. al., 2005).

Winter pea and bell bean cover crops contained the highest N concentration in shoot tissue (Figure 6), which is supported by the literature on leguminous cover crops (Ladd et al., 1981; Snapp et. al., 2005; Gaskell and Smith, 2007). This elevated tissue N for the legume cover crops resulted in greater biomass N that was incorporated into the soil after cover crop termination. In 2014 winter peas contributed a significantly greater amount of N compared to all other cover crops and in 2015 winter peas and bell beans contributed a similar amount of N through biomass incorporation (Figure 8). This did not result in a statistically significant increase in soil N at 30 days after incorporation, however (Table 5). However, soil N after winter pea cover crop incorporation was slightly greater than the control (78 mg/kg in 2014 and 33 mg/kg in 2015, respectively), with bell beans resulting in a similar elevated soil N in 2015.

The incorporation of N-rich biomass affected the soil C/N ratio. When comparing pre-incorporation soil C/N to post-incorporation C/N, both winter peas and bell beans showed a significant reduction in 2014 and 2015. Radish also resulted in a significant decrease in soil C/N in 2015 (Figure 11). Cover crop biomass N showed a negative correlation with soil C/N, confirming the observation that high-N cover crop biomass results in decreased soil C/N after biomass incorporation (Figure 12). Studies have linked decreased soil C/N ratios to increased availability of N for plant uptake (Hadas et al., 1992, Whitmore and Groot, 1997 and Trinsoutrot et al., 2000), indicating that winter peas and bell beans lead to increased available N for vegetable crop uptake following their biomass incorporation.

A decrease in soil C/N can also be caused by a decrease in soil C relative to soil N. We measured a mean decrease in soil C from pre-incorporation to 30 days after cover crop incorporation by 0.8 g/kg in 2014 and 1.8 g/kg in 2015. Soil C did not increase significantly over the course of the study and actually decreased slightly when comparing measurements taken in April 2014 to April 2015 (mean decrease of 7 g/kg). The loss of soil C could be attributed to the annual tillage that occurred to prepare the soil for planting cover crops in the fall and to incorporate the cover crop biomass in the spring, with previous studies indicating that tillage events can lead to substantial loss of soil C in the form of CO_2 (Conant et al., 2007).

The decrease in soil C coincides with a decrease in soil organic matter from April 2014 to April 2015. Despite the fact that the cover crops grown contained a significant amount of C in their biomass, which was returned to the soil through incorporation, we did not measure increases in either soil C or soil OM. This conflicts with studies that have shown cover crops to lead to net increases in soil OM in field conditions (Pieters, 1927; Powlson et al., 1987). It is possible that the winter production of cover crops in the high tunnel did not produce enough biomass C to offset the soil C lost from tillage.

We also found a general trend in decreasing soil pH over time, though bell beans, mustard, and radish resulted in slightly elevated soil pH measurements compared to the control (Figure 13). The decrease in soil pH over time in vegetable production is documented in the literature and attributed to the removal of base cations from plant uptake, with greater ammonium nitrogen application leading to more rapid soil acidification (De Vries and Breeuwsma, 1987; Malhi et al., 1998). The findings of this study point to an ability for bell bean, mustard, and radish cover crops to buffer the decrease in soil pH caused by annual cropping, but additions of liming amendments would still be required to keep soil pH within the ideal range of 6.5 to 6.8 for vegetable crops (Havlin et al. 2005; Splittstoesser 1990).

The increase in soil EC over time in high tunnel cropping systems has been a concern for growers (Blomgren and Frisch, 2007). The results of this study did not point to cover crops as being able to prevent the increase in soil EC within high tunnel vegetable production. In fact, we found a correlation between cover crop N concentration and soil EC ($PCC=0.57$, $p<.0001$) and a correlation between soil N and EC ($PCC=0.36$, $p=0.06$), indicating that N-rich cover crop biomass will increase soil EC due to increased soil N. For most dates cover crop treatments did not result in soil EC that was significantly different than the control (Figure 14). In fact, on some sampling dates (April 2014 and Nov 2015) cover crop treatments resulted in soil EC levels greater than the control. However, for all treaments throughout the study the soil EC remained within the non-saline range of 0-1.3 dS/m (0-1300 µmhols/cm) for a silt loam soil according to Dahnke and Whitney (1988).

While cover crop treatment did not have a significant effect on soil bulk density (BD), BD decreased from 2014 to 2015, from 1.61 to 1.43 g/cm^3 during the two-year cropping cycle. Because no differences were observed between the BD measured in the cover crop plots compared to the untreated control plots, it can be assumed that the decrease in soil BD can be attributed to the production practices, which included annual tillage and the formation of raised plasticulture beds for vegetable production. Cover crops have resulted in improved soil aggregation and porosity in prior studies (Clark ed., 2007; Snapp et al., 2005), which will result in lower soil BD. In the case of this study, however, it appeared that the potential effect of cover crop treatments on soil BD was not as significant as cultural practices such as bed shaping and cultivation.

In this study we observed a positive effect of year on the growth of the cover crops bell beans, mustard, and radish, as reflected in increases in height and biomass measurements (Figure 1, Figure 2) from 2014 to 2015. We can attribute some of this improvement in cover crop growth to increased soil N prior to planting in 2014 compared to the beginning of the study in 2013 due to fertilization practices. Another difference between years that likely had an effect on the growth of cover crop treatments were environmental parameters including temperature and light radiation. Mean high and mean low temperatures during cover crop production in the 2014-2015 season were greater than temperatures during the 2013-2014 season (Table 16), with the winter of 2014-2015 being much more mild than the previous. Temperature has been shown to be a limiting factor in the production of winter crops (Thomsen et al., 2010; Gavito et al., 2001), which can explain the improvement in cover crop growth from year 1 to year 2 of this study. Austrian winter pea, however, remained relatively constant in biomass production and N fixation, demonstrating its ability to perform consistently despite environmental changes. With a biomass N content of 9.4 to 10.8 g N/m^2 (94 to 108 kg N/ha) over the two years of the study, the winter pea cover crop contained an N content equivalent to 50-66% of the N requirement for most vegetable crops (Maynard and Hochmuth, 2007). Although significant improvements in soil quality under these cover crop treatments was not found within the two years of the study, Austrian winter pea demonstrated an ability to contribute an economically significant amount of N within an organic high tunnel vegetable cropping system.

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Tables and Figures

Figure 1. Cover crop height measured on 28 Mar. 2014 and 28 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, Ar. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Letters represent differences between means for year x treatment combinations.

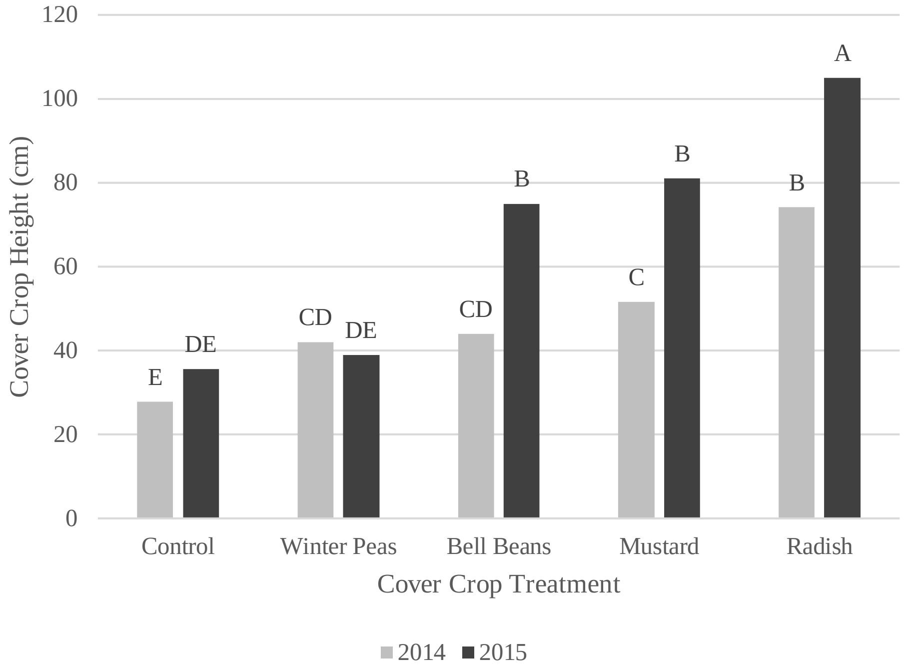


Figure 2. Cover crop shoot dry biomass sampled on 28 Mar. 2014 and 28 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, Ar. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Letters represent differences between means for year x treatment combinations.

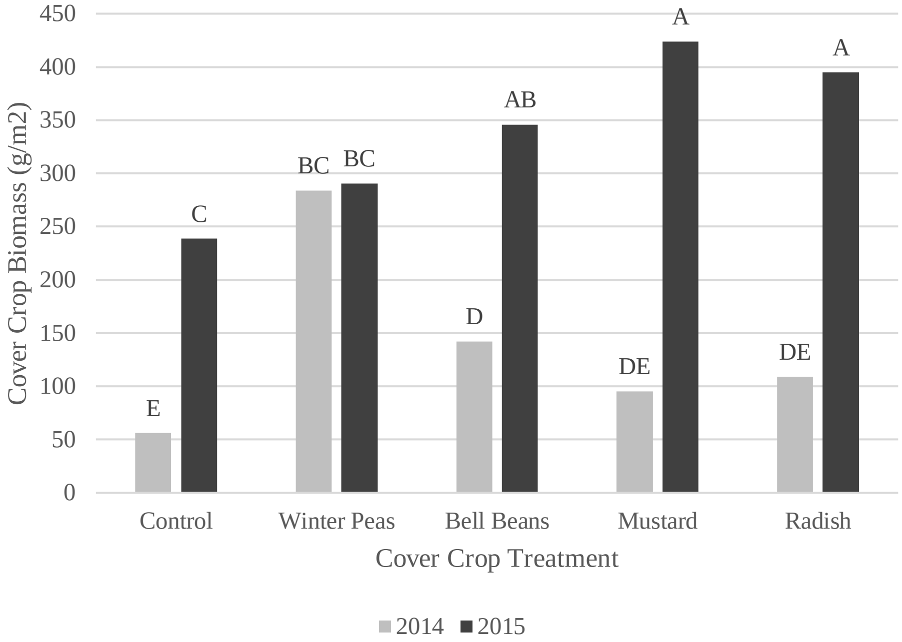


Table 1. Correlation between cover crop variables, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR during the winter seasons of 2013-2014 and 2014-2015. For each relationship the Pearson Correlation Coefficients (PCC) and p-value are included in the table.

		Year	**Cover Crop N%**	**Cover Crop C%**	**Cover Crop C/N**	**Cover Crop Height**	**Cover Crop Biomass**	**Cover Crop Total N**	**Weedy Biomass ****
Year*	**PCC**	1	-0.066	0.754	0.223	0.397	0.771	0.401	.
	p-value*		0.731	<.0001	0.236	0.030	<.0001	0.028	.
Cover Crop Tissue N%	**PCC**	-0.066	1	0.370	-0.952	-0.430	0.082	0.701	-0.046
	p-value	0.731		0.044	<.0001	0.018	0.667	<.0001	0.872*
Cover Crop Tissue C%	**PCC**	0.754	0.370	1	-0.199	0.193	0.677	0.604	-0.417
	p-value	<.0001	0.044		0.292	0.308	<.0001	0.000	0.122*
Cover Crop Tissue C/N Ratio	**PCC**	0.223	-0.952	-0.199	1	0.538	0.137	-0.549	-0.137
	p-value	0.236	<.0001	0.292		0.002	0.470	0.002	0.627*
Cover Crop Height	**PCC**	0.397	-0.430	0.193	0.538	1	0.579	0.072	-0.554
	p-value	0.030	0.018	0.308	0.002		0.001	0.704	0.032*
Cover Crop Biomass	**PCC**	0.771	0.082	0.677	0.137	0.579	1	0.700	-0.613
	p-value	<.0001	0.667	<.0001	0.470	0.001		<.0001	0.015*
Cover Crop Total Biomass N	**PCC**	0.401	0.701	0.604	-0.549	0.072	0.700	1	-0.302
	p-value	0.028	<.0001	0.000	0.002	0.704	<.0001		0.274*
Weedy Biomass**	**PCC**	.	-0.046	-0.417	-0.137	-0.554	-0.613	-0.302	1
	p-value	.	0.872*	0.122*	0.627*	0.032*	0.015*	0.274*	

* n = 30 unless otherwise indicated

** n = 15

Figure 3. Relationship between cover crop height and cover crop dry weight biomass, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR during the winter seasons of 2013-2014 and 2014-2015. Linear $r^2 = 0.34$, n = 30, p-value = 0.001.

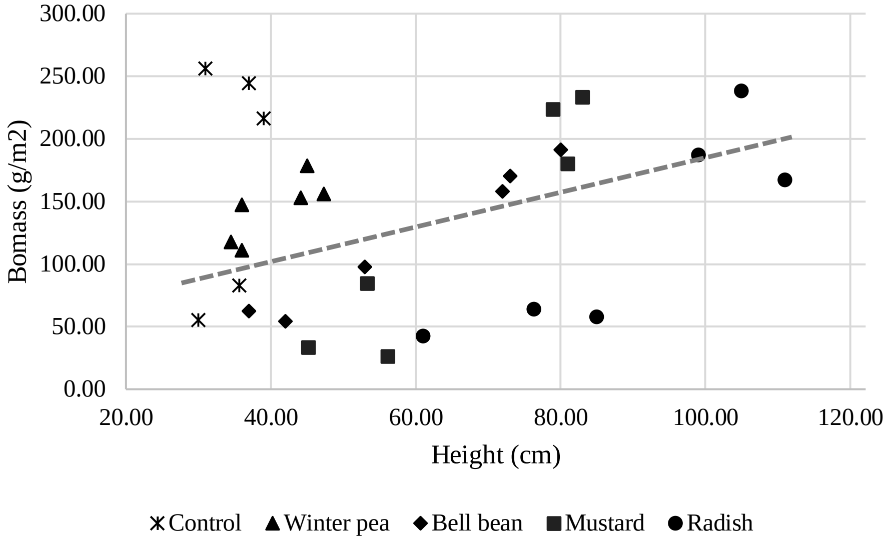


Figure 4. Cover crop and weedy dry biomass (g/m^2), sampled on 28 Mar. 2015, 128 days after planting in a high tunnel in Fayetteville, Ar. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Upper-case letters represent mean separation between the cover crop biomass and lower-case letters represent mean separation between the weedy biomass measurements.

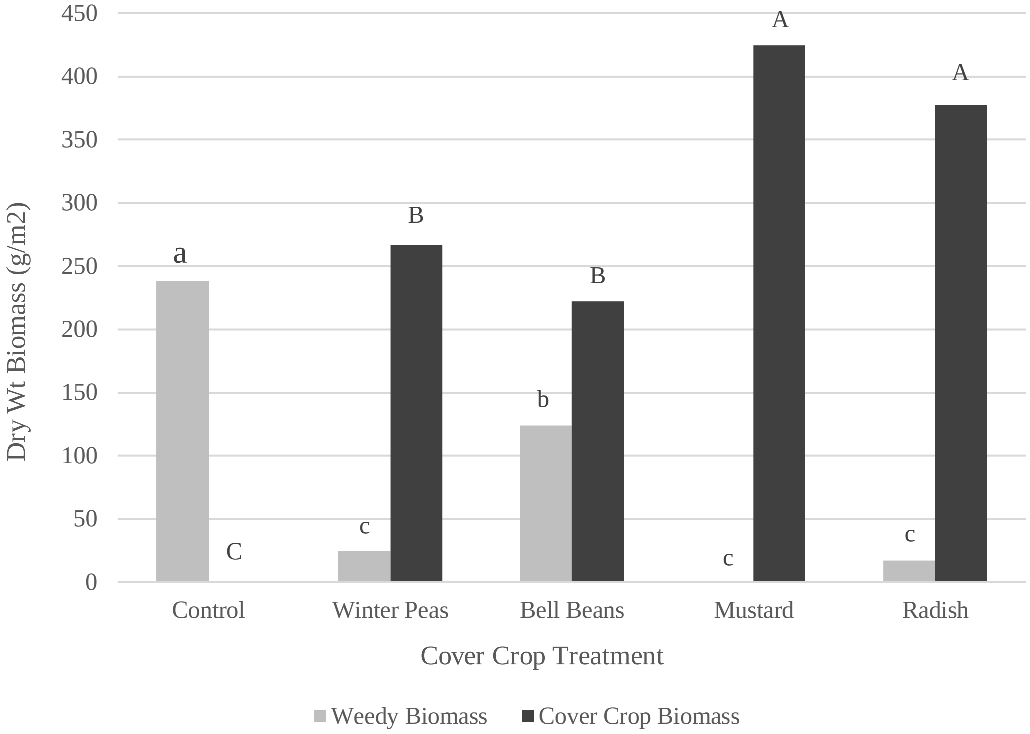


Figure 5. Relationship between cover crop dry weight biomass and weedy biomass, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR during the winter seasons of 2013-2014 and 2014-2015. Linear $r^2 = 0.38$, n=15, p-value = 0.015.

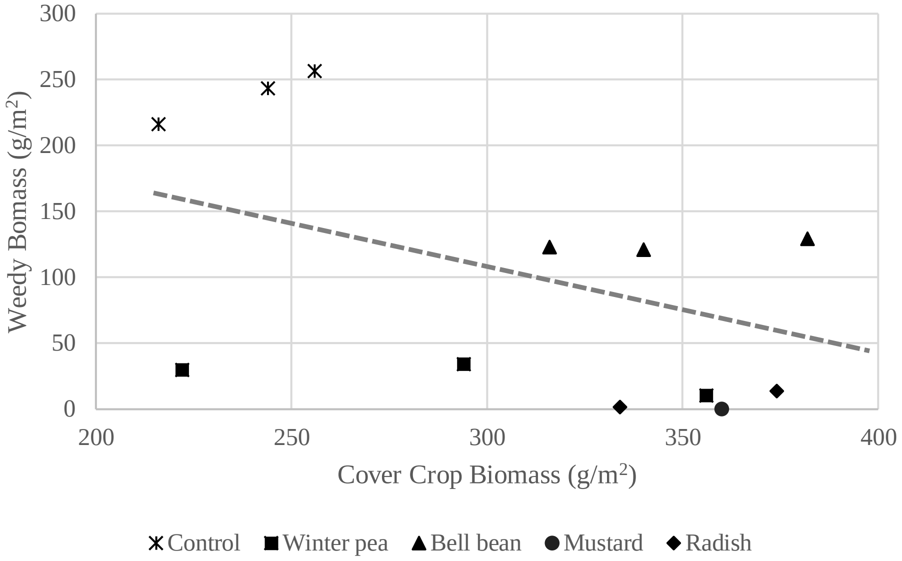


Table 2. Nutrient content of above-ground cover crop biomass sampled on 28 Mar. 2014 and 20 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, Ar. n = 3.

Treatment	-------------------- %	----------------				----------------------- mg/kg	-----------------				
Year	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**	**B**
Control	**0.42**	**3.07**	**1.21**	**0.16**	**0.35**	**214.1**	**1311.0**	**54.5**	**33.1**	**27.6**	**18.9**
2014	0.45	3.19	1.15	0.17	0.37	173.7	991.0	39.8	35.9	36.2	19.4
2015	0.38	2.94	1.27	0.16	0.33	254.5	1631.0	69.2	30.3	19.1	18.4
Winter Peas	**0.36**	**3.68**	**1.35**	**0.28**	**0.25**	**587.5**	**352.2**	**53.8**	**78.6**	**17.9**	**20.5**
2014	0.37	4.17	1.30	0.28	0.25	415.1	623.9	58.2	75.4	25.2	19.8
2015	0.36	3.20	1.39	0.28	0.26	759.9	80.6	49.4	81.8	10.6	21.3
Bell Beans	**0.32**	**3.47**	**1.22**	**0.22**	**0.21**	**1873.9**	**198.4**	**54.2**	**67.8**	**21.3**	**22.1**
2014	0.36	4.26	1.14	0.22	0.23	1243.0	308.3	52.0	74.5	29.0	21.8
2015	0.27	2.67	1.30	0.21	0.18	2504.7	88.6	56.3	61.2	13.7	22.3
Mustard	**0.37**	**3.08**	**1.49**	**0.18**	**0.59**	**193.9**	**675.5**	**37.8**	**32.4**	**21.6**	**29.4**
2014	0.40	2.72	1.70	0.21	0.58	176.6	1243.3	55.9	42.5	38.0	27.7
2015	0.35	3.44	1.28	0.15	0.60	211.2	107.8	19.8	22.4	5.3	31.1
Radish	**0.46**	**3.33**	**1.90**	**0.20**	**0.60**	**749.1**	**537.6**	**27.1**	**28.7**	**17.7**	**27.2**
2014	0.50	3.33	2.24	0.23	0.67	603.5	1052.2	42.2	35.6	31.8	29.0
2015	0.43	3.34	1.56	0.17	0.52	894.6	23.0	12.0	21.7	3.5	25.3
	*	**	**	*	*	*	**	**	*	*	**

* indicates Trt main effect at $p < 0.05$

** indicates Year by Trt interaction effect at $p < 0.05$

Table 3. Cover crop shoot tissue C and N content from samples collected from above-ground cover crop biomass on 28 Mar. 2014 and 20 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, AR.

Treatment Year	**N%**		**C%**		**C/N ratio**	
Control	**1.75**	**C**[z]	**38.81**		**23.48**	**B**
2014	1.82		38.56	cd	22.66	
2015	1.68		39.06	c	24.29	
Winter Peas	**3.78**	**A**	**41.17**		**11.01**	**C**
2014	3.81		38.67	cd	10.32	
2015	3.75		43.67	a	11.7	
Bell Beans	**3.14**	**B**	**41.13**		**13.43**	**C**
2014	3.28		38.83	cd	12.05	
2015	3		43.44	ab	14.82	
Mustard	**1.54**	**CD**	**39.17**		**25.9**	**AB**
2014	1.6		36.93	de	23.26	
2015	1.48		41.41	b	28.53	
Radish	**1.37**	**D**	**38.56**		**28.79**	**A**
2014	1.4		35.52	e	25.85	
2015	1.35		41.59	ab	31.74	
	*		**		*	

* F-test indicates Trt main effect at $p < 0.05$

** F-test indicates Year*Trt interaction effect at $p < 0.05$

[z] Upper-case letters represent means separation between values within the column for main effects. Lower case letters indicate mean separation between values within a column for the interaction effects. Mean separation was performed by LSD at $p < 0.05$. n = 3.

Figure 6. Cover crop shoot tissue N concentration (%) mean values from years 2014 and 2015 pooled. Shoot biomass was sampled on 28 Mar. 2014 and 29 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, AR. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Letters represent differences between treatment means.

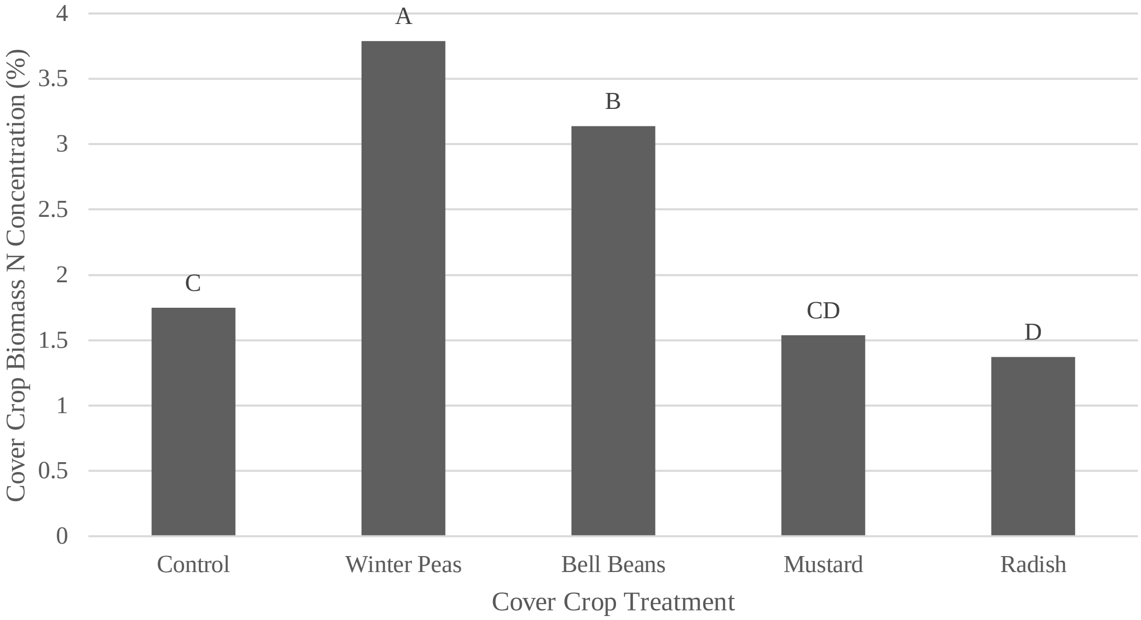


Figure 7. Shoot tissue C concentration sampled from treatments on 28 Mar. 2014 and 29 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, AR. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Letters represent differences between means for year x treatment combinations.

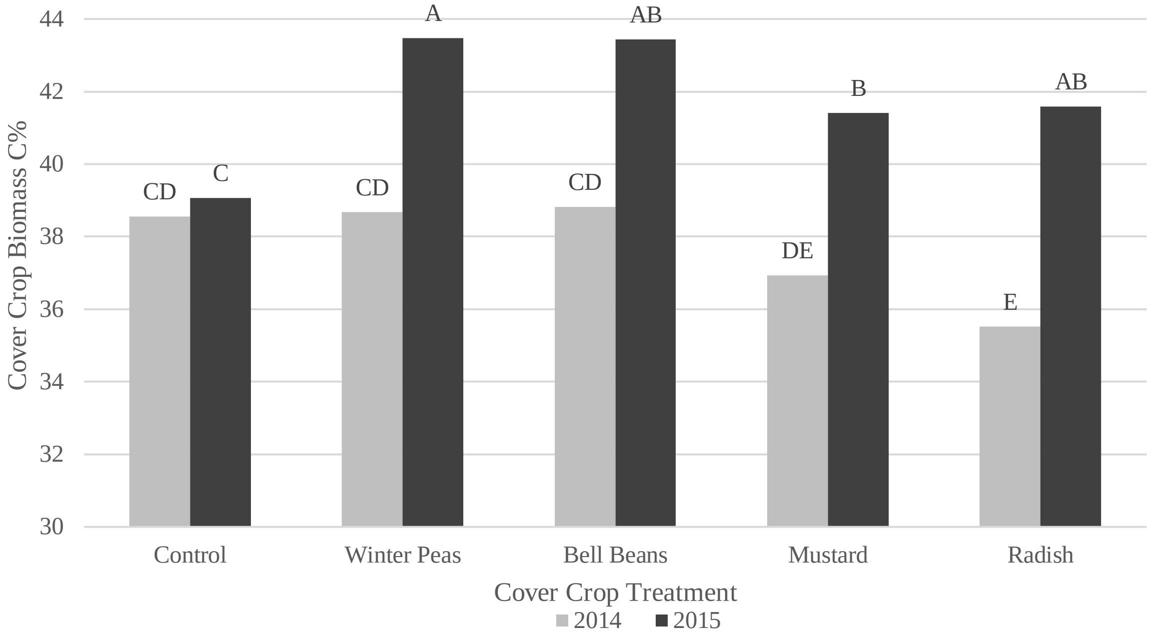


Figure 8. Cover crop biomass N (g/m^2) calculated from shoot biomass sampled on 28 Mar. 2014 and 29 Mar. 2015, 132 and 128 days after planting, respectively, in a high tunnel in Fayetteville, AR. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Letters represent differences between means for year x treatment combinations.

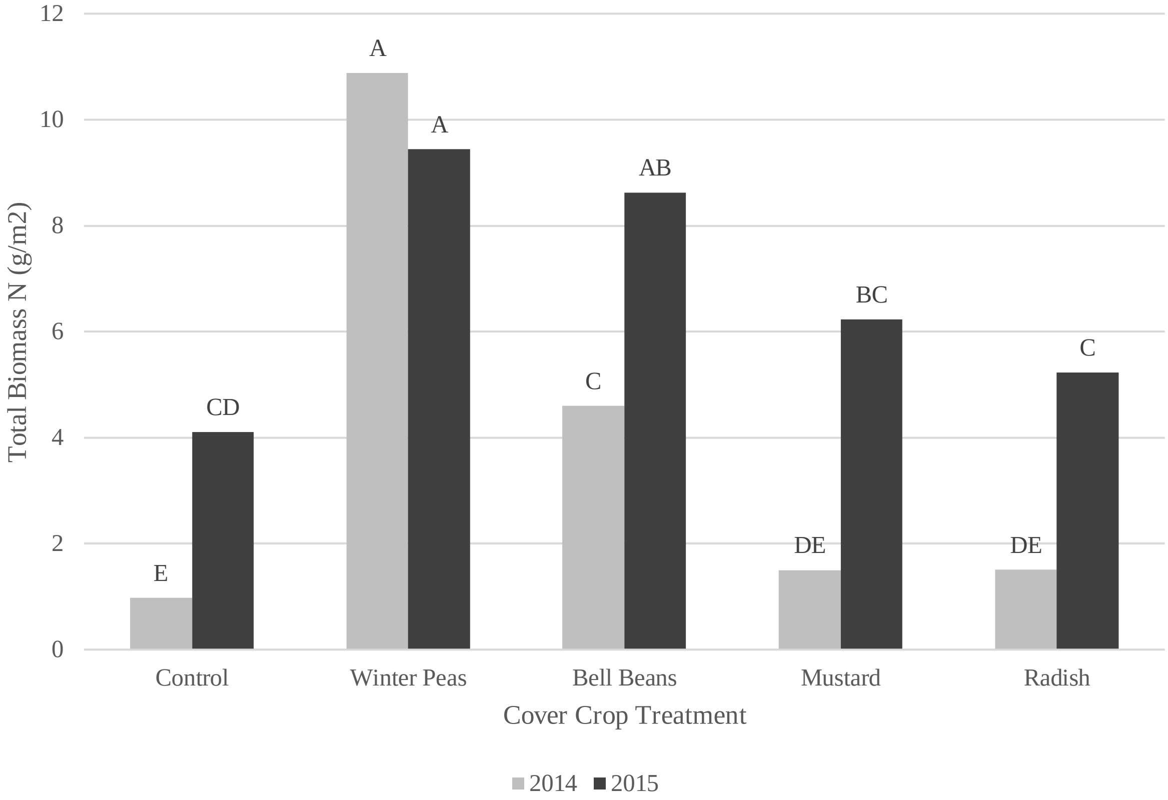


Figure 9. Relationship between cover crop shoot tissue N and cover crop height, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR and sampled on 28 Mar. 2014 and 29 Mar. 2015, 132 and 128 days after planting, respectively. Linear $r^2 = 0.18$, n = 30, p-value = 0.018.

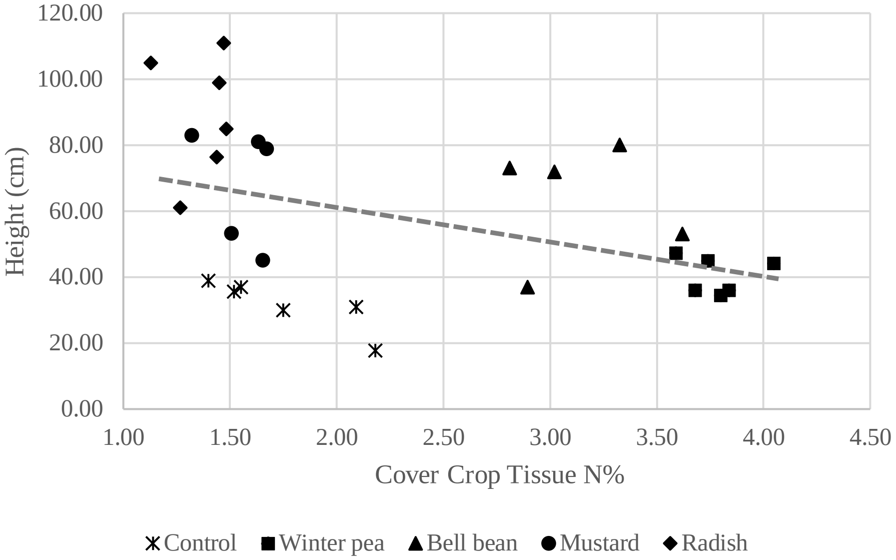


Figure 10. Relationship between cover crop above-ground tissue C and cover crop biomass, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR and sampled on 28 Mar. 2014 and 29 Mar. 2015, 132 and 128 days after planting, respectively. Linear $r^2 = 0.46$, $n = 30$, p-value < 0.0001.

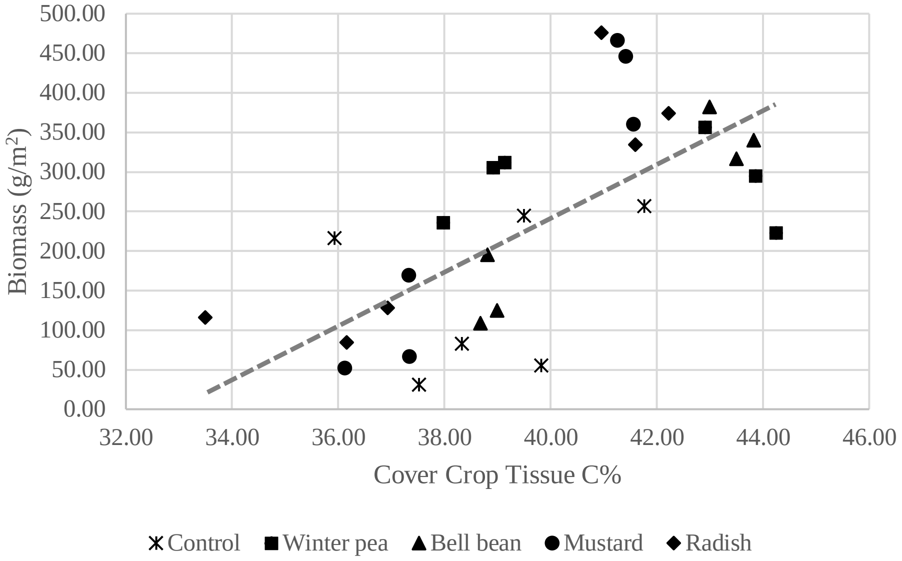


Table 4. ANOVA table of interaction between cover crop treatment and year on soil organic matter (SOM) and bulk density (BD), measured on 25 April 2014 and 28 April 2015. n = 3.

		Soil Variables ($P < F$)	
Factor	DF	SOM	BD
Cover crop	4	0.745	0.495
Year	1	<0.0001	0.000
Cover crop X Year	4	0.835	0.154
Block	4	0.732	0.041

Table 5. ANOVA for interaction between cover crop treatment and date on soil C% soil N% and soil C/N ratio, from soil samples collected on 28 Mar. 2014, 25 April 2014, 28 Mar. 2015, and 28 April 2015. n = 3.

		Soil Variables (P < F)		
Factor	DF	N%	C%	C/N
Cover crop	4	0.500	0.085	0.008
Date	3	0.082	0.001	<.0001
Cover crop X Date	4	0.231	0.086	0.032
Block	8	0.201	0.450	0.747

Figure 11. Soil C/N ratio measured from 15 cm soil cores collected on sampling dates of 28 Mar. 2014, 26 April 2014, 28 Mar. 2015, and 28 April 2015 in a high tunnel in Fayetteville, AR. March sampling dates were prior to cover crop incorporation and April dates were 30 days after incorporation. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units.

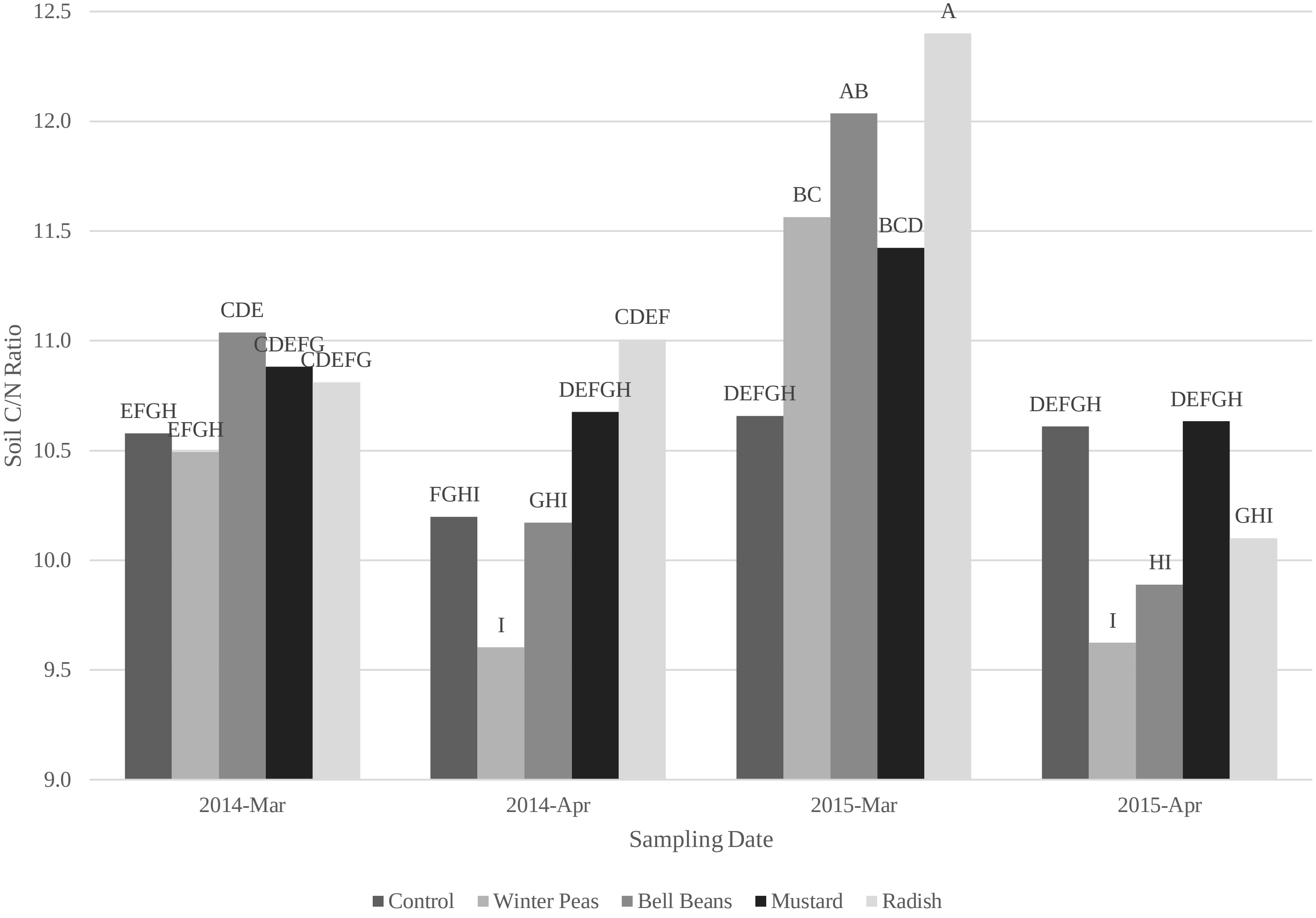


Figure 12. Relationship between cover crop biomass N and soil C/N ratio, as measured from Austrian winter peas, bell beans, 'Kodiak' mustard, and 'Daikon' radish grown in a high tunnel in Fayetteville, AR. Soil C/N ratio was measured from 15 cm soil cores collected on sampling dates of 28 Mar. 2014, 26 April 2014, 28 Mar. 2015, and 28 April. Linear $r^2 = 0.31$, $n = 30$, p-value = 0.001.

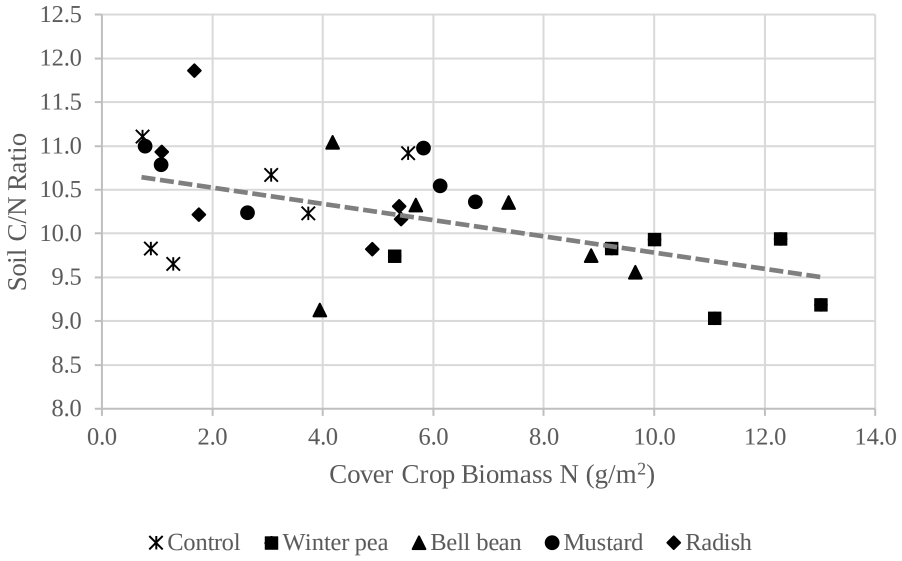


Table 6. Correlation between cover crop variables and soil variables, as measured from Austrian winter peas, bell beans, ‘Kodiak’ mustard, and ‘Daikon’ radish grown in a high tunnel in Fayetteville, AR during the winter seasons of 2013-2014 and 2014-2015. For each relationship the Pearson Correlation Coefficients (PCC) and p-values are stated.

		Soil N%	**Soil C%**	**Soil C/N Ratio**
Cover Crop Tissue N%	**PCC**	0.111	-0.280	-0.549
	p-value*	0.559	0.134	0.002
Cover Crop Tissue C%	**PCC**	-0.356	-0.542	-0.478
	p-value	0.054	0.002	0.008
Cover Crop Tissue C/N	**PCC**	-0.104	0.205	0.429
	p-value	0.586	0.277	0.018
Cover Crop Height	**PCC**	-0.060	0.037	0.089
	p-value	0.751	0.846	0.639
Cover Crop Biomass	**PCC**	-0.231	-0.337	-0.274
	p-value	0.219	0.069	0.142
Cover Crop Biomass N	**PCC**	-0.031	-0.372	-0.558
	p-value	0.872	0.043	0.001

* n = 30

Figure 13. Soil pH measured from 15 cm soil core samples collected on 28 Mar. 2014, 25 April 2014, 8 Aug. 2014, 7 Nov. 2014, 28 Mar. 2015, 28 April 2015, 12 Aug. 2015, and 12 Nov. 2015. March sampling dates are prior to cover crop incorporation, April dates are 30 days after incorporation, August dates are after tomato cropping, and November dates are after broccoli cropping in a high tunnel in Fayetteville, AR. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units. Upper-case letters represent means separation among sampling dates and lower-case letters represent means separation among cover crop treatments.

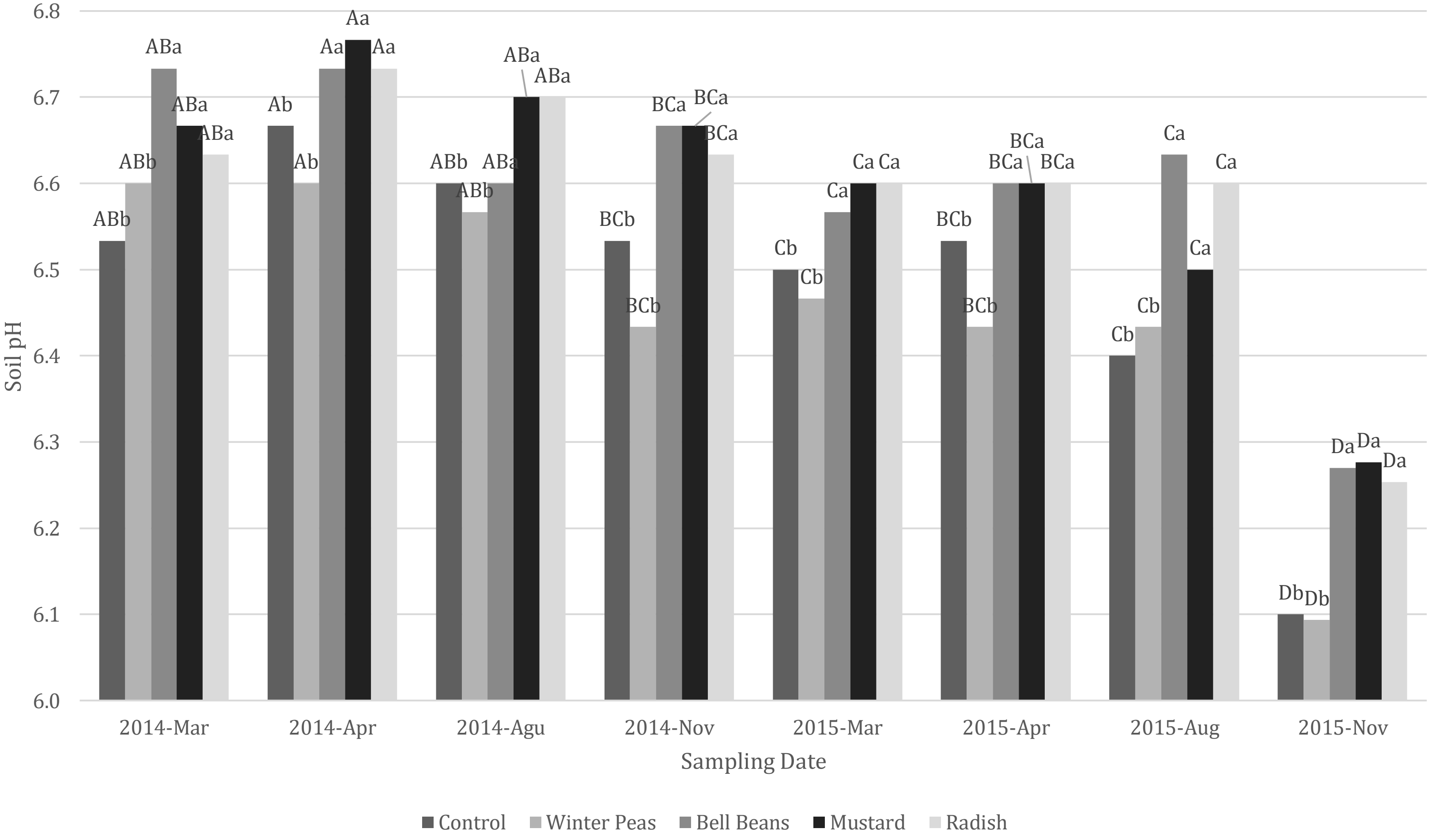
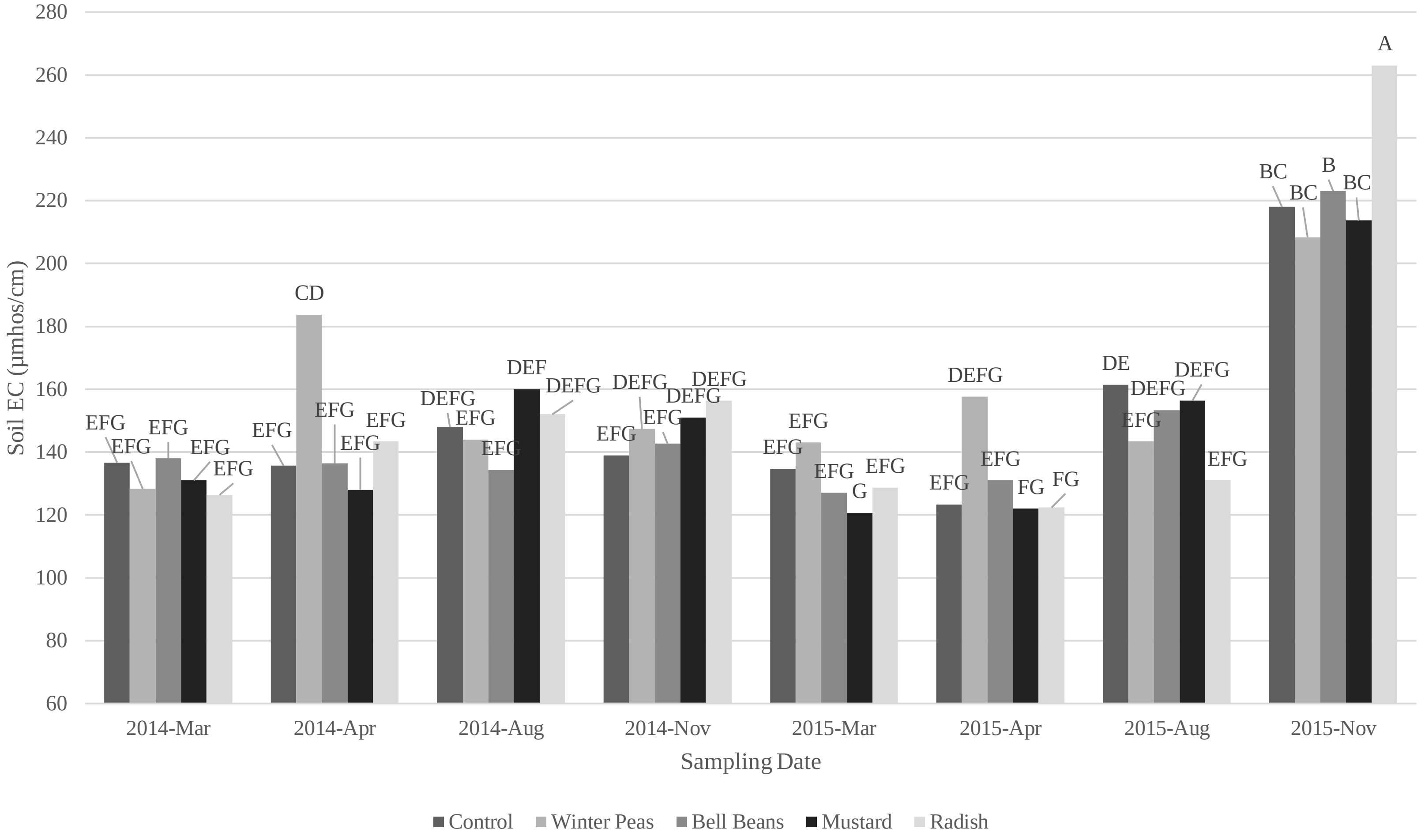


Table 7. Analysis of variance for interaction between cover crop treatment and sampling date for the variables pH, EC, and nutrient levels (P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B) measured from 15 cm soil core samples collected on 28 Mar. 2014, 25 April 2014, 8 Aug. 2014, 7 Nov. 2014, 28 Mar. 2015, 28 April 2015, 12 Aug. 2015, and 12 Nov. 2015. March sampling dates are prior to cover crop incorporation, April dates are 30 days after incorporation, August dates are after tomato cropping, and November dates are after broccoli cropping in a high tunnel in Fayetteville, AR. n = 3.

		Soil Variables (P < F)						
Factor	**DF**	**pH**	**EC**	**P**	**K**	**Ca**	**Mg**	**S**
Cover crop	4	<.0001	0.364	0.733	0.000	0.104	0.002	0.214
Date	7	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cover crop X Date	28	0.995	0.015	0.999	0.713	1.000	0.507	0.018
Block	16	0.000	<.0001	0.085	0.014	0.014	<.0001	<.0001

Factor	**DF**	**Na**	**Fe**	**Mn**	**Zn**	**Cu**	**B**
Cover crop	4	0.063	0.006	0.072	0.828	0.085	0.003
Date	7	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cover crop X Date	28	0.124	1.000	0.978	0.999	1.000	0.946
Block	16	<.0001	0.025	<.0001	0.001	0.173	0.332

Figure 14. Soil EC (µmhos/cm) measured from 15 cm soil core samples collected on 28 Mar. 2014, 25 April 2014, 8 Aug. 2014, 7 Nov. 2014, 28 Mar. 2015, 28 April 2015, 12 Aug. 2015, and 12 Nov. 2015. March sampling dates are prior to cover crop incorporation, April dates are 30 days after incorporation, August dates are after tomato cropping, and November dates are after broccoli cropping in a high tunnel in Fayetteville, AR. Mean separation was performed by LSD at $p < 0.05$. n = 3 experimental units.



CHAPTER 2. EFFECT OF WINTER COVER CROPS ON HIGH TUNNEL VEGETABLE PRODUCTION

Abstract

Four different winter cover crop species, Austrian winter peas (*Pisum arvense*), bell beans (*Vicia faba*), mustard (*Brassica juncea* cv. Kodiak), and Daikon radish (*Raphanus sativus var. longipinnatus*), plus an untreated control were evaluated for their effects on the growth and production of a succession of two vegetable crops, tomato (*Lycopersicon lycopersicum*, cv. 'Plum Dandy') and broccoli (*Brassica oleracea var. italica*, cv. 'Bay Meadows') within a high tunnel system at the University of Arkansas, Division of Agriculture Research and Extension Center in Fayetteville, Arkansas in a two year trial. In-season foliar N concentration and chlorophyll estimates were measured on both vegetable crops, in addition to yield variables and plant biomass. The winter pea cover crop resulted in the greatest tomato foliar N concentration of all treatments in 2015 and a greater leaf chlorophyll estimate than the control over both years of the study. The winter pea cover crop also resulted in greater tomato plant biomass compared to the control in both years of the study. The cover crop treatments did not have a significant effect on tomato yield, however. On the broccoli crop, the cover crop treatments of winter pea and radish resulted in greater broccoli plant biomass than the control across both years of the study. However, cover crop treatments did not result in significant differences for foliar N, leaf chlorophyll estimates, or yield. Yield variables for both broccoli and tomato showed a significant increase from 2014 to 2015 indicating a residual effect of fertility management practices, with increased soil N concentration observed over time.

Introduction

The use of high tunnels for specialty crop production has been increasing in popularity in the United States and throughout the world (Carey et al., 2009; Lamont, 2009). This is due to the many benefits that high tunnel structures provide for specialty crops, including a protected environment from insect and weather stresses, the ability to extend the harvest and production season, increased yield, improved crop quality, and more effective disease and pest management (Carey et al., 2009). Increased marketable production in addition to an advanced or extended harvest season has demonstrated high tunnels to be both practical and economically sustainable for high-value specialty crop production (Lamont et al., 2003).

Multiple vegetable crops are often grown during the same season, planted at high density, to maximize the productivity of the high tunnel space and to capitalize on the ability of the high tunnel to extend the production season through environmental modification (Lamont, 2009). Because of the intensive cropping of annual high tunnel systems, high inputs of organic matter and fertilizer are required to sustain optimal yields (Coleman, 1999; Lamont et al., 2003). For organic vegetable growers, certified through the National Organic Program (USDA, 2000), the use of large amounts of compost and organic fertilizers is a common practice to sustain yields and maintain soil organic matter in high tunnel systems (Milner et al., 2009). Because of the high cost of organic fertilizers and compost, fertilization is the most expensive cultural practice in organic vegetable production, with nitrogen being the most important and costly nutrient to manage in organic systems (Gaskell and Smith, 2007).

The harvest of multiple crops annually from a high tunnel system, coupled with the tillage used to prepare beds and incorporate fertilizers can lead to the rapid depletion of soil organic matter unless regular additions of organic matter are applied (Blomgren and Frisch, 2007). Frequent tillage in a high tunnel system can also lead to hard pans that can restrict water movement through the soil profile and lead to the destruction of soil aggregation that can decrease the soil pore space needed to hold air and water (Blomgren and Frisch, 2007). High tunnel growers minimize the negative effect of tillage on soil quality by minimizing tillage, maintaining permanent beds, and utilizing less destructive methods of soil preparation, such as the broadfork (Coleman, 1999). Intensive production in a limited space with compromised soil quality can also lead to the build-up of high populations of soilborne plant pathogens and root disease problems for vegetable crops (Abawi and Widmer, 2000).

The benefits of cover crops grown in rotation in field vegetable production systems have been well-documented in the scientific literature (Burket et al., 1997; Gaskell and Smith, 2007; Snapp et al., 2005). These benefits demonstrate the potential for solving the previously mentioned problems associated with intensive vegetable production in high tunnels, though the research to date on the application of cover crops in high tunnels is limited.

There has been very limited research conducted on the application of cover crops in high tunnel vegetable production. Available information on the subject is restricted to extension bulletins, newsletters, conference presentations, and production manuals (Baldwin, 2010; Blomgren and Frisch, 2007; Evans et al., 2011; Melendez and Rabin, 2012; Rivard, 2013). Despite negative and dismissive reports on high tunnel cover crops from extension agents and farmers in the Northeast (Blomgren and Frisch, 2007), preliminary studies in New Jersey and Mississippi have shown opportunity for winter cover crops to provide benefits to high tunnel vegetable production, including the uptake of leachable excess nutrients, weed suppression, and spring nitrogen release (Evans et al., 2011; Melendez and Rabin, 2012).

There are legitimate reasons for the applicability of high tunnel cover crops to be questioned, as presented by Blomgren and Frisch (2007) and outlined by Melendez and Rabin (2012). The risk of soil erosion is minimized in a high tunnel, so cover crops are not specifically required to prevent soil loss. Cover crops grown throughout the winter in a warm high tunnel could provide habitat for overwintering pests. Season extension in a high tunnel minimizes the windows of time between crops, which eliminates niches that cover crops usually fill. And lastly, the capital investment in a high tunnel makes growers reluctant to use valuable high tunnel ground to grow a crop that does not provide immediate economic return.

Despite these issues, the reported and potential benefits of high tunnel cover crops justifies further research on the subject. To begin with, the timing of cover cropping in a high tunnel can minimize the negative aspects of the practice. The time-period between mid-November and mid-February is the least productive season for high tunnel vegetable growers in the South due to cold temperatures and lack of light (Dr. C. Rom, personal communication). By selecting this time period to grow a winter cover crop that can tolerate such environmental conditions, the lost revenue stream for the grower is minimized. The modified environment of a high tunnel, with increased soil and air temperatures (Wien, 2009), could also speed the growth of winter cover crops during the stated period in mid-winter, producing more green biomass than would be produced during the same time period in the field. If a green manure crop were able to improve soil quality and decrease the requirement for purchased organic matter and fertilizer inputs, the cost savings for the grower could justify the additional management input.

Intensive vegetable production in a high tunnel requires inputs of organic materials to maintain soil organic matter, preserve soil quality, and ensure long-term productivity (Coleman, 1999; Lamont et al., 2003; Milner et al., 2009). Green manure cover crops have been shown to increase soil organic matter and nutrient cycling (Pieters, 1927; Powlson et al., 1987), and could replace purchased organic inputs in high tunnel production. Winter legumes have shown the potential to contribute significant amounts of nitrogen to subsequent vegetable crops in a field setting (Burket et al., 1997; Gaskell and Smith, 2007), which would reduce purchased fertilizer costs for high tunnel growers if similar rates of nitrogen contribution occurred in the high tunnel system. The deterioration of soil quality and the formation of hard pans due to frequent tillage is a documented problem in high tunnel production, which could be ameliorated by the ability of green manure cover crops to improve soil structure and aggregate formation (Hermawan and Bomke, 1997; Roberson et al., 1991; Tisdall and Oades, 1982) and improve the rooting depth of vegetable crops due to the "bio-drilling" effect of certain cover crops (Weil and Kremen, 2007). The ability of legume and brassica winter green manures to suppress soil-borne pathogens in vegetable crops (Monfort et al., 2007; Zhou and Everts, 2007) is another important benefit that winter cover crops could provide to high tunnel systems.

The ability of winter cover crops to improve the yield and performance of vegetable crops in field production systems have been well-documented in the scientific literature. It is our hypothesis that short-season winter cover crops grown in a high tunnel, then mowed and incorporated, will affect the growth and yield of subsequent vegetable crops.

Research Objective

To evaluate the effects of winter cover crops on the growth and yield of subsequent vegetable crops tomato and broccoli in a high tunnel production system.

Materials and Methods

Experimental Parameters:

This study was conducted at the University of Arkansas, Division of Agriculture Research and Extension Center in Fayetteville, Arkansas (Latitude: 36.1N; Longitude: 94.1W; Altitude: 427m/1400ft; USDA Cold Hardiness Zone 6b; AHS Heat Zone 7), within the organic horticulture research block. The site had a Captina silt loam soil with a pH between 6.5 and 6.7. Crops were grown inside a ClearSpan^{TM} Quonset-style high tunnel (FarmTek, Dyersville, Iowa) with dimensions of 6 m by 41.5 m, covered in a single layer of 6 mm polyethylene plastic glazing with UV protection. Passive ventilation was provided by manually closing or opening sidewall curtains and endwall doors. The high tunnel (HT) was opened for ventilation when the outside temperature exceeded 10 °C in sunny conditions or exceeded 16 °C in overcast conditions, to prevent the temperature inside the high tunnel from exceeding 32 °C and closed when not those conditions. All components of this study were managed in compliance with the USDA National Organic Program (USDA, 2000) requirements for certification, and the site had previously received organic management for 5 years.

This study tested five winter cover crop treatments: 1) nontreated control, 2) Austrian winter peas (*Pisum arvense*), 3) bell beans (*Vicia faba*), 4) mustard (*Brassica juncea* cv. Kodiak), and 5) Daikon radish (*Raphanus sativus var. longipinnatus*), for the effects on growth and yield of a succession of two vegetable crops in a HT system. Vegetable crop variables were measured in two years of repeated study and included estimated leaf chlorophyll, foliar nitrogen concentration, plant biomass, and yield components.

Crop Management:

Following the winter cover crop season, a succession of two vegetable cropsof tomatoes (*Lycopersicon lycopersicum*, cv. 'Plum Dandy') and broccoli (*Brassica oleracea var. italica,* cv. 'Bay Meadows') were be grown The crops were fertilized at a reduced rate of 84 kg N/ha (McCraw et al., n.d.; Kahn et al., n.d.) to determine the ability of the cover crop treatments to supplement fertilizer inputs.

The cover crop treatments were mowed and incorporated on 8 April 2014 and 7 April 2015, 143 and 138 days after planting, respectively (see chapter 1, pages 25-27). Approximately 30 days after the incorporation of the cover crops, two raised beds were created in the high tunnel with a "Junior" Model 1721-D bed shaper (Buckeye Tractor Co., Columbus Grove, Ohio). The beds were oriented parallel to the length of the high tunnel running a length of 36.6 m and were spaced 1.8 m apart on center, measuring 81 cm wide, and raised 10 cm above ground level. The beds were fertilized at 84 kg N/ha or 0.47 kg N/bed. A pelletized organic fertilizer (Bradfield Organics®, Luscious Lawn & Garden™ 3N-0.4P-4.2K) was applied prior to bed shaping and incorporated to a depth of 8 cm during the process of bed shaping.

After fertilization, drip tape irrigation lines (T-Tape Drip Tape, John Deere, Moline, Illinois) were placed in the center of each bed, and the beds were covered with black plastic mulch, using a "Junior" Model 1723 mulch layer (Buckeye Tractor Co., Columbus Grove, Ohio). One drip tape irrigation line with 30 cm (12 in) emitter spacing was placed running the length of each raised bed under the plastic mulch. Irrigation was supplied throughout the vegetable cropping cycles to provide a soil-water tension between 0 and 30 kPa, as measured by tensiometers placed throughout the vegetable beds at measuring depth of 15 cm. When soil-water tension would reach or exceed 30 kPa, drip irrigation would be turned on for 3 to 4 hours, running at an operating pressure of 15 psi using municipal water.

Vegetable Crop Rotation: After the bed establishment, a series of two vegetable crops were grown in a seasonal rotation including tomato (Experiment 1) for 90 days followed by broccoli (Experiment 2) for 80 days. The crops did not constitute a treatment and were analyzed as individual experiments within the study to evaluate the effects of the preceding cover crops.

Experiment 1. Effect of winter cover crops on the growth and yield of tomato.

Tomatoes (*Lycopersicon lycopersicum*, cv. 'Plum Dandy') were raised in the University of Arkansas System Division of Agriculture Horticulture unit, in a quonset-style research greenhouse covered in two layers of polyethylene greenhouse film. Tomato seeds were started on 11 March 2014 and 16 March 2015 and grown for 56 and 46 days, respectively. The tomato transplants were grown in organic potting media (Sunshine® Natural & Organic Professional Growing Mix, Sun Gro Horticulture, Vancouver, Canada) in 72 cell-packs on raised benches 0.9 m tall. Transplants were watered by overhead irrigation on a daily basis and fertilized with an organic fish hydrolysate fertilizer (Neptune's Harvest Fish-Seaweed Blend 2N-1.3P-0.8K) once a week diluted to 250 ppm N. The greenhouse temperature was maintained at 27°C during the day and 16°C at night.

The tomatoes were transplanted into the raised beds in the HT on 6 May 2014 and 1 May 2015 in single-rows, with 46 cm (18 in) between plants, making 5 plants per treatment plot. The two plants bordering the adjacent treatment plots served as guard plants, leaving three treatment plants per plot (Figure 41). Tomatoes were trellised using the stake-and-weave method (Kemble, et al., 2004), with a wooden stake between every three plants in the row and a steel t-post placed every 12 m (40 ft). The beds were fertilized before plating at 84 kg N/ha using a pelletized organic fertilizer (Bradfield Organics®, Luscious Lawn & Garden™ 3N-0.4P-4.2K), which provided half of the recommended N to the tomato crop based on recommendations from McCraw et al. (no year). Transplants were also fertilized with a liquid fertilizer on the day of planting using Neptune's Harvest Fish-Seaweed Blend (2N-1.3P-0.8K) diluted to 250 ppm N with 237 mL applied around the base of each plant.

High Tunnel Pest Management: In 2014 tomato fruitworm (*Helicoverpa zea*) were detected on 12 June and plants were treated with applications of Javelin® WG (active ingredient *Bacillus thuringiensis*, subspecies *kurstaki*) (Certis USA, L.L.C., Columbia, MD) mixed at 10 mL/L applied on 12 June, 26 June, and 15 July. Symptoms of the disease Southern blight (*Sclerotium rolfsii*) were observed on 5 July with plant collapse from the disease first observed on 7 July and continuing thereafter (Figure 42).

In 2015 applications of Javelin® WG were begun on 1 May to proactively prevent seedling damage from the granulate cutworm (*Feltia subterranean*), which had been observed on the subsequent broccoli crop during the previous season, 2014. Javelin® WG was reapplied on 1 June, 6 July, and 21 July to control tomato fruitworm. Contans® WG (active ingredient *Coniothyrium minitans*) was applied as a biological control for white mold (*Sclerotinia sclerotiorum*), which had been observed on the previous cover crop of Austrian winter pea, and for Southern blight (*Sclerotium rolfsii*), which had been diagnosed on the 2014 tomato crop. Contans® WG was mixed in water at 2.64 g/L and applied to the base of each tomato plant on 15 May at 236 mL per plant to achieve an application rate of 4.5 kg/ha. Despite the preventative application of Contans® WG, Southern blight infection was observed on tomatoes on 6 June with wilting and plant collapse occurring on 17 July (Figure 42). Green peach aphids (*Myzus persicae*) were observed in early June 2015 and plants were treated with applications of Aza-

Direct® (active ingredient Azadirachtin [1.2%]) made on 9 June and 6 July 2015 at an application rate of 2.3 L/ha. Spider mites (*Tetranychus* spp.) were observed on 6 June on tomato plants in plots 1, 2, 10, and 15. JMS Style-Oil (active ingredient paraffinic oil 97.1%, JMS Flower Farms, Inc.) was applied to control spider mites on 10 July mixed in water at 10 mL/L. Due to persistence of spider mites, M-Pede® (active ingredient potassium salts of fatty acids 49%, Dow AgroSciences LLC) was applied on 21 July, tank mixed with water at 20 mL/L. All pesticides applied were labeled for use in organic production by the Organic Materials Review Institute (OMRI) (Eugene, Oregon). A total of 3 pesticide applications were made to the tomato crop in 2014 and 7 pesticide applications were made in 2015.

Experimental Variables: Weekly tomato leaf chlorophyll estimates were measured throughout the season from three tomato plants per treatment plot with a SPAD-502Plus Chlorophyll Meter (Konica Minolta, Inc.). Chlorophyll estimates were measured from intervenal leaf tissue of the apical leaflet of the uppermost fully expanded leaf (3rd or 4th from the top) in the main stem (Gianquinto, et al., 2006). Chlorophyll estimates were collected every 7 days from 22 May to 24 July in 2014 and from 26 May to 7 July in 2015. The tomato crop was harvested on a weekly basis beginning on 26 June 2014 and 2 July 2015, which was 51 and 62 days after transplanting, respectively. Harvest continued until 22 July 2014 and 6 Aug. 2015 (26 and 35 days, respectively), at which point all fruit had been harvested. Tomatoes were weighed, counted and sorted to measure total harvest per plot (kg), marketable yield per plot (kg), marketable percent, fruit number per plot, average fruit weight (g), and yield per plant (kg). Tomatoes were sorted by marketability with U.S. No. 1, No. 2, and No. 3 tomatoes considered marketable (USDA, 1991) and tomatoes that did not meet these standards due to physical damage or deformity considered unmarketable. Tomato fruitworm damage and blossom end rot were the primary causes for tomatoes being considered unmarketable.

Three leaf samples (uppermost fully expanded leaf in the main stem) were collected from each of the three treatment plants from each plot (9 subsamples per plot), dried in a forced-air drying oven at 50°C for one week, and ground to pass through a 40 mesh screen using a Cyclone Sample Mill (UDY Corporation, Fort Collins, Colorado). Nitrogen concentration (percent dry weight basis) of the foliar samples was measured by combustion using an Elementar vario EL cube (Elementar Americas, Inc., Philadelphia, PA). In 2014, foliar samples were collected on 24 July at the end of harvest. In 2015 foliar samples were collected on a weekly basis from 26 May (25 days after planting) to 30 June (60 days after planting) and analyzed for N concentration. Plants were removed following the final harvest, with above-ground plant biomass dried at 50°C for 7 days and weighed to measure dry weight biomass.

Experimental Design: The experiment was designed as a split-plot within a randomized complete block design, with cover crop treatments serving as the main plot and year serving as the subplot. There were three blocks of the five cover crop treatments within the HT. Statistical analyses were performed with SAS 9.2 software (SAS Institute, Cary, NC) using PROC MIXED, PROC GLM, and PROC CORR with significant differences determined at an alpha level of 0.10 due to the limited number of replications (n=3).

Experiment 2. Effect of winter cover crops on the growth and yield of broccoli.

Broccoli (*Brassica oleracea var. italica*, cv. ‘Bay Meadows’) was started from seed on 10 July 2014 and 15 July 2015 at the University of Arkansas System Division of Agriculture Horticulture unit, in a quonset-style research greenhouse covered in two layers of polyethylene greenhouse film. Transplants were grown in organic potting media (Sunshine® Natural &

Organic Professional Growing Mix) in 72 cell-packs on raised benches 0.9 m tall. Transplants were watered by overhead irrigation and fertilized weekly with liquid fish hydrolysate (Neptune's Harvest Fish-Seaweed Blend 2N-1.3P-0.8K) diluted to 250 ppm N. The greenhouse temperature was maintained at 27°C during the day and 16°C at night.

Broccoli was transplanted into the HT on 11 August 2014 and 12 August 2015, 4 and 5 days after the tomato plants were removed, respectively. Broccoli was planted at 30 cm between plants in double-rows spaced 46 cm apart in each bed. Transplants were fertilized with Nitron Liquid Fish (2.6N-0.87P-0.22K, Nitron Industries, Fayetteville, AR) on the day of planting with fertilizer diluted to 250 ppm N and applied at 237 mL per plant. During the season broccoli plants were fertigated with liquid fish fertilizer (2.6N-0.87P-0.22K) injected through the drip tape lines on a weekly basis beginning in mid-Aug. to supply a total of 56 kg N/ha for the season, calculated as half of the N fertilizer rate recommended by Kahn, et al (no year).

There were 14 plants per treatment plot, with seven plants in each of two rows. The four plants bordering the adjacent treatment plots were guard plants not included in data, leaving ten treatment plants per plot for data collection (Figure 41).

Pest management: In 2014, plant damage and plant loss from the granulate cutworm was severe after broccoli was transplanted into the high tunnel. Javelin® WG was applied at 1.12 kg/ha on the day of planting (11 Aug.) with repeat applications on 13 Aug., 20 Aug., and 4 Sept. Replanting was required due to plant loss from cutworm damage with 80 broccoli plants replaced on 19 Aug. using extra transplants of the same age as the original plants grown in the greenhouse. With daily high temperatures in the HT ranging from 32 to 36°C during the week after planting, heat stress was apparent resulting in wilting of transplanted broccoli plants. To mitigate heat stress, Surround® WP (Kaolin clay) was sprayed on the broccoli foliage and sprayed on the black plastic mulch to reduce heat retention. Surround® was mixed in water at 60 g/L and sprayed on 14 Aug. and 20 Aug.

In 2015, two days prior to broccoli planting, OxiDate® 2.0 (hydrogen dioxide 27.1% and peroxyacetic acid 2.0%) was injected through the drip tape lines at a 1:200 ratio for 1 hour to control the *Sclerotinia sclerotiorum* and *Sclerotium rolfsii* that had been identified in the high tunnel earlier in the season. Broccoli transplants were sprayed with Javelin® WG and Entrust® (spinosad, Dow AgroSciences LLC) on the day of planting (12 Aug. 2015) to prevent cutworm damage, with repeat applications of Javelin® WG made on 17 Aug., 21 Aug., 9 Sept., and 28 Sept. Surround® WP was sprayed to minimize heat stress on the broccoli seedlings, with applications on 12 Aug., 17 Aug., and 21 Aug. Despite the preventative insecticide applications, cutworm damage was still sustained with 29 plants replaced on 20 Aug. and another 8 plants replaced on 27 Aug from additional broccoli transplants grown in the greenhouse.

Experimental Variables: Weekly plant chlorophyll estimates were measured from three selected broccoli plants per treatment plot with a SPAD-502Plus Chlorophyll Meter (Konica Minolta, Inc.) on a weekly basis throughout the season. In 2014 chlorophyll measurements were collected from 16 Sept. to 4 Oct. and in 2015 measurements were collected from 27 Aug. to 2 Oct. SPAD readings were taken from three points on either side of the midvein at the apical tip of the fifth newest leaf of three randomly selected treatment plants within each plot (Theriault, et al., 2009). The broccoli crop was harvested on a weekly basis throughout the month of October, with both primary inflorescence and side shoots harvested and weighed. The harvested portion from each plot was weighed to determine yield per plot, average yield per plant, and average head weight. In 2015 each harvested head was also measured for head diameter (cm) and stem diameter (mm). Total above-ground biomass was measured per plot on a fresh weight basis following the final harvest. Foliar samples were collected from the fifth newest leaf of three randomly selected treatment plants from each plot during biomass harvest. Broccoli leaf samples excluding petioles were dried in a forced-air drying oven at 50°C for one week, and ground to pass through a 40 mesh screen using a Cyclone Sample Mill (UDY Corporation, Fort Collins, Colorado). Nitrogen concentration (percent dry weight basis) of the foliar samples was measured by combustion using an Elementar vario EL cube (Elementar Americas, Inc., Philadelphia, PA).

Experimental Design: The experiment was designed as a split-plot within a randomized complete block design, with cover crop treatments serving as the main plot and year serving as the subplot. There were three blocks of the five cover crop treatments within the HT. Statistical analyses were performed with SAS 9.2 software (SAS Institute, Cary, NC) using PROC MIXED, PROC GLM, and PROC CORR with significant differences determined at an alpha level of 0.10 due to the limited number of replications (n=3).

Results

Experiment 1. Effect of winter cover crops on the growth and yield of tomato.

Cover crop treatment had a significant effect on tomato estimated leaf chlorophyll (SPAD) and shoot plant dry weight biomass across both years of the study (Table 8). Tomato foliar N, however, was affected by year as a main effect with year 2015 resulting in a higher foliar N concentration mean than 2014, 4.26% and 1.89%, respectively (Figure 15). The sufficiency threshold for tomato N concentration at full flowering was been determined to be 3.5% (Hartz et al., 1989) showing that tomatoes in 2014 were N-deficient. Within the year 2015 there were differences due to treatment for foliar N measurements with the winter pea cover crop resulting in a tomato foliar N that was significantly greater than all other treatments; and all other treatments being similar to the untreated control (Figure 15). Tomato foliar N concentration measured at 4.65% following winter pea in 2015 compared to 4.0% for the control treatment. Within tomato foliar N measured over time in 2015, significant differences were detected between treatment means at 39, 46, and 53 days after planting (Figure 16). For each of these three measurement dates, the winter pea cover crop treatment led to significantly greater tomato foliar N compared to mustard, radish, and the control treatments. The foliar N of tomatoes grown after the bell bean cover crop treatment had similar foliar N levels compared to the winter pea treatment on days 39 and 53. Overall, there was a decreasing trend of tomato N from day 25 to 60.

A positive correlation was found between cover crop treatment biomass N content and tomato foliar N concentration across years 2014 and 2015, with a linear $r^2 = 0.19$ (Table 9, Figure 17). This supports the finding that Austrian winter pea, the cover crop with the highest biomass N content (Figure 8), resulted in an elevated tomato foliar N concentration in 2015. A positive correlation was also found between tomato foliar N concentration and tomato foliar chlorophyll estimates measured in 2014 and 2015, with a linear $r^2 = 0.47$ (Figure 18). This finding is consistent with previous research that has established a relationship between measurements of the hand-held SPAD-502 Chlorophyll Meter with foliar N levels for tomato (Gianquinto, et al., 2006).

For the tomato leaf chlorophyll estimates over the two years of the study, the winter pea cover crop treatment resulted in a significantly greater chlorophyll estimate (51.4) compared to the control and mustard treatments (48.5 and 48.0, respectively) (Figure 19). The bell bean and radish cover crop treatments resulted in tomato leaf chlorophyll estimates that were similar to the winter pea treatment (49.9 and 49.7, respectively). Within the weekly tomato leaf chlorophyll measurements collected during the 2015 season, significant differences were detected between cover crop treatments on day 54 after planting (Figure 20), with the winter pea treatment resulting in greater tomato chlorophyll estimates than the control and mustard treatments. Within 2015 there was a general trend in leaf chlorophyll estimate decline over time, although the tomatoes grown in plots previously planted with winter pea or bell bean tended to stabilize after day 40 while plants of other treatments tended to continue to decline through day 61.

The winter pea cover crop treatment resulted in significantly greater tomato dry weight biomass measured after final harvest in 2014 and 2015 compared to the control and mustard treatments (Figure 21). Mean tomato plant dry weight biomass following the winter pea cover crop across both years averaged 219.8 g compared to 190.2 g following the mustard cover crop and 176.3 g following the control treatment of no cover crop. Bell bean and radish both resulted in a similar tomato plant biomass compared to the winter pea cover crop.

A positive correlation was found between soil N content, measured 30 days after cover crop incorporation, and the tomato plant dry weight biomass, with a linear $r^2 = 0.15$ (Figure 22). This correlation indicates that plots with higher soil N levels were resulting in greater tomato plant biomass. Although cover crop treatments did not result in significant effects on soil N (Table 5), differences were found between the biomass N content of the cover crop species, with winter pea having the greatest biomass N content across both years of the study, with a combined average of 10.2 g N/m^2 (Figure 8). It can be reasoned that the N contained in the cover crop biomass is being made available for tomato crop uptake and resulting in differences in tomato plant biomass.

Year had a significant main effect on the tomato harvest variables of total harvest weight, marketable weight, percent marketable, average fruit weight, and yield per plant (Table 10). For all of these variables there was an increase in 2015 compared to 2014. Tomato yield per plant increased from 2.37 kg/plant in 2014 to 4.63 kg/plant in 2015, which comes to 28,333 kg/ha and 55,352 kg/ha, respectively if 11,955 plants/ha is assumed based on the standard spacing of 1.8 m between rows and 45 cm between plants (Kelley and Boyhan, 2014). This compares to the average tomato yield of 21,296 kg/ha for Arkansas in 2015 (USDA, 2016). In 2015, the winter pea cover crop treatment resulted in an increase in yield per plant by 42% compared to the combined average yield per plant of all other treatments (6.1 kg/plant compared to an average 4.3 kg/plant, respectively), though there is a lack of statistical difference, which can be attributed to large plot variation and small replication number (n=3) (Figure 23). When comparing the winter pea treatment to the nontreated control there is an increase in mean yield per plant by 48%, from 4.1 kg/plant to 6.1 kg/plant, respectively.

A positive correlation was found between tomato foliar N concentration and tomato yield per plant, with a linear $r^2 = 0.53$ (n=30) (Figure 27). Comparing year 2015 to 2014, both mean foliar N and mean tomato yield per plant showed a significant increase in 2015 (Figure 15, Figure 23). In addition, the winter pea cover crop treatment resulted in increased values for both variables in 2015.

The number of tomato fruit harvested per plot did not show statistically significant differences due to cover crop treatments (Table 10); however, it is worth noting that in 2015 the mean number of fruit harvested from winter pea treatment plots (302 fruit) was 56% greater than the mean harvested from the control plots (194 fruit) (Figure 24).

Average tomato fruit weight was affected by a main effect of cover crop treatment across years, with the bell bean cover crop treatment resulting in the greatest mean fruit weight (90.8 g), compared to the lowest average fruit weight from the winter pea treatment plot (75.8 g) (Figure

25). However, no cover crop treatment resulted in an average fruit weight that was significantly different than the untreated control.

The marketable percent of the tomato harvest showed a significant increase from 2014 to 2015 with means of 85.9% and 88.7%, respectively. Within 2014 there were significant differences between treatments with the mustard cover crop treatment resulting in a higher percent marketable tomato yield (89.5%) compared to the control and winter pea treatments (83.7% and 82.7%, respectively) (Figure 26).

Experiment 2. Effect of winter cover crops on the growth and yield of broccoli.

Despite year having a significant main effect on both broccoli foliar N concentration and plant biomass, broccoli leaf chlorophyll estimates were not affected by year (Table 11). The sampling date did have an effect on broccoli leaf chlorophyll, however (Table 12). Looking across all sampling dates, broccoli leaf chlorophyll estimates (SPAD) generally increased from the beginning of the sampling period to the end of the sampling period within each year (Figure 28). In 2015 this trend is most pronounced with the final SPAD measurement on 2 October (71.5 SPAD units) significantly greater that the first measurement on 4 September (68.1 SPAD units). The only date that resulted in significant means separation by treatment was 17 September 2015 ($p = 0.012$, $n = 3$) (Table 14). On this date the radish cover crop treatment resulted in the highest measured leaf chlorophyll estimate at 71.1 SPAD units, being significantly greater than winter pea, bell bean, and the non-treated control (68.6, 68.35, and 66.83 SPAD units respectively).

Broccoli foliar N concentration was affected by year of study, decreasing from 2014 (with a mean of 3.14%) to 2015 (with a mean of 2.91%) (Figure 29). Within 2015 the winter pea cover crop treatment resulted in a foliar N concentration mean (3.12%) that was numerically greater than the control treatment (2.85%) and all other cover crop treatment means, however, no statistical differences were detected at an alpha of 0.10. However, in 2015 the winter pea cover crop was the only treatment that resulted in a broccoli foliar N that exceeded the sufficiency threshold value of 3.0% (Hanlon and Hochmuth, 2000). A positive correlation was detected between the broccoli foliar N seasonal mean and the soil N content measured 30 days after cover crop incorporation (Figure 30). Despite the fact that statistical differences were not detected between cover crop treatment on broccoli foliar N, we can see that the cover crop treatments that increased soil N resulted in a positive effect on broccoli foliar N.

Cover crop treatment did have a significant main effect on broccoli plant biomass across both years of the study (Table 11). The winter pea and radish cover crop treatments resulted in greater broccoli plant fresh weight biomass than the non-treated control, measuring at 808 g/plant, 726 g/plant, and 600 g/plant, respectively (Figure 31). A positive correlation was found between broccoli plant biomass and soil N content, with a linear $r^2 = 0.21$, n =30 (Figure 32).

Year was a significant main effect on the harvest variables of average head weight and side shoot production (Table 15). Average head weight increased from 2014 to 2015, from 116 g/head to 139 g/head, respectively (Figure 34). With calculated yield equivalents of 6,243 kg/ha in 2014 and 7,483 kg/ha in 2015, the broccoli yield for both years of the study were lower than the commercial standard of 9,415 kg/ha for the southeastern US (Sanders, 2001). The yield equivalent assumes 21,780 plants/ha with plants in double rows on plasticulture beds at 20 cm between plants and beds on 1.8 m centers.

While the mean head weight of broccoli grown in winter pea plots remained the same between years, all other treatments resulted in numerical increases in means from 2014 to 2015. On the other hand, side shoot production per plant decreased from 2014 to 2015, from 173 g/plant to 62 g/plant, respectively (Figure 35). Within each year, no cover crop treatment resulted in side shoot production that was statistically different than the nontreated control.

For harvested broccoli characteristics including head diameter and stem diameter there were no significant treatment effects within year. The mean broccoli head diameter was 8 cm across all treatments in 2015 (Figure 36). The mean stem diameter across all treatments in 2015 was 30.5 mm (Figure 37). A positive correlation was found between broccoli stem diameter and soil N content, with a linear $r^2 = 0.53$, n=15 (Figure 38), which supports previous research that has demonstrated the positive impact of N fertilization on broccoli head weight, head diameter, and stem diameter (Schellenberg et al., 2009). Broccoli stem diameter also showed a significant correlation with broccoli head weight, with a positive relationship with a linear $r^2 = 0.42$, n=15 (Figure 39). Through a chain of causation, it appears that increased soil N levels do lead to increased broccoli stem diameter and thus increased broccoli head weight.

Discussion

Despite the fact that cover crop treatments did not result in consistent effects on vegetable crop growth and yield, we observed changes in the high tunnel soil over time that did result in measurable effect on vegetable crops. For tomato there was an increase in foliar N concentration from 2014 to 2015 (Figure 15) and an increase in tomato yield per plant from 2014 to 2015 (Figure 23). Tomato yield increased from an equivalent of 28,333 kg/ha in 2014 to 55,352 kg/ha in 2015, which far exceeded the average tomato yield for Arkansas of 21,296 kg/ha (USDA, 2016). For broccoli there was an increase in average head weight from 116 g/head in 2014 to 139 g/head in 2015 (Figure 34). Compared to the yield standard of 9,415 kg/ha for the southeastern US (Sanders, 2001) the broccoli in this study did not reach commercial yield in either year, with the production equivalent of 6,243 kg/ha in 2014 and 7,483 kg/ha in 2015, however the increase in mean yield between years is relevant to note.

The increase in production from 2014 to 2015 was also seen in the cover crops, with an increase in cover crop biomass, cover crop height, and cover crop biomass N (Figure 1, Figure 2, and Figure 8, respectively). These differences between years can be attributed in part to an increase in soil N from 2014 to 2015. Across all cover crop treatments there was an increase in mean soil N by 402 mg/kg from the beginning of the vegetable crop production cycle (April) to the end of the production cycle (Nov.) in 2014, resulting in a higher soil N available to the cover crop treatments grown in the second year of the study and an increased soil N available to subsequent vegetable crops.

We can attribute this increased fertility in part to organic fertilizers that were applied at a combined annual rate of 168 kg N/ha and appeared to have a residual effect on the growth of cover crops and vegetable crops in 2015. However, when comparing mean soil N across all treatments from April 2014 to April 2015 there was very little change. It appears that the increased soil N from 2014 was incorporated into cover crop biomass, where we observed a significant increase in cover crop biomass N from 2014 to 2015 (Figure 8), but that N captured in cover crop biomass N was not immediately mineralized after cover crop incorporation and was not detected in soil tests conducted in April 2015, 30 days after cover crop incorporation.

Within each year we observed a great amount of plot variability, which appeared to inhibit our ability to detect significant difference between yield variables due to cover crop treatment. For tomato yield per plant in 2015 (Figure 23), this was particularly apparent, with the winter pea treatment resulting in a yield increase of 48% compared to the control, but no statistical differences found due to a great amount of variability between plots. Once source of the variability was disease incidence, with Southern blight (*Sclerotium rolfsii*) being a significant issue in 2015. Looking at the special distribution of Southern blight in Figure 40, it is most prevalent in Block 1 of the high tunnel, with less incidence in Blocks 2 and 3. The disease appeared originate from Block 1 of the high tunnel, with incidence clustered in that area in 2014, but then spreading throughout the tunnel in 2015 despite the organic control materials applied. From the ANOVA of tomato yield variables (Table 10) we can see that block had a significant effect, which we can attribute to the clustered incidence of Southern blight within the high tunnel.

We did observe some cover crop treatment effects on vegetable crop growth and production, however. A correlation was found between cover crop biomass N and tomato foliar N, with increased cover crop biomass N resulting in elevated tomato foliar N concentrations (Figure 17). Within 2015 the winter pea cover crop treatment resulted in tomato foliar N concentrations that were greater than all other treatments (Figure 15) and at the higher end of the sufficiency range of 3.5-4.5% (Hartz et al., 1998). Soil N measurements were also correlated with broccoli foliar N concentration (Figure 30) and broccoli plant biomass (Figure 32), with increased soil N content resulting in increased broccoli foliar N concentration and increased broccoli plant biomass. The cover crop treatments of winter pea and radish resulted in broccoli plant biomass that was significantly greater than the nontreated control across both years of the study (Figure 31).

Soil N content was also correlated with broccoli stem diameter, with increased soil N resulting in increased stem diameter (Figure 38). Stem diameter was also correlated with broccoli head weight in a positive relationship (Figure 39), indicating that increased soil N did have an effect on broccoli yield. We did not measure significant cover crop treatment effects on soil N, but we did measure significant changes in soil C/N after cover crop incorporation. Winter peas resulted in a significant decrease in soil C/N in 2014 when comparing measurements collected on the day before incorporation to measurements collected 30 days after incorporation (Figure 11). In 2015 winter peas, bell beans, and radish cover crop treatments resulted in significant decreases in soil C/N when comparing pre-incorporation levels to 30 day post-incorporation values. Previous studies have linked decreased C/N ratios to increase N availability (Hadas et al., 1992; Whitmore and Groot, 199; and Trinsoutrot et al., 2000), which can explain why we are seeing significant effects from winter pea and radish on vegetable response factors like broccoli plant biomass (Figure 31), which is a variable that shows a positive correlation to soil N content.

Cover crops that accumulated a greater amount of N in their above-ground biomass showed an effect on tomato crop growth. We found a significant correlation between cover crop biomass N and tomato biomass, with increased cover crop biomass N resulting in increased tomato plant biomass (Figure 22). The winter pea cover crop had the greatest biomass N of all cover crop treatments across both years of the study (Figure 8) and also resulted in the greatest tomato plant biomass compared to all other treatments (Figure 21). The winter pea cover crop treatment also resulted in greater estimated tomato leaf chlorophyll than all other treatments (Figure 19). We found a correlation between tomato leaf chlorophyll estimates and tomato leaf N concentration (Figure 18), which is a relationship that is supported by previous studies correlating SPAD measurements to foliar N concentration (Gianquinto, et al., 2006). Tomato leaf N was also positively correlated to tomato yield per plant in this study (Figure 27), which supports the literature on tomato foliar N as an indicator of yield potential (Hartz et al., 1998). In our study the winter pea cover crop resulted in greater tomato foliar N and higher tomato yields in 2015 (Figure 24).

We draw the conclusion that cover crop species that accumulate a greater amount of N in their above-ground biomass result in increased N availability to subsequent vegetable crops after the cover crop biomass is incorporated into the soil. This increase in soil N has an effect on the growth of subsequent vegetable crops as measured in tomato as increased foliar N, leaf chlorophyll estimates, and plant biomass; and measured in broccoli as increased foliar N, plant biomass, and harvested stem diameter. These improvements in vegetable crop growth can result in improvements in harvest yield as seen in the correlation between broccoli stem diameter and head weight and the correlation between tomato foliar N and yield.

In response to our hypothesis we can state that cover crops grown in high tunnels appear to have an effect on the growth of subsequent vegetable crops, with the cover crop species like Austrian winter pea, that accumulate greater amounts of N in above-ground biomass, showing stronger effects. In terms of cover crop effect on yield, the evidence to reject the null hypothesis is not strong, but we do see indications that the improvements in vegetable plant growth under cover crop treatments would lead to yield improvements if plot variation were less of a factor.

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Tables and Figures

Table 8. Analysis of variance of tomato plant growth variables, including leaf chlorophyll estimates (SPAD), foliar N content, and plant dry weight biomass, from tomatoes grown in a high tunnel following cover crop treatments in 2014 and 2015 in Fayetteville, AR. Analysis conducted using SAS PROC GLM. n = 3.

		Tomato plant growth variables (P < F)		
Factor	DF	SPAD	Foliar N	Plant Biomass
Cover crop	4	0.0003	0.188	0.043
Year	1	<.0001	<.0001	0.045
Cover crop X Year	4	0.755	0.435	0.924
Block	4	0.001	0.48	0.067

Table 9. Correlation between cover crop variables and tomato crop variables from study in high tunnel in Fayetteville, AR, 2014-2015. For each relationship, the Pearson Correlation Coefficients (PCC) and p-values are included in the table.

		Tomato Biomass	**Tomato N**	**Tomato SPAD**	**Tomato Total Yld**	**Tomato Mkt Yld**	**Tomato Avg Frt Wt**	**Tomato Yld per Plant**
Year	**PCC**	-0.324	0.946	0.592	0.418	0.445	0.751	0.681
	p-value*	0.081	<.0001	0.001	0.022	0.014	<.0001	<.0001
Cover Crop C	**PCC**	-0.14	0.768	0.604	0.375	0.395	0.538	0.567
	p-value	0.46	<.0001	0	0.041	0.031	0.002	0.001
Cover Crop Biomass	**PCC**	-0.123	0.713	0.548	0.198	0.209	0.505	0.417
	p-value	0.517	<.0001	0.002	0.294	0.267	0.004	0.022
Cover Crop Biomass N	**PCC**	0.193	0.432	0.557	0.166	0.16	0.18	0.316
	p-value	0.306	0.017	0.001	0.38	0.4	0.341	0.089
Soil N	**PCC**	0.385	-0.261	-0.173	-0.045	-0.038	0.035	-0.165
	p-value	0.036	0.164	0.362	0.815	0.843	0.855	0.382
Soil C	**PCC**	-0.041	-0.373	-0.443	-0.145	-0.127	0.074	-0.231
	p-value	0.831	0.042	0.014	0.444	0.504	0.698	0.219
Soil C/N	**PCC**	-0.399	-0.255	-0.505	-0.141	-0.11	0.16	-0.16
	p-value	0.029	0.174	0.004	0.457	0.562	0.397	0.399
Tomato N	**PCC**	-0.171	1	0.686	0.504	0.533	0.721	0.73
	p-value	0.365		<.0001	0.005	0.002	<.0001	<.0001

* n = 30

Figure 15. Tomato foliar N concentration measured from leaf samples collected in 2014 (A) and 2015 (B) from tomatoes grown in a high tunnel in Fayetteville, AR after winter cover crop treatments. Means comparison using Student's t test, letters represent mean separation within each year ($p < 0.10$). NS = no significant difference detected within year. Bars represent standard error from the mean. Dashed line represents sufficiency threshold of 3.5% for tomato foliar N at full flowering (Hartz et al., 1998).

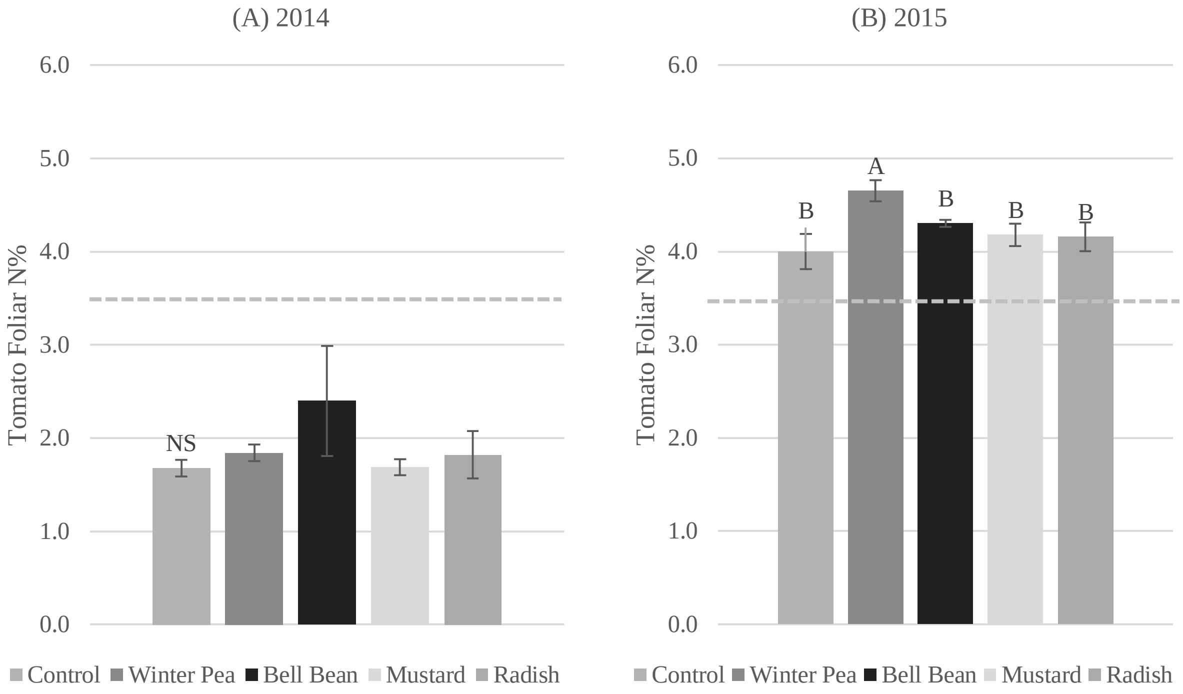


Figure 16. Tomato foliar N measured weekly from 26 May to 1 July 2015 (25 to 60 days after planting) in a high tunnel in Fayetteville, AR in 2015. Means comparison by week using Student's t test; letters represent mean separation between treatments within week ($p < 0.10$). NS = no significant difference detected between means within week.

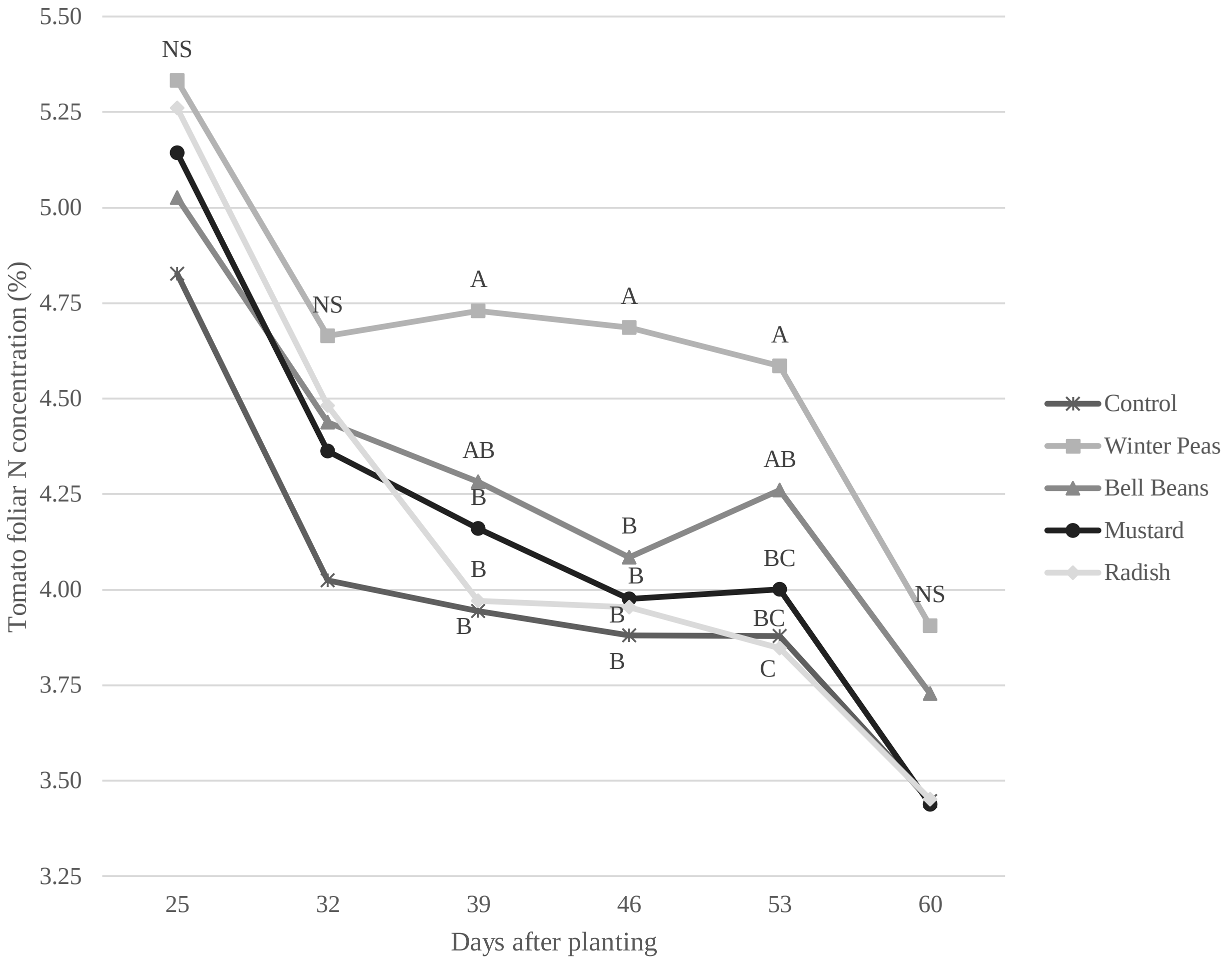


Figure 17. Relationship between cover crop biomass N and tomato foliar N, as measured from winter cover crops and tomato crops grown as a rotation in a high tunnel in Fayetteville, AR during 2014 and 2015 seasons. For 2014 (A) linear $r^2 = 0.01$, n = 15. For 2015 (B) linear $r^2 = 0.14$, n = 15. For 2014 and 2015 years combined (C), linear $r^2 = 0.19$, n=30, p-value = 0.017.

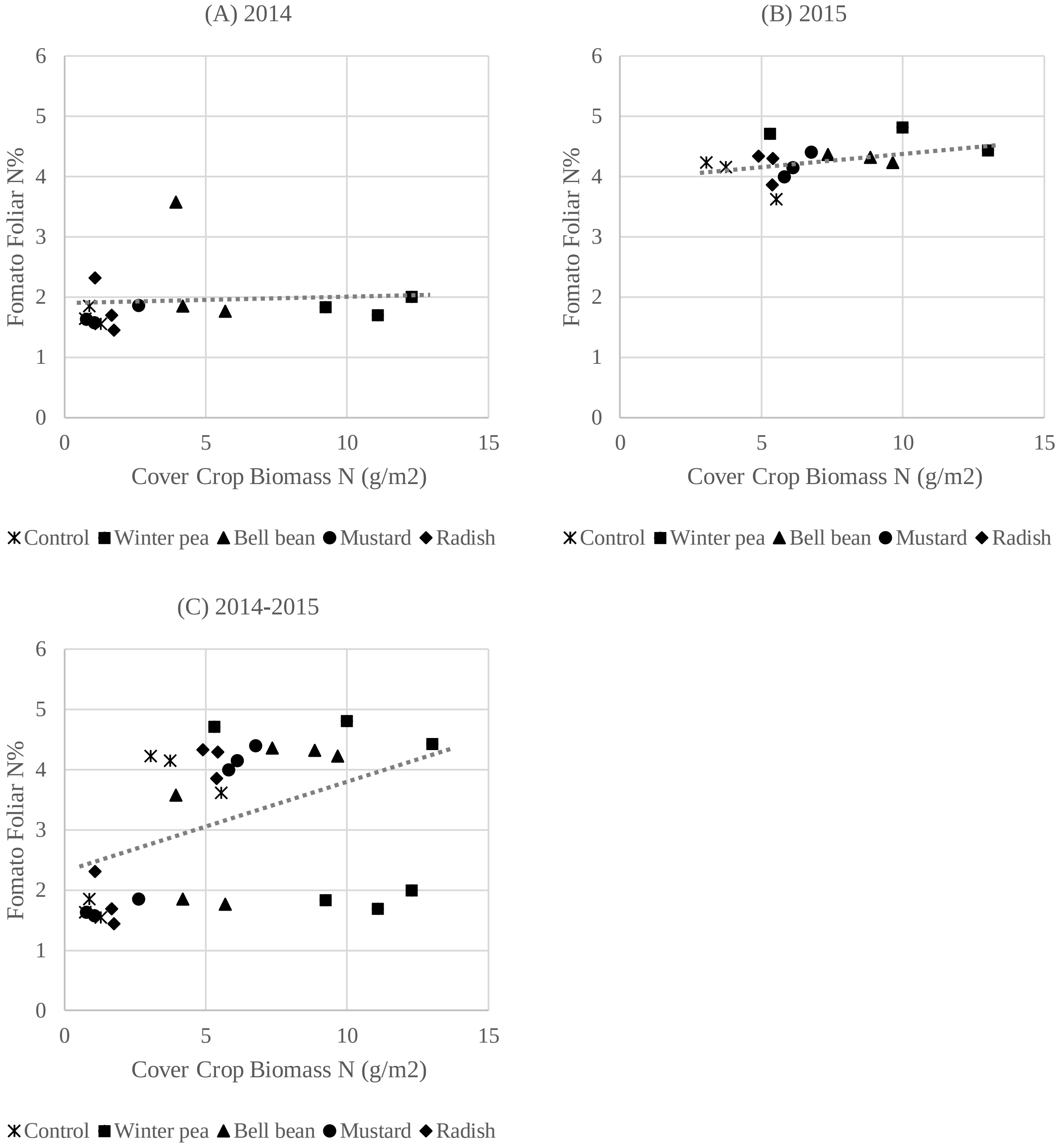


Figure 18. Relationship between tomato foliar N concentration and foliar chlorophyll, as measured from tomatoes grown following winter cover crop treatments in a high tunnel in Fayetteville, AR in 2014 and 2015. For 2014 (A) linear $r^2 = 0.09$, $n = 15$. For 2015 (B) linear $r^2 = 0.73$, $n = 15$. For 2014 and 2015 years combined (C), linear $r^2 = 0.47$, $n = 30$, p-value < 0.0001.

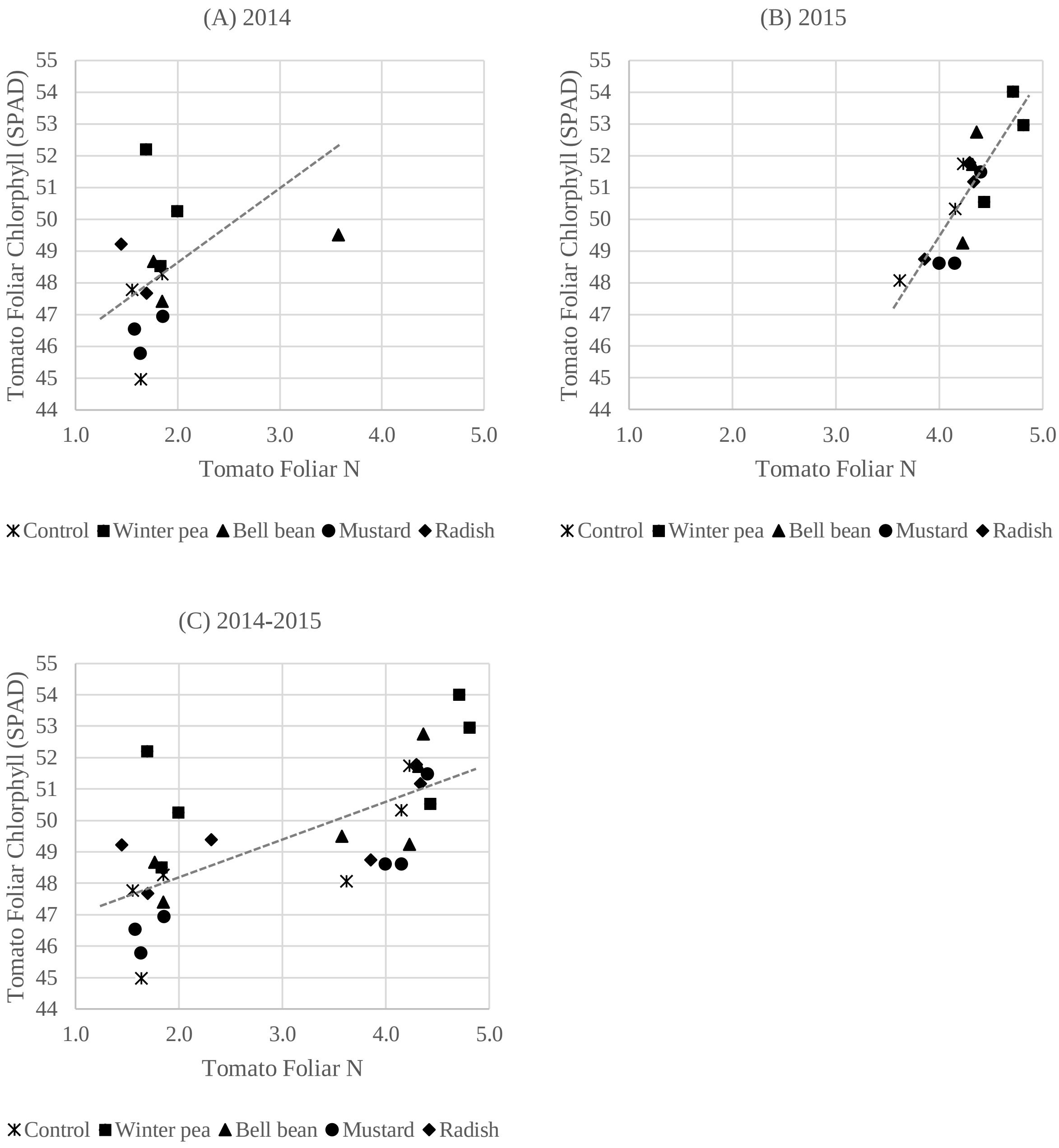


Figure 19. Tomato leaf chlorophyll estimate (SPAD) mean values from tomatoes grown in a high tunnel in Fayetteville, AR in 2014 and 2015 following cover crop treatments. Letters represent mean separation using Student's t-test ($p < 0.10$, $n = 3$).

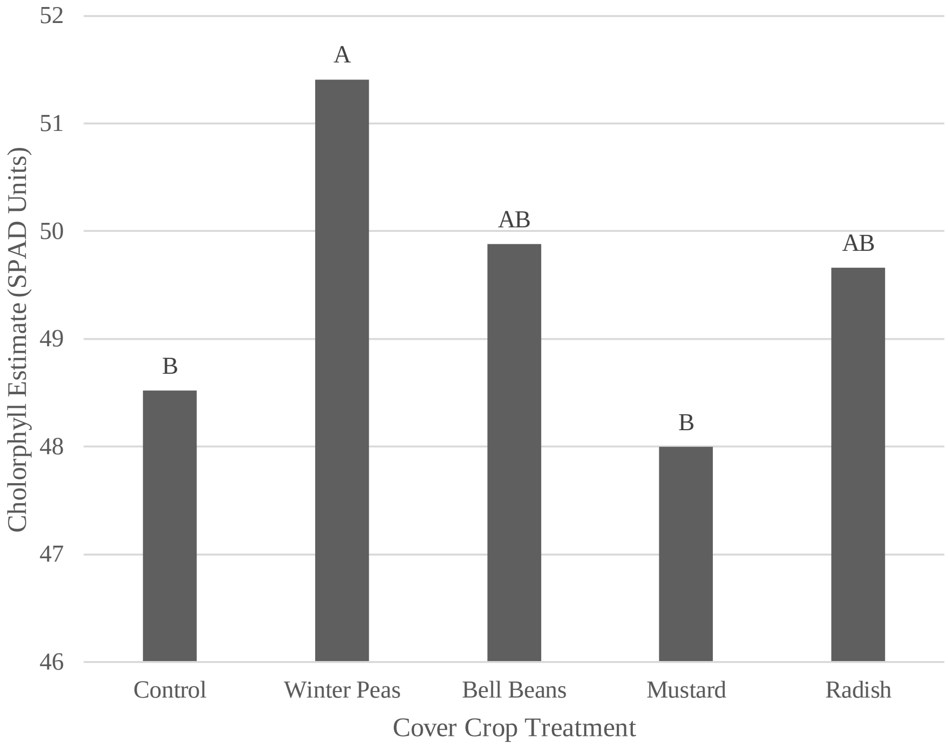


Figure 20. Tomato foliar chlorophyll estimate (SPAD) measured weekly from 26 May to 1 July 2015 (25 to 60 days after planting) in a high tunnel in Fayetteville, AR in 2015. Means comparison by week using Student's t test; letters represent mean separation between treatments within week (p < 0.10).   NS = no significant difference detected between means within week.

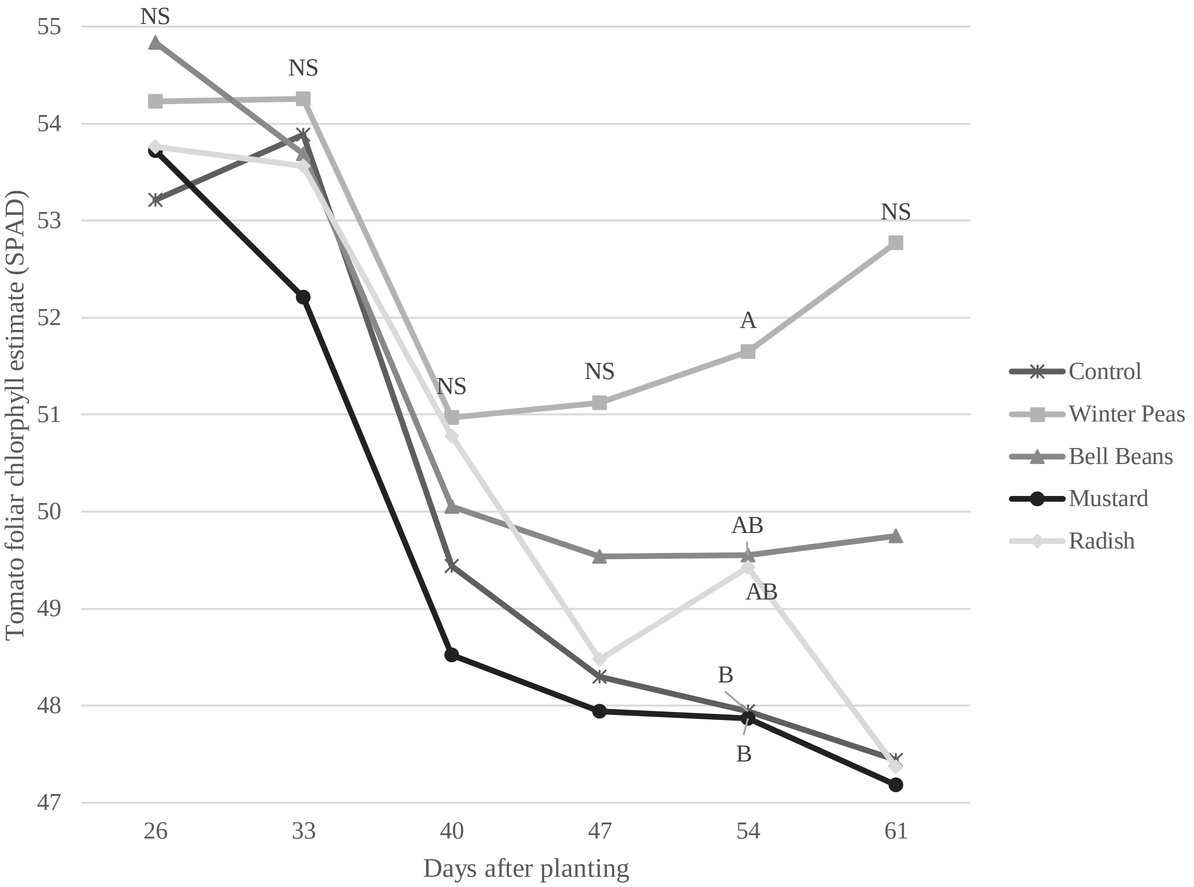


Figure 21. Tomato plant shoot dry weight biomass measured after final harvest in 2014 and 2015 following cover crop treatments grown in a high tunnel in Fayetteville, AR. Bars represent mean values averaged over both years with means comparison carried out using Student's t-test ($p < 0.10$, $n = 3$). Letters represent means separation between treatment means.

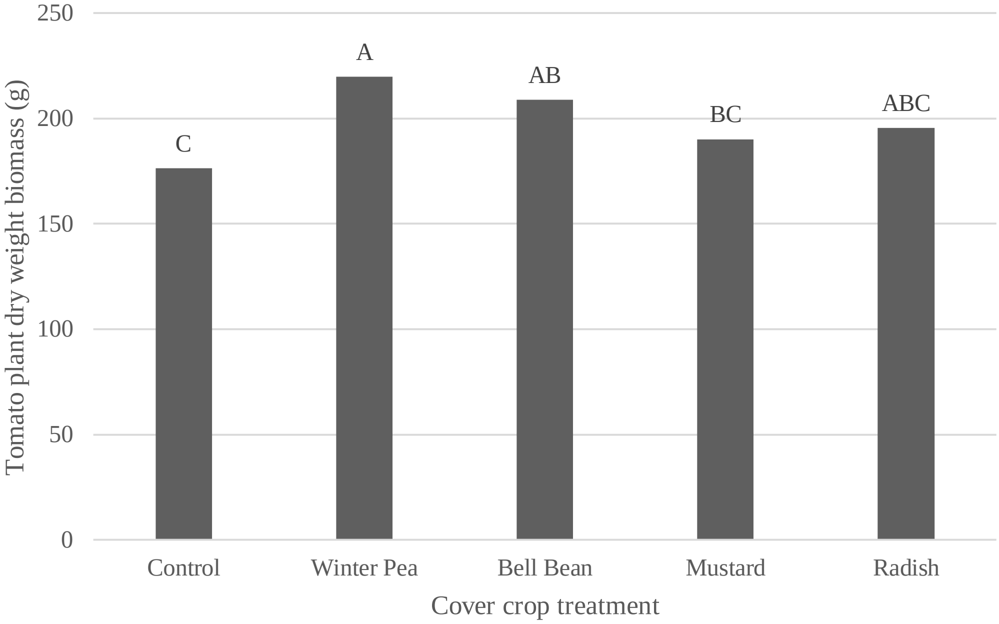


Figure 22. Relationship between soil N and tomato plant dry weight biomass as measured in a high tunnel in Fayetteville, AR over the years 2014 and 2015. Soil samples were collected 30 days after incorporation of cover crop treatments, on 25 April 2014 and 28 April 2015. Tomato biomass measurements were collected following the final tomato harvest in 2014 and 2015. Linear r^2 = 0.15, n = 30, p-value = 0.036.

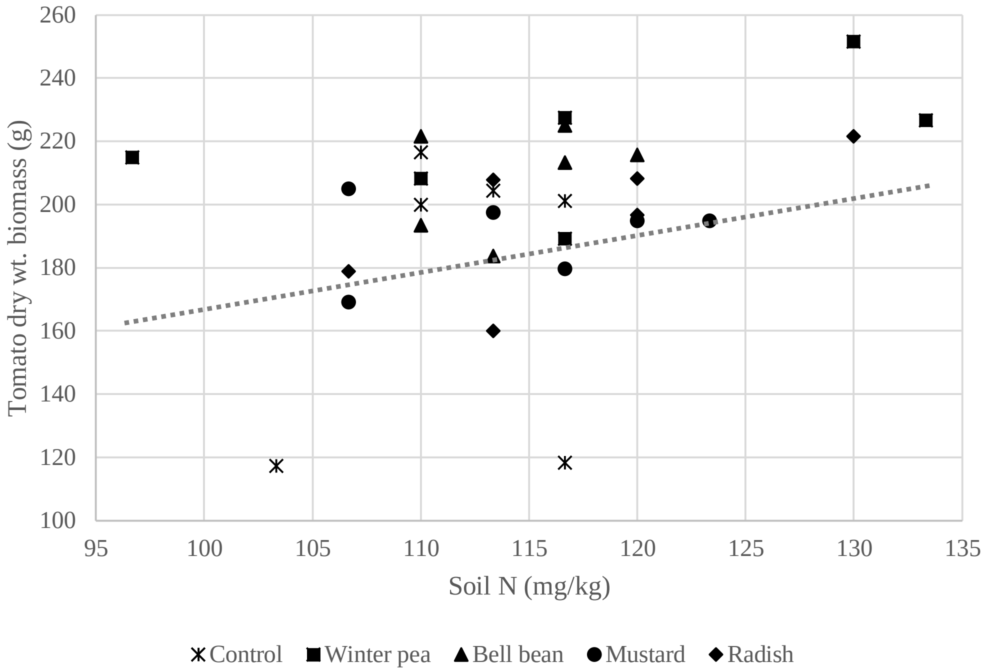


Table 10. Analysis of variance of tomato harvest variables, including total harvest weight, marketable harvest weight, marketable percent, fruit number, average fruit weight, and plant yield, from tomatoes grown in a high tunnel following cover crop treatments in 2014 and 2015 in Fayetteville, AR. Analysis conducted using SAS PROC GLM. n = 3.

		Tomato harvest variables (P < F)					
Factor	DF	Total Weight	Marketable Weight	Marketable Percent	Fruit Number	Avg Fruit Weight	Plant Yield
Cover crop	4	0.792	0.812	0.195	0.559	0.076	0.594
Year	1	0.012	0.007	0.078	0.138	<.001	<.0001
Cover crop X Year	4	0.750	0.702	0.758	0.549	0.259	0.449
Block	4	0.003	0.004	0.000	0.002	0.108	0.078

Figure 23. Tomato yield per plant measured from tomatoes grown in 2014 (A) and 2015 (B) in a high tunnel in Fayetteville, AR following winter cover crop treatments. No significant differences between treatments were detected at $p < 0.10$. Bars represent standard error of the mean.

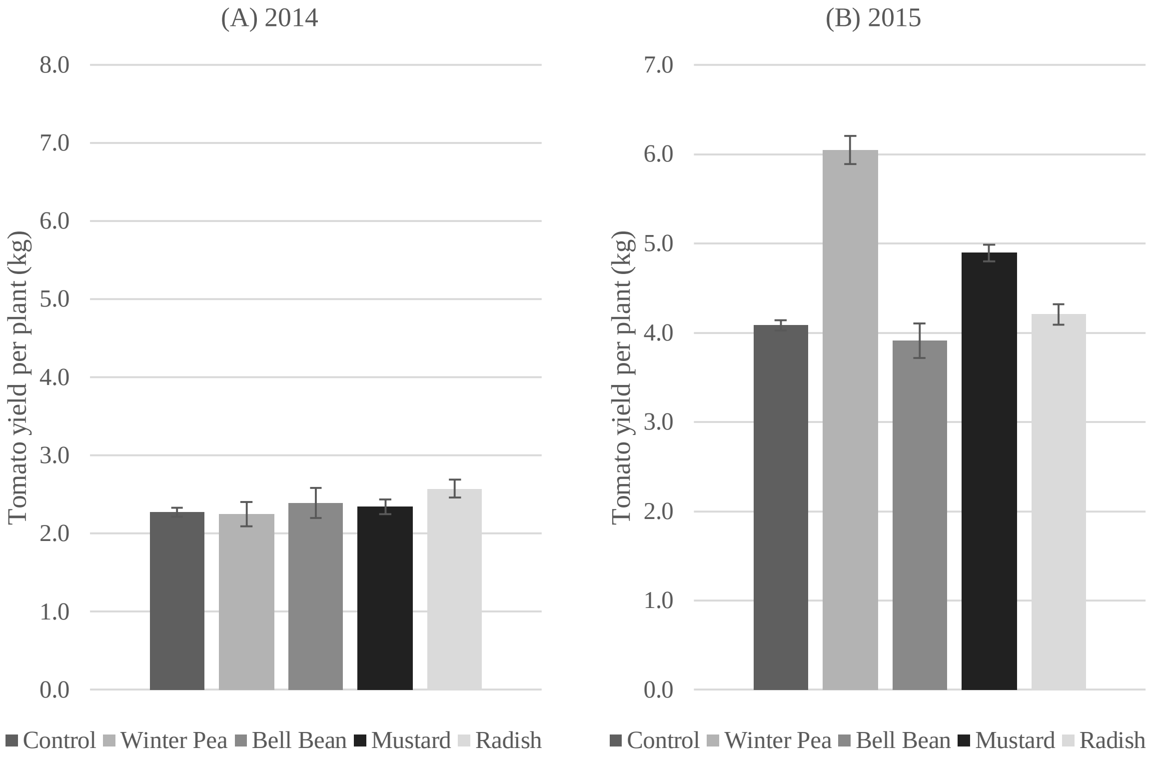


Figure 24. Number of tomato fruit per plot harvested from tomatoes grown in 2014 (A) and 2015 (B) in a high tunnel in Fayetteville, AR following winter cover crop treatments. No significant differences between treatments were detected at $P < 0.10$. Bars represent standard error of the mean.

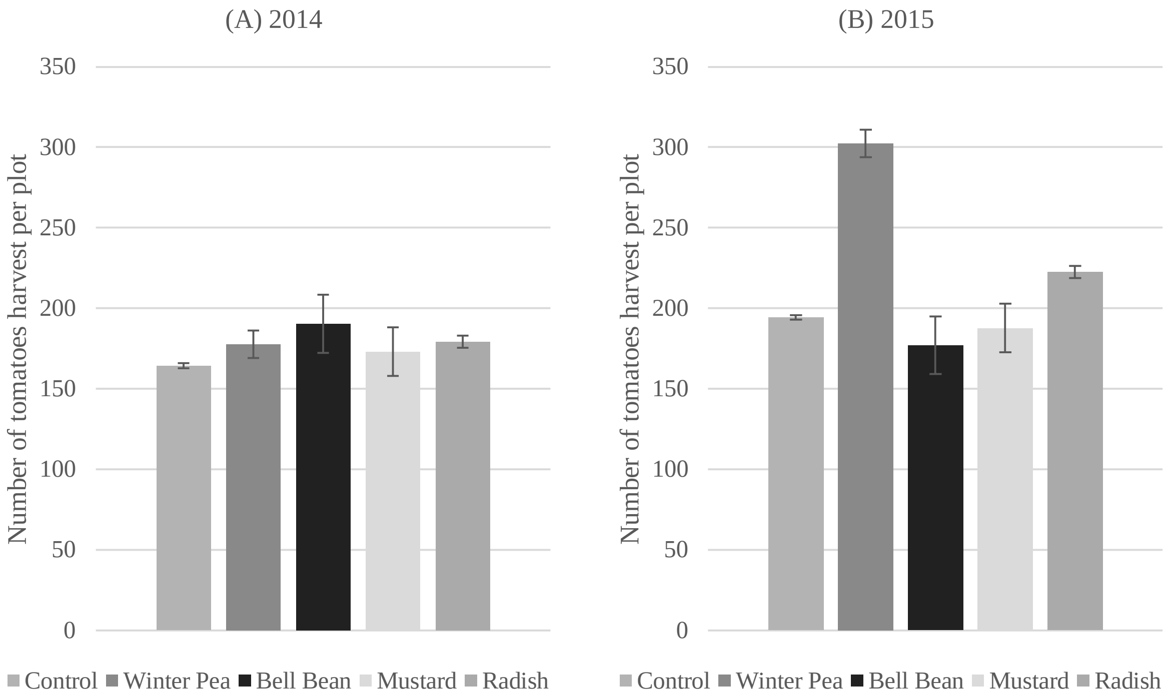


Figure 25. Tomato average fruit weight across years 2014 and 2015, measured from tomatoes grown in a high tunnel in Fayetteville, AR following winter cover crop treatments. Means comparison was conducted using Student’s t test ($p < 0.10$, $n = 3$), with letters representing means separation.

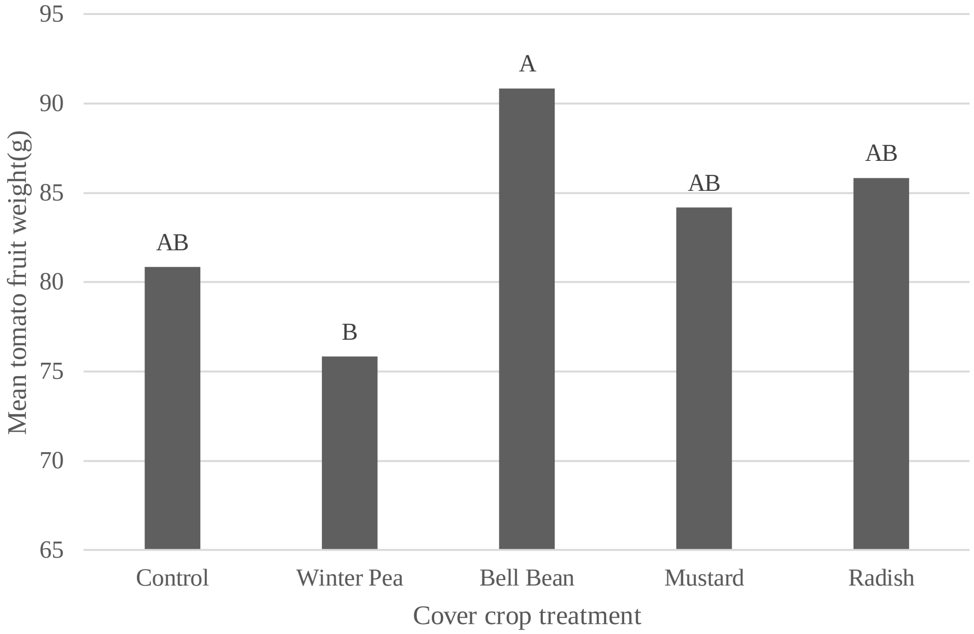


Figure 26. Ratio of marketable tomato harvest compared to total harvest of tomatoes grown in a high tunnel following winter cover crop treatments in 2014 (A) and 2015 (B) in Fayetteville, AR. Means comparison using Student's t-test ($p < 0.10$, $n = 3$). Letters represent means separation. Bars represent standard error from the mean. NS = no significant differences detected between treatment means at $p < 0.10$.

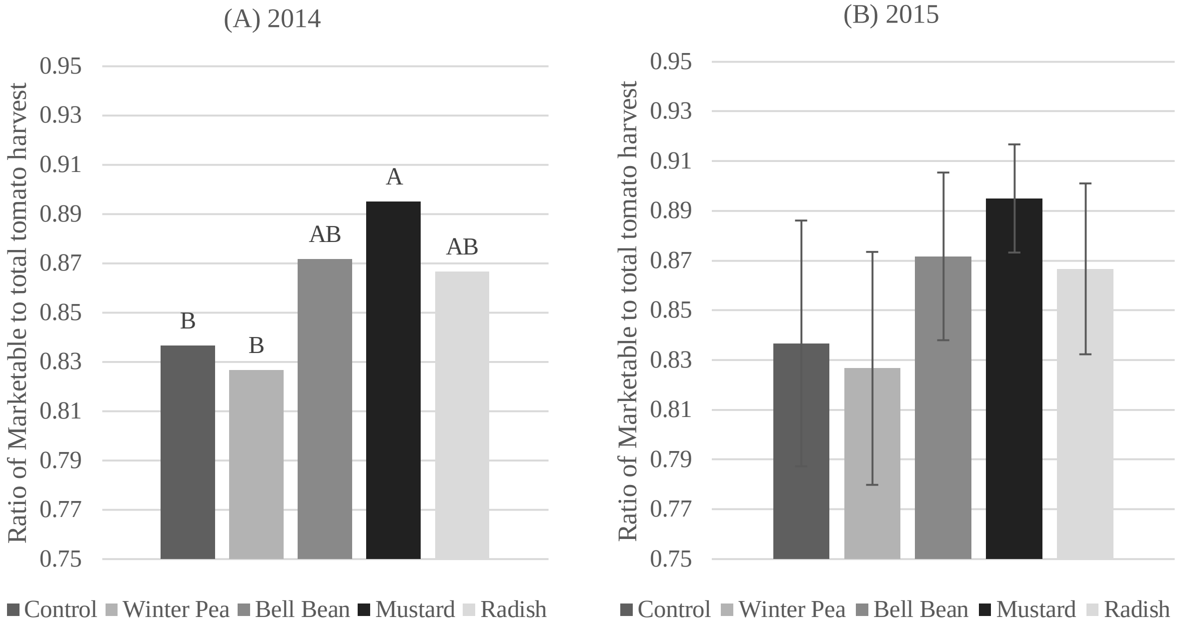


Figure 27. Relationship between tomato foliar N concentration and tomato yield per plant, as measured from tomato crops grown in a high tunnel in Fayetteville, AR. in 2014 and 2015. For 2014 (A) linear $r^2 = 0.02$, $n = 15$. For 2015 (B) linear $r^2 = 0.47$, $n = 15$. For 2014 and 2015 years combined (C), linear $r^2 = 0.53$, $n = 30$, $p < 0.0001$.

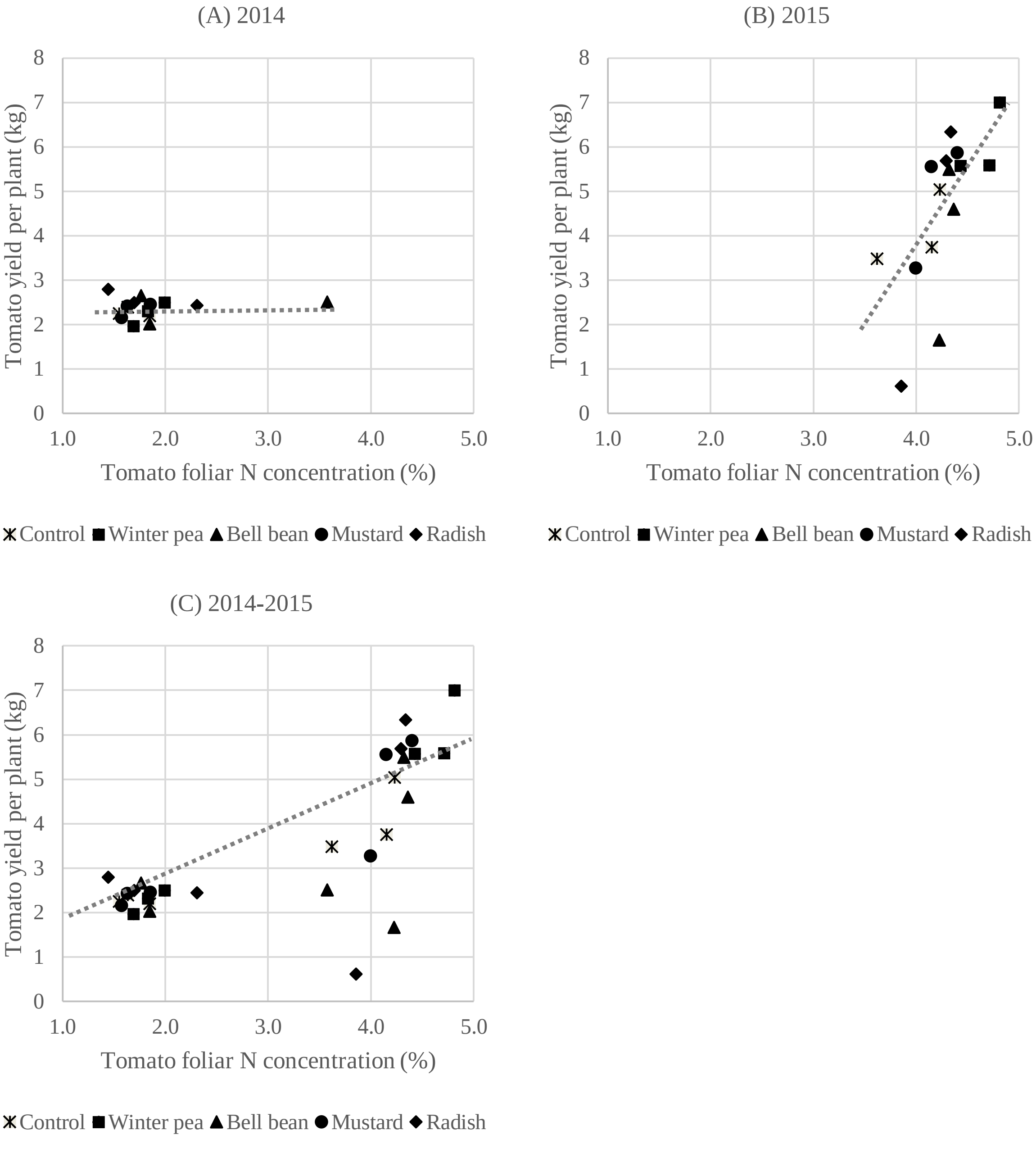


Table 11. Analysis of variance of broccoli variables, including leaf chlorophyll estimates (SPAD), foliar N content, and plant fresh weight biomass, from broccoli grown in a high tunnel in rotation following tomatoes and cover crop treatments in 2014 and 2015 in Fayetteville, AR. Analysis conducted using SAS PROC GLM. n = 3.

		Broccoli variables (P < F)		
Factor	DF	SPAD	Foliar N	Plant Biomass
Cover crop	4	0.400	0.921	0.026
Year	1	0.909	0.036	<.0001
Cover crop X Year	4	0.499	0.725	0.582
Block	4	0.789	0.752	0.065

Table 12. Analysis of variance of the interaction between cover crop treatment and date of measurement on broccoli foliar estimated chlorophyll (SPAD) from broccoli grown in a high tunnel in Fayetteville, AR., following a rotation of winter cover crops and tomato. Chlorophyll measurements were collected on 12 Sept., 16 Sept., 20 Sept., 29 Sept., and 4 Oct. 2014; and 4 Sept., 11 Sept., 17 Sept., 24 Sept., and 2 Oct. 2015. Analysis conducted using SAS PROC GLM. n = 3.

		P > F
Factor	DF	SPAD
Cover crop	4	0.144
Date	9	<.001
Cover crop X Date	36	0.418
Block	21	0.870

Table 13. Correlation between cover crop variables and broccoli crop variables from study in a high tunnel in Fayetteville, AR, 2014-2015. For each relationship, the Pearson Correlation Coefficients (PCC) and p-values are included in the table.

		Broccoli Plant Biomass	**Broccoli Foliar N**	**Broccoli Avg Head Wt**	**Broccoli Head Diam****	**Broccoli Stem Diam****
Year	**PCC**	-0.832	-0.448	0.418	.	.
	p-value*	<.0001	0.013	0.022	.	.
Cover Crop C	**PCC**	-0.571	-0.321	0.228	0.016	0.023
	p-value	0.001	0.084	0.226	0.955	0.935
Cover Crop Biomass	**PCC**	-0.503	-0.361	0.355	0.179	-0.196
	p-value	0.005	0.050	0.054	0.523	0.483
Soil N	**PCC**	0.463	0.474	0.174	0.087	0.733
	p-value	0.010	0.008	0.359	0.758	0.002
Soil C	**PCC**	0.295	0.324	0.012	0.147	0.459
	p-value	0.114	0.081	0.952	0.602	0.085
Broccoli Plant Biomass	**PCC**	1	0.525	-0.115	0.006	0.336
	p-value		0.003	0.546	0.984	0.221
Broccoli Foliar Chlorophyll	**PCC**	0.188	-0.303	0.510	0.541	0.320
	p-value	0.321	0.104	0.004	0.037	0.244
Broccoli Avg Head Wt	**PCC**	-0.115	-0.148	1	0.896	0.649
	p-value	0.546	0.434		<.0001	0.009

* n = 30, except where indicated otherwise

** n = 15

Figure 28. Broccoli leaf estimated chlorophyll (SPAD), all treatments pooled, measured over five weeks in 2014 and 2015 on broccoli grown in a high tunnel in Fayetteville, AR following tomatoes which were preceded by winter cover crops. Means comparison using Student's t-test at $p < 0.10$, $n = 3$. Letters represent separation of means between sampling dates.

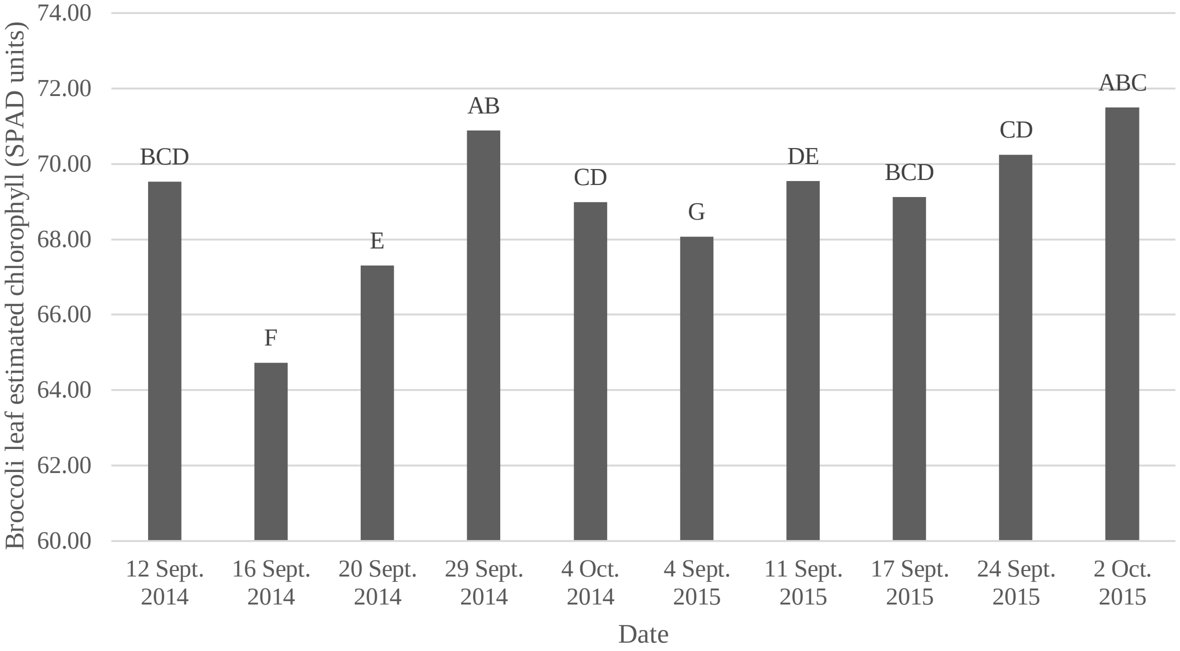


Table 14. Broccoli leaf estimated chlorophyll (SPAD) means by cover crop treatment and date, measured over five weeks in 2014 and 2015 on broccoli grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. Means comparison using Student's t test at ($p < 0.10$, $n = 3$). Letters represent means separation between cover crop treatments within sampling date.

Cover Crop Treatment	-------------------------- 2014 --------------------------					--------------------------- 2015 ----------------------------				
	12-Sep	16-Sep	20-Sep	29-Sep	4-Oct	4-Sep	11-Sep	17-Sep	24-Sep	2-Oct
Control	70.4	62.3	68.6	71.1	67.1	65.9	69.9	66.8 C	70.4	70.1
Winter Pea	70.7	67.8	66.6	71.5	70.5	68.9	68.9	68.6 BC	69.7	70.9
Bell Bean	69.4	63.4	65.1	69.7	69.0	68.1	69.9	68.4 C	70.0	72.3
Mustard	69.0	65.1	68.1	70.2	70.4	68.3	69.7	70.8 AB	71.9	72.3
Radish	68.2	65.1	68.2	71.9	68.0	69.2	69.4	71.1 A	69.3	72.0
P > F	0.77	0.17	0.32	0.47	0.68	0.43	0.97	0.01	0.62	0.212

Figure 29. Broccoli foliar N concentration measured on 6 Nov. 2014 (A) and 5 Nov. 2015 (B) from broccoli grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. No significant differences between treatments were detected using Student's t test at $p < 0.10$. Bars represent standard error from the mean. Dashed line represents foliar N sufficiency threshold of 3.0% for broccoli (Hanlon and Hochmuth, 2000)

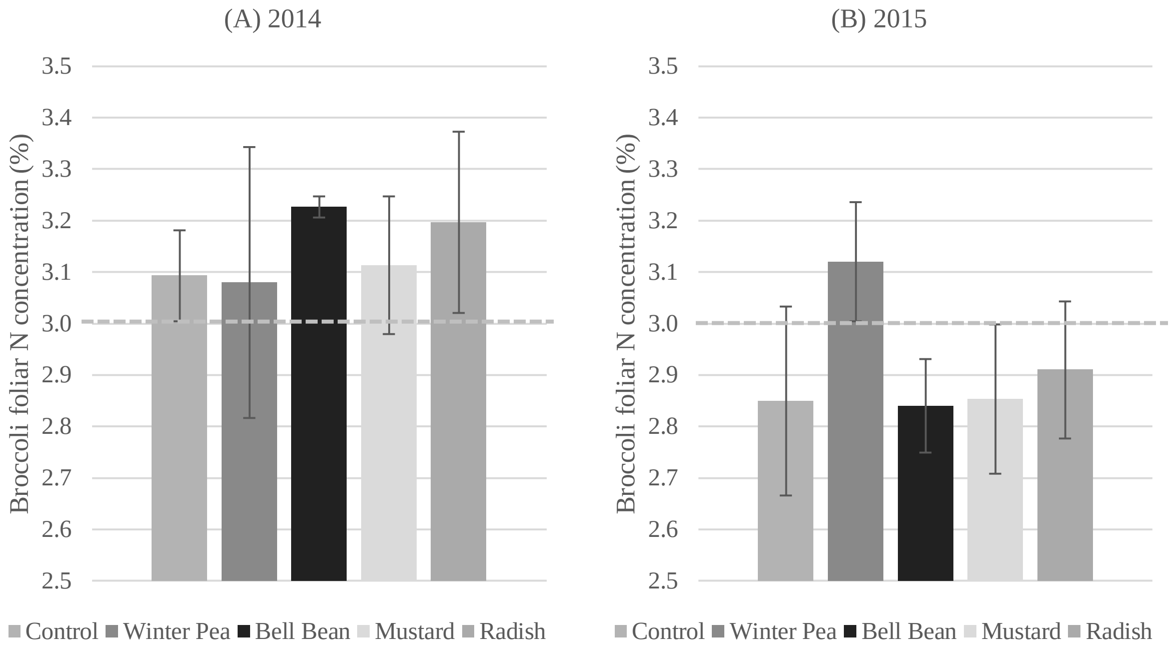


Figure 30. Relationship between soil N content and broccoli foliar N concentration, as measured from broccoli crops grown in a high tunnel in Fayetteville, AR. in 2014 and 2015. Soil N content was measured on 25 April 2014 and 28 April 2015, 30 days after the incorporation of cover crop treatments. Broccoli foliar N was measured from 12 Sept. to 4 Oct. 2014 and from 4 Sept. to 2 Oct. 2015. Linear $r^2 = 0.21$, n=30.

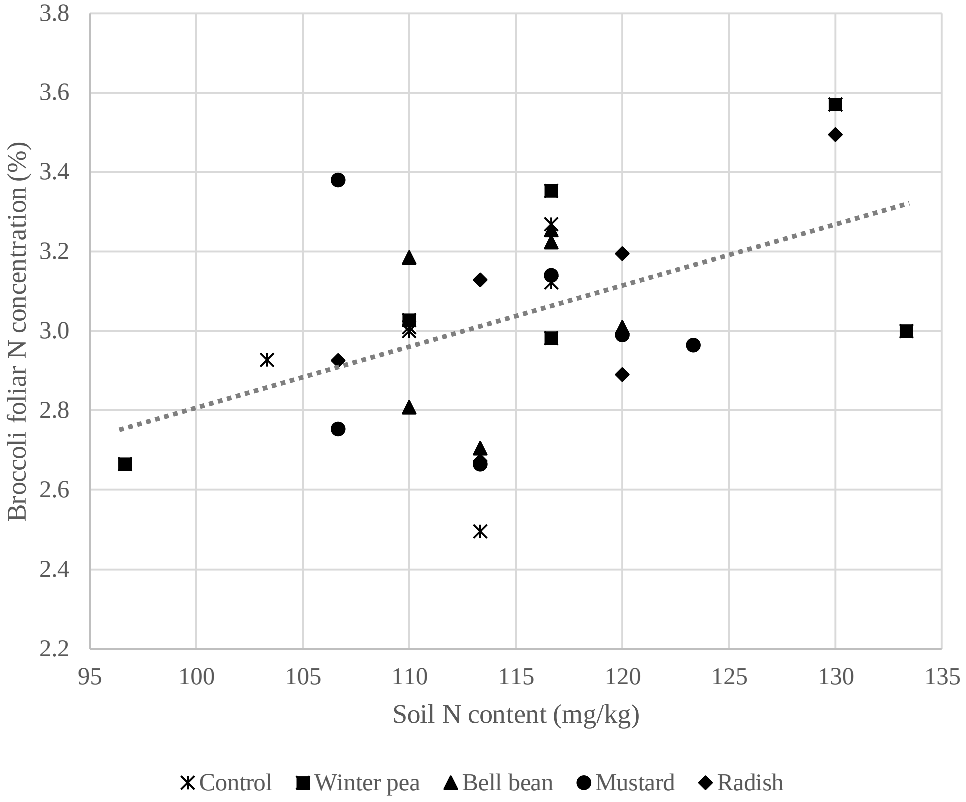


Figure 31. Broccoli plant fresh weight biomass across years measured on 7 Nov. 2014 and 9 Nov. 2015 from broccoli grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. Letters represent means separation by Student's t-test at p < 0.10, n=3.

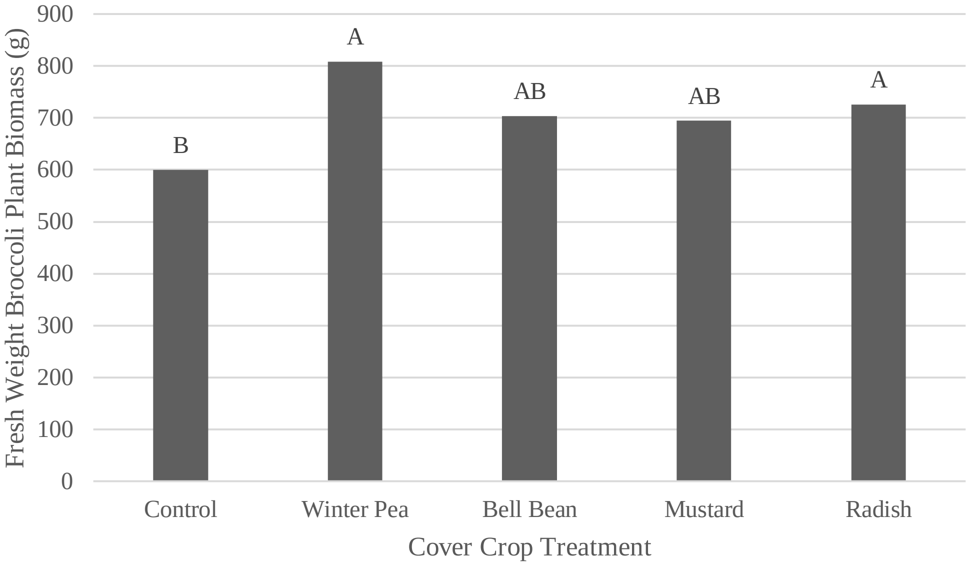


Figure 32. Relationship between soil N content and broccoli plant biomass, as measured from broccoli crops grown in a high tunnel in Fayetteville, AR. in 2014 and 2015. Soil N content was measured on 25 April 2014 and 28 April 2015, 30 days after the incorporation of cover crop treatments. Broccoli biomass was measured 7 Nov. 2014 and 9 Nov. 2015. Linear $r^2 = 0.21$, n = 30.

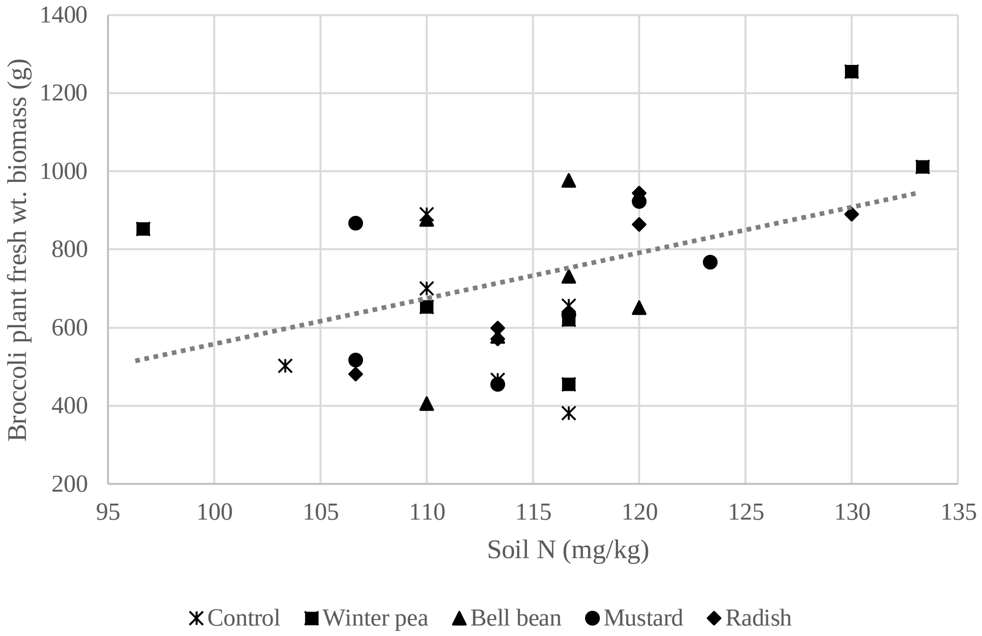


Table 15. ANOVA table of interaction between cover crop treatment (CC) and year on broccoli harvest parameters including total yield per plot, average head weight, and side shoot weight. Broccoli was grown in a high tunnel in Fayetteville, AR from Aug. to the end of Oct. in 2014 and 2015 following tomatoes which were preceded by winter cover crop treatments. Significant main effects ($p < 0.10$) are bolded and shaded. n = 3.

		Broccoli variables (P < F)		
Factor	DF	Total Yield (g)	Avg Head Wt (g)	Side Shoot Wt (g)
Year	1	0.194	0.024	<.0001
Cover crop	4	0.690	0.418	0.769
Year X Cover crop	4	0.218	0.694	0.772
Block(Year)	4	0.378	0.191	0.499

Figure 33. Broccoli total yield per plot, harvested in October 2014 (A) and 2015 (B), grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. No differences were detected between treatment means with Student's t-test at $p < 0.10$, $n = 3$. Bars represent standard error from the mean.

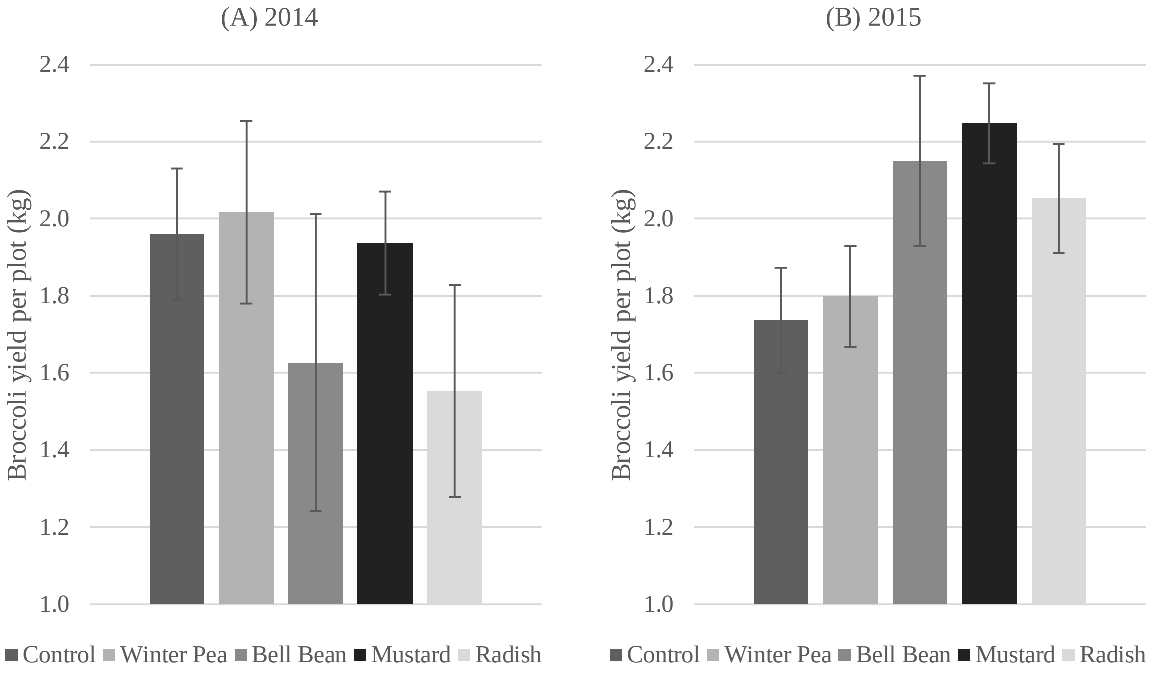


Figure 34. Average head weight of broccoli harvested in October 2014 (A) and 2015 (B), grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. No differences were detected between treatment means with Student's t-test at $p < 0.10$, $n = 3$. Bars represent standard error from the mean.

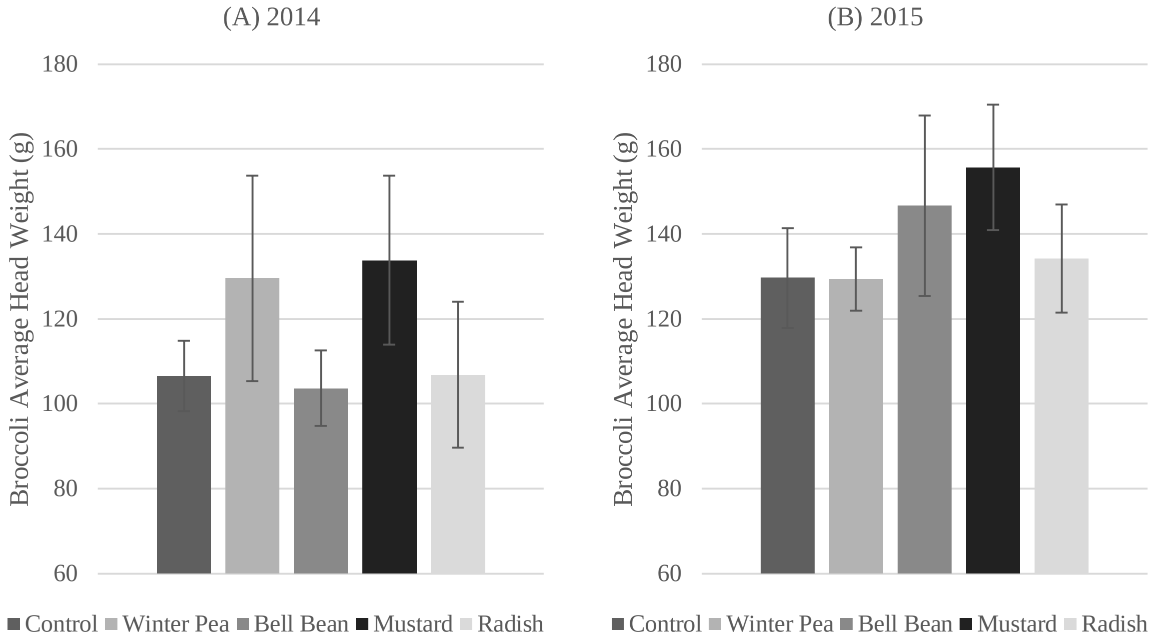
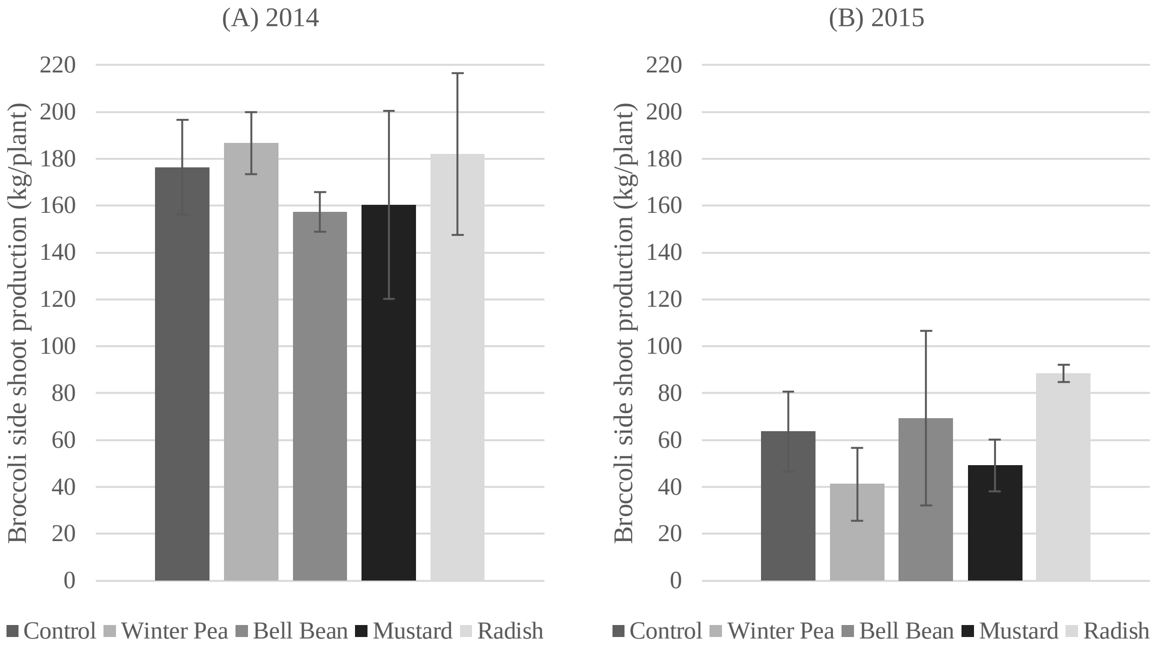


Figure 35. Broccoli side shoot production per plant harvested in October 2014 (A) and 2015 (B), grown in a high tunnel in Fayetteville, AR following a rotation of winter cover crops and tomatoes. No differences were detected between treatment means with Student’s t-test at $p < 0.10$, $n = 3$. Bars represent standard error from the mean.



(A) 2014

(B) 2015

Figure 36. Average broccoli head diameter measured from broccoli harvested in Oct. 2015 from a high tunnel in Fayetteville, AR. Broccoli was grown in rotation with winter cover crop treatments and tomatoes. Bars represent standard error from the mean.

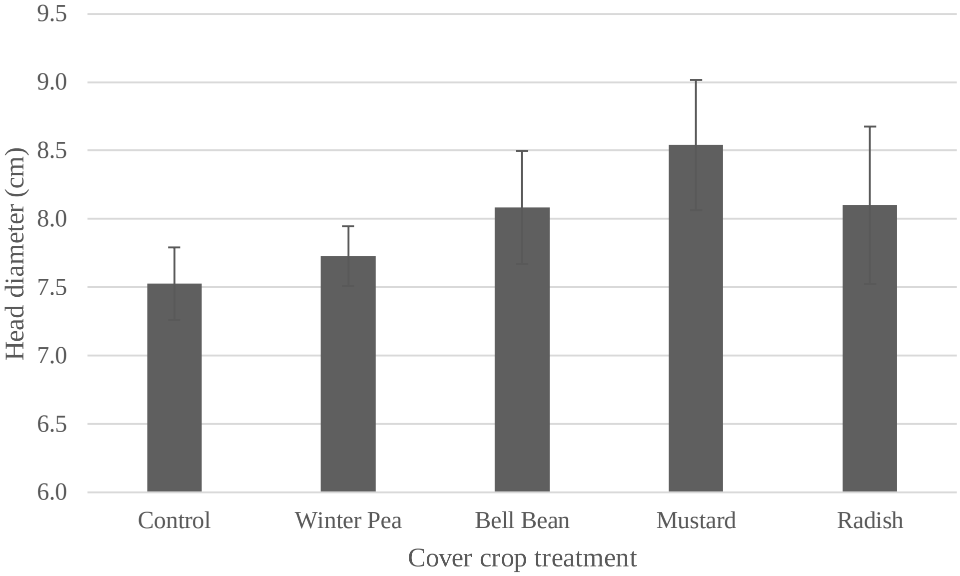


Figure 37. Average broccoli stem diameter measured from broccoli harvested in Oct. 2015 from a high tunnel in Fayetteville, AR. Broccoli was grown in rotation with winter cover crop treatments and tomatoes. Bars represent standard error from the mean.

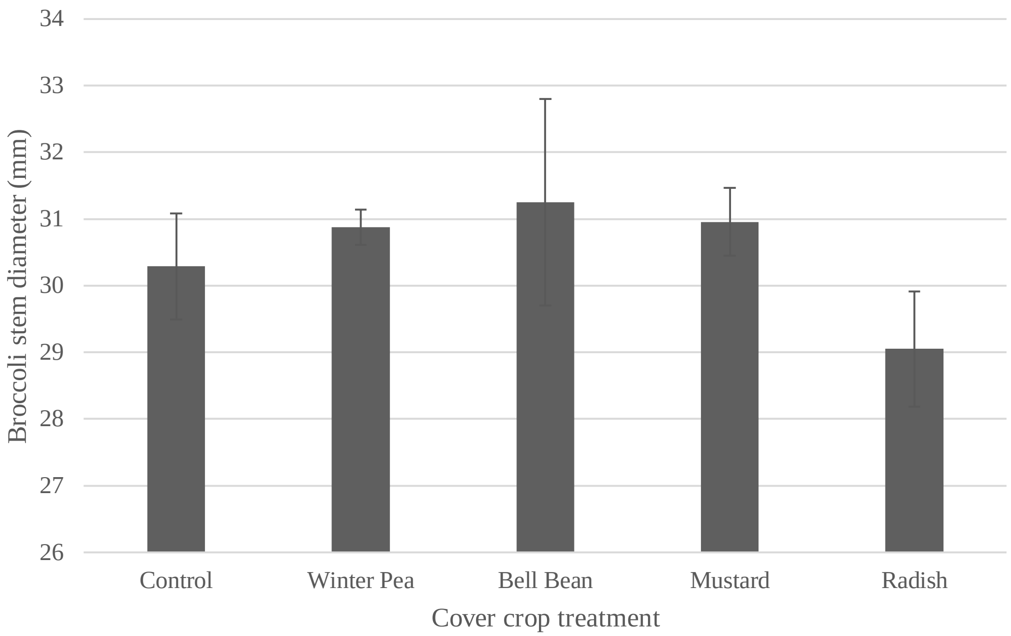


Figure 38. Relationship between soil N content and broccoli stem diameter, as measured from broccoli crops grown in a high tunnel in Fayetteville, AR. in 2014 and 2015. Soil N content was measured on 25 April 2014 and 28 April 2015, 30 days after the incorporation of cover crop treatments. Broccoli stem diameter was measured throughout harvest in October of 2015. Linear $r^2 = 0.53$, n=15.

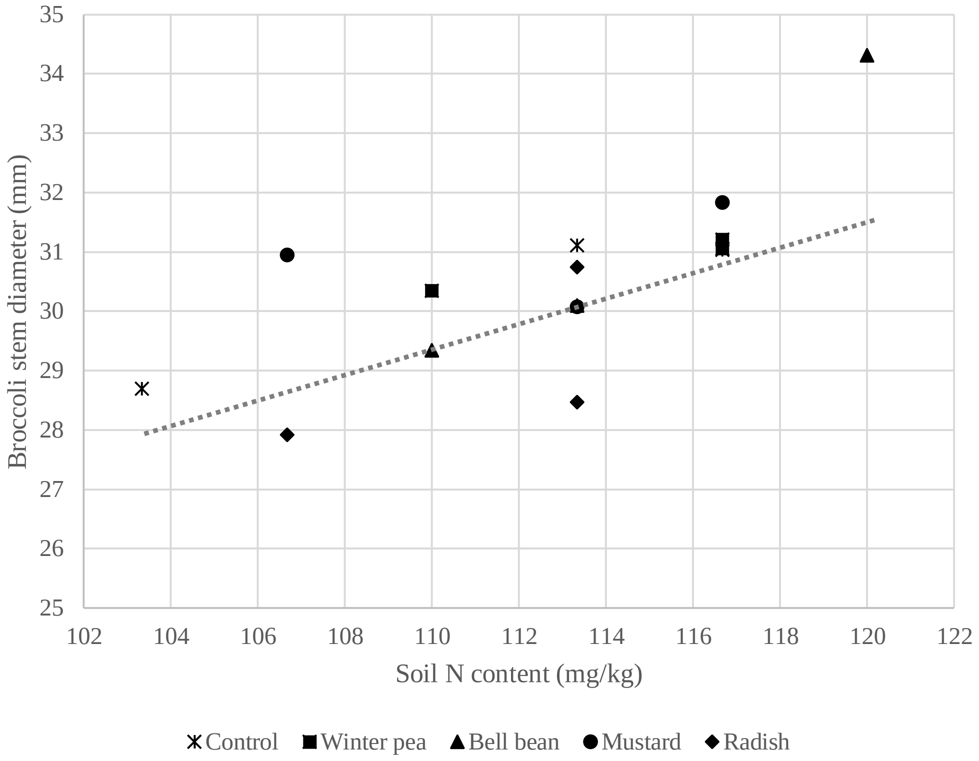
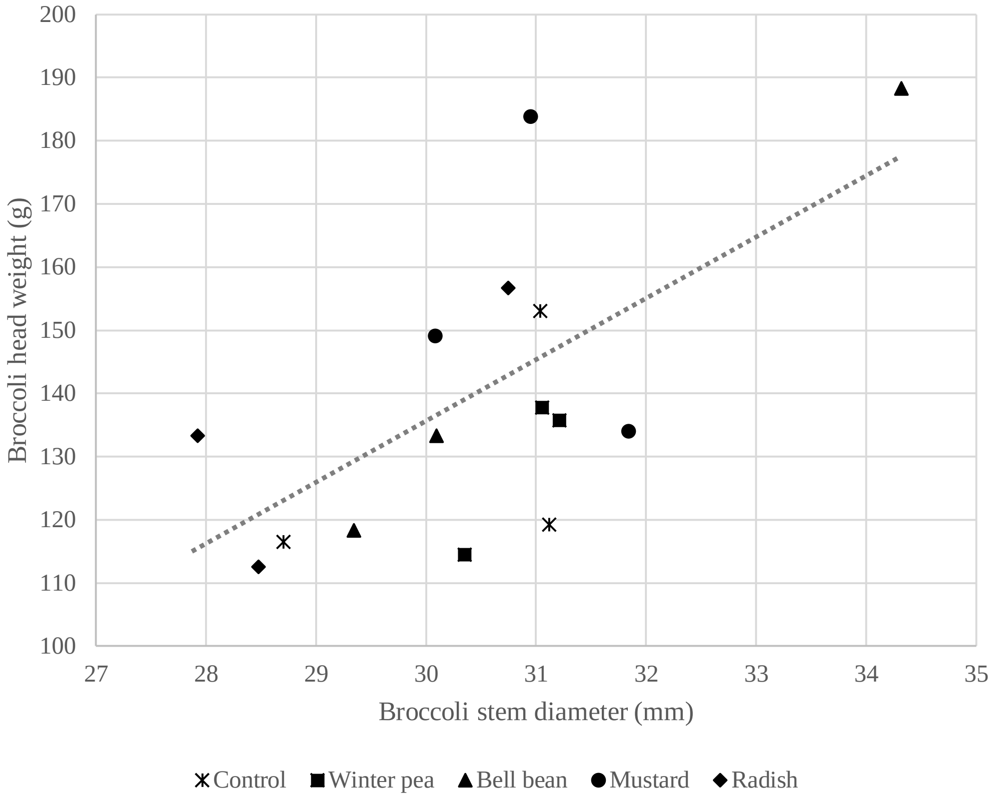
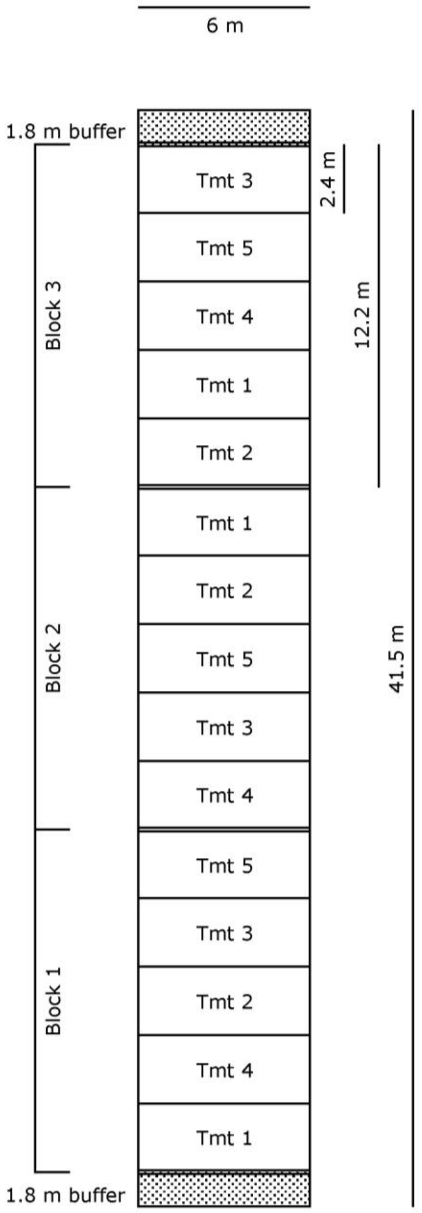


Figure 39. Relationship between broccoli stem diameter and broccoli head weight, as measured from broccoli crop grown in a high tunnel in Fayetteville, AR. in 2015, harvested in October. Linear r^2 = 0.42, n = 15.



APPENDIX

Figure 40. Winter cover crop plot map.



Treatment Key

1 Control
2 Winter Peas
3 Bell Beans
4 Mustard
5 Radish

Plot Size: 2.4 x 6 m = 14.4 m^2

Seeding Rate	per plot
Winter Peas	0.22 kg
Bell Beans	0.22 kg
Mustard	0.04 kg
Radish	0.03 kg

Figure 41. Vegetable crops plot map.

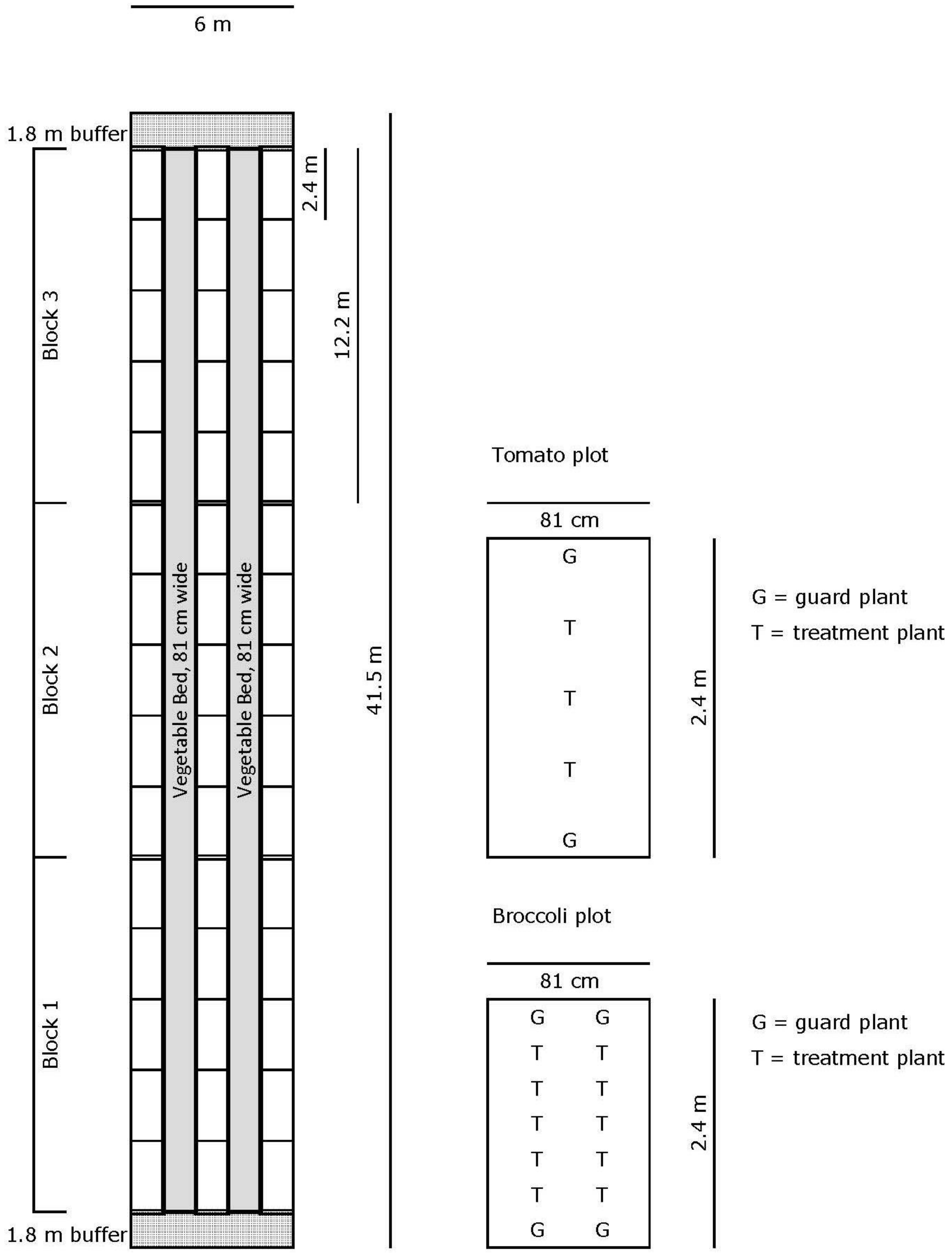


Figure 42. Incidence of Southern blight (*Sclerotium rolfsii*) on tomato plants, 2014 and 2015. Numbers indicate the number of treatment plants per plot that exhibited Southern blight symptoms throughout the season.

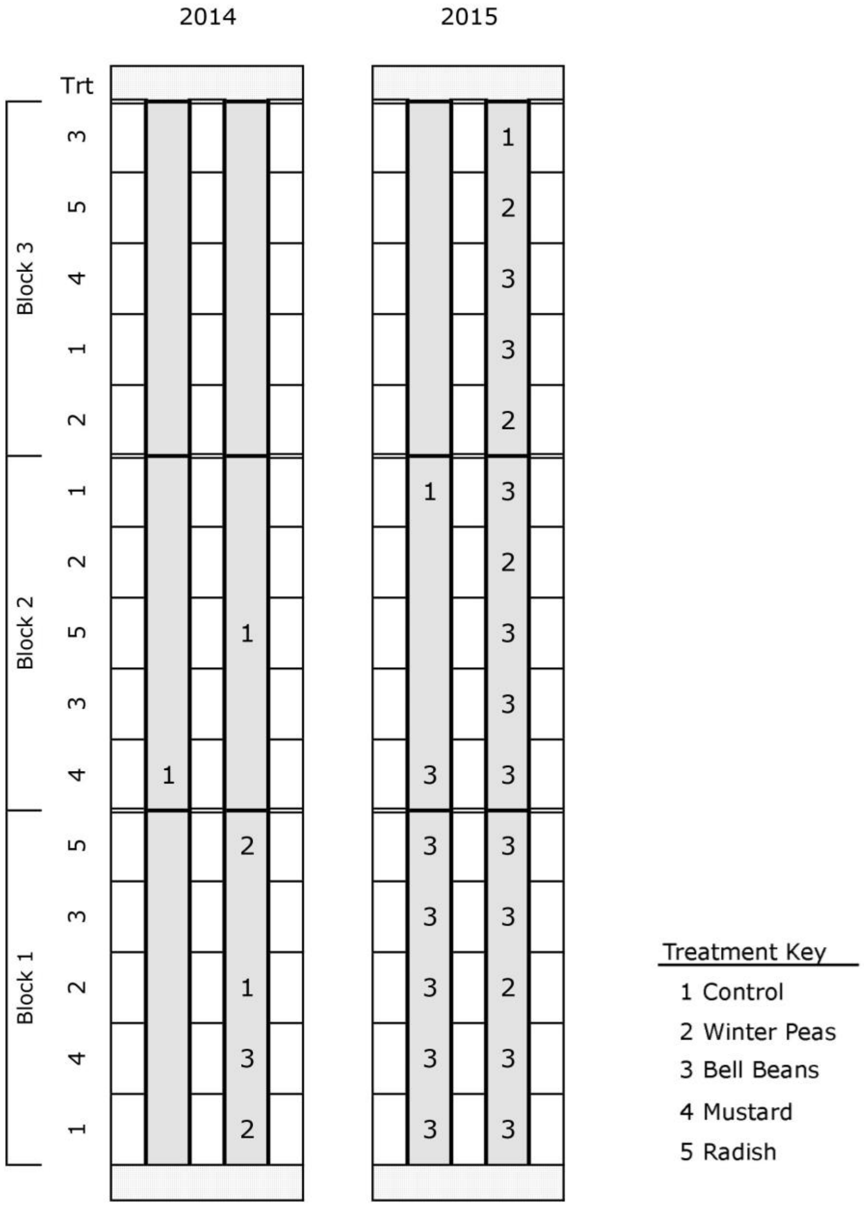


Table 16. Ambient temperature (°C) in high tunnel during study, measured at crop canopy height. Average minimum, maximum, and mean temperatures calculated from hourly temperatures recorded during crop production for each respective crop.

		High Tunnel Ambient Temperature (C)		
		Minimum	Maximum	Mean
Cover crop	2013-2014	-1.5	21.1	7.2
	2014-2015	0.6	19.5	7.6
Tomato	2014	17.7	31.9	24.0
	2015	21.2	34.1	26.8
Broccoli	2014	16.3	32.4	23.0
	2015	14.2	29.4	21.0

Table 17. Daily ambient temperature (°C) in high tunnel during period of cover crop production, 2013-2015, measured at crop canopy height. Daily minimum, maximum, and mean temperatures, calculated from temperatures recorded hourly.

High Tunnel Ambient Temperature (°C)			
Date	Minimum	Maximum	Mean
12/12/2013	0.1	28.7	19.1
12/13/2013	-0.3	6.5	3.6
12/14/2013	-3.6	3.6	2.1
12/15/2013	-5.6	26.0	6.3
12/16/2013	3.2	24.1	10.2
12/17/2013	-0.3	27.2	8.3
12/18/2013	-2.2	20.2	8.3
12/19/2013	10.2	20.2	13.3
12/20/2013	4.4	17.9	10.0
12/21/2013	2.7	7.7	5.2
12/22/2013	-0.3	3.6	1.8
12/23/2013	-5.1	8.2	0.3
12/24/2013	-6.1	26.4	4.8
12/25/2013	-2.7	25.2	5.9
12/26/2013	-4.6	31.2	6.7
12/27/2013	-3.1	23.7	6.7
12/28/2013	-2.7	21.7	5.9
12/29/2013	-5.6	5.3	0.2
12/30/2013	-7.7	18.7	0.2
12/31/2013	-6.1	22.5	4.4
1/1/2014	-2.2	17.1	6.5
1/2/2014	-10.4	17.1	-0.4
1/3/2014	-11.6	27.2	3.0
1/4/2014	-1.3	9.8	3.9
1/5/2014	-12.7	4.1	-3.2
1/6/2014	-16.6	7.3	-9.1
1/7/2014	-13.9	26.0	0.7
1/8/2014	-3.6	11.7	1.2
1/9/2014	1.0	13.7	4.6
1/10/2014	1.4	12.5	7.8
1/11/2014	0.1	31.2	10.1
1/12/2014	0.1	24.8	11.5
1/13/2014	1.9	22.1	11.0
1/14/2014	-2.7	11.7	5.4

1/15/2014	-6.1	14.1	2.4
1/16/2014	1.0	21.7	8.6
1/17/2014	-3.6	21.7	4.9
1/18/2014	-2.2	18.3	6.4
1/19/2014	-4.6	18.3	6.0
1/20/2014	1.9	29.2	11.5
1/21/2014	-6.1	22.1	3.2
1/22/2014	-6.1	24.4	4.3
1/23/2014	-14.6	8.9	-4.0
1/24/2014	-16.6	24.4	-0.9
1/25/2014	-1.7	33.2	10.2
1/26/2014	-2.2	39.7	13.3
1/27/2014	-6.1	2.3	-2.9
1/28/2014	-10.4	24.4	1.3
1/29/2014	-11.6	29.2	2.9
1/30/2014	-4.6	26.8	7.0
1/31/2014	1.9	11.7	7.3
2/1/2014	0.1	11.7	5.8
2/2/2014	-5.6	4.4	-0.3
2/3/2014	-8.2	28.3	4.1
2/4/2014	-1.7	5.3	1.6
2/5/2014	-10.4	5.7	-2.1
2/6/2014	-11.6	18.3	-3.6
2/7/2014	-10.9	10.9	-2.3
2/8/2014	-2.7	12.1	2.5
2/9/2014	-0.8	8.6	2.1
2/10/2014	-4.1	19.1	2.4
2/11/2014	-5.6	27.6	4.7
2/12/2014	-8.2	31.6	6.0
2/13/2014	-3.6	17.1	5.2
2/14/2014	-2.7	14.8	6.3
2/15/2014	-5.1	17.5	5.5
2/16/2014	-0.8	22.1	9.8
2/17/2014	4.4	20.6	12.4
2/18/2014	-1.7	22.1	10.0
2/19/2014	4.4	22.5	12.8
2/20/2014	3.6	21.3	12.6
2/21/2014	-1.3	17.5	8.3
2/22/2014	4.9	21.3	12.3
2/23/2014	1.4	13.7	6.4
2/24/2014	-2.7	17.5	5.9

2/25/2014	-1.7	10.6	4.8
2/26/2014	-8.2	10.6	-1.9
2/27/2014	-8.2	39.3	9.4
2/28/2014	-0.8	13.3	5.2
3/1/2014	-0.8	39.3	11.0
3/2/2014	-8.7	4.9	-2.4
3/3/2014	-10.9	25.6	1.2
3/4/2014	-7.1	36.6	8.1
3/5/2014	-5.1	39.7	9.6
3/6/2014	-0.3	35.8	12.9
3/7/2014	-3.1	21.7	8.3
3/8/2014	2.7	18.7	6.9
3/9/2014	3.6	25.2	10.3
3/10/2014	3.2	29.2	14.1
3/11/2014	9.3	33.2	17.1
3/12/2014	2.3	17.9	9.4
3/13/2014	1.0	23.7	11.6
3/14/2014	7.7	26.4	13.9
3/15/2014	5.3	21.7	13.1
3/16/2014	-0.3	12.9	5.4
3/17/2014	-1.3	26.8	9.0
3/18/2014	4.9	22.5	12.2
3/19/2014	2.7	22.9	10.9
3/20/2014	0.1	27.2	11.9
3/21/2014	5.3	33.2	15.3
3/22/2014	4.1	20.2	11.2
3/23/2014	1.0	24.8	9.8
3/24/2014	0.1	23.3	7.8
3/25/2014	-0.3	25.2	9.6
3/26/2014	-1.3	24.4	7.2
3/27/2014	8.6	32.4	16.3
3/28/2014	5.3	27.9	12.0
3/29/2014	1.9	34.5	14.6
3/30/2014	1.4	26.8	13.3
3/31/2014	10.6	20.9	13.6
4/1/2014	8.2	34.5	18.0
4/2/2014	13.7	26.4	19.7
4/3/2014	13.3	38.4	21.3
4/4/2014	4.1	24.8	13.2
4/5/2014	1.9	30.8	13.4
4/6/2014	7.7	24.4	12.9

4/7/2014	6.9	28.3	14.8
4/8/2014	6.9	17.1	11.4
11/25/2014	0.6	23.3	8.4
11/26/2014	-1.3	20.2	6.2
11/27/2014	-4.1	22.1	3.7
11/28/2014	0.6	21.7	9.9
11/29/2014	10.6	28.7	16.9
11/30/2014	5.7	27.2	16.2
12/1/2014	-0.3	5.7	1.1
12/2/2014	0.1	7.3	2.7
12/3/2014	4.4	11.7	7.0
12/4/2014	6.9	19.8	10.7
12/5/2014	10.2	18.7	13.6
12/6/2014	6.5	12.5	9.0
12/7/2014	5.7	21.3	9.9
12/8/2014	3.2	26.0	10.0
12/9/2014	1.0	24.1	7.8
12/10/2014	-1.3	30.3	10.0
12/11/2014	6.9	17.1	10.2
12/12/2014	8.6	28.7	13.0
12/13/2014	9.8	27.6	14.3
12/14/2014	8.2	26.8	14.5
12/15/2014	5.7	22.5	11.5
12/16/2014	-1.7	8.2	4.0
12/17/2014	-1.7	6.5	2.2
12/18/2014	4.1	9.3	5.8
12/19/2014	5.7	8.2	6.3
12/20/2014	5.3	10.9	7.1
12/21/2014	5.7	16.0	7.7
12/22/2014	2.7	12.1	8.5
12/23/2014	3.6	15.6	6.8
12/24/2014	-0.8	6.9	4.0
12/25/2014	-0.8	20.6	7.1
12/26/2014	4.1	20.2	10.2
12/27/2014	-0.8	10.9	4.8
12/28/2014	-3.1	22.5	3.4
12/29/2014	-4.1	20.9	3.5
12/30/2014	-3.6	10.2	1.8
12/31/2014	-2.2	15.2	2.5
1/1/2015	0.6	6.1	2.7
1/2/2015	2.7	6.9	4.7

1/3/2015	4.9	12.9	6.9
1/4/2015	-6.6	8.2	-0.6
1/5/2015	-8.2	21.7	2.0
1/6/2015	-3.1	23.3	4.8
1/7/2015	-10.9	5.3	-3.5
1/8/2015	-12.7	16.4	-3.1
1/9/2015	-9.3	12.9	-0.8
1/10/2015	-10.9	15.6	-0.6
1/11/2015	1.0	8.2	3.9
1/12/2015	-2.7	4.9	1.7
1/13/2015	-6.6	21.3	2.3
1/14/2015	-5.6	23.7	5.3
1/15/2015	-1.7	22.5	7.1
1/16/2015	-4.1	30.8	7.8
1/17/2015	1.0	26.4	9.8
1/18/2015	-2.7	27.2	9.2
1/19/2015	2.7	36.6	13.1
1/20/2015	-0.3	17.9	5.9
1/21/2015	-3.1	24.4	7.3
1/22/2015	-0.3	14.1	6.5
1/23/2015	-2.7	22.9	4.9
1/24/2015	-3.1	19.4	6.3
1/25/2015	3.6	9.8	6.7
1/26/2015	-1.3	26.4	9.1
1/27/2015	-0.3	26.0	9.6
1/28/2015	4.4	22.1	13.8
1/29/2015	-1.3	14.8	7.2
1/30/2015	-3.6	20.6	4.5
1/31/2015	3.6	12.5	6.6
2/1/2015	-6.1	7.3	2.7
2/2/2015	-8.2	19.8	1.4
2/3/2015	-6.1	26.0	5.9
2/4/2015	-1.3	26.4	5.5
2/5/2015	-6.6	25.6	4.6
2/6/2015	-0.3	29.2	9.8
2/7/2015	3.2	32.0	12.9
2/8/2015	5.3	28.3	14.0
2/9/2015	0.1	15.6	6.7
2/10/2015	-1.3	22.9	7.8
2/11/2015	-1.7	14.1	4.7
2/12/2015	-5.1	22.1	3.8

2/13/2015	-2.7	25.2	6.9
2/14/2015	-1.7	31.2	9.7
2/15/2015	-4.1	19.1	3.7
2/16/2015	-6.6	6.5	-1.7
2/17/2015	-8.7	15.2	-0.2
2/18/2015	-8.2	14.1	-0.8
2/19/2015	-8.7	24.8	3.4
2/20/2015	-3.1	9.8	3.9
2/21/2015	2.3	25.2	8.8
2/22/2015	-3.1	4.4	0.9
2/23/2015	-4.6	7.7	-1.1
2/24/2015	-3.6	22.1	4.1
2/25/2015	-5.1	27.9	6.6
2/26/2015	-6.1	10.9	0.7
2/27/2015	-10.4	4.1	-3.8
2/28/2015	-4.6	4.9	-0.2
3/1/2015	1.0	13.3	4.1
3/2/2015	-0.8	16.0	4.9
3/3/2015	4.1	17.9	8.8
3/4/2015	-4.1	8.2	1.3
3/5/2015	-7.1	21.7	3.6
3/6/2015	-5.1	25.2	7.0
3/7/2015	-0.8	31.2	11.6
3/8/2015	2.3	17.5	9.0
3/9/2015	4.9	16.4	9.5
3/10/2015	4.4	16.0	9.6
3/11/2015	1.0	26.4	11.6
3/12/2015	3.2	24.8	11.7
3/13/2015	10.9	14.4	12.1
3/14/2015	6.5	16.8	11.9
3/15/2015	3.6	31.6	15.4
3/16/2015	6.9	30.8	16.7
3/17/2015	10.6	22.1	15.5
3/18/2015	7.3	16.0	10.3
3/19/2015	7.3	22.5	11.9
3/20/2015	7.3	27.2	13.1
3/21/2015	5.3	20.9	11.6
3/22/2015	8.2	20.6	12.3
3/23/2015	4.1	29.2	15.3
3/24/2015	8.2	26.4	16.7
3/25/2015	4.9	36.6	16.9

3/26/2015	3.2	23.3	11.7
3/27/2015	4.9	21.3	10.1
3/28/2015	3.6	31.6	12.8
3/29/2015	3.6	28.3	13.3
3/30/2015	4.1	32.8	16.5
3/31/2015	9.8	35.8	19.8
4/1/2015	11.3	25.2	17.6
4/2/2015	16.8	26.4	20.5
4/3/2015	11.3	20.6	18.4

Table 18. Daily ambient temperature (°C) in high tunnel during period of tomato production, 2014-2015, measured at crop canopy height. Daily minimum, maximum, and mean temperatures, calculated from temperatures recorded hourly.

High Tunnel Ambient Temperature (°C)			
Date	Minimum	Maximum	Mean
5/15/2014	9.8	35.8	25.2
5/16/2014	6.1	28.3	15.5
5/17/2014	8.9	26.4	15.1
5/18/2014	8.6	29.9	17.5
5/19/2014	13.3	31.6	22.1
5/20/2014	18.7	34.5	25.0
5/21/2014	19.1	35.8	25.9
5/22/2014	15.6	33.6	24.1
5/23/2014	16.4	32.4	24.2
5/24/2014	19.1	33.2	24.4
5/25/2014	15.6	31.6	23.8
5/26/2014	19.1	29.2	22.8
5/27/2014	17.9	29.9	21.3
5/28/2014	16.8	26.0	20.6
5/29/2014	16.4	25.6	20.8
5/30/2014	18.7	28.3	22.4
5/31/2014	17.9	31.6	24.1
6/1/2014	17.9	32.8	24.4
6/2/2014	18.7	33.2	25.0
6/3/2014	19.4	37.9	28.0
6/4/2014	20.6	36.2	27.6
6/5/2014	21.3	33.2	25.7
6/6/2014	20.2	33.6	24.6
6/7/2014	19.4	32.8	24.1
6/8/2014	17.5	19.8	18.8
6/9/2014	16.8	26.4	20.3
6/10/2014	16.4	27.2	19.4
6/11/2014	16.0	30.8	22.1
6/12/2014	16.8	33.2	22.8
6/13/2014	13.7	28.7	21.5
6/14/2014	13.7	31.2	23.4
6/15/2014	17.5	31.2	23.7
6/16/2014	21.3	33.6	27.4
6/17/2014	22.5	33.2	27.4

6/18/2014	22.1	33.2	27.3
6/19/2014	21.7	31.2	25.4
6/20/2014	21.3	34.5	27.4
6/21/2014	19.4	36.2	26.6
6/22/2014	20.9	35.3	26.2
6/23/2014	19.4	28.7	22.3
6/24/2014	18.3	32.4	24.5
6/25/2014	17.9	33.2	22.5
6/26/2014	18.7	34.1	25.2
6/27/2014	20.2	29.9	25.2
6/28/2014	20.9	29.6	24.3
6/29/2014	20.6	34.5	27.4
6/30/2014	22.5	34.1	28.0
7/1/2014	23.3	33.2	27.5
7/2/2014	16.8	29.2	23.9
7/3/2014	12.9	29.6	20.9
7/4/2014	14.4	33.2	24.0
7/5/2014	16.8	34.9	25.1
7/6/2014	20.2	35.8	26.1
7/7/2014	22.9	36.2	28.5
7/8/2014	21.7	35.8	28.2
7/9/2014	18.3	32.4	25.6
7/10/2014	17.9	27.6	21.7
7/11/2014	18.7	36.2	27.3
7/12/2014	20.6	37.1	28.4
7/13/2014	21.3	38.4	29.2
7/14/2014	22.5	32.8	27.1
7/15/2014	14.8	26.4	20.9
7/16/2014	11.3	28.7	19.7
7/17/2014	16.0	24.1	18.8
7/18/2014	14.1	26.4	19.7
7/19/2014	13.3	29.6	21.0
7/20/2014	14.8	33.6	23.8
7/21/2014	16.4	37.9	26.6
7/22/2014	19.4	37.9	28.2
6/1/2015	17.9	29.9	24.5
6/2/2015	14.8	33.2	23.2
6/3/2015	16.8	34.9	25.6
6/4/2015	17.9	36.6	26.6
6/5/2015	18.7	37.1	27.0
6/6/2015	19.4	37.1	27.4

6/7/2015	20.6	37.1	28.1
6/8/2015	18.7	33.2	26.6
6/9/2015	16.8	35.3	26.0
6/10/2015	18.3	37.5	27.4
6/11/2015	20.2	36.6	27.8
6/12/2015	21.7	34.5	27.7
6/13/2015	21.7	33.6	26.2
6/14/2015	21.3	33.6	26.1
6/15/2015	21.7	31.6	24.8
6/16/2015	20.6	29.2	24.0
6/17/2015	20.9	29.6	23.9
6/18/2015	20.9	27.9	22.8
6/19/2015	20.9	29.2	23.7
6/20/2015	19.4	32.4	25.9
6/21/2015	22.5	32.0	26.2
6/22/2015	23.3	32.0	27.2
6/23/2015	23.3	34.5	28.1
6/24/2015	21.7	35.8	28.0
6/25/2015	22.9	34.9	28.3
6/26/2015	21.3	29.6	24.6
6/27/2015	18.7	27.6	22.5
6/28/2015	16.0	32.4	24.2
6/29/2015	19.8	32.4	25.7
6/30/2015	18.7	33.6	25.6
7/1/2015	23.7	34.1	27.9
7/2/2015	21.3	32.4	26.4
7/3/2015	20.6	32.8	24.5
7/4/2015	19.1	31.2	24.6
7/5/2015	20.9	34.5	26.5
7/6/2015	22.1	31.2	26.2
7/7/2015	21.7	25.2	23.8
7/8/2015	21.3	26.0	23.2
7/9/2015	20.9	28.3	23.6
7/10/2015	20.6	33.6	26.2
7/11/2015	22.1	32.8	27.2
7/12/2015	22.1	34.5	27.8
7/13/2015	24.1	35.3	29.1
7/14/2015	25.2	35.3	29.4
7/15/2015	24.4	36.6	29.6
7/16/2015	22.5	34.9	28.4
7/17/2015	24.1	35.8	29.0

7/18/2015	22.5	36.6	29.2
7/19/2015	23.7	37.9	29.7
7/20/2015	23.3	37.5	28.8
7/21/2015	22.1	32.4	25.4
7/22/2015	22.1	34.5	26.5
7/23/2015	21.7	34.1	27.0
7/24/2015	24.1	38.8	29.9
7/25/2015	23.3	39.7	30.1
7/26/2015	23.7	40.6	30.3
7/27/2015	25.6	39.3	31.0
7/28/2015	23.7	39.7	30.8
7/29/2015	22.9	38.8	30.4
7/30/2015	22.1	33.2	27.1
7/31/2015	19.8	37.5	26.8
8/1/2015	17.5	38.4	27.2
8/2/2015	19.8	37.9	28.1
8/3/2015	20.2	37.5	28.0
8/4/2015	20.6	33.2	26.4
8/5/2015	21.3	36.2	26.6
8/6/2015	23.3	34.1	28.2

Table 19. Daily ambient temperature (°C) in high tunnel during period of broccoli production, 2014-2015, measured at crop canopy height. Daily minimum, maximum, and mean temperatures, calculated from temperatures recorded hourly.

High Tunnel Ambient Temperature (°C)			
Date	Minimum	Maximum	Mean
8/2/2014	17.1	49.1	30.0
8/3/2014	18.7	49.6	30.0
8/4/2014	17.9	51.2	31.7
8/5/2014	19.1	52.4	31.1
8/6/2014	19.4	52.9	31.2
8/7/2014	20.6	34.1	27.8
8/8/2014	22.1	32.8	26.2
8/9/2014	20.9	39.7	25.7
8/10/2014	19.8	38.4	27.9
8/11/2014	20.2	33.6	26.2
8/12/2014	15.6	32.0	23.1
8/13/2014	12.9	32.4	22.6
8/14/2014	16.0	36.2	25.1
8/15/2014	18.7	34.5	25.8
8/16/2014	22.5	33.6	26.8
8/17/2014	23.3	36.6	28.7
8/18/2014	20.6	36.6	26.2
8/19/2014	22.5	37.5	29.3
8/20/2014	22.5	37.1	28.8
8/21/2014	24.1	37.1	29.3
8/22/2014	24.8	38.8	30.4
8/23/2014	23.3	39.7	30.3
8/24/2014	20.2	40.6	29.4
8/25/2014	20.6	38.8	29.3
8/26/2014	20.6	37.1	28.8
8/27/2014	20.9	39.3	28.6
8/28/2014	20.6	36.6	27.7
8/29/2014	21.3	34.5	25.6
8/30/2014	21.7	32.4	25.6
8/31/2014	20.9	34.1	27.1
9/1/2014	19.1	32.4	25.6
9/2/2014	18.7	29.9	23.2
9/3/2014	18.3	34.1	25.8
9/4/2014	23.3	35.8	28.4

9/5/2014	21.3	36.6	28.2
9/6/2014	17.1	23.3	20.1
9/7/2014	14.4	31.6	21.6
9/8/2014	18.3	31.2	23.8
9/9/2014	20.6	33.6	26.8
9/10/2014	22.5	36.2	28.0
9/11/2014	17.9	22.5	19.6
9/12/2014	11.3	17.5	14.5
9/13/2014	9.8	22.5	14.1
9/14/2014	10.9	30.8	19.3
9/15/2014	17.9	30.8	22.0
9/16/2014	19.1	26.4	22.0
9/17/2014	18.3	33.6	23.0
9/18/2014	17.5	28.7	21.4
9/19/2014	16.8	29.9	22.7
9/20/2014	17.5	33.6	23.9
9/21/2014	14.8	27.6	21.6
9/22/2014	9.8	26.8	17.3
9/23/2014	9.8	29.6	17.6
9/24/2014	7.7	30.3	17.9
9/25/2014	10.9	32.4	19.8
9/26/2014	12.5	32.0	20.8
9/27/2014	12.1	31.2	20.8
9/28/2014	14.4	31.2	20.7
9/29/2014	14.1	33.6	21.6
9/30/2014	13.7	32.8	21.6
10/1/2014	18.3	32.4	24.9
10/2/2014	17.9	29.9	22.9
10/3/2014	5.3	21.3	13.7
10/4/2014	3.2	22.9	11.4
10/5/2014	8.2	29.9	18.6
10/6/2014	11.3	26.4	19.0
10/7/2014	17.5	35.3	24.2
10/8/2014	18.3	33.2	23.2
10/9/2014	19.4	32.4	24.1
10/10/2014	13.7	20.9	17.8
10/11/2014	10.9	13.7	12.0
10/12/2014	11.7	21.7	15.7
10/13/2014	11.7	20.6	16.6
10/14/2014	9.3	21.3	14.1
10/15/2014	4.9	24.1	12.5

10/16/2014	4.9	34.5	16.4
10/17/2014	10.2	28.3	16.9
10/18/2014	8.2	21.3	13.2
10/19/2014	5.7	25.6	14.1
10/20/2014	10.6	26.0	15.8
8/12/2015	19.8	32.0	27.0
8/13/2015	15.2	34.9	24.3
8/14/2015	16.4	32.8	24.6
8/15/2015	16.4	33.2	24.9
8/16/2015	19.1	36.2	27.1
8/17/2015	20.9	36.6	26.8
8/18/2015	20.6	33.2	26.7
8/19/2015	13.7	24.1	19.2
8/20/2015	11.3	29.2	20.2
8/21/2015	15.6	28.7	21.4
8/22/2015	19.4	29.2	23.9
8/23/2015	19.1	28.3	22.5
8/24/2015	16.4	29.9	22.1
8/25/2015	11.7	34.5	21.7
8/26/2015	14.1	33.6	23.2
8/27/2015	15.2	29.2	21.2
8/28/2015	15.2	29.2	22.6
8/29/2015	20.2	34.5	26.2
8/30/2015	20.6	33.6	26.1
8/31/2015	20.2	35.3	27.0
9/1/2015	19.1	34.1	26.1
9/2/2015	20.2	35.3	26.3
9/3/2015	19.8	34.5	26.3
9/4/2015	19.4	36.2	26.5
9/5/2015	20.2	35.8	27.8
9/6/2015	20.6	37.1	28.4
9/7/2015	21.7	37.1	28.0
9/8/2015	21.3	36.6	26.0
9/9/2015	20.6	32.0	24.2
9/10/2015	19.4	35.3	25.9
9/11/2015	15.2	26.0	20.4
9/12/2015	9.3	24.8	16.3
9/13/2015	11.3	27.2	18.5
9/14/2015	15.6	29.9	21.9
9/15/2015	12.9	31.6	22.1
9/16/2015	17.9	33.2	24.9

9/17/2015	20.6	34.9	26.5
9/18/2015	19.8	34.1	26.4
9/19/2015	16.8	25.6	20.9
9/20/2015	14.4	20.9	17.3
9/21/2015	13.3	33.6	22.0
9/22/2015	15.6	35.3	23.5
9/23/2015	16.0	35.3	23.4
9/24/2015	14.8	32.8	21.1
9/25/2015	13.7	29.6	20.9
9/26/2015	12.1	29.2	20.2
9/27/2015	12.9	29.2	20.2
9/28/2015	14.4	29.9	21.5
9/29/2015	16.0	29.6	22.0
9/30/2015	13.7	22.9	18.6
10/1/2015	9.8	24.1	15.9
10/2/2015	6.1	21.7	13.9
10/3/2015	4.9	22.1	13.9
10/4/2015	8.2	22.5	15.2
10/5/2015	11.7	17.9	14.6
10/6/2015	12.5	27.9	18.7
10/7/2015	12.5	31.2	20.3
10/8/2015	13.7	33.6	21.6
10/9/2015	12.1	20.2	16.9
10/10/2015	6.5	28.3	15.8
10/11/2015	10.2	31.6	20.4
10/12/2015	11.3	28.7	21.6
10/13/2015	4.9	29.2	15.8
10/14/2015	7.3	34.5	19.1
10/15/2015	8.6	34.9	21.3
10/16/2015	6.1	20.9	14.3
10/17/2015	5.7	17.5	11.4
10/18/2015	5.7	26.0	14.0
10/19/2015	6.9	28.7	16.9
10/20/2015	11.3	30.8	19.7
10/21/2015	12.9	29.6	20.1
10/22/2015	12.5	28.3	20.2
10/23/2015	16.4	26.4	19.9
10/24/2015	12.1	18.3	15.8
10/25/2015	10.2	19.1	13.4
10/26/2015	9.3	21.3	14.6
10/27/2015	13.7	18.7	15.5

10/28/2015	8.9	20.2	14.6
10/29/2015	6.9	20.9	11.5