ABRASIVE GRIT APPLICATION FOR INTEGRATED WEED AND NITROGEN MANAGEMENT IN ORGANIC VEGETABLE CROPPING SYSTEMS

BY

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THESIS

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Abstract

Abrasive weed control, or weed blasting, uses sand-blasting technology to propel abrasive grits at weeds, physically destroying their emergent structures. This approach has been successfully tested for use in agronomic crops, though research is needed for horticultural cropping systems. This project aimed to determine the efficacy of weed blasting in vegetable crops and to determine if weed blasting can be combined with mulching to increase the overall effectiveness of each strategy. Five abrasive grit treatments (walnut shell grits, soybean meal fertilizer, Suståne© composted turkey litter fertilizer, a weedy control, and a weed-free control) and four supplemental weed management treatments (straw mulch, biodegradable plastic film, polyethylene plastic film, and a bare soil control) were replicated four times in an organic pepper cropping system near Urbana, IL in 2015 and 2016. Soybean meal, turkey litter, and walnut shell grits, used in conjunction with plastic or bioplastic mulch, all decreased total dry biomass of weeds within the crop row by approximately 80% relative to the weedy control. Total nitrogen availability, measured via ion-resin stakes (PRS probes), decreased by 58% and 55% in soybean meal + bare soil and turkey litter + bare soil plots, respectively, in comparison to the weed free control. There were no significant differences between soybean meal, turkey litter, and the weed free control in plastic, bioplastic, and straw plots. There was no significant decrease in yield compared to the weed free control for turkey litter or walnut shell treatments when combined with either bioplastic or polyethylene mulch or for soybean meal + polyethylene plots. Walnut shell + bioplastic had a significant increase in yield compared to the weedy control. There was no significant difference in fruit quality, measured via BRIX, between grit or mulch

treatments, and there was no significant difference of percent of diseased tissue between grit treatments. These results suggest that AWM can function as an alternative weed control strategy in organic farming, potentially improving the effectiveness of existing weed management techniques (e.g., plastic mulch).

Abrasive weed management (AWM) also has the possibility to serve as a fertilizer application if organic fertilizers are used as abrasive grits. A separate greenhouse experiment aimed to determine the nitrogen mineralization and plant uptake of different organic fertilizers used as abrasive grits. Five abrasive grit treatments (walnut shell grits, soybean meal fertilizer, Suståne© composted turkey litter fertilizer, a weedy control, and a weed-free control), two application rates (400 g/ plot and 800 g/plot), and two tillage treatments (incorporation of top 5cm of soil and no incorporation) were replicated five times in a greenhouse study using Red Russian kale at University of Illinois at Urbana-Champaign's Plant Care Facility in Urbana, IL in 2016 and 2017. The higher N concentrations of turkey litter and soybean meal contributed to higher N mineralization overall in those treatments. The high rate (800 g/plot) of turkey litter, in particular, outperformed the other treatments in tissue N and yield, which was likely due to the higher N mineralization rate. Incorporation of soil amendments significantly affected soil ammonium concentrations and dry yield weight, suggesting that tillage following grit application could contribute to greater soil availability of N and greater plant uptake. Walnut shell, an effective abrasive grit for weed control, was not as effective as a fertilizer in comparison to soybean meal and composted turkey litter. These results suggest that while soybean meal and turkey litter can function as fertilizer amendments when used for abrasive grit application, walnut shell may not provide the same dual benefit.

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CHAPTER ONE

Abrasive grit application as a weed management technique in organic vegetable farming

Introduction

Weed control is one of the most difficult issues faced by organic farmers. Without the use of synthetic herbicides, many organic farmers struggle to effectively control short-term weed issues. While crop rotation and sanitation are effective management techniques for long-term weed management, organic growers need alternative short-term weed management options (Forcella et al. 2011). Tillage is currently the most common method of weed control in organic systems (Forcella et al. 2010). However, without timely employment and ideal soil conditions, tillage becomes less effective at controlling weeds (Wortman 2015). If done too frequently, rotary hoeing, a form of tillage, can cause crop injury and a decline in yield, while too few passes can also cause yield loss due to poor weed control (Taylor et al. 2012; Kluchinski and Singer 2005; Leblanc and Cloutier 2001; Lovely et al. 1958; Mohler et al. 1997).

Because tillage disturbs the soil surface, there is a potential for soil degradation through diminished soil health, such as the loss of soil aggregates and soil organic matter, and an increase of soil erosion (Liebman and Davis 2000; Forcella 2009). Tillage can also contribute to the weed seed bank by distributing new seeds throughout the soil, and subsequent cultivations can bring weed seeds to the surface, potentially allowing for germination (Bond and Grundy 2001; Melander and Rasmussen 2000).

Thermal weed management (TWM) provides alternative short-term weed control techniques for organic growers. Propane flaming, or flame-weeding, provides flexibility to growers because it can be deployed when soils are wet. Flaming also does not disrupt the soil, which helps to minimize weed seed germination, though flaming can increase germination of some species (Ascard 1995; Bond and Grundy 2001; Taylor et al. 2012). Flame-weeding and other TWM techniques use large amounts of energy, however, and only 1% of energy produced for heating of tissues is used in the weeding process. The remaining 99% of heat is lost. (Shrestha et al. 2004; Sirvydas et al. 2006). Due to the nature of TWM, which calls for the hauling of flammable gases and the utilization of open flames, high heat, or hot water, there is a high risk of injury to the operator. There is also the risk of starting an uncontrolled fire, which can lead to field damage (Shrestha et al. 2004).

Soil steaming has less fire risk than flaming, but this method also consumes large amounts of fossil fuels, and current methods are not efficient in controlling weeds (Shreshtha et al. 2004; Melander et al. 2005; Pinel et al. 1999). Soil steaming can also damage crop seeds when employed on directly seeded crops, affecting crop growth (Shrestha et al. 2004). TWM is not recommended for use in crops with shallow or sensitive root systems, and the effects of TWM on beneficial insects and soil microorganisms are not widely researched. TWM has the possibility of killing certain pathogens and pests, but TWM can also adversely affect desired organisms (Shrestha et al. 2004; Bond and Grundy 2001; Mattsson et al. 1990).

Organic and inorganic mulching can offer season-long weed control along with improved crop performance through increases in available water, enhanced efficiency of irrigation systems, and higher crop yields (Sarkar et al. 2007; Sarkar and Singh 2007). Organic mulches, such as hay or straw, tend to be cheaper in comparison to other mulch alternatives. Straw mulch typically improves soil moisture retention and reduces weed growth, but its use as a weed control tactic is less efficient than black plastic films (Anzalone et al. 2010). Schonbeck (1999) found that organic mulches perform best when applied weeks after planting instead of at planting. The needed volume of organic mulches to effectively control for weeds can lead to high transportation costs (Bond and Grundy 2001). Organic mulches are biodegradable, unlike most plastic films, but their decomposition can lead to immobilization of soil nutrients (Bond and Grundy 2001). Organic mulches can also carry weed seeds, which could contribute to the seed bank (Schonbeck 1999).

Plastic and biodegradable plastic films can be used as mulches to suppress weeds, but weeds can emerge through any uncovered space, such as through crop holes or tears in the plastic (Wortman 2015; Schonbeck 1999). Plastic film mulches increase soil temperature and soil air temperature (Lamont 2005; Hill et al. 1982), stabilize soil temperature, and increase water use efficiency (Moreno and Moreno 2008). Polyethylene plastic films are generally affordable and the method of laying plastic films is fully mechanized, reducing needed labor. Irrigation tubing can also be laid at the same time as plastic mulches, further integrating the process and reducing labor (Anzalone et al. 2010).

Plastic mulches only suppress weeds over bed tops, so the alleys between bed tops require alternative weed control methods, such as mowing, tillage, or organic mulches, such as wood chips (Schonbeck 1999). The biggest issue surrounding the use of polyethylene plastic mulches is the matter of their disposal. Polyethylene mulch must be removed after crops are harvested, which uses labor that could be employed elsewhere. The disposal of polyethylene mulch is also a potential barrier as it can be costly and have environmental impacts (Miles et al. 2012; Kasirajan and Ngouajio 2012). Burning of this mulch type can lead to the release of toxic gases into the surrounding area. Recycling of polyethylene mulches is difficult and generally cannot be done directly from the field because the plastic is contaminated with dirt (Miles et al. 2012; Kasirajan and Ngouajio 2012; Hemphill 1993).

The disposal issue surrounding polyethylene mulch has led to the development of biodegradable plastic mulches. Biodegradable plastic mulch degrades into nontoxic compounds, though degradable polymers may remain in the soil as micro-fragments for extended periods of time (Kasirajan and Ngouajio 2012; Miles et al. 2012; Fontanelli et al. 2013). Biodegradable plastic mulches successfully meet the functions of polyethylene plastic films, though they do not increase soil temperatures as high, which may be beneficial in warmer climates (Moreno and Moreno 2008). The main barrier to biodegradable plastic films is the high cost (Fontanelli et al. 2013). Paper mulches are also available and are easier to dispose of than polyethylene mulches. They are generally low cost and can be recycled (Anzalone et al. 2010). Paper mulches, however, are difficult to install and can be damaged by high winds (Anderson et al. 1995; Harrington and Bedford 2004; Anzalone et al. 2010). The fast decomposition rate of paper mulches can lead to poor weed control toward the middle or end of the season (Schonbeck 1999).

Abrasive weed management, or weed blasting, is a novel approach to controlling weeds that has the potential to be combined with other forms of weed management. Modeled after existing sand-blasting technology, abrasive weed management propels agricultural grits at weeds to physically destroy their emergent structures (Wortman 2014). Weed blasting uses compressed air to propel a gritty material as a form of post-emergent weed control (Forcella 2009). Different organic materials have demonstrated their effectiveness as grits for weed blasting, including corn gluten meal, corn cob grits, greensand fertilizer, walnut shell and soybean meal (Wortman 2014). Weed blasting applications have the potential to double as fertilizer applications if organic fertilizers, such as soybean meal, are used as abrasive grits, which could increase crop growth, yield, and profitability of this management tactic.

Weed blasting has been recommended for use in corn, though little research exists for the use of this approach in horticultural crops (Wortman 2014). While greenhouse trials have shown tomatoes and peppers can tolerate weed blasting, field trials are needed to determine the capacity for abrasive grits to suppress weeds without contributing to yield loss for tomatoes and peppers and other horticultural crops. Injuries to stems and other plant material through application of abrasive grits could make crops more susceptible to diseases by providing entry points for pathogens (Forcella et al. 2010). Abrasive weed management could be utilized in conjunction with other management options, such as plastic mulches or straw mulches, to increase their overall effectiveness, though the interaction of these two factors has not been studied.

Research is also needed to determine if the application of organic fertilizers, such as soybean meal or compost, to the soil through weed blasting will increase the availability of soil nitrogen for plant uptake.

Nitrogen from organic sources is slowly mineralized in soil, whereas nitrogen from mineral or synthetic fertilizers is immediately plant available upon entering soil solution. It has been hypothesized that delayed nitrogen availability from organic amendments may be more synchronous with crop demand and improve crop-weed competition (Liebman and Davis, 2000). Delaying fertilizer application or plant availability in soil could serve to starve weeds of nitrogen during early growth stages, while providing crops with nitrogen during stages of higher crop uptake (Liebman and Davis 2000). To this end, abrasive weed management with gritty organic fertilizers may improve crop-weed competition.

This study aimed to determine the effectiveness of abrasive weed control as an alternative weed management option in organic vegetable production. The objectives of this study were to: (1) assess effects of three abrasive grit types on weed suppression and vegetable crop yield, (2) determine soil nitrogen availability and crop uptake from organic fertilizers used as abrasive grits, (3) assess changes in susceptibility of crops to diseases in response to abrasive weed management, and (4) determine the compatibility of weed blasting with straw mulch, polyethylene plastic film, and biodegradable plastic film for in-row weed management.

Materials and Methods

Experimental design

Field experiments were conducted in 2015 and 2016 at the University of Illinois Sustainable Student Farm in Urbana, IL (40.08 N, 88.22W; elev. = 221m). The predominant soil texture is loam (31% sand, 45% silt, and 24% clay). The site cropping history is diversified organic vegetable production, including tomatoes, peppers, and fallow cover crops. The Sustainable Student Farm is managed according to USDA NOP guidelines, but it is not certified.

The experimental design was a factorial randomized complete block design with two factors, abrasive grit and mulch type, and four replicates. The abrasive grit treatments included soybean meal fertilizer (Phyta-grow Leafy Green Special, 7-1-2 NPK; California Organic Fertilizers, Inc., Hanford, California, USA), composted turkey litter (Suståne©, 8-2-4 NPK; Suståne© Natural Fertilizer, Inc., Cannon Falls, Minnesota, USA), walnut shell grit (Kramer Industries, Inc., Piscataway, New Jersey, USA), a weedy control, and a hand-weeded weed-free control. The mulch types included polyethylene plastic, biodegradable plastic (Bio360, Dubois Agrinovation, Saint-Rémi, Quebec, Canada), straw mulch (*Miscanthus spp.*), and a bare soil control. This design resulted in 80 experimental units (5 grit type treatments x 4 mulch type treatments x 4 replicates). Each experimental unit was 3.25 m^2 (4.27m long x 0.76 m wide) and included 9 pepper plants spaced 0.46 m apart.

Crop management

For each experimental site year, raised-beds were shaped with 0.76 m bed tops and 1.22 m alleys, measured from the middle of each bed top. Drip tape irrigation line with 15 cm emitter spacing was laid down the center of each bed top. Peppers were irrigated to maintain 15% volumetric soil moisture within the top 7 cm. Plastic films were laid using a bed shaper/ mulch layer. Miscanthus straw mulch was laid by hand on each bed top to achieve a depth of 7.5 cm. Peppers were transplanted on 22 May 2015 (9 week old crop seedlings) and 24 May 2016 (8 week old crop seedlings). Peppers were first trellised on 2 June 2015 and 16 June 2016 similarly to the basket weave method used in tomatoes (Trinklein 2016). Peppers were fertilized immediately after transplanting with fish emulsion (Ferti-lome Fish Emulsion Fertilizer, 5-1-1 NPK) and seaweed extract (Ohrstrom's Maxicrop Liquid Seaweed, 0-0-1 NPK), each at a 1:100 gallon ratio, to help mitigate the potential for transplant shock. There were no further fertilization applications throughout the season to assess abrasive grits for fertilizer effect. Between-row weeds in alleys were managed with mowing and hand-weeding.

Grit application

Abrasive grits were applied twice per season, when the majority of target weeds were between the cotyledon- and two-leaf stages. Forcella (2012) found that in field corn, two applications was sufficient to optimize weed control. Wortman (2015) found that while additional field passes reduced weed pressure, the difference in weed control was not significant, and two passes may be the most cost efficient option. In 2015, first grit applications were made 14 days after transplanting (DAT) for bare soil, polyethylene plastic, and biodegradable plastic plots and 19 DAT for straw mulch plots. Second grit applications were made 31 DAT for all plots. In 2016, abrasive grits were applied 10 DAT for bare soil, polyethylene plastic, and biodegradable plastic plots and 15 DAT for straw mulch plots (again, due to delayed weed emergence). Second grit applications were made 27 DAT for bare soil, polyethylene plastic, and biodegradable plastic plots and 37 DAT for straw mulch plots.

In 2015, abrasive grits were applied using hand-held, gravity-fed sand-blasting guns (Zendex Tool Corporation; Danbury, Connecticut, USA; Speed Blaster) (Figure 1.1). Compressed air was fed through the gun at approximately 689 kPa using an air compressor (BelAire Compressors; Rock Hill, South Carolina, USA; Model 3G3HH) hauled by a tractor (Kubota; Grapevine, Texas, USA; BX1870-1). Abrasive grits were applied in a continuous strip (20 cm band) within the crop row for bare soil and miscanthus straw mulch plots and within individual planting holes for polyethylene plastic and biodegradable plastic plots. In 2016, abrasive grits were applied using a more automated, prototype abrasive grit applicator similar to that used by Erazo-Barradas (2017) (Figure 1.1). Compressed air was fed through the hoses at around 931 kPa. Due to the lack of pull-trigger on the prototype applicator, abrasive grits were applied in a continuous strip within the crop row for all plots (i.e., grits were applied to plastic mulch between plants). Applicator hoses were cleared of remaining grit between different grit treatments. In both years, one person drove the tractor at 1.6 km hr^{-1} while another person walked behind the tractor holding the applicator and applying the grits. Applicator tips were held 20-30 cm from the base of the plant. In 2015, abrasive grits were sieved through 20/40 mesh. Grits were not sieved in 2016 because the use of the prototype applicator allowed the use of larger and inconsistently sized grits without clogging the nozzles. Application rates differed each year due to the different applicator tools (Table 1.1).

Weed density and biomass

Weed density was measured twice per season. Weeds were counted within two 91 cm x 20 cm quadrats placed within the crop row at 31 DAT in 2015 and 27 DAT in 2016. Weed density was measured a second time 61 DAT (2015) or 59 DAT (2016) using the same approach within the row and also in the area adjacent to the crop row (using the same 91 cm x 20 cm quadrats, but still on the bed-top). Weed counts were separated into broadleaf, grass, and total categories.

Aboveground weed biomass was collected from each plot on 123 DAT in 2015 (all replicates) and 62 DAT (replicates one and two) and 63 DAT (third and fourth replicates) in 2016. Weed biomass was collected earlier in 2016 to prevent seed rain and weed seedbank regeneration. The critical weed-free period for peppers is estimated at around eight to ten weeks after planting (Schonbeck 2014), so earlier sampling of weed biomass was not expected to impact other parameters. Samples were collected from each plot within two 91 cm x 20 cm quadrats placed within the crop row and two 91 cm x 20 cm quadrats placed directly outside the crop row. Quadrats were centered between plants two through four and plants six through eight. Weeds were clipped at the soil surface, sorted by grass and broadleaf, dried to constant mass, and weighed.

Yield

Peppers were harvested at maturity throughout the season and sorted by marketable and non-marketable, counted, and weighed. Harvest data from each treatment were summed across individual harvest days for the entire season for analysis.

Crop growth and leaf greenness

Approximately every two weeks after transplanting, plant height and leaf greenness were measured from three random plants per plot. Plant height was measured as the height of the plant from the base of the stem to the top of the newest, fully emerged leaf extended vertically. Leaf greenness was measured near the center of the newest fully emerged leaf using a handheld greenness sensor (atLEAF+, FT Green LLC, Wilmington, Delaware, USA).

Plant available nitrogen

Soil samples were collected prior to planting to determine baseline nitrogen levels and again after first frost in the fall using soil probes fitted with 46 cm dry sampling tubes 1.9 cm in diameter (Clements Associates, Inc., Newton, Iowa, USA; Model PN001). Four 20 cm cores were removed from each plot within alternating planting holes and aggregated for nitrate and ammonium analysis (Ward Laboratories, Inc., Kearney, Nebraska, USA).

Potentially plant available soil nitrogen was measured using ion exchange resin probes (Western Ag Innovations, Saskatoon, Saskatchewan, Canada; PRS® Probes). Probes were buried to a depth of 14 cm within four alternating planting holes within the soybean meal, composted turkey litter, and weed-free control plots one week after first grit application. One cation probe and one anion probe were buried in each planting hole, for a total of eight probes per plot. Each set of probes remained in the field for two weeks, after which they were replaced by a new set of probes in the exact same location. PRS probes were buried for a total of four, two-week intervals, resulting in an eight-week sampling period (1 to 9 weeks after first grit application). Upon field removal, probes were washed with reverse osmosis water and sent to Western Ag Innovations for nitrate and ammonium analysis.

Crop health and quality

Visual symptoms of plant diseases were scouted weekly and when observed, confirmed via microscopic analysis or lab culture. After confirmation of plant disease, plants were treated with copper hydroxide (Champ® WG, Nufarm Limited, Alsip, Illinois, USA) to curtail the spread of pathogens. During active disease outbreaks, estimates of diseased plant tissue were recorded using visual ratings of three random plants per plot. Visual ratings were recorded in nearest percent estimates (NPEs) and averaged across the three plants in each plot. Ratings from 0 to 15% were estimated to the nearest 1%, but ratings greater than 15% were estimated to the nearest 5%.

Fruit quality was measured using Brix with a handheld refractometer (ATAGO U.S.A., Inc., Bellevue, Washington, USA; PAL-1). Brix readings were collected from one to four peppers per plot, depending on availability, during peak harvest time and averaged within individual plots. The tip of each pepper was used as a subsample to extract juice.

Statistical analysis

Analysis of variance (ANOVA) was performed on all data using the GLIMMIX procedure in SAS (v9.4, SAS Institute, Cary, North Carolina, USA) to determine potential differences among experimental treatments. Year and replicate were treated as random effects, while abrasive grit type and mulch type and their interaction were treated as fixed effects. Year was treated as random due to a lack of grit x year interaction and grit x mulch x year interaction. Repeated measures were used for nitrogen measurements from PRS® Probes, leaf greenness measurement, plant height measurements, and NPEs of diseased tissues. Data for NPEs of diseased tissues in 2015 and 2016 were analyzed separately due to different data collection dates in each year. Least square means were calculated and compared among treatments using the Tukey-Kramer multiple comparisons test with a significance level of $\alpha = 0.05$.

Results and Discussion

Weed density and biomass

Broadleaf weed density within the crop row at 30 DAT (Table 1.2) was influenced by the interaction of abrasive grit and mulch type ($p=0.0002$). Walnut shell + polyethylene plots had fewer broadleaf weeds inside the crop row than weedy control + polyethylene plots and were not different from weed-free control + polyethylene plots. Bare soil plots, regardless of abrasive grit source, had the highest broadleaf densities collected inside the crop row.

Grass density collected inside the crop row at 30 DAT (Table 1.2) was affected by abrasive grit source ($p<.0001$). Weed-free control plots had fewer weeds than turkey litter, soybean meal, walnut shell, and weedy control plots, which were all similar to each other. Grass density inside the crop row was also influenced by mulch type (p<.0001). Bare soil plots had greater grass density inside the crop row than bioplastic, polyethylene, and straw mulch plots, which were statistically similar to each other.

Total weed density collected inside the crop row at 30 DAT (Table 1.2) was driven by the interaction of abrasive grit and mulch type (p=.003). Across all abrasive grit sources, with the exception of the weed-free control, bare soil control plots had the highest densities of total weeds within the crop row.

Grass density collected inside the crop row at 60 DAT (Table 1.2) was explained by a significant interaction of abrasive grit and mulch type (p=.0014). Bare soil control plots, aside from the weed-free control, had the greatest number of grass weeds within the crop row regardless of abrasive grit source, including the weedy control. Bioplastic and polyethylene plastic used in conjunction with an abrasive grit source did not reduce grass density in comparison to the weedy control. Due to the hypogeal emergence of grass plants, Forcella et al. (2010) theorized that AWM may not control for grass weeds as well as for broadleaves, and Wortman (2014) found that AWM had less control over grass weed seedlings for this reason.

Broadleaf density collected inside the crop row at 60 DAT (Table 1.2) was also influenced by the interaction of abrasive grit and mulch type (p<.0001). Broadleaf density followed the same trend as grass density where bare soil control plots had the greatest densities regardless of abrasive grit source, not including the weed-free control. Bioplastic and polyethylene plastic mulches decreased broadleaf density inside the crop row when combined with turkey litter, walnut shell, or soybean meal, compared to their respective weedy control plots.

Following a similar trend, total weed density collected inside the crop row at 60 DAT was affected by the interaction of abrasive grit and mulch type (p<.0001) (Table 1.2). Total weed density was greatest in the bare soil plots regardless of abrasive grit source, not including the weed-free control plots. Polyethylene plastic combined with an applied grit source (turkey litter, walnut shell, or soybean meal) had lower total weed densities than the polyethylene + weedy control plots. Bioplastic + walnut shell plots also had lower weed densities than the bioplastic + weedy control plots. Grass weeds, when analyzed separately, did not follow this trend.

Aboveground weed biomass collected within the crop row (Table 1.2) was driven by the interaction of abrasive grit and mulch type for broadleaf weeds (p<.0001) and total weed biomass (p<.0001). Aboveground grass biomass had no interaction between factors, but was influenced by each effect individually (grit source, p<.0001; and mulch type, p=.0015). Weed-free control plots had the lowest grass biomass, while weedy control plots had the highest, which was expected. Weedy control plots had statistically similar aboveground grass biomass to turkey litter and soybean meal plots, while walnut shell plots had significantly less weedy grass biomass. In laboratory tests to determine the most effective abrasive grit sources, Pérez-Ruiz et al. (2016) found that walnut shell grits outperformed other tested grit sources in the penetration of test papers and in the removal of tested weeds. Wortman (2014) also found that walnut shell was the only abrasive grit source of those tested that consistently reduced weed biomass, regardless of application rate.

Broadleaf aboveground biomass within the crop row was greatest in weedy control + bioplastic and weedy control + polyethylene plastic plots. This same trend was observed in total aboveground weed biomass collected within the crop row. We hypothesize that this result was seen due to the observed size of the broadleaf weeds growing within the bioplastic and polyethylene plots during the 2016 field season. When compared to the broadleaf density and total weed density collected inside the crop row at 60 DAT, the increased biomass of broadleaf weeds and total weeds found within the bioplastic and polyethylene plots seems counterintuitive, unless the individual size of the weeds affected the outcome. Regardless, there was around an 80% decrease in weedy biomass for plastic and bioplastic mulches when used in conjunction with an applied abrasive grit source (turkey litter, soybean meal, or walnut shell), compared to the respective weedy control plots.

Grass density ($p=.0138$), broadleaf density ($p<.0001$), and total weed density ($p<.0001$) collected outside the crop row at 60 DAT (Table 1.3) were influenced by abrasive grit and mulch type. Across all three parameters, bare soil control plots had the highest densities regardless of abrasive grit source, aside from the weed-free control plots. Bioplastic and polyethylene plots had statistically similar outside crop row grass, broadleaf, and total weed densities regardless of abrasive grit source. This was likely due to the nature of plastic film mulch, where weeds generally do not penetrate the film unless there are tears, or through planting holes which would be within the crop row (Schonbeck 1999).

Aboveground weed biomass collected outside the crop row (Table 1.3) was influenced by the interaction of abrasive grit source and mulch type for grasses ($p=.0228$), broadleaf weeds ($p<.0001$), and total weedy biomass ($p<.0001$). Aboveground biomass was highest for grass weeds, broadleaf weeds, and total weed biomass in bare soil control and straw mulch plots regardless of abrasive grit source, not including the weed-free control plots.

Yield

Total yield (p<.0001) and marketable yield (p<.0001) were influenced by the interaction of abrasive grit and mulch. Weed-free control plots in each mulch type out-yielded all grit treatments in the same mulch type (Table 1.4). Yield loss in comparison to the weed-free controls was greatest across all weedy control treatments, emphasizing the importance of keeping the crop row weed free during the season. Walnut shell + bioplastic significantly increased yield from weedy control + bioplastic plots in both marketable and total yield weights. There was no significant decrease in total yield compared to the weed free control for turkey litter or walnut shell treatments when combined with either bioplastic or polyethylene mulches. This was similar to results seen by Wortman (2015), where there were no yield differences between treatments with an abrasive grit and hand-weeded control plots. Similarly, there was no significant decrease in total yield for soybean meal + polyethylene plots compared to the weed free control + polyethylene plots.

Walnut shell + bioplastic plots were the only plots to significantly increase yield over their weedy control counterparts. This coincides with a significant reduction in grass weed density inside the crop row at 30 DAT in bioplastic plots compared to the bare soil control and walnut shell plots in comparison to the weedy control, as well as a reduction in grass weed density inside the crop row at 60 DAT in walnut shell +

bioplastic plots in comparison to weedy control. Walnut shell + bioplastic plots also had similar grass density estimates to the weed-free control. This yield increase also corresponds to a significant decrease in aboveground grass biomass for walnut shell plots in comparison to weedy control plots. Wortman (2015) reported an increase in yields following grit application in comparison to weedy control plots by approximately 44% in tomatoes and 30% in peppers. Forcella (2012) also reported up to a 26% increase in maize yields following abrasive grit application in comparison to weedy control plots. Yield increases in comparison to weedy control plots were only seen in walnut shell + bioplastic treatments, suggesting that grass weeds uncontrolled by AWM could be the cause of the general lack of hypothesized yield increases following grit applications.

Yields, in general, were also expected to increase in plots that used bioplastic and polyethylene plastic mulches. Previous research, as outlined by Lamont (1993), showed that plastic mulches tend to increase crop yields over non-mulched soils. Straw mulch plots, regardless of grit source, did not have significant increases in yield over their corresponding bare soil plots, which was likely due to nitrogen immobilization from the added organic materials through the straw mulch. Organic amendments, such as straw-based mulches or yard waste amendments, tend to have high C:N ratios and lower N concentrations (organic or inorganic), which could lead to the tie up of nutrients (Wortman et al. 2017; Chae and Tabatabai 1986; Hartz and Giannini 1998). With the exception of the weed-free plots, bioplastic and polyethylene plastic increased yields over bare soil plots in soybean meal, turkey litter, walnut shell, and weedy control plots.

Crop growth and leaf greenness

In 2015, leaf greenness was affected by interactions of abrasive grit and mulch type ($p=.0081$), abrasive grit and time ($p=.0029$), and mulch type and time ($p<.0001$). Leaf greenness was highest in weed-free control + bare soil control, weed-free control + bioplastic, and walnut shell + polyethylene treatments (Figure 1.2). Leaf greenness declined over time in the weedy-control plots, which may have been caused by competition for resources, such as soil nitrogen and light (Figure 1.3). Clark et al. (1998) found that weed competition may contribute to a nitrogen limitation for crop plants. As time passed, bioplastic and polyethylene plastic had higher leaf greenness measurements than bare soil control and straw mulch plots (Figure 1.4)**.** Plastic mulch films can increase soil temperatures (Lamont 2005; Hill et al. 1982), which can lead to greater N mineralization (Wilson and Jeffries 1996) and plant uptake (Liu et al. 2003). This effect, combined with reduced weed competition, were likely causes of the higher leaf greenness measurements in the bioplastic and polyethylene plastic plots.

In 2016, leaf greenness was influenced by interactions of abrasive grit and mulch type ($p<.0001$), abrasive grit and time ($p<.0001$), and mulch type and time ($p=.0004$). Leaf greenness was highest in weed-free control + bare soil control, weed-free control + polyethylene, and walnut shell + polyethylene treatments (Figure 1.5). The weed-free control plots had greater leaf greenness starting 49 DAT and remained greater throughout the season (Figure 1.6), which could be due to lack of plant competition with weedy species (Clark et al. 1998). Similar to 2015, polyethylene and bioplastic plots had greater leaf greenness throughout the entire 2016 season (Figure 1.7).

In 2015, plant height was driven by interactions of abrasive grit and mulch (p=.0019) and mulch and time (p=.0008). Plant height was greatest in weed-free control + bioplastic, turkey litter + polyethylene, and walnut shell + polyethylene plots (Figure 1.8). By 59 DAT, straw mulch plots had the lowest plant height measurements, and this trend continued throughout the season (Figure 1.9). This was likely due to nitrogen immobilization from high C:N ratio in straw mulch plots. Total nitrogen levels were significantly lower in straw mulch plots during the fourth burial period of PRS probes, which supports the hypothesis that straw mulch plots had lower nitrogen levels leading to lower plant heights.

In 2016, plant height was influenced by interactions of abrasive grit and mulch (p<.0001) and mulch and time (p<.0001). Plant height measurements were greatest in weedy control + bioplastic, weedy control + polyethylene, and weed-free control + polyethylene plots, though they were statistically similar (Figure 1.10). Plant heights may have been highest in the weedy control plots due to light competition. In competing for light, plants can grow taller in an effort to increase light interception (Zimdahl 2013).

Plant available nitrogen

Pre-season soil samples showed that total nitrogen values among all plots were between 30-40 ppm (Table 1.5). Season-end soil samples showed that total nitrogen levels decreased, likely due to crop uptake and removal (Table 1.6).

Total soil nitrogen collected from PRS probes was influenced by interactions of abrasive grit and mulch type (p<.0001), abrasive grit and time (p=.0012), and mulch type and time (p<.0001) (Table 1.7). Of the treatments measured, total nitrogen was highest in soybean meal + polyethylene, turkey litter + polyethylene, and weed-free control + polyethylene plots (Table 1.8). Total nitrogen decreased by 58% and 55% in soybean meal + bare soil and turkey litter + bare soil, respectively, in comparison to the weed-free control plots. Added fertilizer, in this case soybean meal and turkey litter, can lead to greater N uptake in weedy plants than in crop plants, which may have contributed to the total nitrogen decrease in these treatments (Blackshaw et al. 2003). There was no significant difference between soybean meal, turkey litter, and weed-free control plots with respect to the other mulch treatments (bioplastic, polyethylene, and straw mulch).

Total nitrogen decreased over time for all mulch types, but bare soil and straw mulch plots had sharper decreases over time (Figure 1.11). Straw mulch plots at the fourth burial period had significantly lower overall total nitrogen in comparison to all other mulch types at each burial period. This was likely due to the tie up of nitrogen from high C:N ratio from the organic material used for mulching. Total C and N contents of amendments can affect the mineralization of N sources (Flavel and Murphy 2006). Amendment C:N is typically an indicator of mineralization potential, where amendments with high C:N ratios can lead to the immobilization of N sources (Gale et al. 2006).

Total nitrogen decreased across time for each of the three tested abrasive grit sources, though the decrease was less drastic in the weed-free plots (Figure 1.12). By the fourth burial period, the weed-free plots had significantly more nitrogen than either turkey litter or soybean meal at the same burial period. This may have been because there were less weeds using the available nitrogen in the weed-free plots, which were kept weed-free, than in the soybean meal and turkey litter plots.

Crop health and quality

Sucrose content estimated from Brix measurements (data not presented) of total soluble solids were not significantly different between abrasive grit treatments or mulch treatments, and there was no significant interaction of these factors. These results suggest that the application of grits did not affect fruit quality.

In 2015, NPEs of diseased tissue was affected by significant interactions of abrasive grit and mulch ($p=.036$) and mulch and time ($p<.0001$). NPEs of diseased tissue were highest in walnut shell + bioplastic and weed-free control + bare soil control plots. NPEs of diseased tissue were lowest in weedy control + bare soil control plots (Figure 1.13). Bare soil plots had the lowest NPEs across time (Figure 1.14). In 2016, NPEs of diseased tissue were explained by the significant interaction of mulch and time ($p=.0005$). Bare soil plots followed the same trend as seen in 2015, having the lowest NPEs of diseased tissue across time (Figure 1.15). Dense weeds can contribute to greater disease occurrence in crops by creating optimum conditions for spread of pathogens. However, dense populations of weeds can also reduce disease occurrence by blocking pathogens from reaching the crop plants (Duczek et al. 1996; Krupinsky et al. 2002). In this case, the weed cover in bare soil plots seems to have shielded the crop plants from the airborne spread of bacterial spot (*Xanthomonas campestris pv. vesicatoria*).

Conclusions

Applied abrasive grit + polyethylene plots decreased total weed density at 60 DAT by over 80% compared to the weedy control, with no difference in comparison to the weed-free control plots. Walnut shell + bioplastic decreased total weed density by 86% in comparison to the weedy control, with no difference in comparison to the weed-free control. On average, the use of walnut shell grit reduced total weed density at 60 DAT by 55%, compared to turkey litter at 44% and soybean meal at 53%. There was approximately an 80% decrease in weedy biomass for plastic and bioplastic mulches + applied abrasive grit (regardless of grit type).

Because the critical weed free period for peppers is early season (Schonbeck 2014), weed density collected at 30 DAT may be more important for determining the effectiveness of AWM in controlling weeds than weed density collected at 60 DAT or aboveground weedy biomass. Grass density at 30 DAT was around 90% less in bioplastic, polyethylene, and straw mulch plots in comparison to the bare soil control. Soybean meal and turkey litter decreased grass density by around 35% in comparison to the weedy control, where walnut shell decreased grass density by around 50%.

Broadleaf and total weed density at 30 DAT in walnut shell + bioplastic was 77% less in comparison to the weedy control, where turkey litter + bioplastic was 69% less. Polyethylene mulch used in conjunction with an applied abrasive grit decreased broadleaf and total weed density by over 75% in comparison to the weedy control. These decreases in weed density at 30 DAT correspond to differences in yields depending on the treatment.

Walnut shell + bioplastic plots increased total pepper yield by around 65% in comparison to the weedy control, with no significant decrease of yield in comparison to the weed-free control. Turkey litter + bioplastic, turkey litter + polyethylene, soybean meal + polyethylene, and walnut shell + polyethylene treatments did not significantly decrease total yield in comparison to their weed-free control plots.

Total plant-available nitrogen was highest in weed-free control plots, and in soybean meal and turkey litter plots when combined with polyethylene mulch. Total nitrogen decreased by 58% and 55% in soybean meal + bare soil and turkey litter + bare soil, respectively, in comparison to the weed-free control plots, which may have been due to plant competition between weedy plants and crops.

This study shows that abrasive grit application works well in conjunction with polyethylene and bioplastic mulches. Previous research showed that grit application did not affect the integrity of plastic mulches (Wortman 2015). Polyethylene and bioplastic mulches tended to outperform bare soil control and straw mulch plots in yield, nitrogen availability, and weed control, when used with applied abrasive grit sources.

Walnut shell grits may be most effective for decreasing weed density, especially grasses, which could lead to increased yield relative to non-weeded planting holes in vegetable production. Because peppers are a high-value horticultural crop, the relative expense of AWM is justified through the yield losses seen in the weedy control plots in comparison to the weed-free control plots. Because the weed-free control plots were hand-weeded, there was a significant labor component associated with their weeding process. AWM is beneficial because it decreases that labor component, while still controlling for weeds within the crop row, leading to less yield loss or even zero significant yield loss in comparison to the weedy controls.

CHAPTER TWO

Soil mineralization and plant uptake of nitrogen from organic fertilizers used as air-propelled abrasive grits

Introduction

Weed management is consistently a top priority for farmers, especially organic farmers. Without the use of synthetic herbicides, many organic farmers struggle to control for weeds in the short-term. Conventional farmers also struggle with weed control, largely due to the development of herbicide resistant weeds (Shrestha et al. 2004). Many farmers are turning to physical weed management techniques to supplement their current programs, but more short-term weed management options are needed (Forcella et al. 2011).

Tillage is one of the most common methods of weed control in organic systems (Forcella et al. 2010), but tillage can cause crop injury and yield loss (e.g., rotary hoeing), and reduce soil quality (Taylor et al. 2012; Kluchinski and Singer 2005; Leblanc and Cloutier 2001; Lovely et al. 1958; Mohler et al. 1997; Liebman and Davis 2000; Forcella 2009). Thermal weed management (e.g., flame- and steam-weeding) is an increasingly popular alternative to tillage, but it is energy-intensive, potentially dangerous to the operator, and can cause crop damage and yield loss (Shrestha et al. 2004).

Abrasive weed management is a relatively new physical weed control technique. Using compressed air, abrasive weed management propels grits at weeds to physically abrade emergent structures as a form of post-emergent weed control (Forcella 2009;

Wortman 2014). Different organic materials have demonstrated their effectiveness as grits for weed blasting, including corn gluten meal, corn cob grits, greensand fertilizer, walnut shells and soybean meal (Wortman 2014). The use of organic fertilizers, such as soybean meal or composted turkey litter, as abrasive grits has the potential to increase the profitability of this weed management strategy by combining weed management and fertilizer application into one field pass, eliminating the cost of subsequent materials and field passes when done separately.

Nitrogen from organic sources is slowly mineralized in soil whereas nitrogen from mineral or synthetic fertilizers is immediately plant available upon entering soil solution. Due to the slow mineralization of organic N sources, it is important to consider the release pattern of the fertilizer source and its relation to crop demand (Gaskell and Smith 2007). It has been hypothesized that delayed nitrogen availability from organic amendments may be more synchronous with crop demand and improve crop-weed competition (Liebman and Davis, 2000). Delaying fertilizer application or plant availability in soil could serve to starve weeds of nitrogen during early growth stages, while providing crops with nitrogen during stages of higher crop uptake (Liebman and Davis 2000). To this end, abrasive weed management with gritty organic fertilizers may improve crop-weed competition.

Forcella first noted that abrasive weeding could be utilized as a post-emergent weed control method and a fertilizer application (Forcella 2010 and 2012). The use of this method for post-emergent weed control will delay nitrogen application until most weeds have already emerged, so they would not be able to use the added nitrogen during early growth stages. Typically, weed emergence occurs 7-14 days after transplanting vegetable crops into cultivated soils, which makes vegetable crops an ideal candidate for AWM. Using crop transplants instead of direct sowing helps crops maintain a competitive advantage over weeds because they are at a more advanced growth stage. When weed management strategies have the potential to directly affect crop plants, it is important for those crops to have a size advantage over weeds, which the use of transplants assures (Melander et al. 2005). Because plant damage from abrasive grit application decreases as plants increase in size (Wortman 2014), transplants should have an advantage over directly-sowed crops, furthering the idea that AWM can function as a fertilizer application to promote crop advantage over weeds.

Additions of N fertilizer, however, have the possibility to stimulate the germination of weed seeds in the soil seed bank. This response is variable in field trials, though, due to other interacting factors, such as light and temperature, that stimulate new growth (Dyer 1995). The risk of stimulating weed seed germination with nitrogen fertilizer can be mitigated with precise placement of N fertilizer. Mesbah and Miller (1999) noted reduced weed interference when fertilizer was placed closer to the crop seeds. Ottabong et al. (1999) reported increased crop biomass and yield, while suppressing weed biomass, when fertilizer was applied in deep bands in the crop seed row. Abrasive weeding can result in precise placement of fertilizer grits within the crop rows, which could reduce weed seed germination, growth, and crop interference. However, the precision of grit placement in abrasive weeding can vary depending on soil moisture, surface roughness, residue or mulch cover (e.g., plastic film), and grit velocity.

Soil tillage has the potential to increase nitrogen mineralization of organic amendments. Because nitrogen mineralization is a microbial process, the stimulation of soil microbes through soil disturbance can increase N mineralization (Ouédraogo et al. 2006; Laudicina et al. 2010). In the long-term, soil tillage can lead to soil degradation through the breakdown of soil organic matter (Liebman and Davis 2000). Watts et al. (2010) found in a long-term study that N mineralization was greater for no-till, poultry litter-amended systems in the top 5 cm of soil than in conventional tillage systems. This was attributed to the build-up of soil organic matter over time through reduced tillage, allowing for greater N mineralization, which was supported by Kingery et al. (1996).

This study aimed to determine the capacity for leveraging abrasive weeding as a nitrogen fertilizer application strategy. The objectives of this study were to: (1) quantify the rate and total amount of soil nitrogen mineralization and plant uptake from different organic fertilizers at application rates typical of abrasive weed management applications, and (2) determine the influence of soil incorporation of organic fertilizers on nitrogen mineralization, plant uptake, and crop yield.

Materials and Methods

Greenhouse experiments were conducted in 2016 (30 Nov – 14 Mar) and 2017 (28 Nov – 15 Mar) at the University of Illinois Plant Care Facility in Urbana, IL (40.10N, 88.22W). The experimental design was a factorial randomized complete block design with two factors, abrasive grit and tillage, and five replicate blocks. The abrasive grit treatments included low and high rates of soybean meal fertilizer (Phyta-grow Leafy Green Special, 7-1-2 NPK; California Organic Fertilizers, Inc., Hanford, California, USA), composted turkey litter (Suståne©, 8-2-4 NPK; Suståne© Natural Fertilizer, Inc., Cannon Falls, Minnesota, USA), walnut shell grit (Kramer Industries, Inc., Piscataway, New Jersey, USA), and a null control. The low rate was applied at 1.5 g per pot (an equivalent of 400 pounds per acre) to simulate 50% of applied grit remaining in the root zone and 50% lost to the interrow area, and the high rate was applied at 3 g per plot (800 pounds per acre) to simulate 100% of applied grit remaining in the root zone. The tillage treatments included soil incorporation of the grits within the top 5 cm of soil after grit application compared to no soil incorporation. This design resulted in 70 experimental units per year [(7 grit treatments x 2 tillage treatments x 5 replicates].

Two hundred Red Russian kale plants were planted in a potting mix (Sunshine Mix LC1; SunGro Horticulture, Agawam, Massachusetts, USA) on 30 November 2015 and 28 November 2016. Kale plants were fertilized with 125 ppm of 20-20-20 liquid fertilizer (Peters Professional General Purpose; ICL Specialty Fertilizers; The Netherlands) on 18 December 2015 and 16 December 2016, four days prior to transplant. One kale plant was transplanted into each 8.7 L pot with a uniform volume of non-sterilized top soil (Table 2.1). Transplanting occurred on 22 December 2015 20 December 2016, 22 days after planting. Saucers were placed under each pot to ensure nutrients were not leached from the system during irrigation. Kale plants were irrigated with reverse osmosis water to maintain an average surface soil moisture of 25% volumetric water content (which was approximately field capacity). Each replicate block had an untreated control pot that was solely used to determine surface soil moisture content and inform irrigation scheduling. Greenhouse temperatures were set to 27 degrees Celsius for 16 hours (daytime) and 20 degrees Celsius for 8 hours (nighttime). Supplemental light was used to achieve 16 hours of daylight.

When kale reached suitable height for field application of abrasive grit, premeasured amounts of abrasive grits were added by hand to the surface of each experimental unit and incorporated within the top 5 cm of soil or left unincorporated. This occurred approximately two weeks after transplanting on 1 January 2016 and 3 January 2017, which is consistent with the timing of the first grit application in transplanted vegetable crops (Wortman 2015).

Soil samples were collected from each experimental unit at 0, 7, 14, 28, 42, and 56 days after abrasive grit application. Soil samples were taken to a depth of 10 cm using a scoopula and then weighed to reach a wet weight between 6.0 and 6.5 grams and placed into a 50 mL conical tube. Equipment was rinsed with reverse osmosis water between each sample. In preparation for nitrogen analysis, 20 mL of 2M KCl was placed in each conical tube and shaken for 3 seconds. All tubes were then placed in a shaker unit (Gyrotory Water Bath Shaker G76; New Brunswick Scientific Co., Inc.; Edison, New Jersey, USA) for 1 hour. Folded filter papers (Whatman Filter #2; GE Healthcare Bio-Sciences, Pittsburgh, Pennsylvania, USA) were placed into small beakers, and samples were allowed to gravity drip for around 30 minutes. Filtered samples were placed into 15 mL conical tubes and stored in a freezer (-20 °C). All samples were analyzed for NO_3 and NH_4 concentrations colorimetrically using a SmartChem 170 discrete wet chemistry auto-analyzer (Unity Scientific, Milford, Maryland, USA).

Surface soil moisture was collected at each sampling date in designated soil moisture control pots for each replicate block using a portable soil moisture probe (Dynamax Inc.; Houston, Texas, USA; Model TH2O). Leaf greenness was also measured at each soil sampling date from the newest fully-emerged kale leaf in each experimental unit using a handheld sensor (atLEAF+, FT Green LLC, Wilmington, Delaware, USA).

Kale leaves were harvested regularly as leaves reached a marketable size. At harvest, leaves were counted and fresh weight recorded. Leaves were then dried between 65°C and 100°C to constant mass, and dry weight was recorded. Dried tissue samples were sent to Ward Laboratories (Kearney, NE, USA) twice per year (an early and late harvest) for analysis of leaf tissue nitrogen. Harvest data from each experimental unit were summed across all harvest events for the entire season and analyzed in aggregate.

Analysis of variance (ANOVA) was performed on all data using the GLIMMIX procedure in SAS (v9.4, SAS Institute, Cary, North Carolina, USA) to determine potential differences among experimental treatments. Year and replicate were treated as random effects, while abrasive grit treatment, tillage, and their interaction were treated as fixed effects. Repeated measures were used for leaf greenness data and soil nitrogen concentrations, but the other effects in the model remained unchanged. Tissue nitrogen concentrations were analyzed within individual years due to differences in sampling dates; thus, year was removed from the mixed effects model. Estimates of least squares means were calculated and compared among treatments using the Tukey-Kramer multiple comparisons test with a significance level of $\alpha = 0.05$.

Results and Discussion

Soil nitrogen

Soil NH_4 concentration was influenced by significant interactions of time (days after fertilizer application) and abrasive grit treatment ($p<.0001$), time and tillage treatment ($p=.0062$), and abrasive grit and tillage treatments ($p=.0113$). At 7 days after fertilizer application, soil NH_4 spiked to 1.57 mg/L in the high rate of turkey litter, and to 0.68 mg/L in the low rate of soybean meal (Figure 2.1). Ammonium in the control and walnut shell treatments was consistently lower than in the other grit treatments. Compared to grits left on the soil surface, incorporation of grits increased soil NH_4 at 7, 14, and 56 days after application (Figure 2.2).

Increased soil NH_4 following grit incorporation was most prominent in the high rates of soybean meal (0.4 mg/L) and turkey litter (0.74 mg/L) (Figure 2.3). Incorporation likely increased N mineralization through the stimulation of soil microbial activity, leading to a greater breakdown of organic N sources (Ouédraogo et al. 2006; Gaskell and Smith 2007; Montemurro 2009; Laudicina et al. 2010). Watts et al. (2010) found that conventional tillage treatments had lower C:N ratios than other treatments, suggesting that the incorporation of organic material may lead to a decrease in C:N by distributing organic matter throughout the soil profile.

Soil incorporation (i.e., tillage) in the control and walnut shell treatments had no effect on soil NH_4, which is because of the low N content of walnut shell grits and the lack of added N in the control treatments.

Total N and NO_3 concentrations were not influenced by abrasive grit type or tillage treatments. Time (days after fertilizer application) had a significant effect on Total N concentration ($p=.0002$), NO_3 concentration ($p<.0001$), and leaf greenness ($p<.0001$). All three parameters spiked at 14 days after fertilizer application (Figure 2.4). This is consistent with Stradler et al. (2006), who found that of the organic fertilizers tested, N mineralization occurred primarily in the first 15 days after application. The availability of N likely contributed to the increase in leaf greenness seen at day 14 (Figure 2.4).

Tissue nitrogen

Tissue nitrogen (%) was influenced by the effect of abrasive grit treatment for the early harvest (approximately 4 weeks after grit application) in both 2016 ($p=.0087$) and 2017 ($p=.0002$). In 2016, tissue N was greatest following a high rate of turkey litter and lowest following a high rate of walnut shell grit (Figure 2.5). Turkey litter (8%) had the highest N concentration by weight of the abrasive grits tested, whereas walnut shell (<0.1%) had the lowest. Given the high C:N of walnut shells, a high rate may have led to N immobilization which reduced plant N uptake. Flavel and Murphy (2006) found that the C and N contents of tested amendments affected N mineralization. Gale et al. (2006) also noted that amendment C:N was an indicator of mineralization potential, where high C:N could lead to immobilization of the N source. In 2017, tissue N concentration was greatest in soybean and turkey litter treatments likely due to the low C:N of these fertilizer grits (Figure 2.6).

Yield

All measures of kale yield were influenced by abrasive grit treatment (p<0.0001). Number of leaves harvested, fresh yield, and dry weight, were all greatest when high rates of soybean meal and turkey litter were applied (Figures 2.7 – 2.9). This yield response corresponds to the higher rate of N added through the abrasive grit application of soybean meal and turkey litter, as well as the low amendment C:N of these sources. Low amendment C:N corresponds to a higher N mineralization in comparison to high C:N amendment sources (Gale et al. 2006). Yield across all parameters was lowest in walnut shell and control treatments, which is consistent with soil and tissue N results, suggesting that yield benefits of fertilizer-based abrasive grits are driven in part by increased N input. These parameters had large standard errors, which is explained by a large difference in yield between the two years of this study. In 2016, there were only two harvests, while in 2017 there were four harvests which contributed to larger yield totals.

Dry weight was the only yield parameter influenced by the effect of tillage treatment (p=.0396). Dry weights were around 6% greater when abrasive grits were incorporated in the soil, which is consistent with increases in soil N following incorporation (data not shown). Montemurro (2009) reported that grain yield was higher in conventional tillage treatments than minimal tillage treatments, seeing a 12% decrease in yield when minimal tillage was employed. Watts et al. (2010) reported lower C:N ratios in conventional tillage treatments, noting that the distributed of crop residue throughout the soil profile likely accounted for this result. To this end, the 6% increase in dry yield weights in the incorporated treatments as likely due to several factors, including a lower soil C:N and increased N mineralization through the stimulation of soil microbes.

Conclusion

The high N content of turkey litter and soybean meal contributed to higher N mineralization overall in those treatments. The high rate of turkey litter, in particular, outperformed the other treatments in tissue N and yield, which was likely due to the higher N mineralization rate.

Incorporation of soil amendments significantly affected soil ammonium concentrations and dry yield weight, suggesting that tillage following grit application could contribute to greater soil availability of N and greater plant uptake. However, long term studies suggest this may not be a sustainable approach to increasing N mineralization because of the chance of soil degradation through the loss of soil organic matter (Liebman and Davis 2000; Laudicina et al. 2010; Watts et al. 2010). Mineralization is also affected by soil moisture and soil temperature, so there is the possibility of variation in the field due to weather events or the presence of mulches or other factors that could increase soil moisture and temperature.

Walnut shell is a particularly effective abrasive grit and a potentially low-cost agricultural by-product, but soybean meal and composted turkey litter may provide greater value to the grower in the form of weed control and nitrogen fertility.

Tables and Figures

	2015 Spot spray		2015 Continuous spray		2016 Continuous spray	
Grit	**g m row^{-1}**	**kg ha^{-1}**	**g m row^{-1}**	**kg ha^{-1}**	**g m row^{-1}**	**kg ha^{-1}**
Soybean meal	6.68	82.3	20.4	197	39.4	469
Turkey litter	6.27	87.7	15.0	268	34.6	454
Walnut shell	4.92	64.6	11.8	155	35.7	517

Table 1.1: Average application rate of each abrasive grit in one field pass traveling approximately 1.6 km h^{-1}.

	30 DAT (# of weeds)			60 DAT (# of weeds)			Aboveground biomass (g m^{-2})		
	Grass density	Broadleaf density	Total weed density	Grass density	Broadleaf density	Total weed density	Grass biomass	Broadleaf biomass	Total weed biomass
Bare soil									
Weedy control	26	91 a	130 a	17 a	42 a	66 a	37.0	520 b	624 c
Soybean meal	19	62 ab	81 ab	11 abc	30 a	42 a	28.1	293 ab	351 cd
Turkey litter	29	72 a	110 ab	15 ab	33 a	50 a	73.0	304 ab	453 cd
Walnut shell	15	60 ab	82 ab	6 abcd	27 a	36 a	22.2	238 ab	286 cd
Bioplastic									
Weedy control	6	14 bc	20 bc	3 def	7 b	10 b	51.0	1450 a	1800 a
Soybean meal	5	5 cde	9 cd	2 defgh	2 de	4 bc	15.0	334 ab	438 cd
Turkey litter	3	5 cdef	6 cde	1 defgh	2 cde	4 bc	10.5	257 ab	317 cd
Walnut shell	3	3 cdef	5 cde	0 fgh	1 ef	1 cd	2.97	241 ab	263 cd
Polyethylene									
Weedy control	6	13 bc	19 bc	2 defg	6 bcd	9 b	17.4	1030 a	1220 b
Soybean meal	4	3 cdef	4 cde	1 efgh	0 ef	1 cd	5.55	147 ab	176 cd
Turkey litter	3	2 cdef	3 cde	0 fgh	1 ef	1 cd	3.52	230 ab	243 cd
Walnut shell	3	1 def	2 de	1 efgh	1 ef	1 cd	7.08	134 ab	168 cd
Straw mulch									
Weedy control	4	8 cd	10 cd	3 cdef	8 b	12 b	23.1	246 ab	320 cd
Soybean meal	3	3 cdef	4 cde	2 defgh	6 bc	8 b	7.25	147 ab	195 cd
Turkey litter	4	6 cde	9 cd	4 bcde	7 b	12 b	33.7	43.5 c	124 d
Walnut shell	4	8 cd	10 cd	3 def	8 b	11 b	6.33	76.9 ab	87.2 d

Table 1.2: Weed density sampled at 30 and 60 days after transplanting (DAT) and aboveground weedy biomass. Different letters indicate significant difference among treatments ($p<0.05$). Each parameter was estimated using a subsample taken from two 91 cm x 20 cm quadrats centered between plants two through four and plants six through eight. Different letters indicate significant difference among treatments ($p<0.05$).

	60 DAT (# of weeds)			Aboveground biomass (g m^{-2})		
	Grass density	Broadleaf density	Total weed density	Grass biomass	Broadleaf biomass	Total weed biomass
Bare soil						
Weedy control	31 a	58 a	88 a	142 abc	672 ab	814 ab
Soybean meal	19 abc	51 a	69 a	72.9 abc	664 ab	737 ab
Turkey litter	21 ab	45 a	65 a	168 a	643 ab	811 ab
Walnut shell	18 abcd	37 ab	55 ab	94.0 abc	930 a	1020 a
Bioplastic						
Weedy control	0 d	0 c	0 c	0.00 c	57.6 de	57.6 d
Soybean meal	0 cd	1 c	1 c	23.7 bc	174 cde	197.3 cd
Turkey litter	0 d	0 c	0 c	0.00 c	0.00 e	0.00 d
Walnut shell	0 d	0 c	0 c	0.00 c	16.7 e	16.7 d
Polyethylene						
Weedy control	0 a	0 c	0 c	0.00 c	7.01 e	7.01 d
Soybean meal	0 d	0 c	0 c	26.5 bc	48.0 de	74.4 d
Turkey litter	0 d	0 c	0 c	0.38 c	92.6 cde	93.0 d
Walnut shell	0 d	0 c	0 c	0.00 c	52.1 de	52.1 d
Straw mulch						
Weedy control	5 d	15 bc	20 bc	68.4 abc	396 bcd	464 bc
Soybean meal	7 bcd	14 bc	21 bc	122 abc	349 bcde	472 bc
Turkey litter	9 bcd	16 bc	26 bc	153 ab	393 bcd	546 bc
Walnut shell	6 bcd	16 bc	22 bc	104 abc	430 bc	534 bc

Table 1.3: Weed density sampled at 60 days after transplanting (DAT) and aboveground weedy biomass directly adjacent to and outside the crop row. Each parameter was estimated using a subsample taken from two 91 cm x 20 cm quadrats centered between plants two through four and plants six through eight. Different letters indicate significant difference among treatments ($p<0.05$)

Abrasive grits	Total yield (g m row^{-1})				Marketable yield (g m row^{-1})			
	Bare soil	Bioplastic	Polyethylene	Straw mulch	Bare soil	Bioplastic	Polyethylene	Straw mulch
Weed-free control	4846 ab	4693 ab	5213 a	3670 bcde	3455 abc	3466 ab	3612 a	2500 bcde
Weedy control	599 f	2562 e	3383 cde	930 f	344 g	1673 ef	2430 cde	497 g
Soybean meal	780 f	3201 de	4041 abcd	1370 f	488 g	2180 de	2812 abcd	788 fg
Turkey litter	612 f	3683 bcde	4033 bcd	1257 f	397 g	2501 bcde	2788 abcd	723 fg
Walnut shell	814 f	4020 bcd	4438 abc	1049 f	535 g	2769 abcd	3113 abcd	583 g

Table 1.4: Least square means estimates of total yield (g m row^{-1}) and marketable yield (g m row^{-1}). Different letters next to values for total yield or marketable yield indicate significant differences among treatments ($p<0.05$).

Baseline Soil Characteristics						
	2015			**2016**		
	NO3 (ppm)	**NH4 (ppm)**	**Total N (ppm)**	**NO3 (ppm)**	**NH4 (ppm)**	**Total N (ppm)**
Weed-free control						
Bare Soil	22.1	12.1	34.2	10.6	-	-
Bioplastic	21.3	11.0	32.3	11.3	11.2	22.5
Polyethylene	20.6	13.4	34.0	11.8	10.8	22.6
Straw mulch	20.2	12.6	32.8	12.2	16.0	28.2
Weedy Control						
Bare Soil	19.6	11.3	30.8	8.65	9.78	18.4
Bioplastic	23.6	12.0	35.5	12.2	13.2	25.4
Polyethylene	24.1	14.8	38.9	11.1	11.6	22.7
Straw mulch	23.1	16.4	39.5	10.4	13.4	23.8
Soybean meal						
Bare Soil	25.2	12.3	37.5	10.3	13.4	23.7
Bioplastic	21.3	11.0	32.3	9.68	9.54	19.2
Polyethylene	23.7	13.6	37.3	13.6	11.4	24.9
Straw mulch	21.3	12.7	34.0	10.6	11.1	21.7
Turkey Litter						
Bare Soil	20.8	10.8	31.6	11.4	11.6	23.1
Bioplastic	19.6	12.4	32.0	11.2	12.6	23.8
Polyethylene	21.5	11.5	33.0	10.2	10.2	20.4
Straw mulch	18.8	11.7	30.6	9.23	11.9	21.1
Walnut shell						
Bare Soil	20.3	9.85	30.2	9.62	10.2	19.8
Bioplastic	21.6	10.9	32.5	11.5	11.1	22.6
Polyethylene	26.3	14.1	40.3	11.7	11.8	23.5
Straw mulch	19.7	10.9	30.6	8.87	11.9	20.7

Table 1.5: Baseline soil characteristics taken before planting.

Year-End Soil Characteristics						
	2015			**2016**		
	NO3 (ppm)	**NH4 (ppm)**	**Total N (ppm)**	**NO3 (ppm)**	**NH4 (ppm)**	**Total N (ppm)**
Weed-free control						
Bare Soil	3.27	4.75	8.02	3.45	-	-
Bioplastic	2.57	3.86	6.43	4.72	4.61	9.33
Polyethylene	3.48	4.13	7.61	6.37	4.39	10.8
Straw mulch	2.51	3.54	6.06	2.85	4.22	7.07
Weedy Control						
Bare Soil	3.16	4.48	7.63	4.19	4.77	8.96
Bioplastic	2.94	3.67	6.61	4.13	4.81	8.93
Polyethylene	3.42	3.74	7.16	9.45	4.61	14.1
Straw mulch	3.09	4.28	7.37	3.72	5.48	9.20
Soybean meal						
Bare Soil	3.03	4.06	7.09	5.94	3.60	9.54
Bioplastic	4.10	3.85	7.94	4.51	6.39	10.9
Polyethylene	3.02	3.66	6.68	6.00	4.28	10.3
Straw mulch	3.74	4.49	8.23	2.25	4.59	6.84
Turkey Litter						
Bare Soil	3.48	4.17	7.65	4.65	5.47	10.1
Bioplastic	2.95	3.77	6.72	4.61	5.38	9.99
Polyethylene	4.09	4.73	8.82	7.38	6.08	13.5
Straw mulch	3.32	4.12	7.43	3.56	3.72	7.27
Walnut shell						
Bare Soil	2.57	4.12	6.69	4.73	6.33	11.1
Bioplastic	2.92	4.00	6.92	3.44	3.82	7.26
Polyethylene	3.75	4.10	7.85	7.97	5.11	13.1
Straw mulch	3.49	4.18	7.67	2.82	4.23	7.05

Table 1.6: Year-end soil characteristics taken after final harvest.

Effect	df[a]	NO_3	NH_4	Total N
Abrasive grit	2	0.32	0.13	7.21**
Mulch type	3	69.13***	3.88**	159.86***
Abrasive grit x mulch type	6	7.16***	1.27	11.54***
Time	3	189.62***	18.62***	324.42***
Abrasive grit x time	6	1.33	0.34	3.77**
Mulch type x time	9	9.83***	0.65	8.18***
Abrasive grit x mulch type x time	18	0.86	0.58	0.96

[a] Degrees of freedom.

Table 1.7: F-values for each fixed effect and interaction effect for nitrate, ammonium, and total nitrogen. Significance levels are denoted by * (p<.05), ** (p<.01), and *** (p<.0001).

Abrasive grits	NO_3	Total N
Weed-free control		
Bare soil	175 ab	176 ab
Bioplastic	151 bc	153 bc
Polyethylene	173 ab	175 ab
Straw mulch	66.5 d	69.9 d
Soybean meal		
Bare soil	96.5 cd	98.4 cd
Bioplastic	197 ab	200 ab
Polyethylene	214 a	215 a
Straw mulch	81.7 d	84.2 d
Turkey litter		
Bare soil	108 cd	110 cd
Bioplastic	170 ab	172 ab
Polyethylene	225 a	227 a
Straw mulch	63.6 d	66.0 d

Table 1.8: Estimates of nitrate (μg/ 10 cm^2 per two weeks of burial) and total nitrogen (μg/ 10 cm^2 per two weeks of burial). Different letters indicate significant difference among treatments ($p<0.05$).

Figure 1.1: Experimental abrasive grit applicators used in 2015 (left) and 2016 (right).

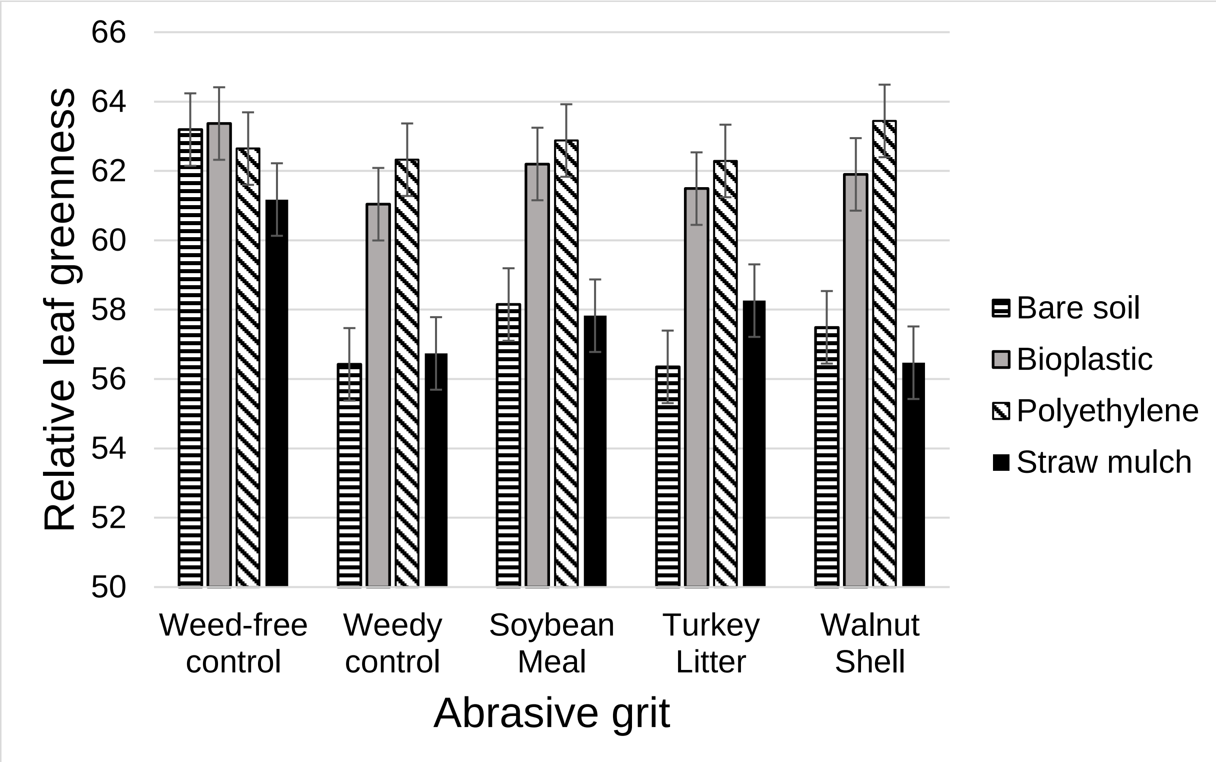

Figure 1.2: Least square means estimates of relative leaf greenness (no units) in 2015 for each abrasive grit + mulch combination. Error bars represent +/- one standard error of the least squares mean.

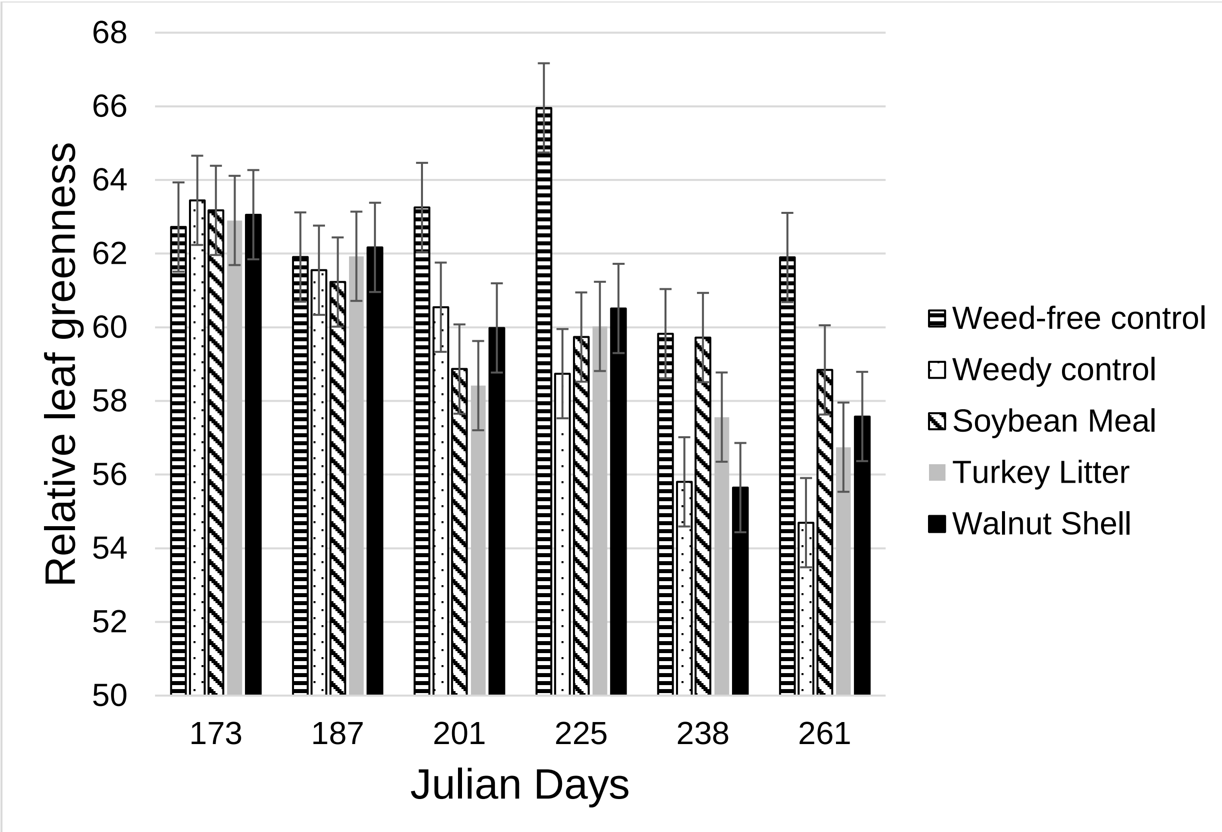

Figure 1.3: Least square means estimates of relative leaf greenness (no units) at each sampling point in 2015 for each abrasive grit treatment. Error bars represent +/- one standard error of the least squares mean.

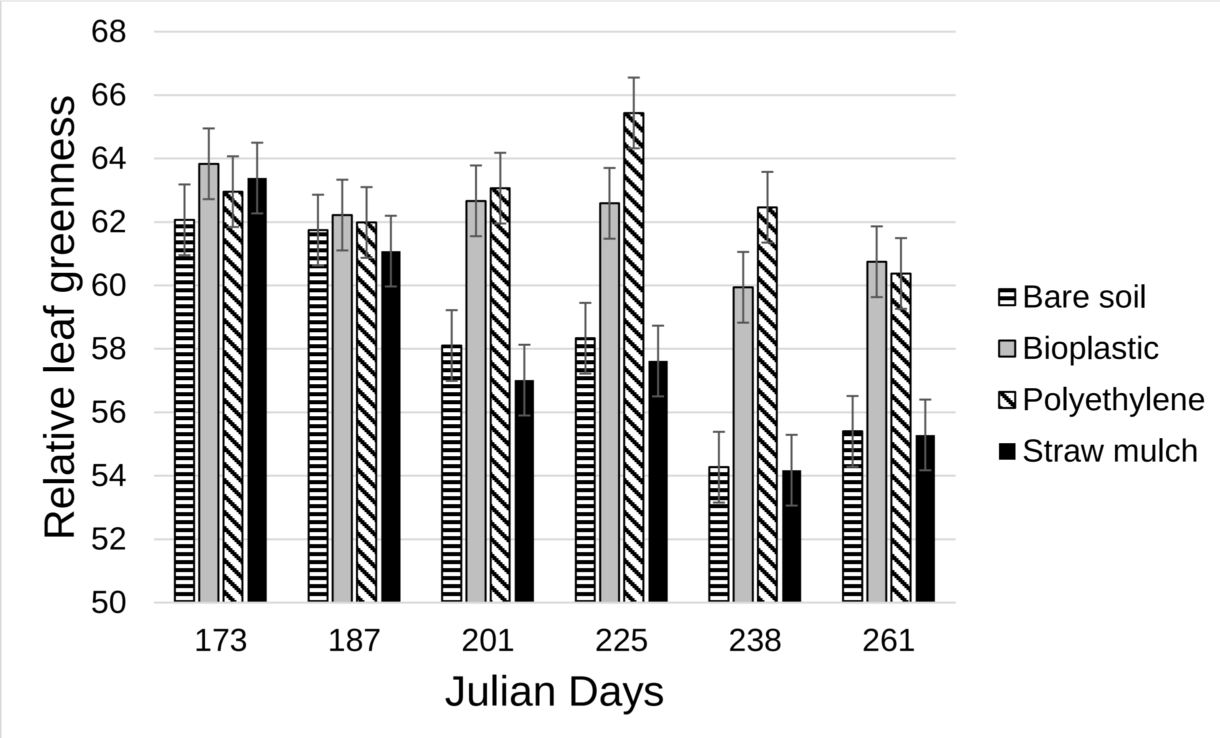

Figure 1.4: Least squares means estimates of relative leaf greenness (no units) at each sampling date in 2015 for each supplemental mulch treatment. Error bars represent +/- one standard error of the least squares mean.

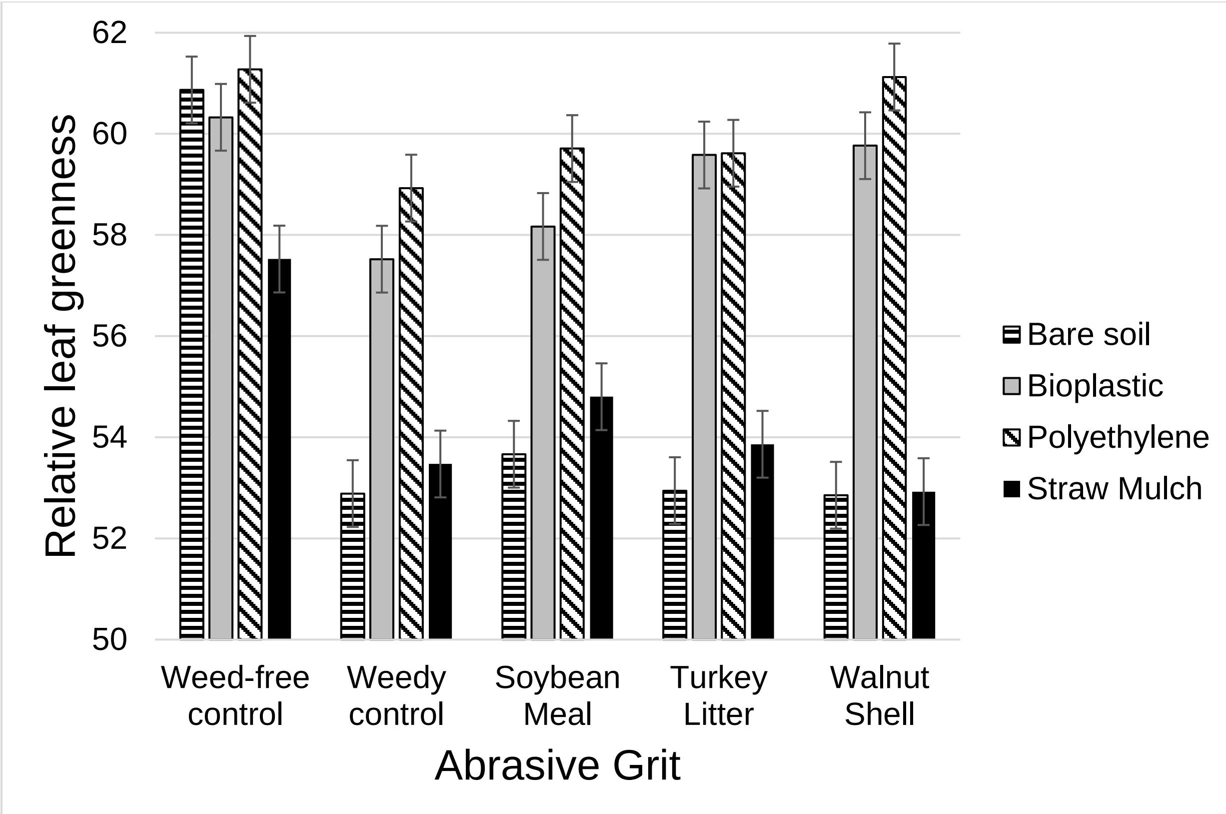

Figure 1.5: Least square means estimates of relative leaf greenness (no units) in 2016 for each combination of abrasive grit treatment and supplemental mulch treatment. Error bars represent +/- one standard error of the least squares mean.

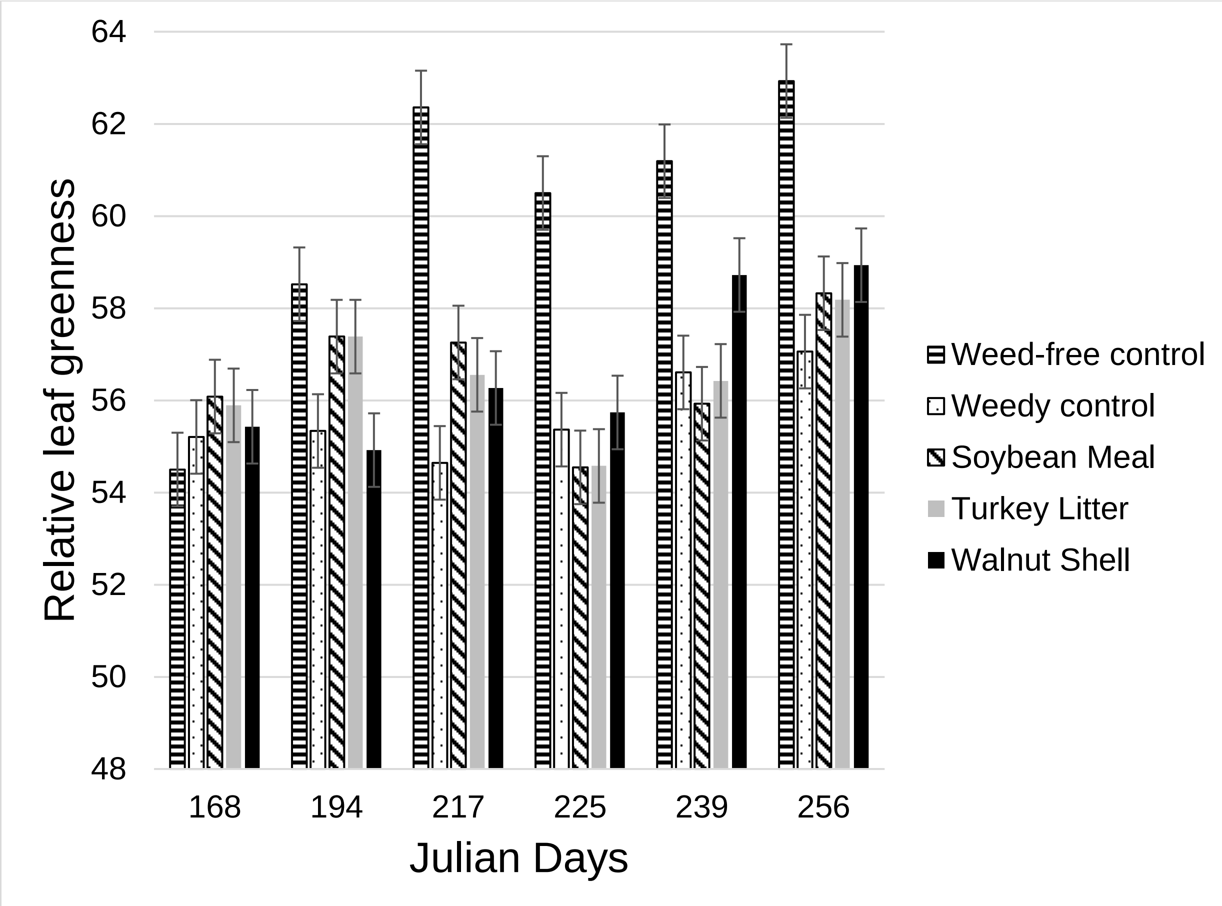

Figure 1.6: Least square means estimates of relative leaf greenness (no units) in 2016 for each abrasive grit treatment at each sampling date. Error bars represent +/- one standard error of the least squares mean.

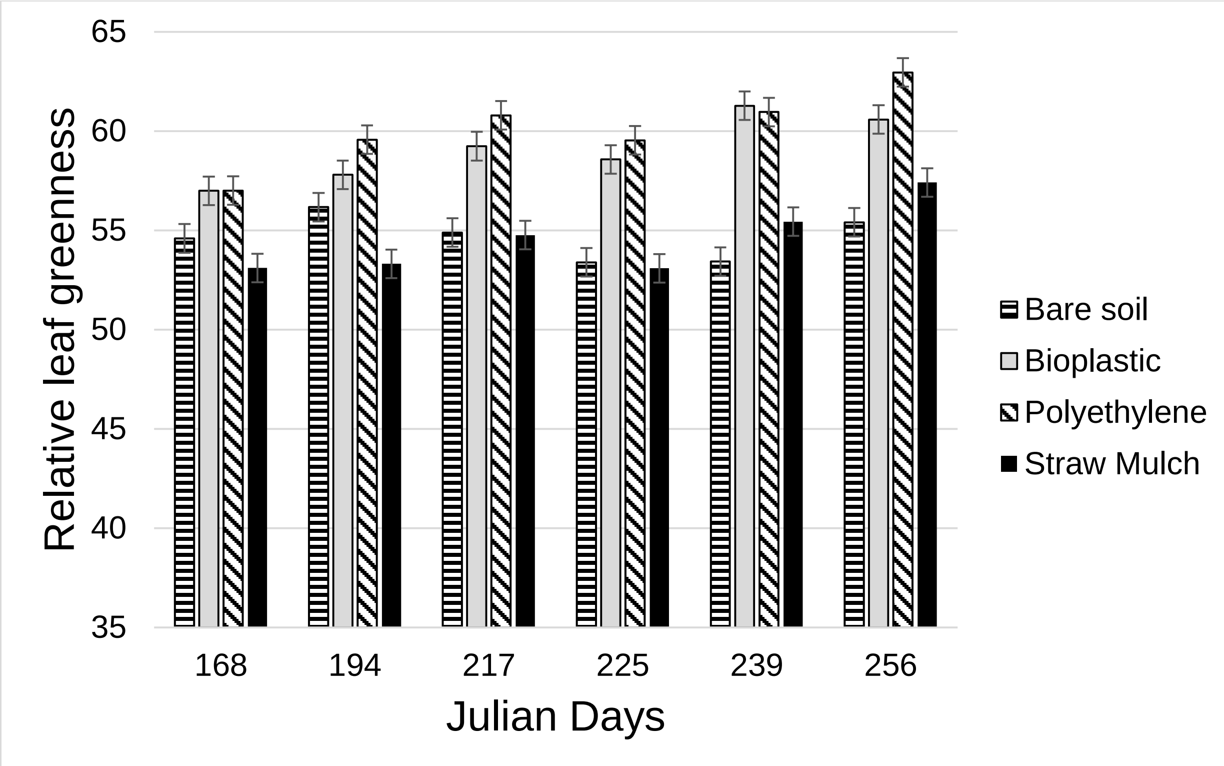

Figure 1.7: Least square means estimates of relative leaf greenness (no units) in 2016 for each supplemental mulch treatment at each sampling date. Error bars represent +/- one standard error of the least squares mean.

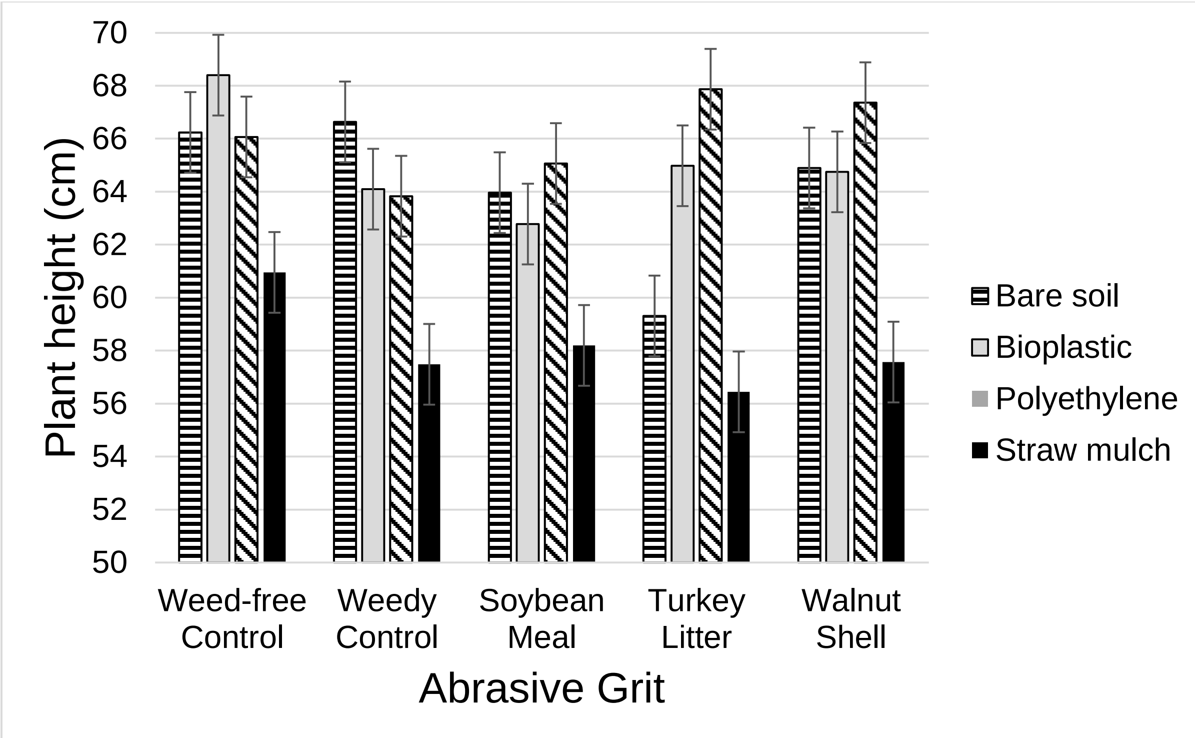

Figure 1.8: Least square means estimates of plant height (cm) in 2015 for each combination of abrasive grit treatment and supplemental mulch treatment. Error bars represent +/- one standard error of the least squares mean.

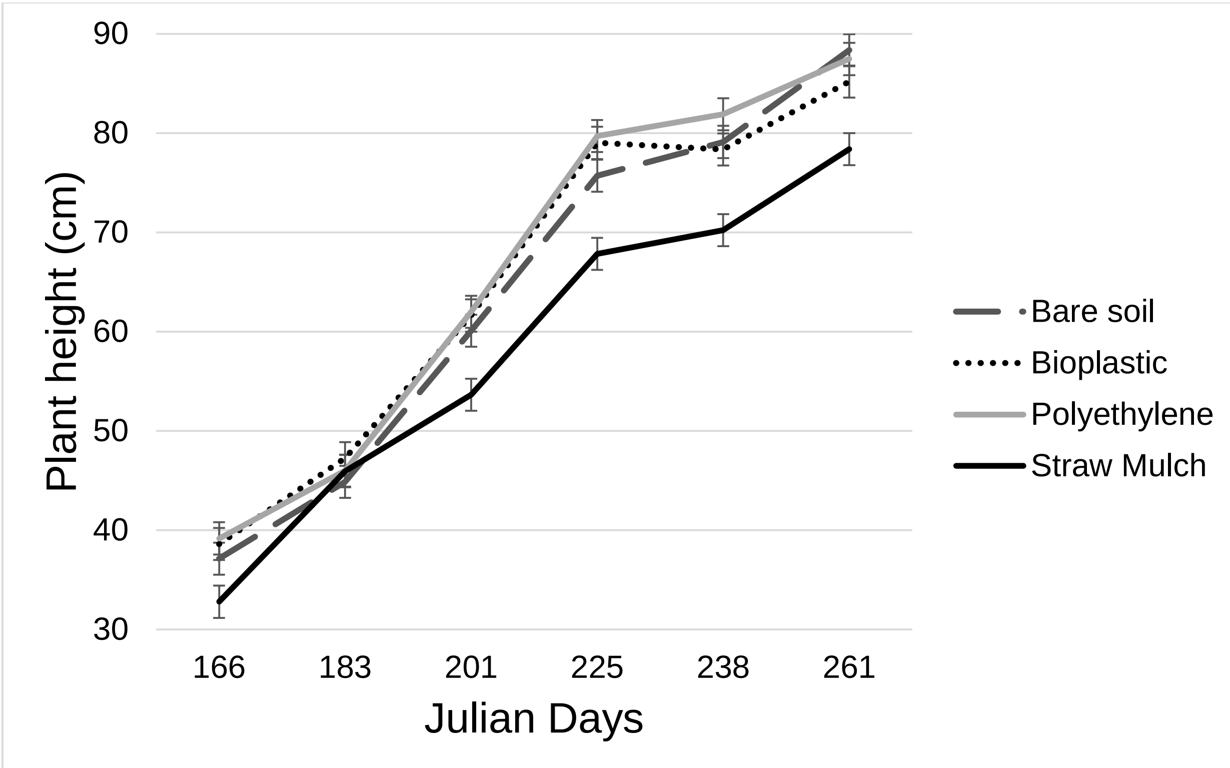

Figure 1.9: Least square means estimates of plant height (cm) in 2015 supplemental mulch treatments at each sampling date. Error bars represent +/- one standard error of the least squares mean.

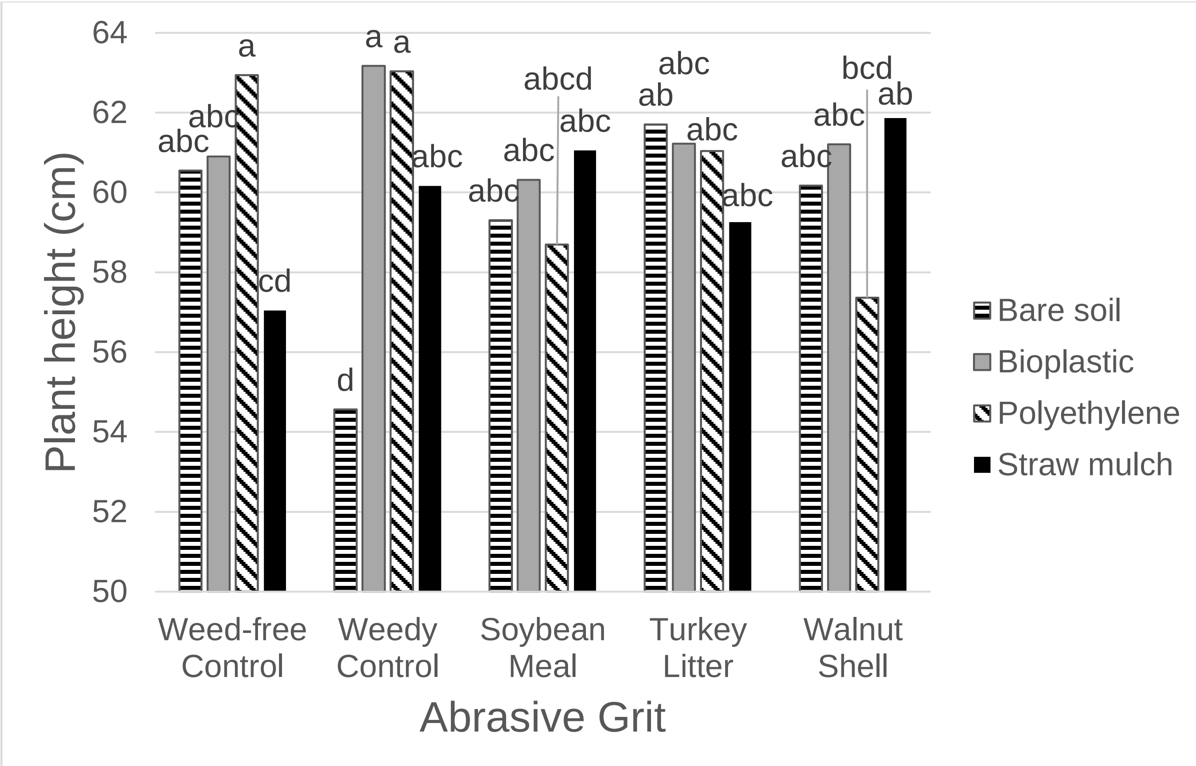

Figure 1.10: Least square means estimates of plant height (cm) in 2016 for each combination of abrasive grit treatment and supplemental mulch treatment. Different letters indicate significant difference among treatments (p<0.05).

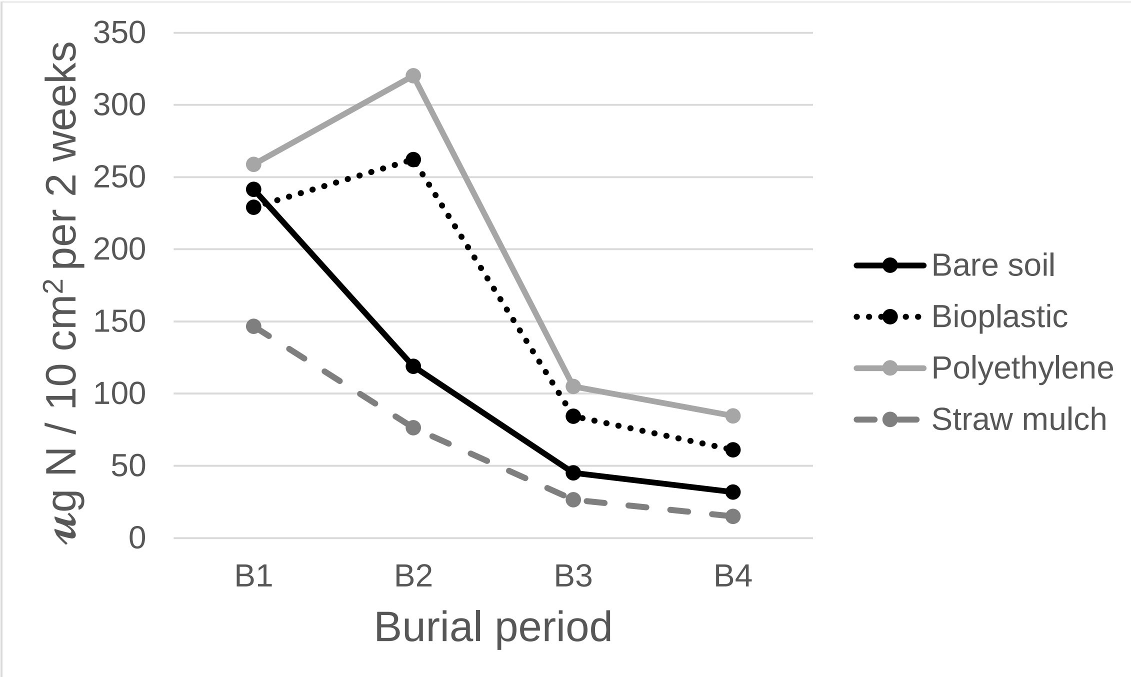

Figure 1.11: Total N (𝓊g/ 10 cm^2 per two weeks of burial) measured via PRS™ probes for each burial period in the supplemental mulch treatments.

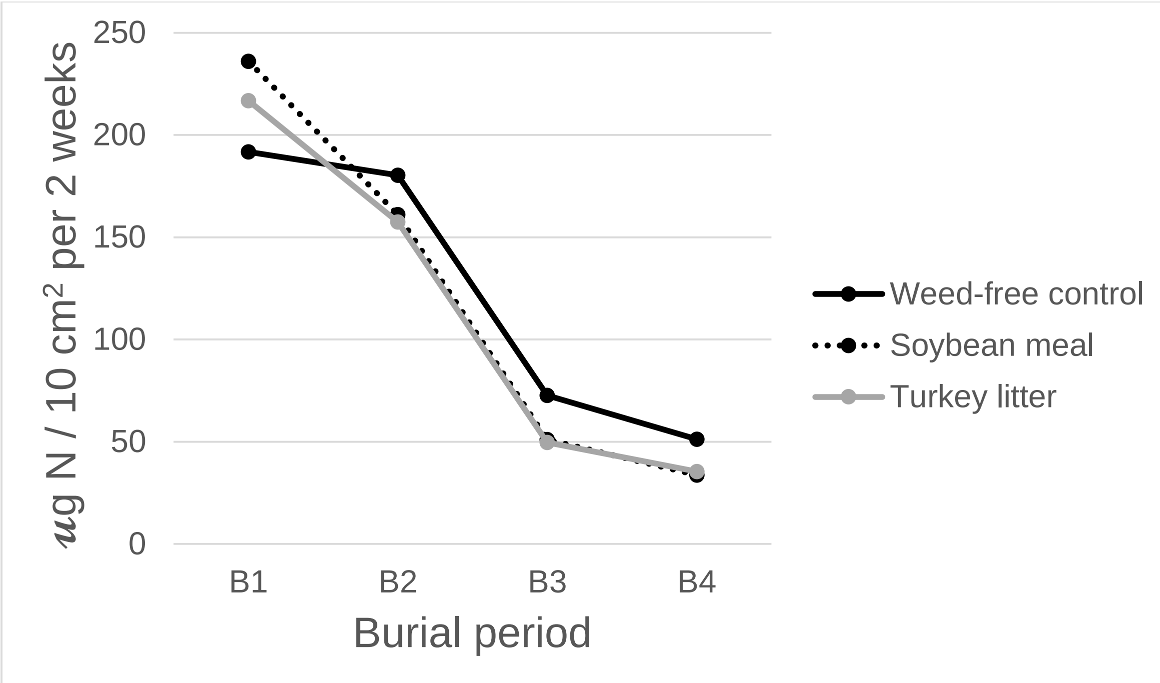

Figure 1.12: Total N (𝓊g/ 10 cm^2 per two weeks of burial) measured via PRS™ probes for each burial period in the sampled abrasive grit treatments.

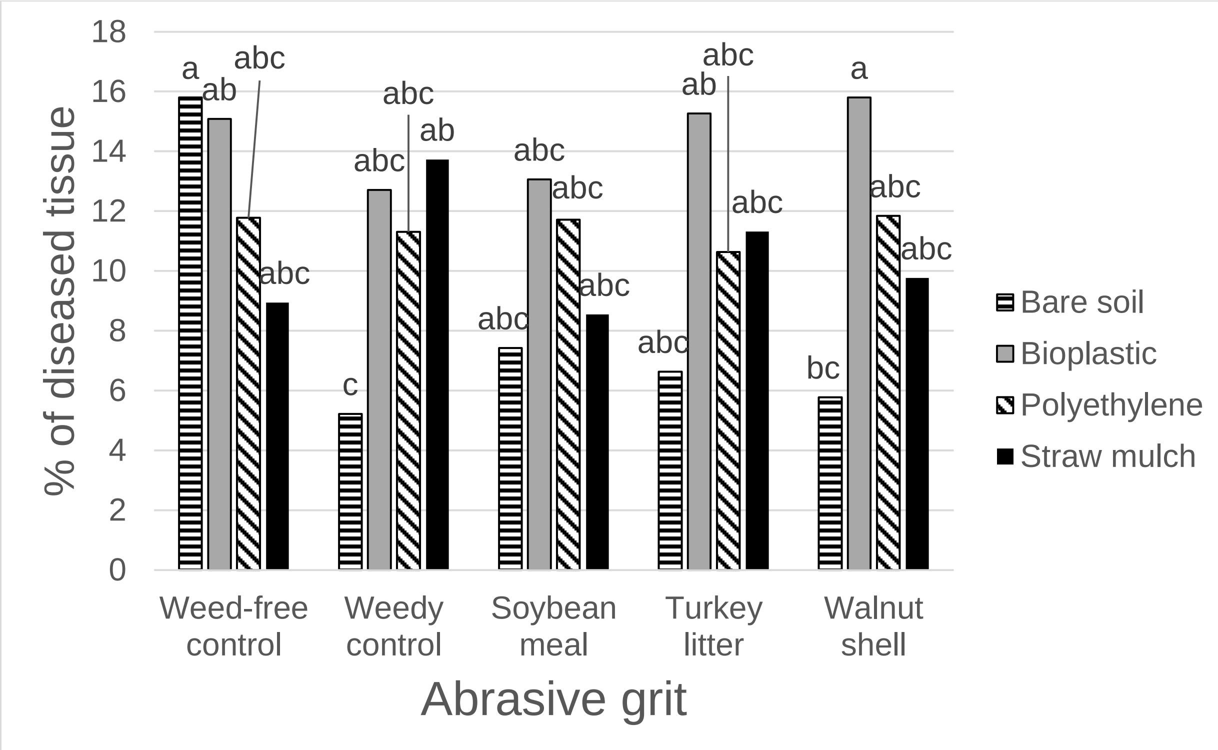

Figure 1.13: Least square means estimates of diseased tissue (%) in 2015 for each combination of abrasive grit treatment and supplemental mulch treatment. Data have been back transformed. Different letters indicate significant difference among treatments (p<0.05).

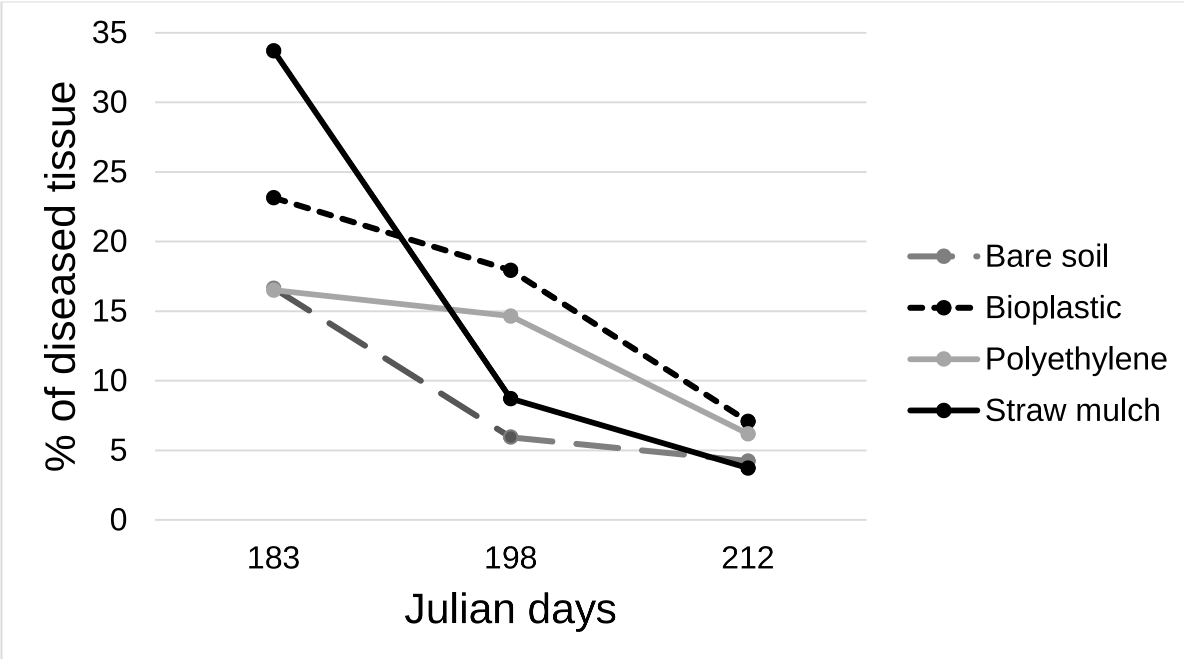

Figure 1.14: Least square means estimates of diseased tissue (%) in 2015 at each sampling date for supplemental mulch treatments. Data have been back transformed.

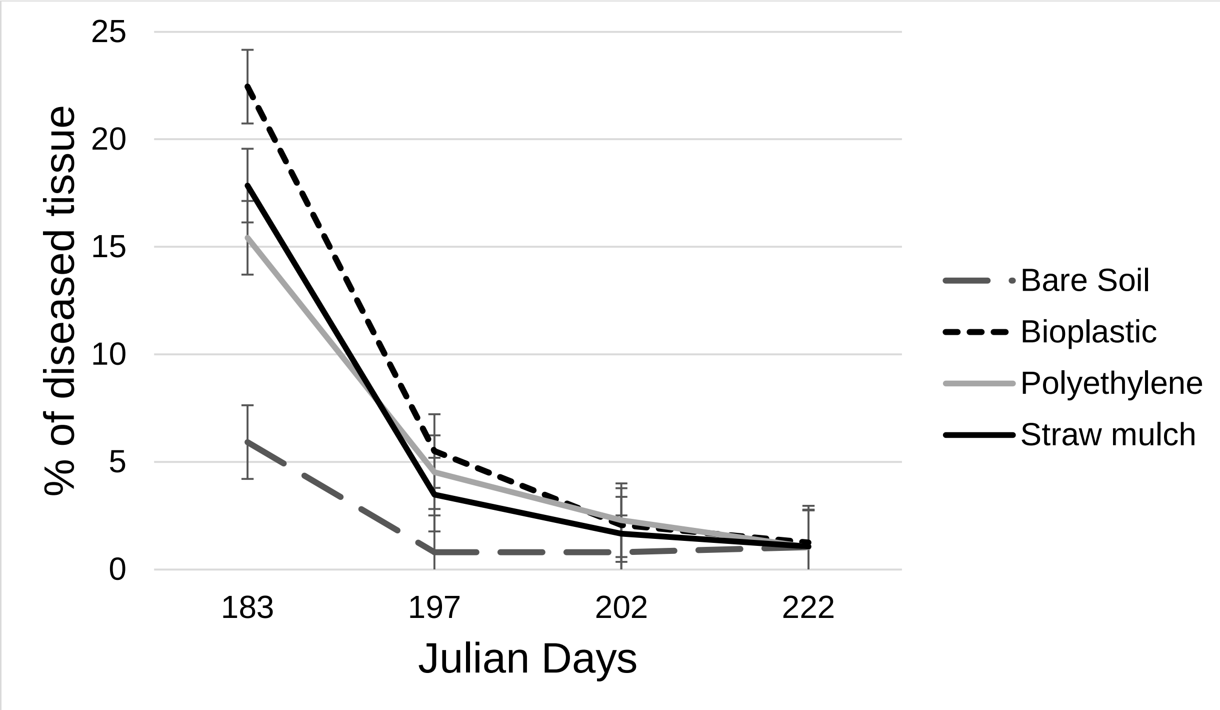

Figure 1.15: Least square means estimates of diseased tissue (%) in 2016 at each sampling date of combination of supplemental mulch treatments. Error bars represent +/- one standard error of the least squares mean.

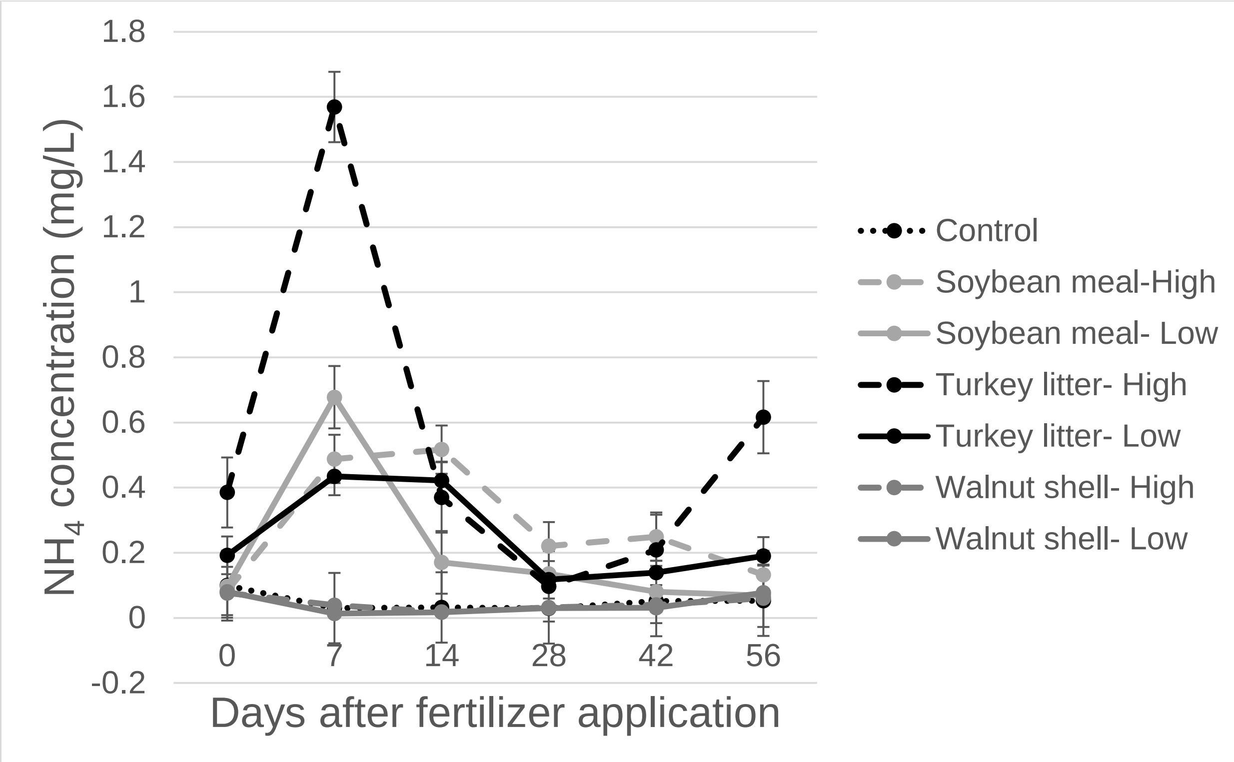

Figure 2.1: NH_4 concentrations (mg/L) of each abrasive grit type/rate at 0, 7, 14, 28, 42, and 56 days after fertilizer application. Error bars represent +/- one standard error of the least squares mean.

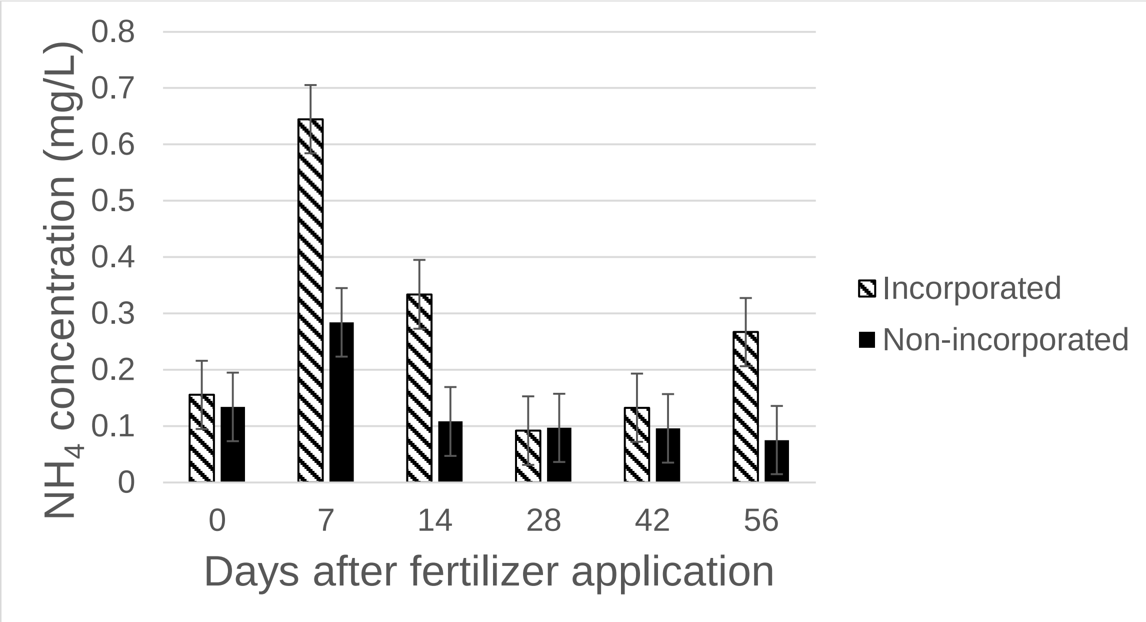

Figure 2.2: NH_4 concentrations (mg/L) of each abrasive grit type/rate when incorporated or left on the soil surface (not incorporated) at 0, 7, 14, 28, 42, and 56 days after fertilizer application. Error bars represent +/- one standard error of the least squares mean.

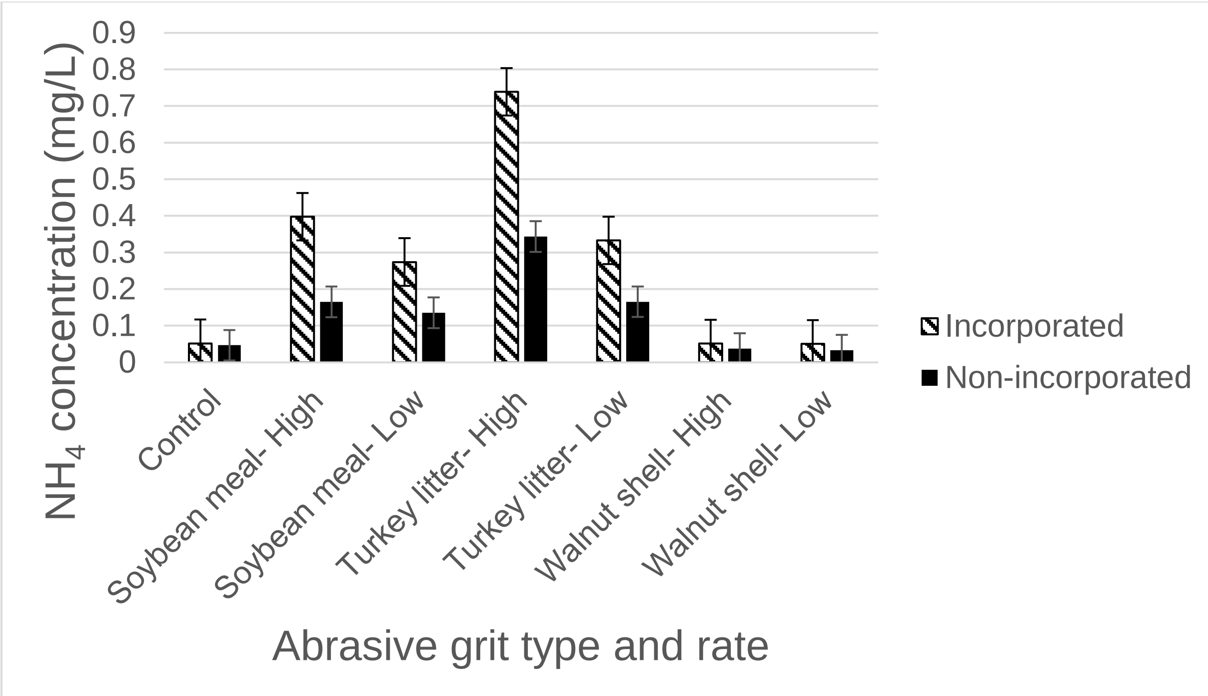

Figure 2.3: Season averages of NH_4 concentrations (mg/L) of each abrasive grit type/rate when incorporated or left on the soil surface (not incorporated). Error bars represent +/- one standard error of the least squares mean.

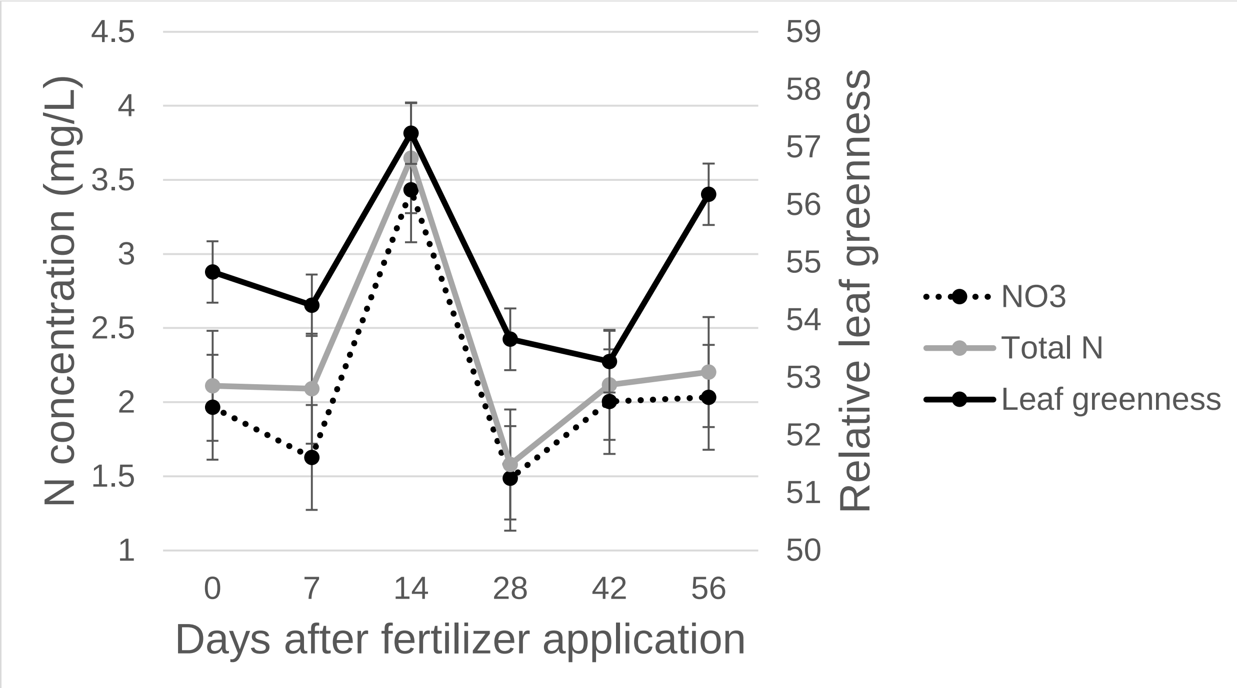

Figure 2.4: Relative leaf greenness (no units), total nitrogen (mg/L), and NO_3 (mg/L) at 0, 7, 14, 28, 42, and 56 days after fertilizer application. Error bars represent +/- one standard error of the least squares mean.

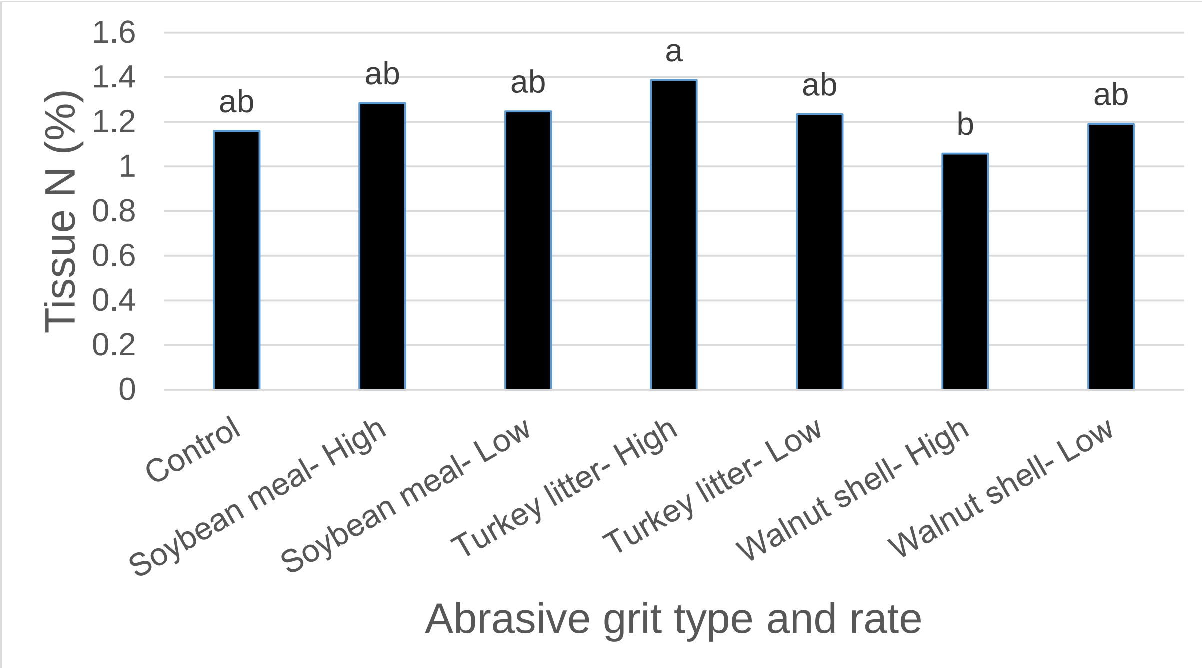

Figure 2.5: Tissue nitrogen (%) of leaf samples taken on 8 Feb 2016 for each abrasive grit treatment/rate. Data have been back transformed. Different letters indicate significant difference among treatments ($p<0.05$).

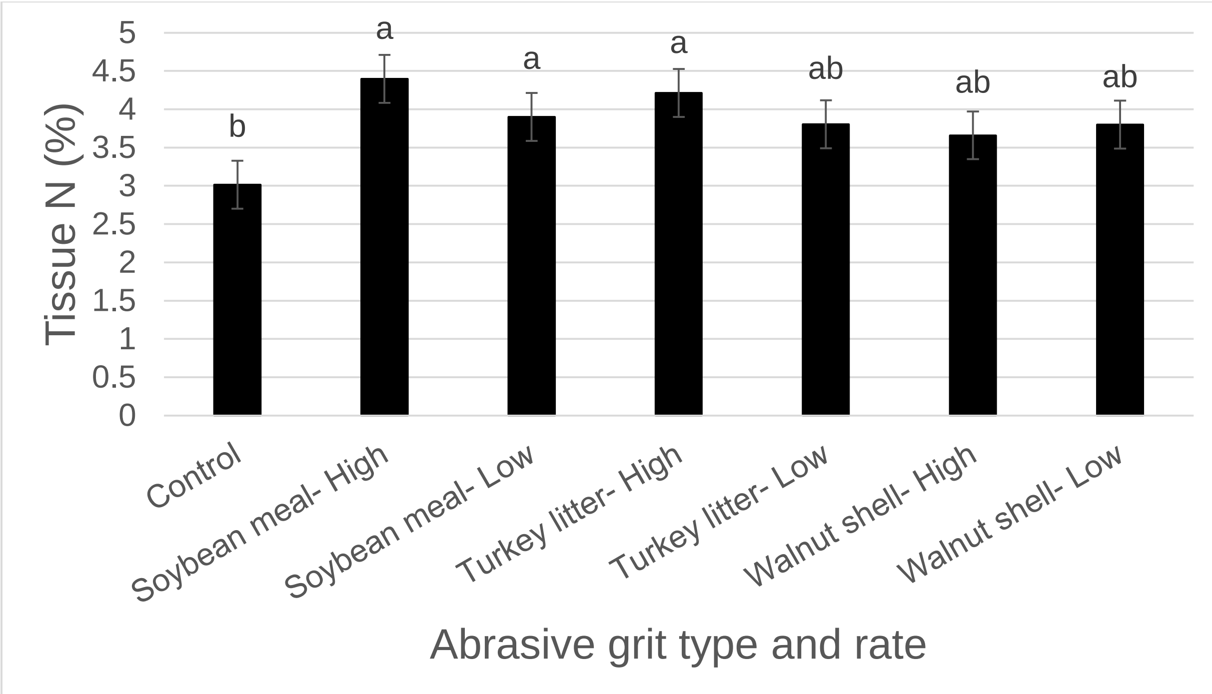

Figure 2.6: Tissue nitrogen (%) of leaf samples taken on 7 Feb 2017 for each abrasive grit treatment/rate. Data have been back transformed. Different letters indicate significant difference among treatments ($p<0.05$).

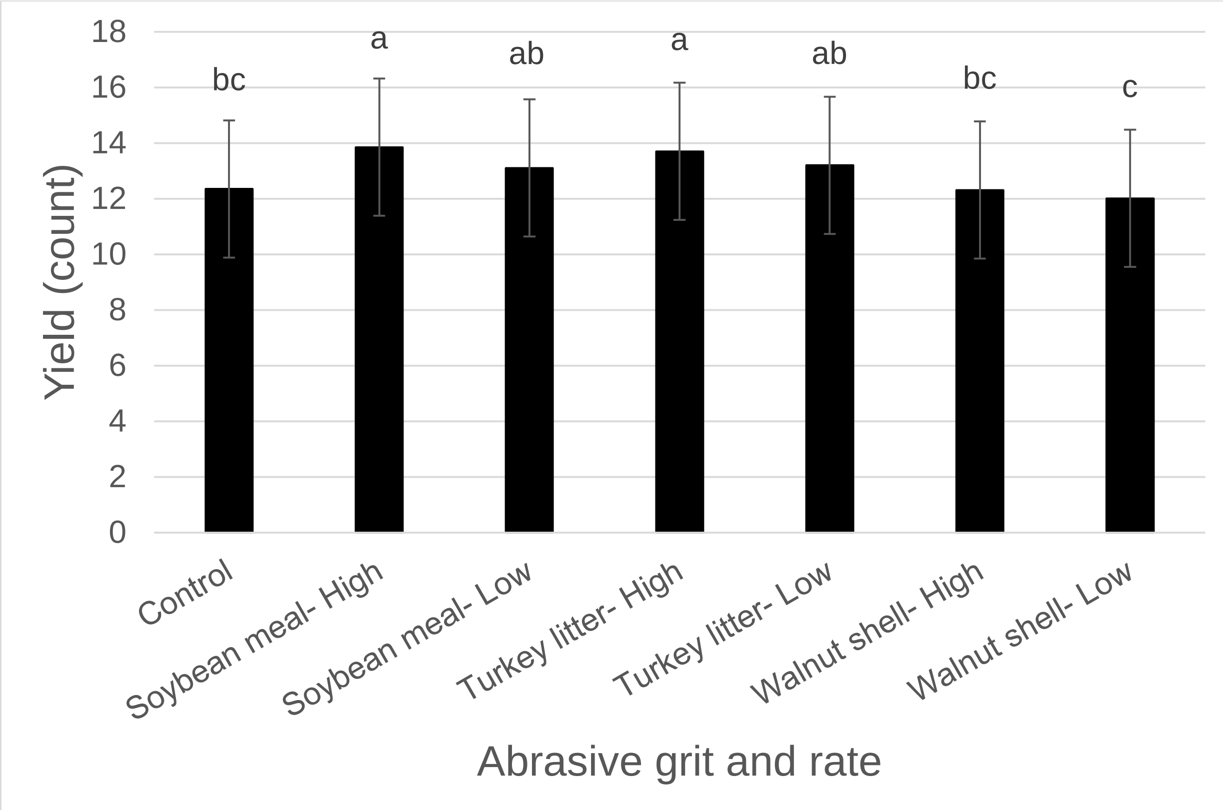

Figure 2.7: Yield, represented as the number of harvested leaves totaled by season, for each of the abrasive grit/rate treatments. Error bars represent +/- one standard error of the least squares mean. Different letters indicate significant difference among treatments (p<0.05).

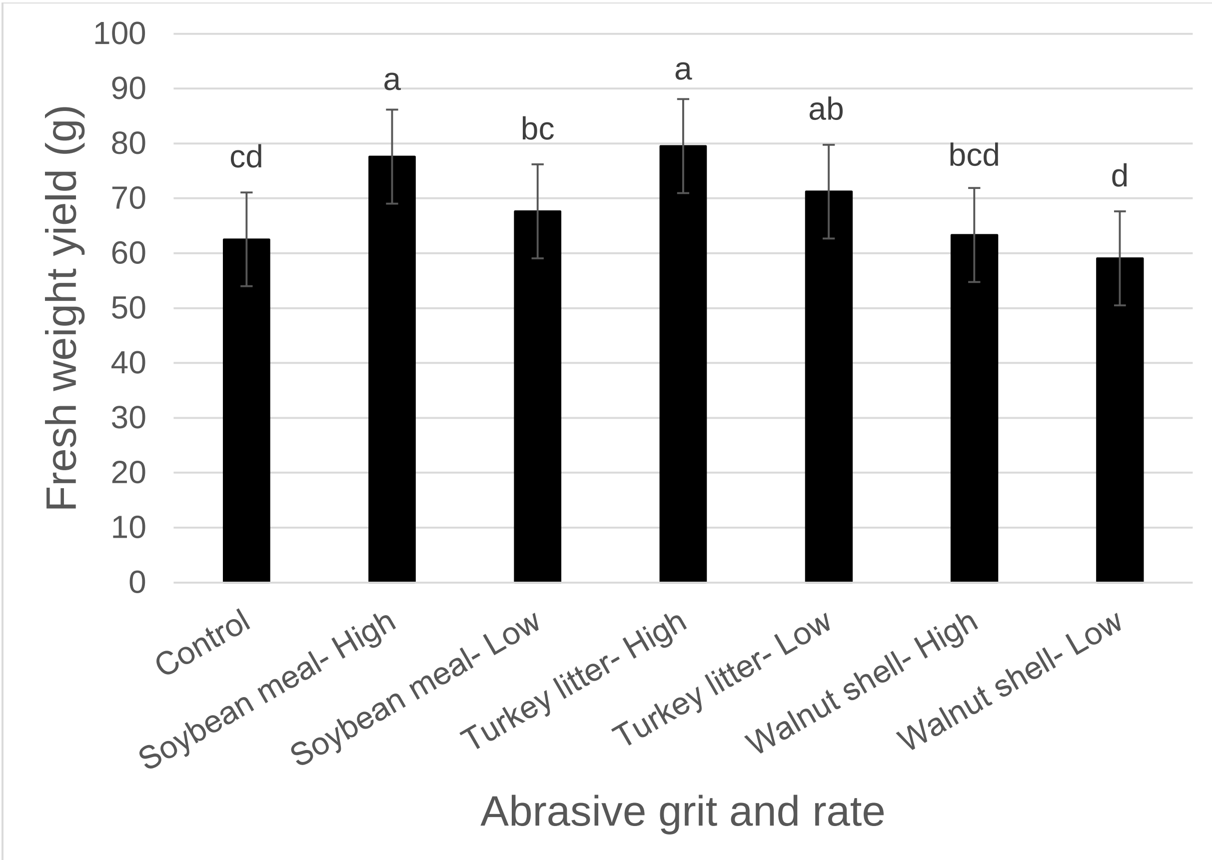

Figure 2.8: Yield, represented as the fresh weight of harvested leaves totaled by season, for each of the abrasive grit/rate treatments. Error bars represent +/- one standard error of the least squares mean. Different letters indicate significant difference among treatments ($p<0.05$).

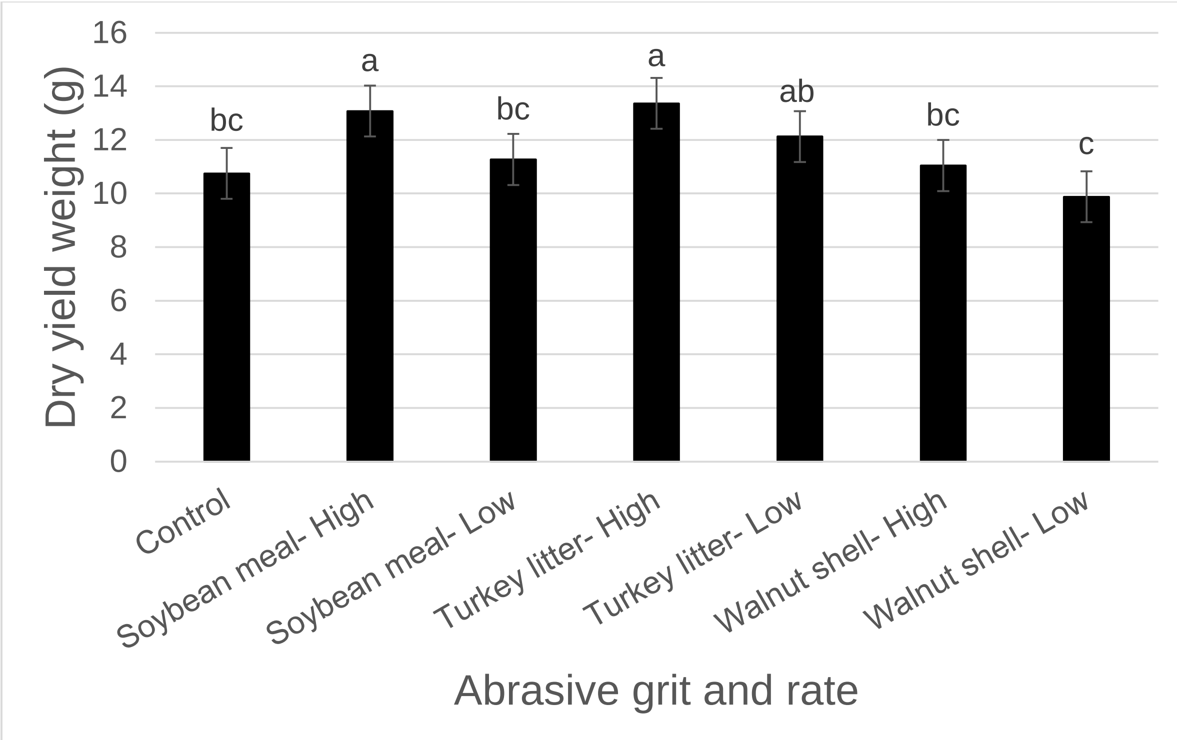

Figure 2.9: Yield, represented as the constant, or dry weight of harvested leaves totaled by season, for each of the abrasive grit/rate treatments. Error bars represent +/- one standard error of the least squares mean. Different letters indicate significant difference among treatments ($p<0.05$).

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