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AIR-PROPELLED ORGANIC FERTILIZER GRITS CAN BE USED TO CONTROL WEEDS AND PROVIDE NITROGEN

BY

MICHAEL CARLSON

A thesis submitted in partial fulfillment of the requirements for the

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Major in Plant Science

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2018

AIR-PROPELLED ORGANIC FERTILIZER GRITS CAN BE USED TO CONTROL WEEDS AND PROVIDE NITROGEN

MICHAEL CARLSON

This thesis is approved as a credible and independent investigation by a candidate for the Master of Science in Plant Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Sharon A. Clay, Ph.D. Thesis Advisor	Date
David Wright, Ph.D. Head, Agronomy, Horticulture and Plant Sciences Department	Date
Dean, Graduate School	Date

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CONTENTS

ABBREVIATIONS

b	slow pool nitrogen mineralization rate
°C	degrees Celsius
GDD	growing degree days
g plant^{-1}	grams per plant
kg ha^{-1}	kilograms per hectare
mm	millimeters
mm day^{-1}	millimeters per day
N_a	available nitrogen in the active pool
plants m^{-2}	plants per meter squared
µg N g soil^{-1}	micrograms of nitrogen per gram soil
µg N g soil^{-1} day^{-1}	micrograms of nitrogen per gram soil per day
y_0	baseline nitrogen

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ABSTRACT

AIR-PROPELLED ORGANIC FERTILIZER GRITS CAN BE USED TO CONTROL WEEDS AND PROVIDE NITROGEN

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2018

Weeds are one of the biggest challenges for organic growers because of the alternative weed control methods. Air-propelled abrasive grit management has been reported to control weed seedlings in corn and soybeans while maintaining yield. This research examined the weed control, corn and soybean yields, nitrogen mineralization, and nitrogen yield responses from grits. The grits used in this research included: Phytaboost Plant Food 7-1-2 (soybean meal), Sustane 8-2-4 and 4-6-4 (turkey litters), and two non-fertilizer grits: Agra Grit (walnut shells) and corn cob meal. Field studies were conducted from 2015 to 2017 in Aurora, SD, Beresford, SD and Morris, MN. Nitrogen mineralization and total nitrogen release from selected grits in two different soils were evaluated in 100 d incubations. The response of corn, wheat, red russian kale and velvetleaf to Sustane 8-2-4, Agra Grit and corn cob meal amended soil was investigated. Agra Grit consistently reduced in-row broadleaf weed biomass in all four site years, whereas when grass weeds were dominant, in-row weed biomass was not reduced with two grit applications. When grit treatments reduced in-row weed density, corn yield increased with fertilizer grits higher than the weed-free check. In-row weed biomass in soybeans was similar among treatments, but when total weed biomass was reduced, the soybean yields were 31 to 55% greater in the grit treatments than weedy checks. Organic fertilizer grits increased soil available nitrogen with 50 to 70% of nitrogen mineralized. Non-fertilizer grits immobilized soil available nitrogen. Plant height and dry weight of wheat, red russian kale, and velvetleaf were greater when the soil was amended with Sustane 8-2-4 compared with Agra Grit, corn cob meal, and no-grit control, although fresh weights and relative greenness were similar among treatments. The use of organic fertilizer grits provide a source for nitrogen for all plants in the targeted area, whereas non-fertilizer grits may immobilize nitrogen. Corn and soybean yields can be increased when two applications of air-propelled grits reduce weed density, regardless the type. Grits may provide nitrogen for the crop but weed control is critical as additional nitrogen also may stimulate weed growth.

CHAPTER 1.

INTRODUCTION.

1.1. Status of Organic Agriculture in the United States.

In the United States, organic agriculture has grown with consumers demand for food grown without chemicals. Producers have found that organic crop production is profitable (Derksen et al., 2002). The organic food industry sales grew at a faster rate, 10.8%, than conventional food industry, 2.2% in 2015 (OTA, 2016). Organic food sales expanded from $3.2 billion in 2008, to $6.2 billion in 2016 (Burns, 2016). While the organic food industry has increased in the past decade, the organic food sales were only 5% of total food industry sales in 2016 (USDA, 2017b). In the United States, 93% of organic food products are purchased in conventional and natural supermarkets (OTA, 2016), and 69 and 79% of families in South Dakota and Minnesota, respectively, purchased at least one organic product in 2015. The development of the organic food industry provides an opportunity for economic diversification for many farmers.

The increase in the organic food market has resulted in an increased number of farms producing organic products. The number of organic certified farms increased from 10,903 in 2008 to 12,634 in 2014, an increase of 1731 farms (USDA, 2017a); and across the country organic certified cropland expanded from 2.2 in 2008 to 2.7 million acres in 2016 (USDA ,2017a). Fresh food crops increased in acreage from 217,000 acres in 2008 to 305,000 acres in 2016 (USDA, 2017a). In the Upper Midwest, the acres of organic corn and soybeans declined 7% over the same time period (USDA, 2017b). This decrease contradicts the 2016 Ag Census on Organic Production, which found that 39%

of organic producers intended to increase their acres of organic production (USDA, 2015). In addition, large food companies, like General Mills, Ardent Mills, and Quaker Oats are looking to increase the amount of certified organic grains to fulfill their product needs (Roseboro, 2016). The decrease in organic acres may be linked to the difficulty of controlling weeds (Moynihan, 2016; Walz, 2004).

The increase in organic food sales has outpaced the expansion of organic food production, which helps create a premium for organic products. The price premium for organic certified corn and soybeans can be substantial when compared with conventional corn and soybeans (Moynihan, 2016). For example, organic feed grade corn price was \$8.33 bu^{-1} in November 2017, whereas a December 2017 corn contract was \$3.86 bu^{-1} (USDA, 2017c; CME, 2017a). The organic feed grade soybean price was \$17.08 bu^{-1} in November 2017, whereas in November 2017 conventional soybean grain contract price was \$9.57 bu^{-1} (USDA, 2017c; CME, 2017b).

The interest from organic growers and food companies to expand production of organic certified row crops, like corn and soybeans, justifies the increased research efforts of weed control for organic production.

1.2. Problematic weeds in corn and soybeans.

Many weeds consume resources more quickly and grow more rapidly than the crop (Deen et al., 2003). Across North America weed interference caused on average a 50% yield loss in corn trials (Soltani et al., 2016). The yield loss from corn is generally proportional to the number of weeds present but not always one-to-one. Gianessi et al. (2002) reported that for every kilogram of weed dry matter, there is a reduction of around one kilogram of corn dry matter. As the light, nutrients and water cannot be taken up both by the crop and weeds, the crop yield is reduced proportionally (Rajcan and Swanton, 2001). In soybeans, uncontrolled weeds are highly competitive as yield losses have ranged from 8 to 79% (Sikkema and Dekker, 1987; Van Acker et al., 1993), depending on weed emergence to crop, densities and weed species (Cowan et al., 1998; Dielman et al., 1996; Hamill et al., 2004; Hock et al., 2006). Soybean yield loss from weed competition for light, water and nutrients and also nonresource limiting factors like light quality have also been documented to affect soybean growth (Harper, 1977; Green-Tracewicz et al., 2011, 2012). More recent research suggest crops may respond to weeds at a genetic level. Horvath et al. (2015) reported that the *PHYTCHROME INTERACTING FACTOR 3* gene in soybeans was upregulated in plots with weed stress and suggested that this gene, in relation to genes involved in shade avoidance response to Arabidopsis, is important for the response of soybeans to weeds.

Studies have documented weed interference in corn depends on the species of weeds, row spacing, emergence of weeds and location of the weed in comparison with the crop (Van Delden et al., 2002; Murphy et al., 1996; Mulugeta and Boerboom, 2000; Cardina et al., 1995; Donald and Johnston, 2003). In corn, broadleaf weeds exhibit varying degrees of interference on corn growth and yield. The pigweed species (*Amaranthus* spp.) are troublesome in corn and widespread in the Midwest (Bridges and Anderson, 1992; Knezevic et al., 1994, 1997). Redroot Pigweed (*Amaranthus* *retroflexus*) has been documented to reduce corn yield by at least 5% in Canada with only 0.5 plants m^{-1} row when emerged at or before the 4-leaf corn stage, whereas redroot pigweed emerging after the 7-leaf corn stage did not reduce corn yield (Knezevic et al., 1994). Clay et al. (2005b) reported that redroot pigweed reduced corn yield up to 14% in one year across all planting dates, but there were no differences in corn yield with redroot pigweed interference in the other year. Common waterhemp (*Amaranthus rudis*) has been reported to reduce corn yield by 56% with a density of 11 plants m^{-2} (Bensch et al., 2003). Common lambsquarters (*Chenopodium album*) has been reported to be a common weed in corn in the Midwest (Forcella et al., 1992). The corn yield loss from common lambsquarters varied across the Midwest, depending on location, weed density and emergence timing of the weed (Fisher et al., 2004). The reduction of corn yield from velvetleaf (*Abutilon theophrasti*) varies, as Scholes et al. (1995) reported up to 33% yield loss, whereas Clay et al. (2005b) reported velvetleaf that emerged early in the corn crop before V2, reduced corn yield up to 10%.

Grass weeds also interfere with a corn crop in varying degrees. Barnyardgrass (*Echnichloa crus-galli*) sown before corn emergence has been reported to reduce corn yield up to 30% in South Dakota (Clay et al., 2005b) and up to 26 to 35% in Canada (Bosnic and Swanton, 1997). Plants in the foxtail family (*Setaria* spp.) are common weeds in Midwest corn fields (Bridges and Anderson, 1992). Giant foxtail (*Setaria faberi*) has been reported to reduce corn yield up to 40% with 100 plants m^{-1} row in Michigan (Fausey et al., 1997), whereas in Wisconsin 168 plants m^{-1} row did not reduce corn yield (Langton and Harvey, 1994). Green foxtail (*Setaria viridis*) that emerges within a few days of corn emergence had a maximum range in yield reductions from 31 to 49% and may have competed for water in a dry year (Weaver, 2001).

Broadleaf weeds have been documented to cause varying degrees of yield loss (Shurtleff and Coble, 1985; Weaver, 2001; Bensch et al., 2003). Palmer Amaranth (*Amaranthus palmerii*), common waterhemp, and redroot pigweed at population of 8 plants m^{-2} reduced soybean yield by 79, 56 and 38%, respectively (Bensch et al., 2003). Clay et al. (2005b) reported that redroot pigweed cohorts that were planted early at a density of 1.3 plants m^{-2} reduced soybean yield only in one year of a two-year study, whereas late plantings did not influence yield. Common waterhemp in a soybean crop for four weeks reduced yield by 13% whereas season long interference reduced soybean yield up to 43%, with varying densities from 239 to 1315 plants m^{-2} during a three-year study (Hager et al., 2002). Velvetleaf interference in soybean has been reported to reduce yield from 33 to 46% when velvetleaf emerged at the same time as the crop (Clay et al., 2005b). Lindquist et al. (1995) reported that velvetleaf at different densities did not influence soybean yield when velvetleaf competitiveness was reduced due to pathogen infection. Harrison (1990) documented that in ideal conditions a common lambsquarters density of two plants m^{-1} row for five weeks, or one plant m^{-1} row for 7 weeks reduced soybean yield by more than 5%. Additional research in common lambsquarters interference in soybean determined that maximum yield loss up to 61% was dependent on the density when weeds emerged at the same time as the crop (Conley et al., 2003). Time of removal also influenced yield loss of soybean with up to a maximum yield loss of 20% from common lambsquarters left in crop for up to 10 weeks, whereas when common lambsquarters were removed earlier at 3, 5, and 7 weeks, the soybean yield was not reduced.

Barnyardgrass at a density of 13 weeds m^{-2} had no effect on soybean yield when planted before, at, or after soybean emergence (Clay et al., 2005b). However, a density of 100 plants m^{-2} reduced soybean yield from 99 to 32% when barnyardgrass emerged with the soybeans or at V2 (Cowan et al., 1998). Vail and Oliver (1993) reported that barnyardgrass densities of 42, 100, and 250 plants m^{-2} that emerged with soybean, reduced soybean yield by 10, 25, and 50% respectively. Green foxtail is a more vigorous competitor with soybeans than barnyardgrass and has been reported to reduce soybean yield up to 80% with a density of 128 plants m^{-2} (Weaver, 2001). The lower density of weeds needed to reduce soybean yield in green foxtail compared with barnyardgrass suggest that a single green foxtail plant reduces soybean yield more than a single barnyardgrass plant. Volunteer corn has been reported to reduce soybean yield in 76 cm rows by 10% with only 4 plants m^{-2}, and by 51% from 44 plants m^{-2} (Alms et al., 2015). Narrow row soybeans, 19 cm, with 0.5 volunteer corn plants m^{-2} reduced soybean yield by 10%, and 16 plants m^{-2} reduced soybean yield by up to 41% (Marquadt et al., 2012).

Weed interference in corn and soybeans occurs in varying degrees depending on weed species, weed density, and crop growth stage. For many crops the greatest yield reduction occurs during the early crop growth stages. As organic certified growers cannot utilize synthetic chemicals to control weeds, research should be focused on methods to control weeds during the early growing season.

1.3. Importance of early season weed control.

Weeds interfere with crops in different ways; by reducing yield, reducing harvest efficiency, and contaminating grain, which can lead to dockage (Hartzler, 2003). Weeds that emerge before or with the crop have the greatest interference with crops, and the yield reduction from weed interference depends on the duration the weeds are present in the crop (Bosnic and Swanton, 1997; Cowan et al., 1998; Knezevic et al., 1994).

The critical period of weed control (CPWC) has been defined multiple ways as a "span of time between that period after seeding or emergence when weed competition will no longer reduce crop yield" (Zimdahl, 1988), or as the time interval needed to keep a crop weed free to prevent yield loss (Swanton and Weise, 1991), or the estimated duration of weed control needed to prevent crop yield loss from weed interference (Hall et al., 1992). In the first part of the growing season, right after crop emergence, the available resources, light, water and nutrients are typically adequate for weed and crop growth. As both crops and weeds grow during the season there is a continued and increasing demand on limited resources. Thus, when weeds begin to interfere with crop growth marks the beginning of the CPWC (Norsworthy and Oliveira, 2004). The latest time the crop needs to be weed-free to prevent yield loss is the end of the critical weed free period (Norsworthy and Oliveira, 2004).

The time frame for CPWC in corn varies depending on study parameters. Hall et al. (1992) determined that the beginning of CPWC in corn ranged from the V2 to V6 growth stages (Ritchie et al., 1997). The range of the beginning of the CPWC was attributed to the different environments, and weed species and densities present at each study location. A study of CPWC in no-till corn differed with the beginning at the 6-leaf stage and the end ranging from the 9- to 13-leaf stage (Halford et al., 2001). Norsworthy and Oliveira (2004) determined that the CPWC in corn varied with weed density, species, or planting dates of corn. They reported that the CPWC began at V1- up to the V5-leaf corn stage and ended at the V5- to V10-leaf stage. A study of CPWC of corn in the Midwest determined that the beginning of CPWC ranged from emergence to V7-leaf stage with the end ranging from V5- to R1-anthesis (Evans et al. 2003). Evans et al. (2003) determined that the large variation of CPWC was due to the differences in nitrogen fertilizer, as the increase in nitrogen from 0 to 120 kg ha^{-1}, delayed the beginning and shortened the ending of the CPWC.

Moriles et al. (2012) studied interference in corn growth, yield and gene response from low light (40%) shade, nitrogen, and weed stresses. The low light present until V2 leaf stage reduced corn biomass greater than 50% at V2, and at V12 light-stressed plants still were smaller than nonstressed plants. Grain yields of shaded and non-shaded plants were similar unless shade was present in the crop up to V8. Nitrogen stress did not have an effect on vegetative growth but did reduce grain yield by 40%. In both years, weed stress up to V6 reduced corn grain yield, but only in one of the years did weed stress up to V2 reduce corn vegetative growth. Principle component analysis was used to determine the differential expressed genes of weed and shade stressed plants. Plants under weed or shade stress had more gene expression patterns in common than nonstressed or nitrogen stressed plants, which could mean that the shade from weeds present in corn could be a major reason why weeds reduced corn yield. Hansen et al. (2013) reported that in response to plant population corn down regulated photosynthesis.

The CPWC in soybeans also varies depending on growing conditions and location. In Ontario, the critical weed free period was observed from emergence to the 4^{th} trifoliate stage, V4, and the critical time of weed removal ranged from V2 to R3 (Van Acker et al., 1993). Halford et al. (2001) documented that CPWC in no-till soybeans began at V1- to V2-leaf stage and ended at the R2 growth stage, which was longer than in conventionally tilled cropping systems. The critical time of weed removal in soybeans varied depending on row width. Knezevic et al. (2003) reported that the critical time of weed removal began at V2 in wide row (76 cm) and V4 in narrow row (19 cm) soybeans. In glyphosate resistant soybean cropping systems, after an application of glyphosate at V2, the critical time of weed removal began at R1 in narrow (19 cm) rows and V5 in wide (76 cm) rows (Mulugeta and Boerboom, 2000). Soybeans planted in wide rows reduce early season crop tolerance to weeds, which need earlier weed management than in narrow rows (Knezevic et al., 2003). Green-Tracewicz et al. (2012) determined that the CPWC in soybean in low red-far red light, which was used to mimic a weedy field setting, was V1 to V3 growth stages and soybeans had increased shoot internode length and a reduction of soybean biomass accumulation.

1.4. Organic weed control methods.

Organic weed control has been ranked as a high priority by organic producers (Jerkins and Ory, 2016), in Europe (Peigne et al., 2015), and North America (Moynihan, 2016). The challenges with weed control in organic cropping systems stems from the requirement that commercial produced pesticides not be applied to organic fields (Greene, 2016). Because synthetic chemicals are not used, organic producers must rely on alternative methods for weed control. Alternative weed control methods employed by organic producer's center around cultural and physical weed control methods.

Cultural weed control can be defined as a collection of methods to reduce weed competition by enhancing the competitive ability of the crop (Barberi, 2002). Creating a cropping sequence that alternates between different season crops, differences in nutrient needs, and cover cropping can help prevent the creation of a highly specialized weed community (Buhler, 1999). By creating a flexible cropping system, the risk of a weed community adapting to a specified system is reduced (Barberi, 2002). A common cultural weed control method is the use of a dense cover crop mat to suppress weeds (Carr et al., 2013; Mirsky et al., 2011; Mischler et al., 2010; Teasdale et al., 2007). The cover crop used to suppress weeds in organic systems hinges on the need for a heavy cover crop biomass. However, certain cover crops, such as rye grass, may regrow and compete with the crop (Mischler et al., 2010; Clark et al., 2017). The cover crop may also immobilize nitrogen in the cropping system depending on time of termination (Smeltekop et al., 2002), which can have a negative impact on organic corn in Missouri (Clark et al., 2017). The variety of crops used for cultural weed control change the planting time. In addition, differences in tillage and seedbed preparation timing will control weeds that germinate at different times in the growing season and will lower the density of weeds in the crop row (Melander et al., 2005). The diversification of cropping systems has been documented to provide long-term weed management in organic systems in the U.K. (Welsh, 1999).

Common cultural weed control methods are to vary the planting dates, population and row spacing. Narrow row spacing has been documented to reduce weed biomass and interference (Malik et al., 1993; Yelverton and Coble, 1991). Weed biomass has been reported to decrease when crop densities increase (Mohler, 1996). The effectiveness of high crop densities to suppress weeds depends on the biology of the crop and weeds (Mohler, 2001). Weiner et al. (2001) reported that increased spring wheat density and uniform planting decreased weed biomass by 60%. In Michigan with soybeans planted on 76-cm rows, weed biomass was lowest when soybeans were planted at 432,000 seeds ha^{-1}, compared with 308,000 and 185,000 seeds ha^{-1} (Rich and Renner, 2007). Place et al. (2009) reported that increasing the soybean seeding rates from 432,000 to 556,000 seeds ha^{-1}, on 76-cm rows improved weed control. While narrow row spacing and increasing planting densities have been reported to decrease weed interference, 85% of corn growers, and 44% of soybean growers in Minnesota and Iowa plant on 76-cm rows (Dupont Pioneer, 2014; Jeshke and Lutt, 2017). Producers chose to plant soybeans into 76-cm rows in order to use existing corn planting equipment, and reduce the potential for disease pressure, with more air movement through the canopy with wide than narrow rows, and to allow for inter-row cultivation (Jeshke and Lutt, 2017).

Weed management and control methods must be able to response to growers needs and many physical weed control methods can work within the short weed control timeframe. Physical weed control has been defined as the removal of weeds by physical or mechanical means, such as tillage or flaming. Many physical weed control methods, such as tillage, are employed before crop emergence to provide a weed free seed bed at planting (Leblanc and Cloutier, 1996; Forcella, 2014). This is achieved by cultivating prior to planting (Boyd et al., 2006). The optimum timing for cultivation or tillage for weed control in crops depends on the competitive ability of the crop (Turner et al., 1999) and weed growth stage (Pullen and Cowell, 1997). Early season tillage has been documented to reduce weed interference in crops (Cirujeda et al., 2007). The control of weeds depends on the depth at which the weed seeds were buried and the size of the weed (Baerveldt and Ascard, 1999), but it has also been found that burying broadleaf weeds to greater than 1-cm or cutting the weeds at the surface are excellent mechanical weed control methods (Jones et al., 1995, 1996).

While mechanical weed control is effective in controlling weeds between-rows, in-row weed control is a major problem for organic growers (Van Der Weide et al., 2008). The most common mechanical in-row weed control methods are hand cultivating, harrowing, finger and torsion weeders, and weed blowers. Harrowing field crops occurs across the whole field, rather than just in the crop row, and is used to kill weeds that have just emerged before or after planting (Lampkin, 1990). If harrowing is performed post-emerge to the crop, harrowing can cause crop injury (Kurstjens and Perdok, 2000).

Rasmussen (1998) documented that additional passes with a harrow reduced post-emergence weed density and biomass in wheat, but decreased yield because of soil coverage on the crop. In additiona, added cultivations can stimulate weed germination (Kees, 1962). Torsion and finger weeders control weeds in the crop row by burying (Kurstjens and Bleeker, 2000) or uprooting the growing weeds (Bleeker et al., 2002). Torsion and finger weeding are gentler on the crop than harrowing but they need accurate steering to minimize damage to the crop (Van Der Weide et al., 2008). Weed blowers, like the Pneumat system, work by blowing the weeds in the crop row up and out of the soil (Lutkemeyer, 2000). The Pneumat system also needs precise steering and slow driving as the increase in speed has been found to increase crop damage (Van Der Weide et al., 2008).

Flame weeding is another physical method of weed control and can be defined as the use of propane burners to generate temperatures of up to 1900°C which raises the temperature of the leaves rapidly and kills them without burning, as the plant cells are ruptured (Ascard, 1995). Flame weeding can be used when the soil is too wet for mechanical control (Bond and Grundy, 2001) and has no soil disturbance, which can reduce the number of weed seeds in the germination zone. Flame weeding can be performed both pre- and post-emerge as a non-selective weed control method, but the lack of selectivity can lead to problems in crop safety (Ascard, 1995). Pre-emergence can provide enough weed suppression for fast growing crops to get to canopy (Cisneros and Zandstra, 2008), but does not provide a residual control to avoid yield reduction from late emerging weeds (Ascard, 1995). An application rate of 94 to 112 liters per hectare of propane provided 90% control of broadleaf weeds, such as velvetleaf, redroot pigweed, common waterhemp and kochia, when flamed at less than the 5-leaf weed growth stage (Knezevic and Ulloa, 2007). Using the same rate to control broadleaf weeds provided 80% control of grass species, such as yellow and green foxtail, and barnyardgrass (Ulloa et al., 2010 a, b). Post-emergence flaming is time sensitive to avoid crop damage (Campbell, 2004). Heat tolerant plants, like corn, can have the flame directed at the base of the plant to control in-row weeds up to the V10 growth stage (Diver, 2002). These post-emergent flaming applications can be performed under a hood for heat-sensitive plants, like soybean, to minimize crop damage (Ascard, 1995). Soybeans must be mature enough to allow post-emergent flaming applications that do not damage the leaves of the crops, which can pose problems with flame weeding as weeds are best controlled at the seedling growth stages with the growing point at the apex (Cisneros and Zandstra, 2008; Knezevic and Ulloa, 2007).

Despite advances in physical weed management, organic growers are not completely satisfied with the tools available and the suppression of weeds achieved (Baker and Mohler, 2014). Weed control research needs to update existing weed management strategies for better control in organic crop production (Cloutier et al., 2007; Van Der Weide et al., 2008; Harker and O'Donovan, 2013) and focus on the efficacy of integrated weed management (Leibman and Davis, 2009).

Air-propelled abrasive grit management was first proposed by Norremark et al. (2006). Forcella (2009a, b, 2012) demonstrated that agricultural grits, like corn cob meal and walnut shells, can control weed seedlings just as effectively as non-agricultural derived grits, like sand, in both greenhouse and field settings. In field settings of corn, the use of two in-row grit applications early in the season reduced weeds and increased corn grain yields (Forcella, 2012) and maintained high corn silage yields (Erazo-Barradas, 2016). Early in-row grit applications had varying effects on weed control and corn grain yield depending on application timing and frequency (Erazo-Barradas et al., 2017). Forcella (2013) demonstrated that soybeans can tolerate in-row grit applications at early growth stages, after the VC growth stage. The early season in-row grit applications from VE to V2 soybean growth stages reduced dry weed biomass to be statistically similar to the season-long weed-free check, and no single or combination of grit applications reduced soybean yield (Forcella, 2013).

While propelled abrasive grit management has been proven to control weeds and maintain or not reduce crop yields, previous studies have focused on the use of grits from corn cobs, or walnut shells. However, the use of products that contain nitrogen may control weeds and reduce nutrient losses. Wortman (2015) and Braun (2017) documented that the organic fertilizer soybean meal controlled in-row weeds just as well as non-fertilizer grit sources, like corn cob meal that had previously been used in field research. In-season use of organic nitrogen amendments like composted poultry manure increased lettuce yield by up to 175% (Little et al., 2015) and corn yield was similar when amended with poultry litter compared with conventional fertilizer (Sistani et al., 2008). Soybean meal and turkey litter have been documented to provide an additional 35 to 105 kg N ha^{-1} (Wortman, 2015) in a vegetable production system when applied as a grit to control weeds. The effect on crop yield and weed control with organic fertilizers, like soybean meal, and turkey litter, have not been studied in air-propelled abrasive grit organic corn or soybean cropping systems.

1.5. Organic nitrogen sources release nitrogen at varying rates.

Supplemental nitrogen sources approved for use in organic cropping systems include animal byproducts, such as feather meal, fish meal, blood meal, animal manure and litter, compost and seed meals, such as soybean meal (OMRI, 2017). The nitrogen release rates of many organic amendments have been measured in laboratory soil incubations (Agehara and Warnacke, 2005; Flavel and Murphy, 2006; Pansu et al., 2003). The nitrogen supply for organic amendments depends on the initial availability of inorganic nitrogen present in the amendments and the long-term rate of mineralization or immobilization (Flavel and Murphy, 2006). Understanding and managing the nutrient cycling from organic amendments depends on the decomposition rate and the influence on the nitrogen processes in the soil (Ambus et al., 2002; Gabrielle et al., 2004). By understanding nitrogen mineralization rates organic producers can match the release pattern to the plant requirement (Flavel and Murphy, 2006).

The carbon to nitrogen ratio (C:N) of composts and plant residues has been used predict how much nitrogen will be mineralized (Sikora and Szmidt, 2001; Nicolardot et al., 2001; Hadas et al., 2004). Determining the quality of the carbon and nitrogen rather than just the total amounts have the greatest influence on decomposition (Kogel-Knaber, 2002; Vigil and Kissel, 1995; Wang et al., 2004; Flavel and Murphy, 2006). Pelletized poultry litter, vermicompost, straw based compost and two green waste composts, all with differing C:N ratios, were incubated in soil, the long-term mineralization rates were similar but the amount of nitrogen and the time at which inorganic nitrogen was released differed (Flavel and Murphy, 2006).

The nitrogen availability of organic amendments is dependent on its chemical composition because of the biological decomposition required to make the nitrogen available for plants (Fox et al., 1990; Ajwa et al., 1998; Kumar and Goh, 2003). Nitrogen availability of organic amendments is also dependent on the soil environment (Sims, 1986; Vigil and Kissel, 1995; Seneviratne et al., 1998; Whalen et al., 2001; Cookson et al., 2002) including soil moisture and temperature (Agehara and Warnacke, 2005; Hartz and Johnstone, 2006; Gaskell et al., 2006). Nitrogen mineralization differed among organic fertilizers and incubation temperatures from 10 to 25°C, as more nitrogen mineralized at higher temperatures (Gaskell et al., 2006). Studying release of nitrogen from organic amendments can help better implement effectiveness of supplemental nitrogen applications in organic systems (Poffenbarger et al., 2015). Unlike synthetic fertilizers, studying nitrogen mineralization from organic can be difficult because of the chemical variability in organic fertilizers (Gaskell and Smith, 2007).

Organic fertilizers typically contain 5 to 15% nitrogen and generally release this nitrogen over a period of three months (Stadler et al., 2006; Sexton and Jemison, 2001). Sustane® turkey litter is an aerobically composted turkey litter approved for use as U.S. organic fertilizers (Sustane, 2016). Turkey litter has been documented to have different nitrogen release rates in different soil types (Sistani et al., 2008; Gordillo and Cabrera, 1997). In a field experiment, raw poultry litter had a similar pattern of NH_4 release as a NH_4NO_3 fertilizer amendment, whereas NO_3 was released from poultry litter compost in the first year (Cooperbrand et al., 2002). While turkey litter has been studied and reported to be a viable nitrogen source for crops, the composted Sustane turkey litter does not have published nitrogen mineralization rates, which could be different from earlier work done in turkey litter because of the sources of turkey litter are different and composting processes vary (Gaskell and Smith, 2007).

Phytaboost Plant Food 7-1-2 has been suggested as a viable option to provide nitrogen to crops while weeding in the row with propelled abrasive grit management system (Forcella et al., 2010; Wortman, 2015). Soybean meal requires microbial mineralization before crops can take up the nitrogen, but is generally fast release (Mikkelsen and Hartz, 2008). In a study of greenhouse tomato transplants, soybean meal increased shoot dry weight and was similar to other crop seed meals (Gagnon and Berrouard, 1994). In field settings soybean meal applied at 168 kg N ha^{-1} returned 75% of nitrogen applied over three months (Sexton and Jemison, 2011). The differences in rate of mineralization of soybean meal when applied as a propelled abrasive grit for weed control should be further studied to understand how this organic fertilizer will affect both crop and weed growth.

Walnut shells, such as Agra Grit, have been investigated for their use as a propelled abrasive grit to control weeds (Braun, 2017; Wortman, 2015). Previous studies using walnut shells did not determined its nitrogen mineralization rate. If it is to be used as a grit for weeding, the influence of walnut shells on soil nitrogen and plant uptake should be studied to determine the effect on crop yield and weed control.

1.6. Variable weed response to nitrogen.

Nitrogen is the most difficult nutrient to manage for organic crop production and for non-legume plants to obtain from the soil (Mikkelsen and Hartz, 2008). Developing and understanding fertilization strategies that enhance the competitive ability of the crop and minimize weed competition is important (Cathcart and Swanton, 2003; DiTommaso, 1995). Blackshaw and Brandt (2008) suggested that nitrogen fertilization strategies that favor crop growth over weeds are needed. Blackshaw et al. (2003) reported that depending on weed species, the response to nitrogen varied for shoot biomass, but overall increasing nitrogen increased shoot biomass of most weeds. It has also been suggested that common lambsquarters, redroot pigweed and green foxtail, may be disadvantaged by targeted fertilizer applications (Blackshaw et al., 2003). In a long-term no-till study, the increased application of nitrogen fertilizer decreased foxtail grass weeds in South Dakota (Anderson et al., 1999). Sweeney et al. (2008) reported that the influence of nitrogen on weed germination and growth was species dependent as well as influenced by environmental conditions and seed source, but generally, increased nitrogen increased weed biomass in the field. The variation in weed and crop response to nitrogen should be studied especially when a new method of organic fertilizer delivery is meant to also control weeds.

Nitrogen has widely been documented to have a positive effect on corn growth and yield (Shapiro and Wortman, 2006; Licht and Al-Kaisi, 2005; Noellsch et al., 2009; Tremblay et al., 2012). Mitchell and Tu (2005) reported that the use of poultry litter as a primary nitrogen fertilizer in corn was similar to the use of a synthetic ammonium nitrate. Wheat response to nitrogen depends on location and timing of nitrogen application (Maidl et al., 1998; Chen et al., 2008). Wheat response to poultry litter was generally lower when compared to synthetic nitrogen fertilizer, such as urea, in a study in Arkansas (Slaton et al., 2008). Velvetleaf has exhibited a positive response to nitrogen fertilizer and it decreased corn yield when it emerged early in the growing season (Barker et al., 2006). Velvetleaf has been reported to have a positive biomass response when composted poultry litter was added to the soil, most likely due to the added nitrogen, as velvetleaf did not respond to just phosphorus added to the soil (Little et al., 2015). Braun (2017) reported an increase in fresh yield, dry weight and leaves harvested from red russian kale when turkey litter was applied. These species show a positive response to nitrogen and poultry litter products, and they should be investigated to understand the growth response from Sustane turkey litter and grits with high C:N that could be used in propelled abrasive grit management.

1.7. Hypothesis and Research objectives.

The hypotheses of these studies were that the use of various abrasive grits, turkey litter, walnut shells, and soybean meal, applied at early growth stages of corn and soybeans will decrease weed interference with a concomitant increase in crop yield. In addition, corn treated with grits that have higher nitrogen content will experience increased crop growth and yield due to increased nitrogen availability.

The overall objective of this study was to test the efficacy of different grits used in air-propelled abrasive grit management to provide in-row post-emergent weed control. Between-row weed control was accomplished by flaming or cultivation. The novelties of this research include the different grits used for abrasion in both corn and soybeans. Mineralization rates of nitrogen release from grits applied at several rates used in air-propelled abrasive grit were examined in laboratory incubations. In addition, the growth response of selected plants to grits applied in the soil was examined in greenhouse studies.

CHAPTER 2.

Evaluation of weed control and yield of corn and soybeans with organic fertilizers and walnut shells as air-propelled abrasive grits.

2.1. Abstract.

Weed interference in organic cropping systems is the number one problem for organic producers, and current organic-compatible weed control methods do not provide enough control. Abrasive grit management is a new physical weed control method that uses grit to abrade the tissue of small weeds and has been documented to reduce weed density and biomass while increasing corn yields. This research examined the weed control and crop yield of corn and soybeans with three organic fertilizer type grits: Phytaboost Plant Food 7-1-2 (soybean meal), Sustane 8-2-4 and 4-6-4 (turkey litter), and one non-fertilizer grit, Agra Grit (walnut shells). Grits were applied twice in-row during the critical weed-free period, at V2 and V5 in corn and V1 and V3 in soybean. Between-row weed control was done by cultivation or flaming. Agra Grit was the only grit treatment in corn to reduce in-row weed biomass from 23 to 87%, although when grass weeds were dominant, in-row weed biomass was not reduced. When in-row weed density was reduced, corn yields increased with fertilizer grit treatments, generally having yields greater than the weed-free check treatment. In soybeans the in-row weed biomass did not differ among all treatments in any of the six site-years, but when total (in-row + between-row) weed biomass was reduced, grit treatments had higher yields than the season-long weedy check.

2.2. Introduction.

Organic certified cropland acres have increased from 2.2 million in 2008 to 2.7 million acres in 2016 (USDA, 2017a). The increase in certified organic acres also matches the interest by large food companies in expanding the number of organic grain crop acres in the United States (Roseboro, 2016). Weeds have been ranked as very to extremely problematic by organic producers in North America (Moynihan, 2016; Walz, 2004) and have been ranked as the top research priority by producers (Jerkins and Ory, 2016). Even with the advances in physical weed management, organic producers are not satisfied with available methods of weed control (Baker and Mohler, 2014) and are interested in new methods.

Air-propelled abrasive grit management is an emerging method for in-row physical weed control that uses grits to abrade leaf and stem tissues, which can kill small weeds (Forcella, 2009a). Norremark et al. (2006) proposed this idea, which differs from the air-compression Pneumat system, proposed by Lutkmeyer (2000), that only uses compressed air to blow the weeds in the crop row up and out of the soil. Agricultural grits, such as walnut shells and corn cobs, have been reported to control broadleaf weed seedlings, just as effectively as sand, in both greenhouse and field settings (Forcella, 2009a, b, 2012; Forcella et al., 2010). Two applications of grit in the corn row and cultivation between the rows during the early growing season reduced weed biomass and increased corn grain yield (Forcella, 2012). Erazo-Barradas et al. (2017) reported that two applications of in-row grit and between-row cultivation or flaming provided the best season-long weed control and highest grain yield of corn. Early season in-row grit applications in soybean from VE to V2 growth stages reduced dry weed biomass to be similar to the season-long weed-free check, and did not reduce soybean yield (Forcella, 2013).

Previous studies have focused primarily on the use of corn cobs and other low-N grits to control weeds in the crop row using propelled abrasive grits. However, nitrogen is the most difficult nutrient for organic producers to manage (Mikkelsen and Hartz, 2008). Forcella et al. (2010) and Wortman (2014) suggested that organic fertilizers may provide similar weed control as low-N grits and double as a nitrogen fertilizer application. The placement of organic fertilizer grits in the crop row rather than as a broadcast application could reduce weed nitrogen uptake and thereby limit weed biomass (Blackshaw, 2005). Organic soybean meal, a nitrogen fertilizer, was reported to provide similar weed control as corn cobs when used as an abrasive grit (Wortman, 2015; Braun, 201), and depending on application rate, it has been calculated to provide an additional 35 to 105 kg nitrogen ha^{-1} (Wortman, 2015). Poultry litter when banded next to the corn row generates greater corn yield and nitrogen uptake than a broadcast application of poultry litter (Adeli et al., 2012). Turkey litter has been reported to reduce in-row weeds in field-grown organic tomato and pepper crops, and also increase yield of kale in greenhouse settings (Braun, 2017). The ability to both control weeds and provide nitrogen fertilizer for organic crops could help reduce production costs (Forcella et al., 2010). Organic nitrogen fertilizers as propelled abrasive grits have been studied recently in organic vegetable crops but have not been studied in agronomic crops, such as corn and soybean.

The goal of this study was to evaluate the combination of different in-row air-propelled abrasive grits, including organic fertilizers such as Sustane® turkey litter and Phytaboost Plant Food soybean meal, in combination with between-row flaming or cultivation for weed control and evaluate their effects on corn and soybean yield. The specific objectives of this study were to determine the effects of grit type on (i) weed control, (ii) weed biomass, (iii) corn nitrogen relative greenness and stem diameter, (iv) and corn and soybean grain yield.

2.3. Materials and Methods.

Corn.

Field studies were planted into conventionally managed fields in 2015 and 2017 at the Swan Lake Research Farm in Morris, MN (45°40'N, 95°48'W), and into fields in transitioning into organic production in 2016 and 2017 at the Aurora Research Field Station in Aurora, SD (44°18'N, 96°40'W), providing four site-years of corn production (Table 2.1).

The soil type at Morris was a Barnes loam (fine, loamy, mixed, Pachic Udic Hapludoll). This soil is very deep and well drained with saturated zones occurring within a depth of 1 to 1.5 meters. The sand, silty, and clay content is 390, 370 and 240 g kg^{-1}, respectively, with an organic matter content of 106 g kg^{-1}. The soil was formed from glacial sediments from the late Wisconsin glaciation.

Table 2.1. Field research location descriptions, city and state, organic certification status and soil information at Aurora Research Field Station, Swan Lake Research Farm, and Southeast Research Farm.

Research Location	City, State	Organic Status	Soil Description
Aurora Research Field Station	Aurora, SD	In transition	Brandt silty clay loam, 0-1 percent slope (Fine-silty, mixed superactive, frigid Calcic Hapludoll)
Swan Lake Research Farm	Morris, MN	Conventional	Barnes loam, 0-1 percent slope (fine-loamy, mixed, Pachic Udic Hapludoll)
Southeast Research Farm	Beresford, SD	Organic Certified	Egan- silty clay loam 0-1 percent slope (fine-silty, mixed, mesic Udic Haplustolls

The soil type in Aurora is a Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludoll). This soil is very deep, well drained and was formed from silty materials that overlay sand and gravel in outwash plains, the permeability is moderate in the upper part and very rapid in the underlying materials. The sand, silty, and clay content is 300, 490, 210 g kg^{-1}, respectively, with an organic matter content of 150 g kg^{-1}. The field has a 0 to 1% slope.

The individual treatments consisted of a combination of in-row grit and between-row weed control. The in-row weed control treatments included two fertilizer grades of commercially available turkey litter product (Sustane 8-2-4, and Sustane 4-6-4), a crushed walnut shell product (Agra Grit), and crushed and pelletized soybean meal (Phytaboost Plant Food 7-1-2) (Table 2.2). Grit particle size averaged 0.42 mm, although Phytaboost Plant Food 7-1-2 was sieved through a 0.84 mm sieve to minimize large particle sizes. Between-row weed control treatments were either flaming or cultivation. Season-long weedy and weed-free checks were included to compare with weed control and yield at weed control extremes (0 to 100%). The season-long weed-free treatment was hand-weeded once a week or as needed throughout the growing season until one week after canopy closure.

Table 2.2. The in-row grit treatments and between-row weed control treatments in both corn and soybean experiments.

In-Row	Between-Row
Agra Grit	Cultivate Flaming
Phytaboost Plant Food 7-1-2[1]	Cultivate Flaming
Sustane 8-2-4	Cultivate Flaming
Sustane 4-6-4[2]	Cultivate Flaming
None	Cultivate Flaming
Season-Long Weedy Check	None
Season-Long Weed-Free Check	Hand weeded

[1]Phytaboost treatments were only applied in Aurora in 2015 and 2016, Beresford in 2015, and Morris in 2016.

[2] Sustane 4-6-4 was not applied in Morris in 2015.

The corn experiments were established as a randomized complete block design or an augmented randomized complete block split-plot design with four replications per treatment. In Morris in 2015 the individual treatments in the randomized complete block design were the combination of the in-row grit and between-row weed control (2 types) whereas in Morris in 2017 and Aurora in 2017 the individual treatments in the randomized complete block design were the in-row grit treatments with a single between-row treatment (tillage only). In Aurora in 2016, the individual treatments in the augmented randomized complete block split-plot design were the combination of the in-row grit treatment and between-row weed control, as the full plot treatment was the in-row grit treatment and the split was the between-row weed control. The randomized complete block split-plot design in Aurora in 2016 was augmented by assigning the between-row treatments with no in-row next to each other so the cultivating or flaming would occur at a constant speed and application. All years and locations had a treatment with no in-row grit applications, only with between-row weed control. Individual treatment plots at Morris in 2015, and both locations in 2017 measured 9m long, whereas the plots in 2016 in Aurora measured 6 m long. All plots were 3 m wide, consisting of four corn rows spaced 76-cm apart. Corn was planted at 79,000 seeds ha^{-1} at Morris on April 16th, 2015, Aurora on May 11th, 2016, and May 5th, 2017, and at 86,000 seeds ha^{-1} in Morris on May 11th, 2017 (Table 2.3). Grit applications did not affect corn stand densities in all locations or years. Corn seed was planted at a depth of 3.5 cm, when the soil temperature at depth was 14°C. The corn hybrids planted were NK N31H-3000GT in Morris in 2015 and 2017, Dekalb 49-72 RIB and Dekalb 45-65 RIB in Aurora in 2016 and 2017, all hybrids were BT, and glyphosate and glufosinate resistant.

Table 2.3. The planting date, corn hybrid, day length and harvest date at each at each location and year.

Year	Location	Planting Date	Hybrid	Day length	Harvest Date
2015	Morris	April 16th	NK N31H-3000GT	93	October 1st
2016	Aurora	May 7th	Dekalb 49-72 RIB	99	October 5th
2017	Aurora	May 5th	Dekalb 45-65 RIB	95	November 5th
	Morris	May 11th	NK N31H-3000GT	93	October 31st

GT = Glyphosate tolerant

RIB = refuge in a bag

The grit treatments were applied twice in corn, at V2 and V5 corn growth stages (Table 2.4). About 800 kg ha^{-1} of grit was applied at each application using a grit applicator [PAGMan (Propelled Abrasive Grit Management)] (Erazo-Barradas et al., 2017). Blasting distance, angle and pressure influence the efficacy of the machine, thus each of these were held as constant as possible across trials and years as described in Erazo-Barradas et al. (2017). The PAGMan has four sets of two nozzles, one for each side of the crop row. The nozzles were aimed below the first corn leaf at a 45° angle to the soil with weeds about 10 cm from the tip of the nozzle. The grit had a spray pressure of 690 kPa and the application speed was 2.5 km hr^{-1}. Grits defoliate the plant and injure the apical meristem of dicotyledons (Forcella, 2009a).

In 2015 and 2016 the between-row cultivation and flaming occurred at the V5 corn growth stage after the final grit application (Table 2.4). In 2016 and 2017, due to high between-row weed densities, an additional cultivation was done after the V2 corn application at all locations and treatments except in the season-long weedy check. In 2017 all treatments were cultivated, and flaming was dropped, as there were no differences between weed control with flaming or cultivation the previous years. Cultivation was performed by using a four-row John Deere® 886 cultivator with spring tines driven at 5 km hr^{-1}. The flame weeder consisted of 5 burners spaced 15 cm apart under a hood that uses propane (FLAMEWEEDERS.com 5 Torch Model #500). A cane connects the torch to a 4.5 kg propane tank supply that is carried on a backpack. The burners were positioned about 18 cm above the soil surface. The flaming treatments were applied at 2.5 km hr^{-1} that delivered about 50 kg ha^{-1} of propane.

Table 2.4. Dates and crop growth stage of weed density measurements, in-row and between-row weed applications, weed biomass, corn stem diameter and relative greenness measurements in corn at Morris in 2015 and 2017, and Aurora in 2016 and 2017.

Year	Location	Initial Density	1st grit application	1st between-row cultivation	2017 Between-row application density	2nd grit application	Post grit between-row weed control	Post treatment weed density	Weed Biomass/ corn diameter and relative greenness
2015	Morris	May 16th (V2)	May 16th (V2)	-	-	June 2nd (V5)	June 3rd (V5)	June 10th (V6)	August 27th (R4)
2016	Aurora	June 7th (V2)	June 7th (V2)	June 7th (V2)	-	June 15th (V5)	June 15th (V5)	June 22nd (V6)	July 15th (V12)
2017	Aurora	June 1st (V2)	June 2nd (V2)	June 3rd (V3)	June 5th (V3)	June 23rd (V5)	June 23rd (V5)	June 30th (V6)	August 1st (VT)
	Morris	June 6th (V2)	June 6th (V2)	June 8th (V3)	-	June 26th (V5)	June 29th (V5)	July 3rd (V6)	July 25th (VT)

Weed measurements were recorded prior to the first grit application and a week after the final grit treatments (Table 2.4). Density measurements, height and leaf stage by weed species were recorded from the center two rows within 10-cm of the top row, and the between-row areas were centered 20-cm from the crop row. In 2017, an additional density measurement was conducted at the V3-V4 corn growth stages after the first grit application and before the second grit application in Aurora plots.

Weeds were harvested in 0.1 m^2 in both yield rows and one area in the between-row at peak weed biomass at the R4 corn growth stage in 2015, V12 corn growth stage in 2016, and VT in corn in 2017 (Table 2.4). Weeds were separated by location and functional group, grass or broadleaf. Weeds were dried at 60°C until constant weight and weighed. Corn stem diameter and SPAD meter relative greenness were measured at the same time that weeds were harvested in 2016 and 2017. Relative greenness of 20 corn plants from each plot, 10 plants from each of the center two rows, was measured using a Konica Minolta SPAD meter (Konica Minolta, Japan) on the newest leaf with a visible collar. Two corn plants from each yield row were measured for stem diameter between the 1st and 2nd inter-node closest to the ground using calipers that measured to 0.1 mm (Fisher Scientific, MA).

Corn was harvested after physiological maturity. At Morris in 2015 and 2017 the harvest area was the two center rows by 10 m long, and at Aurora in 2016 and 2017 the harvest area was two center rows by 6 m long. The corn at Morris was harvested using a two row MF-8XP small plot combine and adjusted to 15.5% moisture, whereas the

Aurora corn was hand-harvested with total cob weight and number of cobs harvested per plot recorded. Twenty cobs from the two center rows were weighed separately and set aside to be dried at 60°C. The dried cobs were weighed, shelled, and grain weight determined. Total corn grain yield in Aurora was estimated from weight of dry grain from 20 cobs and adjusted to 15.5% moisture.

Soybean.

Four site-years of soybean data were obtained from fields in organic transition at Aurora, SD and a conventional field in 2016 at Morris. In addition, two site-years were obtained from field studies planted into an organic certified field in 2015 and 2017 at the Southeast Research Farm in Beresford, SD (43°23'N, 96°54'W) (Table 2.1).

The Aurora and Morris soils were previously described. The soil type at Beresford is an Egan-Clarno-Tetonka complex silty clay loam (fine-silty, mixed, mesic Udic Haplustoll) (Table 2.1). The soil is very deep, well drained, and moderately permeable soil and was formed from silty sediments that overlay glacial till on uplands. The sand, silt, and clay content is 150, 550, 300 g kg^{-1}, respectively, with an organic matter content of 342 g kg^{-1}. This field has a 0 to 1% slope.

The soybean experiments were established in an augmented randomized complete block, split-plot design at Aurora on June 9th, 2015 and May 19th, 2016, in Beresford on June 9th, 2015 and in Morris on May 4th, 2016 (Table 2.5). The soybean experiments in Aurora and Beresford in 2017 were established as a randomized complete block design on May 30th and May 24th (Table 2.5). Treatments were replicated four times. Individual treatment plots measured 3 m long at Aurora in 2015, 6 m long in 2016 and 9 m long in 2017. At Morris in 2016 the individual treatment plots measured 6 m long. The plots at Beresford measured 6 m long in 2015 and 9 m long in 2017. All plots were 3 m wide, consisting of four soybean rows. Soybean seeding rate varied upon location and year (Table 2.5) in rows spaced 76 cm apart. Soybean seed was planted at a depth of 2.4 cm, when the soil temperature at depth was 18°C. Soybean varieties planted at Aurora were Asgrow 1431 in 2015, Asgrow 1433 in 2016, both glyphosate resistant varieties, and Asgrow 17X7 in 2017 a glyphosate and dicamba resistant variety (Table 2.5). At Morris in 2016 the soybean variety planted was Croplan LC1142 with glufosinate resistance (Table 2.5). The soybean varieties planted in Beresford were IA2014RA12 in 2015 and Viking 0.1955AT in 2017, both of which were organic certified (Table 2.5). Grit applications did not affect soybean growth stages at any locations or years.

The in-row and between-row weed control treatments were the same as the corn treatments previously described. The grit treatments were applied twice in soybeans at the V1 and V3 soybean growth stages, with an additional application at V5 at Aurora in 2015 (Table 2.6). The sub-plot treatment of cultivation or flaming was done at the V5 soybean growth stage after the final grit application (Table 2.6). In 2016 and 2017, due to high between-row weed densities an additional cultivation was done after the V1 application in all treatments except in the season-long weedy check. In 2017 all treatments were cultivated as there were no differences between weed control with flaming or cultivation in the previous years. At Beresford in 2017 a rotary hoe application occurred before and after the V1 grit application in all plots including the season-long weedy control.

Weed density measurements were recorded prior to the V1 soybean grit application and a week after the final treatments (Table 2.6). Weed density was measured in the same method as in corn. In 2017 an additional density measurement was conducted at the V2 soybean growth stage at Aurora and Beresford after the first grit application and before the second grit application (Table 2.6).

Weed biomass was harvested in the 0.1 m^2 in the same method as corn, at peak weed biomass at the R4 soybean growth stage in 2015, R2 in 2016 and 2017 (Table 2.17). Weeds were separated by location and functional group, grass or broadleaf.

Soybeans were harvested after physiological maturity. All soybean plots were harvested using a two row MF-8XP small plot combine. The soybean harvest area was the two center rows in all years, by 3 m long at Aurora in 2015. In Aurora in 2016 and at all other locations the plot length harvested was 6 m. The soybean grain was weighed and adjusted to 13% moisture. A 100-g seed subsample from each individual soybean plot was used to determine oil and protein content using near infrared spectroscopy in transmission mode (Baianu et al., 2012) (Infratec 1229 grain analyzer, Foss, MN).

Table 2.5. The planting date, planting rate, soybean variety, maturity group and harvest date at Aurora, Beresford and Morris in 2015, 2016 and 2017.

Year	Location	Planting Date	Plant Rate	Variety	Maturity group	Harvest Date
			seeds ha^{-1}			
	Aurora	June 9th	395,000	Asgrow 1431	1.4	October 22nd
2015	Beresford	June 9th	395,000	IA2014RA12	2.1	October 20th
	Aurora	May 19th	395,000	Asgrow 1433	1.4	October 14th
2016	Morris	May 4th	431,000	Croplan LC1142	1.1	September 9th
	Aurora	May 30th	395,000	Asgrow 17X7	1.7	October 11th
2017	Beresford	May 24th	420,000	Viking 0.1955 AT	1.9	October 17th

Table 2.6. Dates and crop growth stage of weed density measurements, in-row and between-row weed control, weed biomass in soybean at Aurora, Beresford and Morris in 2015, 2016 and 2017.

Year	Location	Initial Density	1st grit application	1st between-row cultivation	2017 Between-row application density	2nd grit application	Post treatment between-row weed control	Post treatment weed density	Weed Biomass
2015	Aurora[1]	June 29th (V1)	June 30th (V1)	-	-	July 8th (V3)	July 14th (V5)	-	September 8th (R4)
	Beresford	June 24th (V1)	June 26th (V1)	-	-	July 10th (V3)	July 15th (V5)	-	September 2nd (R4)
2016	Aurora	June 8th (V1)	June 8th (V1)	June 8th (V1)	-	June 23rd (v3)	June 26th (V5)	July 1st (V6)	July 20th (R2)
	Morris	May 26th (V1)	June 1st (V1)	June 1st (V1)	-	June 17th (v3)	June 21st (V5)	June 28th (V6)	July 19th (R2)
2017	Aurora	June 15th (V1)	June 15th (V1)	June 15th (V1)	June 23rd (V2)	June 29th (V3)	July 2nd (V5)	July 7th (R1)	July 31st (R2)
	Beresford[2]	June 16th (V1)	June 16th (V1)	June 18th (V1)	June 23rd (V2)	June 27th (V3)	June 28th (V4)	July 3rd (R1)	July 28th (R2)

[1]Soybeans at Aurora had an additional in-row grit application on July 14th, the V5 soybean growth stage.

[2]Additional rotary hoe applications were performed at this location on June 5th at the V1 growth stage, and June 7th at the V2 growth stage.

Statistical Analysis.

Analysis of variance (ANOVA) was used to analyze the collected data for the variables: total weed biomass, in-row and between-row weed biomass, broadleaf and grass biomass, corn stem diameter and relative greenness, and corn and soybean yield. Each location was analyzed separately because of differences in weed density, weed biomass, and yield of the corn or soybeans. When the data were analyzed as a mixed model ANOVA for the randomized complete block split-plot design, there were no differences in weed biomass or yield for the between-row treatments within the in-row grit treatments, so the between-row treatments were pooled within the in-row grit treatment and a randomized complete block design model was used. The linear statistical model for a randomized complete block design (Steel and Torie, 1996) is the following:

$$y_{ij} = \mu + \alpha_i + \beta_j + \epsilon_{ij}$$

where Y_{ij} is the mean observation in the β^{th} block of the α^{th} grit application:between-row application (cultivation or flaming) effect, μ is the overall mean, α_i is the grit application effect of treatment i^{th} where $\Sigma_i \alpha_i = 0$, for $i = 1, \ldots, 12$, β_j is the effect in block $j^{th}$where $\Sigma_j \beta_j = 0$, for $j = 1, \ldots, 4$, and $\epsilon_{ij} \sim iid$ $\mathrm{N}(0, \sigma_e^2)$ is the random error effect. The in-row grit treatment + between-row grit treatments were the fixed effects, and the blocks were the random effects.

To estimate the mean squares for each variable, data from both checks were included and an ANOVA was completed using the library agricolae (de Mendiburu, 2009) in R (R Core Team, 2017). The season-long weedy and weed-free controls were included to compare with all other treatments (Piepho et al., 2006). A season-long weed-free check was used in the experiment to provide an estimate of the maximum yield potential without weed competition for each site-year environment, as each location and year has differences because of weather and crop management. The season-long weedy check was included in the experiment to provide an estimate of the maximum weed competition at each location because the natural weed populations differed among field.

2.4. Results and Discussion.

Corn.

Morris 2015.

Climate. In 2015, the average monthly temperatures in April, June, September and October were warmer than the 30-year average (1980-2010). The average monthly temperature in 2015 in May, July, and August were similar to the 30-year average (Table 2.7). The cumulative precipitation in 2015 was lower than the 30-year average in April, June, July, September, and October. The cumulative precipitation in August in 2015 was similar to the 30-year average (Table 2.7). The cumulative precipitation over all of 2015 was 21% lower than the 30-year average, with 34% of the precipitation occurring in the month of May. The cumulative growing degree days in 2015 was higher than the 30-year average in April, June, September and October, whereas the months of May, July, and August had similar growing degree days to the 30-year average (Table 2.7). The cumulative growing degree days for the growing season was 8% higher than the 30-year average.

Table 2.7. At Morris, MN the average monthly temperature (ºC), monthly cumulative precipitation (cm), and monthly cumulative growing degree days (base 10 ºC) in 2015, 2016, 2017 and 30-year average (1980-2010). Climate data obtained from www.NOAA.gov. Cumulative growing degree days calculated with the following equation ((Tmax-Tmin)/2)-Tbase, where Tmax = max daily temperature, Tmin = minimum daily temperature, base temperature = 10 ºC.

Month	Temperature (°C)				Cumulative precipitation (cm)				Cumulative growing degree days (base 10°C)			
	2015	2016	2017	30-year average	2015	2016	2017	30-year average	2015	2016	2017	30-year average
April	8.3	7.1	7.6	6.6	2.0	5.2	6.5	5.9	93	71	61	68
May	13.9	15	13.5	13.8	14.9	4.3	9.2	7.2	177	200	153	171
June	20.4	20.2	19.8	19.0	3.8	4.5	10.1	10.2	308	304	292	273
July	21.8	21.4	22	21.3	7.4	18.4	2.3	9.9	366	350	365	344
August	20.1	20.8	18.5	20.1	8.5	9.4	17.5	8.5	316	335	264	312
September	19	16.7	17.1	15.0	3.2	4.3	10.5	7.4	285	218	226	192
October	10.5	9.6	8.7	7.4	3.8	8.7	6.9	6.7	98	86	87	78
Cumulative	-	-	-	-	43.6	54.8	63.0	55.3	1559	1564	1448	1438

Weed species and control. There were no weeds present at either grit applications in Morris in 2015, and no in-row or between-row weed control could be calculated.

End-of-season weed biomass. As no weeds were present at either grit applications in Morris in 2015 the end-of-season weed biomass is the natural variation within the field. The between-row total weed biomass was 83% of the total weed biomass (in-row + between-row weeds) in the season-long weedy check. The between-row total weed biomass was similar among grit treatments and the season-long weed-free treatment (Table 2.8), which averaged 173 kg ha^{-1}. The cultivation and flame only treatments had similar between-row weed biomass as the season-long weedy check and averaged 660 kg ha^{-1}. The broadleaf between-row weed biomass was 99% of the total between-row weed biomass and followed a similar pattern of weed biomass (Table 2.8). There was no grass between-row weed biomass among all treatments.

The total in-row weed biomass was 17% of the total weed biomass (in-row + between-row weeds) in the season-long weedy check. The total in-row weed biomass of grit treatments, season-long weed-free and cultivation-only treatments were similar (Table 2.8), averaged 52 kg ha^{-1} and lower than the flame-only treatment, 316 kg ha^{-1}. The Phytaboost Plant Food 7-1-2, Sustane 8-2-4, and cultivation-only treatments had similar total in-row weed biomass as the season-long weedy check, 137 kg ha^{-1} (Table 2.8). The broadleaf in-row weed biomass was 99% of the total in-row weed biomass in the season-long weedy check. The grit treatments, cultivation-only, season-long weedy and weed-free treatments had similar and lower in-row broadleaf weed biomass, averaged

Table 2.8. At Morris in corn in 2015 the between-row, in-row, broadleaf, and grass weed biomass, measured on August 27th, and grain yield (kg ha^{-1}). Letters describe significant differences $\alpha = 0.1$. Values in parentheses in weed density are percent (%) control compared to season-long weedy check.

	Between-row weed biomass			In-row			
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass	Yield
	kg ha^{-1}						
Agra Grit + BR	119 c (83)	117 c (83)	0	14 c (87)	13 b (88)	7.5	11981 c
Phytaboost Plant Food 7-1-2 + BR	163 c (73)	151 bc (78)	0	99 bc	97 b (29)	0	12033 c
Sustane 8-2-4 +BR	254 bc (63)	254 bc (63)	0	111 bc	107 b(21)	0	12281 b
Cultivation-Only	583 ab	542 ab	0	31 bc	31 b (77)	0	12086 b
Flame-Only	711 a	693 a	0	316 a	305 a	9	10643 d
Season-Long Weedy Check	687 a	677 a	0	137 b	136 b	0	10334 d
Season-long Weed-Free	156 c	156 bc	0	26 bc	22 b	0	12690 a
P-value	0.01	0.02	0	0.02	0.03	0.25	0.01

+ BR = with between-row weed control.

68 kg ha^{-1}, than the flame-only treatment, 136 kg ha^{-1} (Table 2.8). The grass in-row weed biomass was similar among all treatments ($p = 0.25$) and averaged 2.4 kg ha^{-1}.

Yield. The grain yield differed ($p = 0.01$) among grit treatments and lower than the season-long weed-free, 12690 kg ha^{-1} (Table 2.8). The Agra Grit and Phytaboost Plant Food 7-1-2 had similar yield as the cultivation-only treatment, averaged 12,033 kg ha^{-1}, which was lower than the Sustane 8-2-4 treatment, 12,281 kg ha^{-1}, and higher than both the flame-only and season-long weedy treatment (Table 2.8).

Morris 2017.

Climate. The average monthly temperatures during April, September, and October were warmer than the 30-year average (1980-2010) (Table 2.7). The average monthly temperatures during May, June, and July were similar to the 30-year average, and the average temperature in August was cooler than the 30-year average (Table 2.7). The cumulative precipitation in April, May, August, and September was 10, 28, 105, and 42% greater than the 30-year average (Table 2.7). The cumulative precipitation in July was only 23% of the 30-year average, whereas the months of April and October had similar cumulative precipitation to the 30-year average. The cumulative precipitation over the whole growing season was 14% higher than the 30-year average (Table 2.7). The cumulative growing degree days during the 2017 growing season was similar to the 30-year average (Table 2.7).

Weed species and control. Broadleaf weeds accounted for more than 99% of the in-row weeds before and after all grit applications. The predominant weed species present before the first grit application was redroot pigweed whose seedlings were 2.5- to 7-cm tall. After the second grit application the predominant weed species included redroot pigweed with plants 17- to 25-cm tall, and common purslane (*Portulaca oleracea*) seedlings that germinated after the grit applications and were less than 1-cm tall. Grass weeds, primarily barnyardgrass, were sparse and accounted for less than 0.1% of the in-row density before application.

The weed density present across the plots varied and therefore control was determined by examining the pre-grit application and comparing with the density after the second grit application. The total in-row (broadleaf + grass weeds), broadleaf in-row, and grass in-row weed densities were not reduced by any grit treatment (Table 2.9). The total in-row weed density of the Sustane 8-2-4 and 4-6-4 grit treatments increased by 243 and 12% after the second grit application (Table 2.9). The total in-row weed density of the cultivation-only treatment increased from 3 to 168 plants m^{-2} from before the first to after the last grit application (Table 2.9). The broadleaf in-row weed density of the Agra Grit and Sustane 8-2-4 grit treatments were numerically reduced by 50 and 4%, whereas the Sustane 8-2-4 had a 275% increase in broadleaf weed density (Table 2.9). The in-row grass weed density of all grit treatments increased after the second grit application (Table 2.9). The between-row weed density averaged 118 plants m^{-2} before cultivation, and 0 plants m^{-2} after cultivation for all treatments with between-row weed control.

Table 2.9. At Morris in corn in 2017, the total, broadleaf and grass in-row weed density (plants m^{-2}) before and after all grit applications and a paired t-test to compare the densities.

	In-row weed density								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	------------------------------ plants m^{-2} ------------------------------								
Agra Grit	243	143	0.36	239	120	0.28	0	23	0.17
Sustan 8-2-4	41	141	0.82	35	131	0.78	4	10	0.06
Sustane 4-6-4	75	84	0.88	73	70	0.96	3	14	0.34
Cultivation-Only	3	168	0.03	0	164	0.03	12	4	0.90
Season-Long Weedy Check	276	240	0.79	273	208	0.64	3	35	9E-04
Season-long Weed-Free	10	0	0.08	0	0	-	10	0	0.09

End-of-season weed biomass. The total between-row weed biomass was 79% of the total weed biomass (in-row + between-row weeds) in the season-long weedy check. The total between-row weed biomass of all grit and cultivation-only treatments were similar to the season-long weed-free treatment, 0 kg ha^{-1}, and lower than the season-long weedy check, 5725 kg ha^{-1} (Table 2.10). The broadleaf between-row weed biomass of all grit and cultivation only-treatments were similar to the season-long weed-free treatment, 0 kg ha^{-1}, and lower than the season-long weedy check, 5105 kg ha^{-1} (Table 2.10). The grass between-row weed biomasses of all grit and cultivation-only treatments were similar to the season-long weed-free treatment, 0 kg ha^{-1}, and lower than the season-long weedy check, 620 kg ha^{-1} (Table 2.10).

The total in-row weed biomass was 31% of the total weed biomass (in-row + between-row weeds) in the season-long weedy check. The total in-row weed biomass differed ($p = 0.06$) among grit treatments (Table 2.10). The total in-row weed biomass of Agra Grit was similar to the season-long weed-free check with a 52% reduction, whereas both the Sustane 8-2-4 and 4-6-4 treatments had similar total in-row weed biomass as both the cultivation-only treatment and the season-long weedy check (Table 2.10) and averaged 2555 kg ha^{-1}. The broadleaf in-row weed biomass was 88% of the total in-row weed biomass in the season-long weedy check. The broadleaf in-row weed biomass was similar among all grit treatments and cultivation-only, and the season-long weedy check and averaged 1953 kg ha^{-1}. The Agra Grit and cultivation-only treatments had similar broadleaf in-row weed biomass as the season-long weed free check (Table 2.10). In-row grass weed biomass was 12% of the total in-row weed biomass in the season-long weedy

Table 2.10. At Morris, MN in corn in 2017 the between-row, in-row, broadleaf and grass weed biomass (kg ha^{-1}) collected on July 25th. Letters denote significant differences at $\alpha = 0.1$. Values in parentheses in are percent (%) control compared to the season-long weedy check.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	------------------------------ kg ha^{-1} ------------------------------					
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	1247 bc (52)	1240 ab (46)	7 ab (77)
Sustane 8-2-4 +BR	0 b (100)	0 b (100)	0 b (100)	2588 a	2465 a	120 ab (51)
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	2473 ab	2340 a	133 ab (57)
Cultivation-Only	0 b (100)	0 b (100)	0 b (100)	1555 ab (40)	1428 ab (38)	128 ab (58)
Season-Long Weedy Check	5725 a	5105 a	620 a	2603 a	2293 a	310 a
Season-long Weed-Free	0 b	0 b	0 b	0 c	0 b	0 b
P-value	0.02	9.79E-07	0.07	0.06	0.05	0.08

+ BR = with between-row weed control.

check. All grit and cultivation-only treatments had similar grass in-row weed biomass as both the season-long weedy and weed-free checks (Table 2.10), whereas the season-long weedy check, 310 kg ha^{-1}, was not similar to the season-long weed-free check, 0 kg ha^{-1}. The grass in-row weed biomass of the grit treatments averaged 108 kg ha^{-1}, a 65% reduction compared to the grass in-row weed biomass in the season-long weedy check.

Corn relative greenness and stem diameter. The relative greenness of the corn was lowest (27.8) for the season-long weedy check, the weed-free and grit treatments had similar greenness values (38.7) (Table 2.11). The cultivation-only treatment had similar relative greenness (32.9) as the Agra Grit and Sustane 4-6-4 treatments, and the season-long weedy check (Table 2.11). The corn stem diameter did not differ among treatments ($p = 0.33$) when measured at V12 and the average diameter among all treatments was 21.0 mm (Table 2.11).

Yield. All grit and cultivation-only treatments had similar grain yields and averaged 6059 kg ha^{-1} and were similar as the season-long weedy check of 3635 kg ha^{-1} (Table 2.11). The Sustane 8-2-4 and 4-6-4, and cultivation-only treatments had similar grain yield as the season-long weed-free check, which had a yield of 9201 kg ha^{-1} (Table 2.11).

Table 2.11. At Morris in 2017 in corn the relative greenness (SPAD), stem diameter (mm), and corn grain yield (kg ha^{-1}). Letters denote significant differences at $\alpha = 0.1$.

Treatment	Relative greenness	Stem diameter	Yield
	-- SPAD --	-- mm --	-- kg ha^{-1} --
Agra Grit + BR	37.1 ab	22.4	4968 b
Sustane 8-2-4 + BR	40.6 a	20.8	6008 ab
Sustane 4-6-4 + BR	38.2 ab	21.1	7039 ab
Cultivation-Only	32.9 bc	20.5	6223 ab
Season-Long Weedy Check	27.8 c	18.3	3653 b
Season-Long Weed-Free	40.8 a	23.2	9201 a
P-value	0.02	0.33	0.07

+ BR = with between-row control

Aurora 2016.

Climate. The average monthly temperature in May, June, October, and November were 10, 14, 26, and 50% warmer than the 30-year average (1980-2010) (Table 2.12). The average monthly temperature in July, August, and September were the same as the 30-year average. The cumulative precipitation in the months of July, August and September were 66, 35, and 75% greater than the 30-year average (Table 2.12). The months of May, June, and October had 20, 23 and 12% lower cumulative precipitation as the 30-year average, and the month of November had similar cumulative precipitation as the 30-year average (Table 2.12). The cumulative precipitation during the growing season was 30% higher in 2016 than the 30-year average. The Aurora location in 2016 received more growing degree days (Base 10°C) than the 30-year average in the months of May, June, September, and October by 14, 21, 13, and 11% (Table 2.12). The cumulative growing degree days in July and August were similar to the 30-year average. The cumulative growing degree days over the growing season were 10% greater than the 30-year average (Table 2.12).

Weed species and control. The weeds present before grit and between-row weed control applications were green and yellow foxtail species ranging from 1- to 4-cm in height, and common lambsquarters ranging in height from 1- to 2-cm. After both grit applications grass weeds were more prevalent as the predominant weeds present were green and yellow foxtail species ranging from 8- to 11-cm in height and barnyardgrass ranging in height from 6- to 12-cm.

The weeds present in the field varied among treatments and replications within the field (Table 2.13). All grit treatments reduced ($t < 0.05$) total in-row weed density by an average of 50% after both grit applications when compared to the initial weed density (Table 2.13). The total in-row weed density of the cultivation- and flame-only treatments did not differ between the before and after grit densities (Table 2.13). The broadleaf in-row weed density, that only made up 4% of the total weed density, was not reduced ($t > 0.15$) after two grit applications (Table 2.13), which initially averaged 6 plants m^{-2}, and after both applications averaged 3 plants m^{-2}. The grit treatments reduced grass in-row weed density ($t < 0.05$) by at least 42% compared to the initial grass in-row weed densities (Table 2.13). The grass in-row weed density of the cultivation and flame-only treatments did not differ between the before and after grit densities (Table 2.13). The between-row weed densities before flaming or cultivation were 70 plants m^{-2} across the field and were reduced 100% to 0 plants m^{-2} after the weed control treatments.

Table 2.12. Aurora, SD average monthly temperature (ºC), monthly cumulative precipitation (cm), and monthly cumulative growing degree days (base 10 ºC) in 2015, 2016, 2017 and 30-year average (1980-2010). Climate data obtained from www.NOAA.gov. Cumulative growing degree days calculated with the following equation ((Tmax-Tmin)/2)-Tbase, where Tmax = max daily temperature, Tmin = minimum daily temperature, base temperature = 10 ºC.

	Temperature (C)				Cumulative precipitation (cm)				Cumulative growing degree days (base 10°C)			
Month	2015	2016	2017	30-year average	2015	2016	2017	30-year average	2015	2016	2017	30-year average
May	14.8	14.6	13.3	13.3	11.2	6.0	9.7	7.5	145	186	156	163
June	19.6	21.3	20.1	18.7	5.4	8.4	3.1	10.9	284	324	297	267
July	21.7	21.6	22.7	21.3	9.3	13.8	11.9	8.3	349	350	379	343
August	19.5	20.9	15.8	20.1	16.1	10.5	11.2	7.8	298	336	269	315
September	18.4	16.3	16.7	15.0	4.1	9.6	11.6	5.5	267	220	226	195
October	10.2	9.6	8.6	7.6	2.6	4.6	6.4	5.2	104	94	88	85
November	3.1	4.2	-0.1	-0.7	2.9	2.2	0.3	2.4	-	-	-	-
Cumulative	-	-	-	-	51.6	55.1	53.9	42.6	1447	1510	1415	1368

[1] Yearly cumulative precipitation 2017 are from May to October.

Table 2.13. At Aurora in 2016 in corn, the in-row total, broadleaf and grass weed density (plant m^{-2}) before and after all grit applications, and paired t test values. Values in parentheses are percent (%) control compared to before weed density.

	In-row weed density								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	plants m^{-2}								
Agra Grit	113	61 (46)	0.009	7	4	0.14	99	54 (45)	0.03
Phytaboost Plant Food 7-1-2	80	36 (55)	0.01	4	4	0.73	76	35 (57)	0.02
Sustane 8-2-4	77	29 (62)	3.97E-05	6	3	0.33	71	39 (45)	1.01E-15
Sustane 4-6-4	65	42 (35)	0.04	9	1	0.47	64	37 (42)	0.01
Cultivation-Only	127	69	0.45	18	13	0.47	109	56	0.48
Flame-Only	117	57	0.24	9	8	0.72	106	49	0.24
Season-Long Weedy Check	120	135	0.76	3	5	0.74	104	108	0.93
Season-long Weed-Free	84	0	0.05	5	0	0.25	79	0	0.08

End-of-season weed biomass. The total between-row weed biomass was 58% of the total weed biomass (in-row + between-row) in the season-long weedy check. The total between-row weed biomass of all grit treatments, cultivation- and flame-only, and season-long weed-free treatments were similar, 0 kg ha^{-1}, and lower than the season-long weedy check which averaged 533 kg ha^{-1} (Table 2.14). The broadleaf between-row weed biomass was 46% of the total between-row weed biomass in the season-long weedy check. The broadleaf between-row weed biomass of all grit treatments, cultivation- and flame-only, and season-long weed-free treatments were similar, 0 kg ha^{-1}, and lower than the season-long weedy check which averaged 246 kg ha^{-1} (Table 2.14). The grass between-row weed biomass was 54% of the total between-row weed biomass in the season-long weedy check. The grass between-row weed biomass of all grit treatments, cultivation- and flame-only, and season-long weed-free treatments were similar, 0 kg ha^{-1}, and lower than the season-long weedy check, which averaged 287 kg ha^{-1} (Table 2.14).

The total in-row weed biomass was 42% of the total weed biomass (in-row + between-row) in the season-long weedy check. The total in-row weed biomass among grit treatments had slight differences ($p = 0.07$) (Table 2.14). Agra Grit, Phytaboost Plant Food 7-1-2, and Sustane 8-2-4 had similar total in-row weed biomass as the season-long weedy check and averaged 349 kg ha^{-1}. The Sustane 4-6-4 grit treatment had the lowest total in-row weed biomass and had a similar total in-row weed biomass as the season-long weed-free check, Sustane 8-2-4, Agra Grit, and flame-only treatments (Table 2.14). The cultivation-only treatment had the highest total in-row weed biomass and averaged

1007 kg ha^{-1} (Table 2.14). The broadleaf in-row weed biomass was 2% of the total in-row weed biomass in the season-long weedy check. The broadleaf in-row weed biomass was similar among grit treatments, flame-only, and season-long weedy and weed-free treatments and had an average biomass of 26 kg ha^{-1}, whereas the cultivation-only treatment had the highest broadleaf in-row weed biomass and averaged 406 kg ha^{-1} (Table 2.14). The grass in-row weed biomass was 98% of the total in-row weed biomass in the season-long weedy check. The grass in-row weed biomass was similar ($P = 0.15$) among all treatments and averaged 244 kg ha^{-1}.

Corn relative greenness and stem diameter. The relative greenness of the corn leaves varied by treatment ($P = 0.03$) (Table 2.15). All grit treatments had higher relative greenness values than the cultivation- and flame-only and season-long weedy check and were similar to the season-long weed-free check (Table 2.15). The Sustane 8-2-4, Phytaboost Plant Food 7-1-2 and season-long weed-free had similar high relative greenness values. The cultivation- and flame-only treatments had similar relative greenness values as the season-long weedy check, whereas the flame-only treatment had the lowest relative greenness. The corn stem diameter did not differ ($p = 0.14$) among treatments and averaged 24.4 mm (Table 2.15).

Table 2.14. At Aurora in 2016 in corn the between-row, in-row, broadleaf and grass weed biomass (kg ha^{-1}) collected on July 15th. Letters denote significant differences at $\alpha = 0.1$. Values in parentheses are percent (%) control compared to season-long weedy check.

Treatment	Between-row weed biomass			In-row weed biomass		
	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	---------- kg ha^{-1} ----------					
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	298 bcd	8 b	262
Phytaboost Plant Food 7-1-2 + BR	0 b (100)	0 b (100)	0 b (100)	389 b	6 b	383
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	0 b (100)	323 bc	7 b	293
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	99 cd	19 b	80
Cultivation-Only	0 b (100)	0 b (100)	0 b (100)	1007 a	406 a	357
Flame-Only	0 b (100)	0 b (100)	0 b (100)	322 bcd	132 b	196
Season-Long Weedy Check	533 a	246 a	287 a	387 bc	7 b	380
Season-Long Weed-Free	0 b	0 b	0 b	0 d	0 b	0
P-value	0.001	0.002	0.04	0.07	0.0003	0.15

+ BR = with between-row weed control.

Table 2.15. At Aurora in 2016 in corn the relative greenness (SPAD), stem diameter (mm), and corn grain yield (kg ha^{-1}). Letters denote significant differences at α= 0.1.

Treatment	Relative greenness	Stem diameter	Yield
	-- SPAD --	-- mm --	-- kg ha^{-1} --
Agra Grit + BR	40.6 b	24.7	10779 cd
Phytaboost Plant Food 7-1-2 + BR	42.2 ab	23.9	12012 b
Sustane 8-2-4 + BR	43.6 a	25.0	13576 a
Sustane 4-6-4 + BR	41.2 b	24.2	11778 bc
Cultivation-Only	39.6 c	24.5	10833 bcd
Flame-Only	38.2 c	24.9	10220 d
Season-Long Weedy Check	39.5 c	22.9	10162 d
Season-Long Weed-Free	41.7 ab	25.3	10772 cd
P-value	0.03	0.14	3.00E-05

+ BR = with between-row weed control.

Yield. The corn grain yield differed among treatments (p = 3.00E-05) (Table 2.15). The Sustane 8-2-4 and Phytaboost Plant Food 7-1-2 grit treatments were not similar but both yielded higher than the season-long weed-free treatment. The Sustane 4-6-4 treatment had similar yield as the Phytaboost Plant Food 7-1-2, Agra Grit, cultivation-only and season-long weedy check, whereas the yield of the Agra Grit treatment was similar to both the season-long weedy, weed-free and flame-only treatments and averaged 10,571 kg ha^{-1}.

Aurora 2017.

Climate. The average monthly temperature in the months of September, October, and November were 11, 13, and 14% warmer than the 30-year average (1980-2010) (Table 2.12). The average monthly temperature of August was 21% cooler than the 30-year average, whereas the months of May, June, and July had similar average monthly temperatures as the 30-year average. The cumulative precipitation in May, July, August, September, and October was 30, 43, 44, 111, and 23% higher than the 30-year average (Table 2.12). The cumulative precipitation in June, and November were 72 to 88% lower than the 30-year average. The cumulative precipitation during the growing season was 27% greater than the 30-year average (Table 2.12). The cumulative growing degree days were higher than the 30-year average in June, July, and September by 11, 10, and 16% (Table 2.12). The cumulative growing degree days in May, and October were similar to the 30-year average, whereas the month of August and 21% lower cumulative growing degree days compared to the 30-year average. The cumulative growing degree days over the whole growing season were similar to the 30-year average.

Weed species and control. The species present before the grit application were green and yellow foxtails ranging from 1- to 4-cm in height, and common lambsquarters ranging in height from 1- to 2-cm. Between the two grit applications the predominant weeds present were 2- to 8-cm green and yellow foxtails, and a smaller number of common lambsquarters ranging in height from 2- to 6-cm. After both grit applications, there were more grass weeds present than broadleaf weeds. The yellow foxtail and barnyardgrass were the predominant weed species present after all weed control measures were enacted, and had an average height of 4- to 12-cm.

The total in-row weed density (broadleaf + grass weeds) after the first grit application was reduced (t = 0.08) only by Sustane 4-6-4 by 45%, whereas all other grit treatments and cultivation-only did not reduce total in-row weed density after the first grit application (Table 2.16). All treatments increased the total in-row weed density after the second grit application. The broadleaf in-row weed density after the first grit application was only reduced (t = 0.07) by Agra Grit by 23%, whereas all other grit treatments and cultivation-only treatments did not reduce broadleaf in-row weed density after the first grit application (Table 2.16). All treatments increased the broadleaf in-row weed density after the second grit application. The grass in-row weed density after the first grit application was only reduced (t = 0.04) by Sustane 4-6-4 by 40%, whereas all other grit and cultivation-only treatments did not reduce grass in-row weed density after the first grit application (Table 2.16). All treatments increased the grass in-row weed density after the second grit application.

The between-row weed density before cultivation was similar among all treatments and averaged 318 plants m^{-2}, and after both cultivations the between-row weed densities were 0 plants m^{-2}, a 100% reduction compared to initial weed density.

Table 2.16. At Aurora in corn in 2017 the total, broadleaf and grass in-row weed density (plants m^{-2}) before and after the first grit application and paired t-test values. The in-row weed density was not reduced after the second grit application when compared to the density before the second grit application. Values in parentheses are the percent (%) weed control compared to before the grit application.

	1st Grit Application								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	---- plants m^{-2} ----								
Agra Grit	391	340	0.23	193	146 (23)	0.07	199	155	0.42
Sustane 8-2-4	391	258	0.39	165	108	0.31	226	150	0.45
Sustane 4-6-4	420	231 (45)	0.08	168	79	0.13	253	153 (40)	0.04
Cultivation-Only	421	254	0.15	143	125	0.69	279	129	0.03
Season-Long Weedy Check	410	468	0.10	225	254	0.42	185	214	0.17
Season-Long Weed-Free	518	0	0.004	245	0	0.01	273	0	0.04

End-of-season weed biomass. The total between-row weed biomass was 42% of the total (in-row + between-row broadleaf and grass weeds) weed biomass in the season-long weedy check. The total between-row weed biomass (broadleaf + grass weeds) of all grit, cultivation-only and season-long weed-free treatments were similar, 0 kg ha^{-1}, and lower than the season-long weedy check which averaged 3155 kg ha^{-1} (Table 2.17). The broadleaf between-row weed biomass was 51% of the total between-row weed biomass in the season-long weedy check. All grit, cultivation-only and season-long weed-free treatments had similar broadleaf weed biomass, 0 kg ha^{-1}, and were lower than the season-long weedy check, which averaged 1615 kg ha^{-1} (Table 2.17). The grass between-row weed biomass was 49% of the total between-row weed biomass in the season-long weedy check. All grit, cultivation-only, and season-long weed-free treatments had similar broadleaf weed biomass, 0 kg ha^{-1}, and were lower than the season-long weedy check, 1540 kg ha^{-1} (Table 2.17).

The total in-row weed biomass (broadleaf + grass weeds) was 58% of the total weed biomass in the season-long weedy check. The total in-row weed biomass of the grit and cultivation-only treatments were similar to the season-long weedy check and averaged 4489 kg ha^{-1}, and higher than the season-long weed-free check, 0 kg ha^{-1} (Table 2.17). The broadleaf in-row weed biomass was 37% of the total in-row weed biomass in the season-long weedy check. The broadleaf in-row weed biomass was similar among all treatments ($p = 0.37$) and averaged 1312 kg ha^{-1}. The grass in-row weed biomass was 63% of the total in-row weed biomass in the season-long weedy check. All grit, and

Table 2.17. At Aurora in corn in 2017 the between-row, in-row, broadleaf, and grass weed biomass (kg ha^{-1}) collected on July 25th. Letters describe significant differences $\alpha = 0.1$. Values in parentheses in weed density a re percent (%) control compared to season-long weedy check.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	------------------------- kg ha^{-1} -------------------------					
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	4365 a	1025	3340 a
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	0 b (100)	4863 a	1700	3163 a
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	4445 a	1685	2760 a
Cultivation-Only	0 b (100)	0 b (100)	0 b (100)	4788 a	1855	2858 a
Season-Long Weedy Check	3155 a	1615 a	1540 a	4283 a	1612	2670 a
Season-Long Weed-Free	0 b	0 b	0 b	0 b	0	0 b
P-value	1.78E-08	0.004	6.00E-05	0.006	0.37	0.04

+ BR = with between-row weed control.

cultivation-only treatments had similar grass in-row weed biomass as the season-long weedy check and averaged 2958 kg ha^{-1}, all higher than the season-long weed-free check, 0 kg ha^{-1} (Table 2.17).

Corn relative greenness and stem diameter. The relative greenness of the corn leaves was lowest for the season-long weedy check, 24.4, whereas all grit treatments had similar relative greenness, 45.5, and were higher than the season-long weedy check and lower than the season-long weed-free check, 56.2 (Table 2.18). The cultivation-only treatment had similar relative greenness as the Agra Grit, and Sustane 4-6-4 treatments (Table 2.18). The corn stem diameters were similar among all grit, and cultivation-only treatments and averaged 18.7 mm, and were higher than the season-long weedy check, 12.3 mm, and lower than the season-long weed-free check, 22.1 mm (Table 2.18). The Sustane 8-2-4 corn stem diameter was similar to the season-long weed-free check (Table 2.18).

Yield. The corn yield differed (p = 7.14E-07) among grit treatments (Table 2.18). The season-long weed-free treatment had the highest grain yield, 7588 kg ha^{-1}, and the season-long weedy check had the lowest yield of 71 kg ha^{-1} (Table 2.18). All grit treatments and the cultivation-only treatment had higher yields than the season-long weedy check and lower than the season-long weed-free check (Table 2.18). The Sustane 8-2-4 treatment had the highest yield among grit treatments, 5706 kg ha^{-1}, whereas the Agra Grit, Sustane 4-6-4 grit treatments and the cultivation-only treatment had similar yields and averaged 3535 kg ha^{-1}.

Table 2.18. At Aurora in 2017 in corn the relative greenness (SPAD), stem diameter (mm), and corn grain yield (kg ha^{-1}). Letters denote significant differences at $\alpha = 0.05$.

Treatment	Relative greenness	Stem diameter	Yield
	-- SPAD --	-- mm --	-- kg ha^{-1} --
Agra Grit + BR	43.3 bc	17.3 b	3351 c
Sustane 8-2-4 + BR	48.2 b	20.1 ab	5706 b
Sustane 4-6-4 + BR	44.8 bc	19.1 b	3930 c
Cultivation Only	40.7 c	18.2 b	3324 c
Season-Long Weedy Check	24.4 d	12.3 c	71 d
Season-Long Weed-Free	56.2 a	22.1 a	7588 a
P-value	3.68E-07	8.99E-05	7.14E-07

+ BR = with between-row weed control.

Corn Discussion.

There was inconsistent weed control in corn with each of the grits. Only Sustane 4-6-4 decreased total in-row weed densities both in 2016 and 2017 in Aurora, but only after the first grit application in 2017. This lack of control is different than previous research, which reported that two applications of grit reduced weed density in pepper and tomato by 63 and 80% (Wortman, 2015), or by 60% in grain corn (Erazo-Barradas et al., 2017). Erazo-Barradas et al. (2017) reported a 50% reduction of in-row weed density after one grit application, which differs from the data from Aurora in 2017 where after one grit application the highest reduction of total in-row weed density was 45% by the Sustane 4-6-4 treatment (Table 2.16). Wortman (2015) used Phytaboost Plant Food 7-1-2 and Agra Grit grits that were used in this study to control weeds in tomato and peppers but used a hand-held sandblaster that requires the operator to manually point the nozzle at the weeds, whereas this study used the PAGMan, which attaches to the back of a tractor on the three point hitch, which can sway over rows even with precise steering of the tractor. Erazo-Barradas et al. (2017) and Forcella (2012) used corn cob grit, a soft grit like Sustane and Phytaboost Plant Food 7-1-2), and suggested that the use of soft grit organic fertilizers should be able to control weeds similar to sand or other hard grits, like crushed walnut shells (Agra Grit). At Morris in 2015 and 2017, and Aurora in 2016 and 2017 the low between-row weed densities after flaming or cultivation are similar to the results reported by Erazo-Barradas et al. (2017), who used the grit sprayer along with flaming or cultivation to provide adequate weed control.

The 100% reduction of total, broadleaf and grass between-row weed biomass at Aurora in 2016 and 2017, and in Morris in 2017 indicates that the additional cultivation at the V2 corn growth stage helped control between-row weeds before they were too large to control with flaming or cultivation later in the season. The between-row weeds in Morris in 2015 also germinated after the cultivation and flaming applications, which have been reported to increase seedling germination (Mulugeta and Boerboom, 2000). This later flush of weeds, after the critical weed free period, did reduce corn yield which contradicts what Cardina et al. (1995) reported that late flush of weeds may not affect yield.

The only grit treatment in the corn studies to reduce total in-row weed biomass in more than one site year was the Agra Grit treatment. Both Sustane 8-2-4 and Phytaboost Plant Food 7-1-2 did not reduce total in-row weed biomass during any year or at either location. The inconsistent reduction of total in-row weed biomass from two applications of grit may have resulted from higher weed densities, as Erazo-Barradas et al. (2017) reported that in one year of the study there were higher weed densities and no reduction of total in-row weed biomass. The lack of reduction of total in-row weed biomass at Morris in 2015 could be due to a late flush of weeds emerging after grit applications, as no weeds were present at the time of grit applications. At Aurora in 2016, 89% of the total in-row weed biomass was from grass weeds, which are difficult to control with abrasive weed management (Forcella et al., 2010; Wortman, 2015) as the growing point if below ground at the time of grit application (Wortman, 2014). The lack of control of total in-row weed biomass in 2016 in Aurora could not be attributed to excess nitrogen from the organic fertilizers, as the Agra Grit treatment had similar total in-row weed biomass as the season-long weedy check, Phytaboost Plant Food 7-1-2 and the Sustane turkey litters. The high density of grass weeds present in the crop row in Aurora in 2017 could have also contributed to the similar total in-row weed biomass among the grit treatments and the season-long weedy check. At Morris in 2017 91% of the total in-row weed biomass were broadleaf weeds, but between the two grit applications the broadleaf weeds received enough rain to grow larger than the seedling stage, which have been reported to need 10 split second (<1s) applications of grit, which applied 0.023 kg grit, to be controlled (Forcella, 2009b). The speed at which the PAGMan travels over the field, 2.5 km hr^{-1} or 0.69 m sec^{-1}, sprays 1.01E-04 kg grit at the spray area next to the crop row. The PAGMan would need to travel across a field at 0.01 km hr^{-1}, or use different nozzles to provide enough grit to control broadleaf weeds of this size.

The broadleaf in-row weed biomass was similar among grit treatments in 3 of 4 site years reported. In Morris in 2015 the differences in the broadleaf in-row weed biomass was from multiple flushes of weeds that emerged in early June after grit applications, as no broadleaf weeds were present at either grit application. In Aurora in 2016 the low number of broadleaf weeds present in the field could be why the broadleaf in-row weed biomass was similar among treatments. At Aurora in 2017 the broadleaf in-row weed biomass was similar before and after the first grit application for both Sustane turkey litters and after the second grit application, which could have been due to a misapplication of grit as a different set of field workers had to work the PAGMan to spray grit on this field. The lack of control of broadleaf in-row weeds at Morris in 2017 would be due to the large size of broadleaf weeds at the time of application, as they were larger than 2.5 cm at first grit application, and they grew to be larger than 6 cm before the second grit application. The overall lack of difference of broadleaf in-row weed biomass among grit treatments and the season-long weedy check would mean that more precise applications of grit at times that are focused around small weed stages are needed.

The grass in-row weed biomass varied among site years and locations. In Morris in 2015 all treatments were similar, which could be because all plots had weeds that emerged after the grit applications and had an inherently low grass in-row weed biomass. In 2016 at Aurora there was large variability of grass in-row weeds as the season-long weedy check was similar to all grit treatments, except the Sustane 4-6-4 treatment that reduced grass in-row weed biomass by 69%. In 2017 at Aurora, the grass in-row weed biomasses of the grit treatments were similar to the season-long weedy check, which could be because of the very high grass in-row weed densities that were not reduced after two grit applications. In 2017 at Morris the low grass in-row weed densities could be the reason why the grass in-row weed biomass of the grit treatments was similar to both the season-long weedy and weed-free checks. A high grass weed density could pose problems for propelled abrasive grit management, as overall grit type did not influence grass in-row weed biomass because the grit applications occurred when the growing point of the grass weeds was still below the ground, making these plants harder to control (Wortman, 2014). More than two sequential applications of grit at early corn growth stages may be able to provide some suppression or control of grass in-row weeds.

The use of a SPAD-meter has been reported to be a useful diagnostic aid to study the effect of nitrogen on corn (Bullock and Anderson, 1998; Smeal and Zhang, 1994; Waskom et al., 1996; Hawkins et al., 2007; Rorie et al., 2011), and SPAD readings have been reported to have a strong relationship to corn leaf chlorophyll content (Schlemmer et al., 2005) and/or leaf nitrogen content (Rorie et al., 2011; Rostami et al., 2008). When using a SPAD-meter to measure relative greenness in corn, a non-fertilized control is needed to be able to compare among treatments (Schepers et al., 1992). In 2 of 3 site years, the grit treatments were similar to each other with plants having the same relative greenness. The differences between years and locations could be due to the different hybrids planted at each location, or weed density as a plant stress (Schepers et al., 1992; Lindquist et al., 2010). The relative greenness values associated with Sustane 8-2-4 and Phytaboost Plant Food 7-1-2 were higher than the season-long weed-free check in 2016 at Aurora, which could mean that the nitrogen from the grit was sequestered by the corn plant as there was no nitrogen fertilizer applied to the field. At Morris and Aurora in 2017 the grit treatments had similar relative greenness values. The lower than ordinary precipitation in Aurora in 2017 may have inhibited the movement of the nitrogen to the corn zone.

The differences in corn stem diameter between location and years could be due to the different corn hybrids planted which have been reported to have different stem diameters (Beiragi et al., 2011; Shaw and Loomis, 1950; Kelly, 2011). Stem diameters potentially predict corn yield (Kelly, 2011). The differences in stem diameter in Aurora in 2017 had a similar pattern as the corn grain yield as the largest stem diameter was the season-long weed-free check, which had the highest corn grain yield. Similarily, the Sustane 8-2-4 had a similar stem diameter as the season-long weed-free check and had the second highest corn grain yield. All grit treatments had higher stem diameters than the season-long weedy check, and a similar response in yield was seen. An alternative predictor of corn grain yield may have been to measure the plant height at V12 and use the interaction of plant height and corn stem diameter as others have reported (Kelly, 2011).

The growing point of corn does not emerge from the soil until about V6 (Ritchie et al., 1997) so if there was any crop damage from grit applications, plant regrowth can occur and should not affect final yield. In this study, grit was aimed at the base of corn and while some damage to the corn leaves was observed the plants continued to grow. The corn yields for the season-long weed-free check were not similar among all four site years, as the season-long weed-free yield was 12690 kg ha^{-1} in Morris in 2015 and 9201 kg ha^{-1} in 2017, and in Aurora the yield was 10772 kg ha^{-1} in 2016 and 7588 kg ha^{-1} in 2017 ($p = 0.34$). Weeds reduced the season-long weedy check by 19% in Morris in 2015 and by 60% in 2017, and in Aurora in 2016 by 6% and by 99% in 2017. The precipitation after grit applications for one month was 11.2 cm in Morris in 2015 and 2.3 cm in 2017, and in Aurora in 2016 it was 20.6 cm and 12.9 cm in 2017. In-row weed biomass has been reported to reduce corn yield less than between-row weed biomass (Donald and Johnson, 2003).

The added nitrogen from Sustane 8-2-4 may have increased the corn yield at Morris in 2015 as this treatment had similar total in-row weed biomass as the season-long weedy check. Sustane 8-2-4, Agra Grit and Phytaboost Plant Food 7-1-2 all appeared not to control in-row weeds at Morris in 2015 which may have been reduced corn yield from the competition. The additional nitrogen added from Sustane 8-2-4 and Phytaboost Plant Food 7-1-2 could have made it possible for these treatments to have higher yields than the season-long weed-free treatment at Aurora in 2016. The Phytaboost Plant Food 7-1-2 and Sustane 8-2-4 had the highest total in-row weed control of 55 and 62% ($t < 0.01$) and the added nitrogen may have helped maintain higher yields than the season-long weed-free treatment. In 2017 at both Morris and Aurora the grit treatments did not reduce in-row weeds and had similar total in-row weed biomass among grit treatments and the season-long weedy check. The nitrogen from the Sustane 8-2-4 treatment may not have moved into the corn root zone in in 2017 in Morris because of the low amount of rain that occurred after the grit applications, whereas in Aurora in 2016 the higher than average rainfall after the grit applications may have moved the nitrogen from Sustane 8-2-4 and Phytaboost Plant Food 7-1-2 into the corn root zone. The smaller amount of rain in 2017 in Aurora may have moved the nitrogen from the Sustane 8-2-4, but the high density of grass weeds in the crop row may have offset any extra nitrogen provided to the corn crop.

The reduction of the between-row weed biomass in corn may have had a larger influence on corn yield in this study than the reduction of in-row weeds, as yields were similar in all site years among grit and cultivation- and flame-only treatments. If weeds were controlled during the critical weed free period with two applications of grit + between-row cultivation or flaming, corn yield can be sustained or increased through the use of organic nitrogen fertilizers.

Soybean.

Aurora 2015.

Climate. The average monthly temperatures in May, September, October, and November were 11, 23, 34, and 300% higher than the 30-year average (1980-2010) (Table 2.12). The months of June, July, and August had similar average monthly temperatures as the 30-year average. The cumulative precipitation in the months of May, July, August, and November were 49, 12, 106, and 21% higher than the 30-year average (Table 2.12). The cumulative precipitation in June, September, and October were 50, 25, and 50% less than the 30-year average. Over the whole growing season, from May to November, the cumulative precipitation was 21% higher than the 30-year average (Table 2.12). The cumulative growing degree days in the month of May were 11% lower than the 30-year average, whereas those of the fall months of September and October were 37 and 22% higher than the 30-year average. The cumulative growing degree days in June, July, and August were similar to the 30-year average, as well as the cumulative growing degree days over the growing season, from May to October, were similar to the 30-year average (Table 2.12).

Weed species. The predominant weeds present before the grit applications were common lambsquarters ranging in height from 2- to 4-cm, and redroot pigweed ranging in height from 2- to 6-cm, with a smaller amount of green foxtail plants that were 1- to 5-cm tall. The in-row weed densities were only measured before all grit applications and averaged 706 plants m^{-2}. The broadleaf weeds were 75% of the total weed density and grass weeds were 25% of the total weed density.

End-of-season weed biomass. The total between-row weed biomass was 62% of the total weed biomass (in-row + between-row broadleaf and grass weeds) in the season-long weedy check. The total between-row weed biomass was similar ($p = 0.18$) among grit, cultivation- and flame-only treatments and the season-long weedy check and averaged 7085 kg ha^{-1}. The broadleaf between-row weed biomass was 58% of the total between-row weed biomass in the season-long weedy check. The broadleaf between-row weed biomass was similar ($p = 0.32$) among grit, cultivation- and flame-only treatments and the season-long weedy check, and averaged 3172 kg ha^{-1} (Table 2.19). The grass between-row weed biomass was 42% of the total between-row weed biomass in the season-long

Table 2.19. At Aurora in soybean in 2015 the between-row, in-row, broadleaf, grass weed biomass, and grain yield (kg ha^{-1}). Letters denote significant differences $\alpha = 0.1$.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	---------------------------- kg ha^{-1}			----------------------------		
Agra Grit + BR	8844	3638	5206	5703	2800	2925
Phytaboost Plant Food 7-1-2 + BR	1664	496	1168	3900	3264	2068
Sustane 8-2-4 + BR	6978	3386	3952	5863	3051	2812
Sustane 4-6-4 + BR	7774	4009	3765	3368	1785	1387
Cultivation Only	11,072	2560	8512	6719	3951	2677
Flame Only	3563	2466	1097	7272	5537	1735
Season-Long Weedy Check	9703	5646	4057	5734	2693	3041
Season-Long Weed-Free	-	-	-	-	-	-
P-value	0.18	0.32	0.14	0.46	0.58	0.65

+ BR = with between-row weed control.

weedy check. The grass between-row weed biomass was similar ($p = 0.14$) among grit, cultivation- and flame-only treatments and the season-long weedy check and averaged 3965 kg ha^{-1} (Table 2.19).

The total in-row weed biomass was 37% of the total weed biomass in the season-long weedy check. The total in-row weed biomass was similar ($p = 0.46$) among grit treatments, cultivation- and flame-only, and the season-long weedy check, and averaged 5508 kg ha^{-1}. The broadleaf in-row weed biomass was 47% of the total in-row weed biomass in the season-long weedy check. There were no differences ($p = 0.58$) among grit treatments, cultivation- and flame-only, and the season-long weedy check, and broadleaf in-row weed biomass averaged 3297 kg ha^{-1}. The in-row grass weed biomass was 53% of the total in-row weed biomass in the season-long weedy check. There were no differences ($p = 0.65$) among grit treatments, cultivation- and flame-only, and the season-long weedy check, and averaged 2378 kg ha^{-1}.

Yield, protein and oil content. The soybean yields were similar ($p = 0.80$) among all treatments (Table 2.20), with an average yield of 1620 kg ha^{-1}. The protein content of the soybeans were similar ($p = 0.15$) among all treatments (Table 2.20), with an average protein content of 35.7%. The oil content of the soybeans were similar, 18.9% ($p = 0.17$) among all treatments (Table 2.20).

Table 2.20 At Aurora in 2015 in soybean the yield (kg ha^{-1}) and protein and oil (%).

		Grain	
Treatment	Yield	Protein	Oil
	-- kg ha^{-1} --	------------ % -------------	
Agra Grit + BR	1569	36.1	19.1
Phytaboost Plant Food 7-1-2 + BR	1591	35.6	19.1
Sustane 8-2-4 + BR	1412	35.4	18.8
Sustane 4-6-4 + BR	1701	35.4	19.0
Cultivation Only	1623	35.8	18.9
Flame Only	1881	35.7	19.0
Season-Long Weedy Check	1557	35.7	18.8
Season-Long Weed-Free	1626	35.7	18.8
P-value	0.80	0.15	0.17

+ BR = with between-row weed control.

Aurora 2016.

Weed species and control. The predominant weed species before grit applications were common lambsquarters ranging in height from 1- to 2-cm, redroot pigweed ranging in height from 0.5- to 2-cm, and green and yellow foxtails ranging in height from 0.5- to 2-cm. After both grit applications, the weed population shifted to grass weeds. The weeds present after the grit applications were barnyardgrass ranging in height from 2- to 14-cm, and green and yellow foxtails ranging in height from 6- to 10-cm.

The initial total in-row weed density (broadleaf + grass weeds) averaged 198 plants m^{-2}. All grit treatments reduced ($t < 0.05$) total in-row weed density and had an average reduction of 61% (Table 2.21). The cultivation- and flame-only treatments had similar reduction of total in-row weed density as the grit treatments (Table 2.21). The broadleaf in-row weeds made up 38% of the total in-row weeds in the season-long weedy check. The broadleaf in-row density was inconsistent across the field and ranged from an average of 60 plants m^{-2} in the season-long weedy check, to 148 plants m^{-2} in the Phytaboost Plant Food 7-1-2 treatment (Table 2.21).The broadleaf in-row weed density was reduced ($t < 0.1$) by all grit treatments, cultivation- and flame-only treatments and had an average reduction of 69% (Table 2.21). The reduction of broadleaf in-row weeds was similar among all weed control treatments.

The grass in-row weeds made up 62% of the total in-row weeds in the season-long weedy check. Grass in-row weeds were inconsistent among treatments and ranged from an average of 46 plants m^{-2} in the flame-only treatment, to 125 plants m^{-2} in the Agra Grit treatment before all grit treatments. The two grit treatments reduced grass density from 53 to 79% when compared to the initial density (Table 2.21). The between-row weed density was 150 plants m^{-2} before flaming or cultivation and was 0 plants m^{-2} after the flaming or cultivation, a 100% reduction compared to the initial densities.

Table 2.21. At Aurora in soybean in 2016, the total, broadleaf, and grass in-row weed density (plants m^{-2}) before and after all grit applications and paired t-test values. Values in parentheses are percent (%) control compared to before weed density.

	In-row weed density								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	---- plants m^{-2} ----								
Agra Grit	204	91 (56)	0.01	79	43 (62)	0.09	125	48 (62)	0.04
Phytaboost Plant Food 7-1-2	214	91 (57)	0.02	148	60 (59)	0.02	66	31 (53)	0.05
Sustane 8-2-4	193	72 (67)	4E-04	99	39 (61)	8E-04	111	23 (79)	0.04
Sustane 4-6-4	211	61 (70)	0.003	113	36 (68)	0.01	80	36 (55)	0.02
Cultivation Only	169	85 (50)	9E-04	100	16 (84)	0.007	69	69	1.00
Flame Only	128	40 (68)	0.01	81	18 (78)	0.002	46	23 (50)	0.07
Season-Long Weedy check	158	141	9E-04	60	29	0.13	98	113	0.47
Season-Long Weed-Free	206	0	0.002	116	0	0.02	80	0	0.03

End-of-season weed biomass. The total between-row weed biomass was 60% of the total weed biomass (in-row + between-row broadleaf and grass weeds) in the season-long weedy check. All grit treatments, cultivation- and flame-only treatments had similar total between-row weed biomass as the season-long weed-free check, 0 kg ha^{-1}, a 100% reduction compared to the season-long weedy check, which averaged 1930 kg ha^{-1} (Table 2.22).

The total in-row weed biomass was 41% of the total weed biomass in the season-long weedy check. The total in-row weed biomass did not differ ($p = 0.26$) and averaged 535 kg ha^{-1} among all grit treatments, cultivation- and flame-only treatments, season-long weedy check and season-long weed-free treatments (Table 2.22). The broadleaf in-row weed biomass was 17% of the total in-row weed biomass in the season-long weedy check. The broadleaf in-row weed biomass differed ($p = 0.07$) with Agra Grit, Phytaboost Plant Food 7-1-2, Sustane 8-2-4, and flame-only treatments having at least 72% less broadleaf in-row weed biomass than the season-long weedy check treatment (Table 2.22). The Sustane 4-6-4 and cultivation-only broadleaf in-row weed biomasses were similar to the season-long weedy check (Table 2.22). The grass in-row weed biomass was 83% of the total in-row weed biomass in the season-long weedy check. The grass in-row weed biomass averaged 62% lower biomass than in the season-long weedy check (Table 2.22). Grit treatments, and cultivation- and flame-only treatments grass in-row weed biomass was similar and averaged 405 kg ha^{-1}. The Sustane 8-2-4 and 4-6-4 treatments had similar grass in-row weed biomass as the season-long weed-free treatment, 0 kg ha^{-1} (Table 2.22).

Table 2.22. At Aurora in soybean in 2016 the between-row and in-row broadleaf and grass weed biomass (kg ha^{-1}) collected on July 20th. Letters denote significant differences at α= 0.1. Values in parentheses are percent (%) control compared to the season-long weedy check.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	------------------------- kg ha^{-1} -------------------------					
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	737	35 b (84)	567 b (49)
Phytaboost Plant Food 7-1-2 + BR	0 b (100)	0 b (100)	0 b (100)	500	62 b (72)	461 b (51)
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	0 b (100)	269	37 b (83)	232 bc (79)
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	369	123 ab (44)	246 bc (78)
Cultivation Only	0 b (100)	0 b (100)	0 b (100)	589	143 a (35)	446 b (60)
Flame Only	0 b (100)	0 b (100)	0 b (100)	500	52 b (76)	480 b (56)
Season-Long Weedy check	1930 a	1152 a	778 a	1321	219 a	1102 a
Season-Long Weed-Free	0 b	0 b	0 b	0	0 b	0 c
P-Value	1.40E-05	0.0005	0.0005	0.26	0.07	0.007

+ BR = with between-row weed control.

Yield, protein and oil content. The soybean yield differed (p – 3.17E-05) and was about three times greater than the soybeans in 2015 in Aurora. All grit treatments had higher yields than the season-long weedy check (Table 2.23). Phytaboost Plant Food 7-1-2, Sustane 8-2-4, cultivation- and flame-only treatments had similar yields as the season-long weed-free check and averaged 4599 kg ha^{-1}. The Agra Grit and Sustane 4-6-4 treatments had similar and lower yields than the season-long weed-free check and other grit treatments but still significantly higher than the weedy check (Table 2.23). The protein content of the soybeans was similar (p = 0.25) among all treatments and averaged 34%. The oil content of the soybeans was similar (p = 0.36) and averaged 19%.

Table 2.23. At Aurora in 2016 in soybean the yield (kg ha^{-1}) and protein and oil (%). Letters denote significant differences at $\alpha = 0.05$.

		Grain	
Treatment	Yield	Protein	Oil
	-- kg ha^{-1} --	----------- % ------------	
Agra Grit + BR	4224 bc	34.4	18.7
Phytaboost Plant Food 7-1-2 + BR	4642 a	34.3	18.8
Sustane 8-2-4 + BR	4406 ab	33.9	18.9
Sustane 4-6-4 + BR	4018 c	34.2	18.8
Cultivation Only	4496 ab	34.2	18.9
Flame Only	4594 ab	34.6	18.6
Season-Long Weedy Check	3369 d	35.0	18.5
Season-Long Weed-Free	4856 a	34.7	18.7
P-value	3.17E-05	0.25	0.36

+ BR = with between-row weed control.

Aurora 2017.

Weed species and control. The predominant weed species before grit applications were green and yellow foxtails, 1- to 2-cm in height. After the first grit application and before the second grit application, the predominant weed species were green and yellow foxtails, 4- to 6-cm in height. After both grit applications the predominant weed species were green and yellow foxtails ranging in height from 8- to 12-cm.

The total in-row weed density before the grit applications averaged 62 plants m^{-2}. The total in-row weed density was not reduced after one application of grit, regardless of type. The Sustane 8-2-4 and cultivation-only treatments had 33, and 150% increases in total in-row weed density after the first grit application (Table 2.24). The grit treatments broadleaf in-row weed density after the first grit application was similar ($t > 0.52$) to the initial density (Table 2.24). The cultivation-only broadleaf in-row weed density increased by 300% after the first grit application when compared to the initial density. The grit treatments and cultivation-only treatment grass in-row weed density was similar ($t > 0.22$) to the initial density (Table 2.24).

The grit treatments total in-row weed density after the second grit application was similar ($t > 0.26$) to the total in-row weed density before the second grit application. The total in-row weed density in the cultivation-only treatment was reduced by 56% compared to the density before the second grit application. All grit treatments had similar broadleaf in-row weed density after the second grit application as before the second grit application. The cultivation-only treatment reduced broadleaf in-row weed density by 65% after the second grit application. All grit treatments and cultivation-only treatment had similar grass in-row weed density after the second grit application as before the second grit application.

The between-row weed density before both cultivations was 46 plants m^{-2}. After both cultivations the between-row weed density was 0 plants m^{-2}, a 100% reduction in weeds.

End-of-season weed biomass. The total between-row weed biomass was 60% of the total weed biomass (in-row + between-row broadleaf + grass weeds) in the season-long weedy check. All grit treatments and cultivation-only treatment had similar total between-row weed biomass as the season-long weed-free check, 0 kg ha^{-1}, a 100% reduction compared to the season-long weedy check, 2660 kg ha^{-1} (Table 2.25).

The total in-row weed biomass was 40% of the total weed biomass in the season-long weedy check. The total in-row weed biomass differed ($p = 0.03$) among treatments. All grit treatments and cultivation-only treatment had similar total in-row weed biomass as the season-long weedy check and averaged 1845 kg ha^{-1}. Sustane 4-6-4 was the only grit treatment to have similar in-row weed biomass as the season-long weed-free check, whereas all other treatments had higher total in-row weed biomass (Table 2.25). The broadleaf in-row weed biomass was 48% of the total in-row weed biomass. All treatments had similar ($p = 0.29$) broadleaf in-row weed biomass and

Table 2.24. At Aurora in soybean in 2017 the in-row total, broadleaf, and grass weed density (plants m^{-2}) before and after the first applications. All grit treatments had similar total, broadleaf, and grass weed density values after the second grit application as before the second grit application. Values in parentheses are the percent (%) weed control compared to before the grit application.

	1st Grit Application								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	------------------------------- plants m^{-2} -------------------------------								
Agra Grit	68	68	1	23	29	0.80	45	39	0.53
Sustane 8-2-4	69	92	0.03	24	5	0.52	45	50	0.74
Sustane 4-6-4	44	66	0.58	30	35	0.71	10	31	0.22
Cultivation Only	54	135	0.07	15	65	0.003	39	70	0.38
Season-Long Weedy Check	66	243	0.09	21	159	0.11	45	85	0.06
Season-Long Weed-Free	0	0	-	0	0	-	0	0	-

Table 2.25. At Aurora in soybean in 2017 the between-row, in-row, broadleaf, and grass weed biomass (kg ha^{-1}). Letters describe significant differences $\alpha = 0.1$. Values in parentheses are percent control (%) compared to the season-long weedy check.

Treatment	Between-row weed biomass			In-row weed biomass		
	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	------------------------------ kg ha^{-1}			------------------------------		
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	2703 a	1553	1170
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	0 b (100)	1823 ab	1050	1078
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	1003 bc (43)	918	905
Cultivation Only	0 b (100)	0 b (100)	0 b (100)	1925 ab	817	1108
Season-Long Weedy Check	2660 a	585 a	2075 a	1773 ab	850	923
Season-Long Weed-Free	0 b	0 b	0 b	0 c	0	0
P-value	0.002	0.09	0.02	0.03	0.29	0.20

+ BR = with between-row weed control.

averaged 865 kg ha^{-1}. The grass in-row weed biomass was 52% of the total in-row weed biomass. The grass in-row weed biomass was similar (p = 0.20) among all treatments and averaged 864 kg ha^{-1}.

Yield, protein and oil content. The soybean yield differed (p = 0.006) among treatments (Table 2.26). The season-long weed-free treatment had the highest yield, 2890 kg ha^{-1}, and was similar to the Sustane 4-6-4 treatment, which averaged 2681 kg ha^{-1} (Table 2.26). The Agra Grit, Sustane 8-2-4, cultivation-only and season-long weedy-check had similar yields, whereas the Sustane 8-2-4 and cultivation-only treatments had similar soybean yields as the Sustane 4-6-4 treatment (Table 2.26). The protein content of the soybeans was similar (p = 0.23) and averaged 34.4%. The oil content of the soybeans was similar (p = 0.58) and averaged 18.0%.

Table 2.26. At Aurora in 2017 in soybean the yield (kg ha^{-1}) and protein and oil (%). Letters denote significant differences at α= 0.05.

		Grain	
Treatment	Yield	Protein	Oil
	-- kg ha^{-1} --	---------- % ------------	
Agra Grit + BR	1975 c	34.3	18.1
Sustane 8-2-4 + BR	2249 bc	34.1	18.1
Sustane 4-6-4 + BR	2681 ab	34.6	17.9
Cultivation Only	2116 bc	34.2	18.1
Season-Long Weedy Check	1880 c	34.3	17.9
Season-Long Weed-Free	2890 a	34.8	17.8
P-value	0.006	0.23	0.58

+ BR = with between-row weed control.

Beresford 2015

Climate. The average monthly temperatures of May, June, July, and August were similar to the 30-year average (1980-2010), whereas the average monthly temperatures of September and October were 16 and 22% warmer than the 30-year average (Table 2.27). The cumulative precipitation in May, June, and October were 13, 15, and 51% lower than the 30-year average, whereas the cumulative precipitation in July, August and September were 61, 156, and 23% greater than the 30-year average (Table 2.27). The cumulative precipitation over the growing season, May to October, was 25% greater than the 30-year average (Table 2.27). The cumulative growing degree days were the same as the 30-year average in the months of May, June, July, and August, whereas the cumulative growing degree days in September and October were 27 and 25% greater than the 30-year average (Table 2.27). The cumulative growing degree days over the growing season, May to October, was the same as the 30-year average (Table 2.27).

Weed species. The predominant weed species before grit applications were common lambsquarters and redroot pigweed ranging in height from 1- to 4-cm. The density before grit applications was 311 plants m^{-2}, 89% of which were broadleaf weeds.

End-of-season weed biomass. The total between-row weed biomass was 39% of the total weed biomass in the season-long weedy check. The total between-row weed biomass was similar among grit treatments, cultivation- or flame-only treatments and the season-long weedy check and averaged 1383 kg ha^{-1}. The broadleaf between-row weed biomass was 100% of the total between-row weed biomass in the season-long weedy

Table 2.27. The Beresford, SD average monthly temperature (ºC), monthly cumulative precipitation (cm), and monthly cumulative growing degree days (base 10 ºC) in 2015 and 2017 and 30-year average (1980-2010). Climate data obtained from www.NOAA.gov. Cumulative growing degree days calculated with the following equation $((T_{max}-T_{min})/2)-T_{base}$, where Tmax = max daily temperature, Tmin = minimum daily temperature, base temperature = 10 ºC.

Month	Temperature (C)			Cumulative precipitation (cm)			Cumulative growing degree days (base 10		
	2015	2017	30-year average	2015	2017	30-year average	2015	2017	30-year average
May	14.6	14.2	15.1	8.0	17.0	9.2	186	179	196
June	21.0	22.0	20.5	9.4	10.4	11.1	320	339	311
July	22.3	24.3	22.8	13.4	4.1	8.3	364	417	381
August	19.9	19.2	21.6	18.4	2.6	7.2	318	289	351
September	19.3	17.6	16.6	9.1	5.9	7.4	293	261	230
October	11.5	9.6	9.4	2.7	11.4	5.5	141	115	113
Cumulative	-	-	-	61.0	51.4	48.7	1622	1600	1582

check. All grit treatments, cultivation- and flame-only and season-long weedy check had similar broadleaf between-row weed biomass and averaged 1461 kg ha^{-1}. The grass between-row weed biomass was 0% of the total between-row weed biomass. The grass between-row weed biomass of all grit treatments, cultivation- and flame-only and season-long weedy check had similar grass between-row weed biomass and averaged 60 kg ha^{-1}.

The total in-row weed biomass was 72% of the total weed biomass in the season-long weedy check. The total in-row weed biomass was similar among all grit treatments, cultivation- and flame-only and season-long weedy check had similar broadleaf between-row weed biomass and averaged 3521 kg ha^{-1}. The broadleaf in-row weed biomass was 99% of the total weed biomass in the season-long weedy check. The broadleaf in-row weed biomass was similar among all grit treatments, cultivation- and flame-only and season-long weedy check had similar broadleaf between-row weed biomass and averaged 3265 kg ha^{-1}. The grass in-row weed biomass was less than 1% of the total weed biomass in the season-long weedy check. The grass in-row weed biomass was similar among all grit treatments, cultivation- and flame-only and season-long weedy check had similar broadleaf between-row weed biomass and averaged 239 kg ha^{-1}.

Yield, protein and oil content. The soybean yields were similar ($p = 0.31$) among treatments (Table 2.29). The average yield among treatments was 2861 kg ha^{-1}. The protein content of the soybeans were similar and averaged 38%. The oil content of the soybeans were similar and averaged 18%.

Table 2.28. At Beresford, SD in soybean in 2015 the between-row, in-row, broadleaf and grass weed biomass (kg ha^{-1}) collected on September 2nd.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	----------	----------	---------- kg ha^{-1}	----------	----------	----------
Agra Grit + BR	867	690	176	2485	2311	175
Phytaboost Plant Food 7-1-2 + BR	3095	2955	140	4190	3962	228
Sustane 8-2-4 + BR	2728	2728	0	4101	3869	116
Sustane 4-6-4 + BR	1295	1295	0	3617	3497	120
Cultivation Only	105	0	105	4293	3817	476
Flame Only	131	131	0	2233	1676	557
Season-Long Weedy Check	1461	1461	0	3729	3725	0
Season-Long Weed-Free	-	-	-	-	-	0
P-value	0.38	0.39	0.74	0.20	0.90	0.72

+ BR = with between-row weed control.

Table 2.29. At Beresford in 2015 in soybean the yield (kg ha^{-1}) and protein and oil (%).

		Grain	
Treatment	Yield	Protein	Oil
	-- kg ha^{-1} --	---------- % -------------	
Agra Grit + BR	3011	38.0	18.3
Phytaboost Plant Food 7-1-2 + BR	2760	37.6	18.3
Sustane 8-2-4 + BR	2723	38.0	17.9
Sustane 4-6-4 + BR	2358	37.8	18.2
Cultivation Only	3262	37.8	18.1
Flame Only	3138	37.9	18.2
Season-Long Weedy Check	2695	37.5	18.3
Season-Long Weed-Free	2944	38.0	18.4
P-value	0.31	0.60	0.43

+ BR = with between-row weed control.

Beresford 2017.

Climate. The average monthly temperature of May, June, July, September, and October were similar to the 30-year average (1980-2010), whereas the average monthly temperature of August was 11% lower than the 30-year average (Table 2.27). The cumulative precipitation in May and October was 84, and 107% greater than the 30-year average (Table 2.27). The cumulative precipitation in July, August, and September was 51, 64, and 20% lower than the 30-year average, and the cumulative precipitation in June was similar to the 30-year average (Table 2.27). The cumulative precipitation during the growing season, May to October, was similar to the 30-year average. The cumulative growing degree days in May, June, July, and October had similar growing days as the 30-year average, whereas the month of August had 18% lower growing degree days, and the month of September had 13% more growing degree days compared to the 30-year average. The cumulative growing degree days over the growing season, from May to October, was similar to the 30-year average.

Weed species and control. Broadleaf weeds were the only species present in 2017. Before the first grit application the predominant weeds were redroot pigweed ranging in height from 1- to 2-cm. After the first grit application, and before the second grit application, the predominant weed was redroot pigweed ranging in height from 3- to 6-cm. After the second grit application, redroot pigweed ranging in height from 10- to 14-cm, and common lambsquarters ranging in height from 1- to 4-cm were the predominant weeds.

The initial total in-row weed density was similar among grit treatments, cultivation-only treatment and season-long weedy check and averaged 104 plants m^{-2}. The Sustane 4-6-4 and cultivation-only treatments reduced total in-row density after the first grit application by 28, and 32%, whereas the total in-row weed density before and after the first grit application in the Agra Grit and Sustane 8-2-4 treatments was similar ($t > 0.26$). Grit treatments did not reduce total in-row weed density after the second grit application (Table 2.30). The Agra Grit and Sustane 8-2-4 treatments had increases of 138, and 51% of total in-row weed density, whereas the season-long weedy check had a 288% increase of total in-row broadleaf weed density (Table 2.30). The Sustane 4-6-4 and cultivation-only treatments had similar total in-row densities before and after the second grit application (Table 2.30).

Table 2.30. At Beresford in soybean in 2017 the in-row total (broadleaf + grass) weed density (plants m^{-2}). The broadleaf weed density was 99.9% of the total in-row weed density.

	In-row total weed density					
	1st grit application			2nd grit application		
Treatment	Before	After	t-value	Before	After	t-value
	------------------------ plants m^{-2} -----------------------					
Agra Grit	91	64	0.26	64	152	0.02
Sustane 8-2-4	115	106	0.48	106	160	0.09
Sustane 4-6-4	118	85 (28)	0.04	85	213	0.15
Cultivation Only	103	70 (32)	0.03	70	140	0.15
Season-Long Weedy Check	93	105	0.54	105	303	0.05
Season-Long Weed-Free	0	0	-	0	0	-

End-of-season weed biomass. The total between-row weed biomass was 30% of the total weed biomass in the season-long weedy check. The total weed biomass of the grit treatments, cultivation-only treatment and season-long weed-free check were similar and averaged 0 kg ha^{-1}, a 100% reduction compared to the season-long weedy check, 2050 kg ha^{-1} (Table 2.31).

The total in-row weed biomass was 70% of the total weed biomass in the season-long weedy check. The total in-row weed biomass was similar ($p = 0.11$) among treatments and averaged 3529 kg ha^{-1}. The broadleaf in-row weed biomass was 100% of the total between-row weed biomass in the season-long weedy check. The broadleaf in-row weed biomass was similar ($p = 0.10$) among treatments and averaged 3504 kg ha^{-1}.

Yield, protein and oil content. The soybean yield was similar ($p = 0.24$) among treatments (Table 2.32) and averaged 1386 kg ha^{-1}. The protein content of the grit treatments and cultivation-only treatment was similar, and averaged 35.0%, and higher than the season-long weed-free protein content, 33.9% (Table 2.32). The Agra Grit and cultivation-only treatments had similar protein content as the season-long weedy check, 35.8% (Table 2.32). The oil content of the grit treatments and cultivation treatment was similar and averaged 18.6%, and lower than the season-long weed-free check oil content 19.2 % (Table 2.32). The Agra Grit and cultivation-only treatments oil content was similar to the oil content season-long weedy check, 18.3% (Table 2.32).

Table 2.31. At Beresford in soybean in 2017 the between-row, in-row broadleaf weed biomass (kg ha^{-1}). There was no grass weed biomass. Letters describe significant differences $\alpha = 0.1$. Values in parentheses are percent (%) control compared to season-long weedy check.

	Between-row weed biomass		In-row weed biomass	
Treatment	Total	Broadleaf	Total	Broadleaf
	---------- kg ha^{-1} ----------			
Agra Grit + BR	0 b (100)	0 b (100)	5178	5073
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	3975	3975
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	3465	3420
Cultivation Only	0 b (100)	0 b (100)	3738	3738
Season-Long Weedy Check	2050	2050	4820	4820
Season-Long Weed-Free	0 b	0 b	0	0
P-value	0.06	0.07	0.11	0.10

+ BR = with between-row weed control.

Table 2.32. At Beresford in 2017 in soybean the yield (kg ha^{-1}) and protein and oil (%). Letters denote significant differences at α = 0.05.

		Grain	
Treatment	Yield	Protein	Oil
	-- kg ha^{-1} --	---------- % -----------	
Agra Grit + BR	1235	35.3 ab	18.5 bc
Sustane 8-2-4 + BR	1353	34.8 b	18.7 b
Sustane 4-6-4 + BR	1443	34.9 b	18.7 b
Cultivation Only	1423	35.2 ab	18.5 bc
Season-Long Weedy Check	1223	35.8 a	18.3 c
Season-Long Weed-Free	1640	33.9 c	19.2 a
P-value	0.24	0.0005	7.92E-05

+ BR = with between-row weed control.

Morris 2016.

Climate. The average monthly temperature of April, May, June, July, and August were similar to the 30-year average (1980-2010), whereas the average monthly temperature in September and October were 11 and 30% warmer than the 30-year average (Table 2.7). The cumulative precipitation in the months of April, May, June, and September were 12, 40, 56, and 42% lower than the 30-year average (Table 2.7). The cumulative precipitation in the months of July and August were 11 and 86% greater than the 30-year average (Table 2.7). The cumulative precipitation over the growing season, from April to October, was similar to the 30-year average of 55.3 cm (Table 2.7). The cumulative growing degree days in the months of April, July, August, and October were similar to the 30-year average, whereas the months of May, June, and September were 17, 11, and

14% higher than the 30-year average (Table 2.7). The cumulative growing degree days over the whole growing season, from April to October was similar to the 30-year average (Table 2.7).

Weed species and control. The predominant weed species were common lambsquarters ranging in height form 0.5- to 1.5-cm, redroot pigweed ranging in height from 0.5- to 1.5-cm, and green foxtail ranging in height from 0.5- to 3-cm. After both grit applications, the green foxtail was the predominant weed and was 3- to 16-cm tall.

The initial total in-row weed density varied among the treatments and ranged from an average of 26 plants m^{-2} in the Agra Grit treatment, to 141 plants m^{-2} in the season-long weed-free check (Table 2.33). The total in-row weed density in the Phytaboost Plant Food 7-1-2, Sustane 4-6-4 and cultivation-only treatments were reduced by 35, 68 and 54% after both grit applications when compared to the density before grit applications. The total in-row weed density after both grit applications in Agra Grit, Sustane 8-2-4 and flame-only treatments was similar to the initial density (Table 2.33). The broadleaf in-row weed density was inconsistent across the field and ranged from an average of 7 plants m^{-2} in the Sustane 4-6-4 treatment, to 62 plants m^{-2} in the Phytaboost Plant Food 7-1-2 treatment (Table 2.33). The broadleaf in-row weed density in Phtyaboost Plant Food 7-1-2 and flame-only treatments were reduced by 44 and 67% after two grit applications, whereas all other treatments had similar broadleaf in-row weed density before and after both grit applications. The grass weed density was

Table 2.33. At Morris in soybean in 2016 the total, broadleaf and grass in-row weed density (plants m^{-2}) before and after all grit applications and the paired t-test values. Values in parentheses are percent (%) control compared to before weed density.

	In-row weed density								
	Total			Broadleaf			Grass		
Treatment	Before	After	t-value	Before	After	t-value	Before	After	t-value
	plants m^{-2}								
Agra Grit	26	60	0.54	13	13	0.91	26	17	0.18
Phytaboost Plant Food 7-1-2	99	64 (35)	0.05	62	35 (44)	0.02	38	29	0.36
Sustane 8-2-4	83	41	0.11	9	10	0.84	74	31 (58)	0.06
Sustane 4-6-4	34	11 (68)	0.09	7	6	0.45	19	4	0.22
Cultivation Only	35	16 (54)	0.06	20	13	0.32	15	3 (80)	0.03
Flame Only	60	27	0.79	54	18 (67)	0.09	6	9	0.60
Season-Long Weedy Check	61	88	0.15	54	72	0.22	7	16	0.48
Season-Long Weed-Free	141	0	0.06	34	0	0.01	5	0	0.23

inconsistent across the field and ranged from an average 5 plants m^{-2} in the season-long weed-free check, to 74 plants m^{-2} in the Sustane 8-2-4 treatment (Table 2.33). The grass in-row weed density after both grit applications in the Sustane 8-2-4 and cultivation-only treatments was reduced by 58 and 80% when compared to the initial density (Table 2.33). The grass in-row weed density after both grit applications in Agra Grit, Phytaboost Plant Food 7-1-2, Sustane 4-6-4 and flame-only treatments was similar to the initial density (Table 2.33).

End-of-season weed biomass. The total between-row weed biomass was 55% of the total weed biomass in the season-long weedy check. All grit treatments, cultivation- and flame-only treatments had similar total between-row weed biomass as the season-long weed-free check, 0 kg ha^{-1}, a 100% reduction compared to the season-long weedy check, 2122 kg ha^{-1} (Table 2.34).

Table 2.34. At Morris in soybean in 2016 the between-row, in-row, broadleaf and grass weed biomass (kg ha^{-1}) collected on July 19th. Letters denote significant differences at $\alpha = 0.1$. Values in parentheses are percent (%) control compared to the season-long weedy check.

	Between-row weed biomass			In-row weed biomass		
Treatment	Total	Broadleaf	Grass	Total	Broadleaf	Grass
	------------------------------------ kg ha^{-1}---- -------------------------					
Agra Grit + BR	0 b (100)	0 b (100)	0 b (100)	1048	473	114 b (84)
Phytaboost Plant Food 7-1-2 + BR	0 b (100)	0 b (100)	0 b (100)	876	468	253 ab (65)
Sustane 8-2-4 + BR	0 b (100)	0 b (100)	0 b (100)	1450	928	521 ab (29)
Sustane 4-6-4 + BR	0 b (100)	0 b (100)	0 b (100)	1931	1506	136 b (81)
Cultivation Only	0 b (100)	0 b (100)	0 b (100)	1587	1433	155 b (79)
Flame Only	0 b (100)	0 b (100)	0 b (100)	1523	1234	289 ab (60)
Season-Long Weedy Check	2122 a	2018 a	104 a	1714	985	729 a
Season-Long Weed-Free	0 b	0 b	0 b	0	0	0 b
P-value	2.00E-16	2.00E-16	0.02	0.26	0.43	0.09

+ BR = with between-row weed control.

The total in-row weed biomass was 45% of the total weed biomass in the season-long weedy check. The total in-row weed biomass was similar ($p = 0.26$) and averaged 1266 kg ha^{-1}. The broadleaf in-row weed biomass was 57% of the total in-row weed biomass. The broadleaf in-row weed biomass was similar ($p = 0.43$) and averaged 878 kg ha^{-1}. The grass in-row weed biomass was 43% of the total in-row weed biomass. The in-row grass weed biomass was reduced by all grit treatments from 29 to 84% when compared to the season-long weedy check (Table 2.34). The grit treatments, cultivation- and flame-only treatments had similar grass in-row weed biomass as the season-long weed-free check and had an average biomass of 210 kg ha^{-1}. The Phytaboost Plant Food 7-1-2, Sustane 8-2-4 and flame-only treatments had similar grass in-row weed biomass as the season-long weedy check (Table 2.34).

Yield, protein and oil content. The soybean yield of the grit treatment was similar and averaged 3037 kg ha^{-1}, and higher than the season-long weedy check yield of 1956 kg ha^{-1} (Table 2.35). The Phytaboost Plant Food 7-1-2, Sustane 8-2-4 and 4-6-4 treatments had similar yields as the season-long weed-free check, 3472 kg ha^{-1} (Table 2.35). The Sustane 4-6-4 and Agra Grit treatments had similar yields as the cultivation- and flame-only treatments, whereas the cultivation-only treatment had a similar yield as the season-long weedy check (Table 2.35). The protein content of the soybeans was similar ($p = 0.48$) and averaged 35.5%. The oil content of the soybeans was similar ($p = 0.42$) and averaged 19.3%.

Table 2.35. At Morris in 2016 in soybean the yield (kg ha^{-1}), and protein and oil content (%). Letters denote significant differences at $\alpha = 0.05$.

Treatment	Yield	Grain Protein	Grain Oil
	-- kg ha^{-1} --	----------- % ------------	
Agra Grit + BR	2852 bc	35.3	19.3
Phytaboost Plant Food 7-1-2 + BR	3254 ab	35.7	19.3
Sustane 8-2-4 + BR	3086 ab	35.6	19.1
Sustane 4-6-4 + BR	2956 abc	35.6	19.1
Cultivation Only	2520 cd	35.4	19.4
Flame Only	2657 bc	35.5	19.2
Season-Long Weedy Check	1956 d	35.3	19.3
Season-Long Weed-Free	3472 a	35.4	19.5
P-value	9.83E-05	0.48	0.42

+ BR = with between-row weed control.

Soybean discussion.

There was inconsistent weed control in soybeans with all grits, except Sustane 4-6-4. The Sustane 4-6-4 grit reduced weed densities after both grit applications by 71 and 68% at Aurora and Morris in 2016, whereas in 2017 Sustane 4-6-4 only reduced weed density after the first grit application in Beresford. In corn, two grit applications of corn cob meal reduced weed densities by 60% (Erazo-Barradas et al., 2017). When the same grits were used in pepper and tomato, two grit applications reduced in-row weed densities by 80 and 63% in comparison to the weedy control (Wortman, 2015). The lack of control in sobyean rows could be due to the size and species distribution of the weeds. Soybeans are planted later than corn in the Upper Midwest, which could allow for larger weeds at the time of grit application compared to the time of application in corn. Wortman (2014,

2015) and Forcella (2011) reported that grass weeds had decreasing densities with increasing number of grit applications, but control was more pronounced in broadleaf weeds. Wortman (2014) demonstrated that grass weeds were difficult to control with abrasive weeding because the meristematic tissue is located beneath the soil surface. The lack of control after the second grit application in 2017 in Beresford could be due to the size of the broadleaf weeds, which were 3- to 7-cm tall, which have been reported to need more grit applications the larger the plant (Forcella, 2009b). The similar control of between-row weed densities in 2016 and 2017 at all locations is similar to the results found in the corn study and reported by Erazo-Barradas et al. (2017) which used the same type of between-row weed control methods.

The 100% reduction of total, broadleaf and grass between-row weed biomass at Aurora in 2016 and 2017, Morris in 2016, and Beresford in 2017 indicates that the additional cultivation at the V1 soybean growth stage helped control between-row weeds before they were too large to control with flaming or cultivation later in the season. The between-row weeds in Aurora and Beresford in 2015 were not controlled with a single cultivation or flaming at the V5 soybean stage as the weeds were too large to be buried deep enough with cultivation (Baerveldt and Ascard, 1999) or to be controlled with a single flame application (Knezevic and Ulloa, 2007). The lack of control of the between-row weeds during the critical weed free period and after reduced the soybean yield in 2015 at both Aurora and Morris.

The lack of control of in-row weed biomass in 2015 at both Aurora and Beresford and at Aurora in 2017 could be due to the misapplication of grit from the PAGMan, as the team was new to the PAGMan both years. Forcella (2012) reported similar issues with using the hand-held grit applicators for the first year and changes were implemented to ensure control of in-row weeds the second year of the study. The field used for research in 2015 at Aurora was previously used as an experimental study field for air-propelled abrasive grit the year prior that did not reduce weed densities in the crop row (Erazo-Barradas et al., 2017). The high weed densities in Aurora in 2015, almost 200% more than any other site year, may have been too high to achieve control with air-propelled abrasive grit management. The lack of difference of in-row weed biomass from the season-long weedy check in Aurora and Morris in 2016 could be from the variability of the density of the weeds across the field, as weeds do not generally have a uniform density across a field (Cardina et al., 1997; Forcella et al., 1997; Colbach et al., 2000). The in-row weed biomass of the grit treatments may have been similar to the season-long weedy check in Beresford in 2017 because of the two post-emergence rotary hoe applications, as Place et al. (2009) documented that post emerge rotary hoe operations reduced both weed density and biomass.

The broadleaf in-row weed biomass was similar among all treatments in 5 of 6 site years reported. In 2015 at Beresford and Aurora the lack of difference of broadleaf in-row weed biomass among grit treatments and the season-long weedy check can be attributed to misapplication of the grit as the team was new to the PAGMan that year. The broadleaf in-row weed biomass is similar in 2016 in Morris as there was not a consistent broadleaf weed pressure in the crop row across all of the treatments and blocks within the experiment. In 2017 the broadleaf in-row weeds in Beresford were larger than desired to provide control of the weeds, as they were 3- to 7-cm tall at the time of application. In 2017 in Aurora the predominant weeds were foxtails, so the smaller density of broadleaf weeds could be the reason for the lack of difference of broadleaf in-row weed biomass among the grit treatments and the season-long weedy check. The only site year to reduce broadleaf in-row weed biomass was Aurora in 2016 when the grit was sprayed at the crop row when broadleaf weeds were less than 2 cm tall, which has been reported to be the optimal time to spray grit to control broadleaf weeds (Forcella, 2009a, 2009b).

The grass in-row weed biomass varied among site years and locations. Only 2 of 6 site years reduced grass in-row weed biomass. In 2015 at Aurora the grit treatments had similar grass in-row weed biomass as the season-long weedy check, which could be attributed to the misapplication of grit with the PAGMan. In 2015 at Beresford there was very low grass in-row weed density and biomass, less than 200 kg ha^{-1}, whereas the misapplication of the grit from the PAGMan did not reduce grass in-row weed biomass. Grit treatments in both Aurora and Morris in 2016 had lower grass in-row weed biomass than the season-long weedy check, which could because of the low grass densities and a more precise application of grit than the previous year. There was less than 800 kg ha^{-1} of grass in-row weed biomass with at least 50% reduction of the biomass in both Aurora and Morris in 2016. In 2017 the soybeans at both Aurora and Morris had no grass in-row weed biomass compared to the season-long weedy check, but also did not have any reduction of grass in-row weed densities after the two grit applications. Grass weeds are more difficult to control with air-propelled abrasive grit management system (Forcella et al., 2010) because the meristematic tissue is located beneath the ground at the time of application (Wortman, 2015).

The season-long weed-free yield varied among site years and could be due to the climate at each location during the growing season. The season-long weed-free yields in Aurora were 1626 kg ha^{-1} in 2015, 4856 kg ha^{-1} in 2016, and 2890 kg ha^{-1} in 2017, and in Beresford were 2695 kg ha^{-1} in 2015, and 1640 kg ha^{-1} in 2017, and in Morris in 2016 it was 3472 kg ha^{-1}. The season-long weed-free check in both Aurora and Beresford in 2015 were not adequately weeded to provide an actual weed-free environment for the soybeans. The weeds both in and between the crop row reduced soybean yield in Aurora by 31% in 2016, by 35% in 2017, in Morris by 44% in 2016, and in Beresford by 25% in 2017. The lack of between-row and in-row weeds in all treatments in 2015 resulted in very low yields as the yields in Aurora that were less than half of the country average. In 2016 the season-long weed-free yield was almost 300% larger, as both in-row and between-row weeds were weeded throughout the growing season and the average growing degree days and temperatures helped maintain a suitable growing season. In 2016 the grit treatments had higher yields than the season-long weedy check in both Aurora and Morris but were similar to the cultivation- and flame-only treatments. Phytaboost Plant Food 7-1-2 and Sustane 8-2-4 grit treatments could have provided nitrogen to the soybean along with reduced in-row weeds to produce similar yields as the season-long weed-free check in Aurora and Morris in 2016, as nitrogen has been reported to have a positive effect on soybean yield (Osborne and Riedell, 2006; Salvagiotti et al., 2008). The beginning of the 2017 growing season both Aurora and Beresford had cumulative precipitation that was above average and delayed planting which could have reduced the soybean yield of the season-long weed-free checks which averaged 2890 kg ha^{-1} and 1640 kg ha^{-1}. The between-row weeds were controlled in 2017 whereas the in-row weeds were not reduced after two grit applications and the in-row weed biomass was not reduced by grit treatments. The yield of the soybeans in Aurora in 2017 was similar among grit treatments, cultivation-only and season-long weedy checks, whereas in Beresford all treatments were similar which could be due to the rotary hoeing that occurred across the whole field. The in-row weeds contributed more to soybean yield reduction than the between-row weeds, which would agree with what both Pike et al. (1990) and Stoller et al. (1987) reported that weeds closer to the soybean row have been reported to be more detrimental to crop row than the between-row weeds. At sites where weed density was decreased after two in-row grit applications and between-row cultivation or flaming in the critical weed free period a reduction of weed biomass often resulted in increased soybean yields when compared to the season-long weedy check.

The protein and oil content were similar among all treatments in 5 of 6 site years. In Beresford in 2017 the higher weed biomass in a treatment resulted in a higher protein content, and lower oil content of the soybeans. The use of air-propelled abrasive grit management, regardless of grit type, with between-row cultivation or flaming does not seem to change the protein or oil content of soybeans.

2.5. Conclusion.

The similar weed control from different grit types would mean that the use of organic fertilizers is an effective method to control weeds when applied to small weeds, under 3-cm in height. The similar end-of-season weed biomass among grit treatments and the season-long weedy check implies that there was not a season-long control of weeds. The lack of season-long control reported in these studies could mean that grit applications should be focused on weed size, rather than applications at specific crop growth stages as Erazo-Barradas et. al. (2017) suggested. When weed densities decreased after two grit applications, corn and soybean yield was higher than the season-long weedy check, but not as high as the season-long weed-free yield in soybeans. The use of organic fertilizers as grits can potentially increase corn and soybean yields, under the right environmental conditions, as the added nitrogen would provide supplemental nitrogen for the crop. The use of air-propelled abrasive grit management should be considered as a tool to use in conjunction with between-row weed control techniques to reduce weed interference and sustain or increase crop yields.

CHAPTER 3

Nitrogen mineralization from selected air-propelled abrasive grits, and response of indicator plants to selected grits.

3.1. Abstract.

Weeds are the main problem in organic cropping systems. The use of air-propelled abrasive grits aimed at the crop row may provide weed control and an opportunity to simultaneously add slow-release fertilizers, which could influence the growth of the crop and weeds. Nitrogen mineralization from differing grits were estimated with two soil incubations, and a greenhouse experiment was performed to study the response of indicator plants to soils amended with grits. In the first soil incubation the nitrogen release of Sustane 8-2-4, a turkey litter grit, was documented over 112 d, whereas the second soil incubation documented the nitrogen mineralization of Agra Grit (walnut shell), corn cob meal, Phytaboost Plant Food 7-1-2 (soybean meal), Sustane 8-2-4 and Sustane 4-6-4 (turkey litter) over 183 d. Corn, wheat, red russian kale and velvetleaf were used as indicator plants to measure nitrogen response from soil amended with Sustane 8-2-4, Agra Grit corn cob meal and a no-grit control by measuring plant height, relative fresh weight and dry weight, and relative greenness. Organic fertilizer grits increased nitrogen availability whereas non-fertilizer grits decreased available nitrogen. The estimated nitrogen mineralization rates differed between soil incubations. The organic fertilizer grits released from 50 to 70% of the nitrogen applied, whereas the increasing amount of non-fertilizer grits decreased the percent of nitrogen mineralized. The plant height response and dry weight of wheat, red russian kale and

velvetleaf was greater with Sustane 8-2-4 amended soil, whereas plant response in soil amended with non-fertilizer grits did not differ from the no-grit control. Organic nitrogen fertilizer grits provided some nitrogen, whereas non-fertilizer grits immobilized soil nitrogen but did not impede plant growth.

3.2 Introduction.

Air-propelled abrasive grit management has been reported to control broadleaf and grass weeds (Forcella, 2009a, b; Forcella et al., 2010) and to control weeds in row crop and vegetable field settings (Erazo-Barradas et al., 2017; Forcella, 2012; Forcella, 2013; Wortman, 2015; Braun, 2017). Previous studies have used non-fertilizer grits, like corn cob meal and walnut shell. Forcella et al. (2010) and Wortman (2014) suggested the use of pelletized organic fertilizers to be used as grits may provide abrasive grit weeding and a method to increase crop fertility simultaneously. Soybean meal, an organic fertilizer, has been reported to provide similar weed control as non-fertilizer grits, and provide nitrogen for crops (Wortman, 2015). A greenhouse study using red russian kale and Sustane, a composted turkey litter product; had increased dry weight compared with red russian kale treated with walnut shell grit (Braun, 2017). The nitrogen mineralization pattern from various grits used in propelled abrasive grit management has not been reported, nor has their effects on weed control.

Understanding the nitrogen cycling from abrasive grits placed in the crop row can help determine if (and the amount) of nitrogen that maybe available for crop growth during the growing season. The grits may provide some nitrogen needed for crop growth and yield. The initial availability of inorganic nitrogen present in organic amendments and long-term rate of mineralization or immobilization changes the nitrogen supply from organic amendments (Flavel and Murphy, 2006). Nitrogen mineralization rates of many organic amendments have been measured in laboratory soil incubations (Agehara and Warnacke, 2005; Flavel and Murphy, 2006; Pansu et al., 2003; Poffenbarger et al., 2015). The carbon (C) to nitrogen (N) ratio of organic amendments have been reported to determine if they mineralize or immobilize soil nitrogen (Sikora and Szmidt, 2001; Nicolardot et al., 2001; Hadas et al., 2004). The soil environment changes the nitrogen availability of organic amendments (Vigil and Kissel, 1995; Whalen et al., 2001; Cookson et al., 2002), including the soil moisture and temperature (Agehara and Warnacke, 2005; Hartz and Johnstone, 2006; Gaskell et al., 2006).

Poultry litter, an organic amendment, typically contains 4 to 15% nitrogen and generally releases this nitrogen over a period of three months (Stadler et al., 2006; Sexton and Jemison, 2011). In a field experiment, raw poultry litter had a similar pattern of NH_4 release to the NH_4NO_3 fertilizer amendment, whereas very little NO_3 was released in the first year from any poulty litter when composted (Cooperband et al., 2002). Sustane-® turkey litter is an aerobically composted turkey litter approved for U.S. certified organic systems as organic fertilizers (Sustane, 2016) and has been used as an abrasive grit to control weeds in organic cropping systems. While turkey litter has been studied and reported to be a viable nitrogen source, the composted Sustane turkey litter does not have published nitrogen mineralization rates, which could be different from earlier work done in turkey litter because the sources of turkey litter and the composting processes vary (Gaskell and Smith, 2007). Sustane turkey litters is produced by composting the mixture of turkey manure and bed shavings in a twenty-six week long thermophilic composting process.

Soybean meal, such as Phytaboost Plant Food has been suggested as a possible option to provide nitrogen to crops while weeding in the row with propelled abrasive grit management system (Forcella et al., 2010; Wortman, 2015). Soybean meals require microbial mineralization before crops can take up the nitrogen but is generally a fast-release organic fertilizer, within days of application (Mikkelsen and Hartz, 2008). In a study of greenhouse tomato transplants, soybean meal increased shoot dry weight and was similar to other crop seed meals (Gagnon and Berrouard, 1994). In field settings soybean meal applied at 168 kg nitrogen ha^{-1} returned 75% of nitrogen applied over three months (Sexton and Jemison, 2011). The differences in rate of mineralization of soybean meal when applied as a propelled abrasive grit for weed control should be further studied to understand how this organic fertilizer may affect plant growth.

Walnut shell grit, such as Agra Grit, have been investigated for their use as a propelled abrasive grit to control weeds (Braun, 2017, Wortman, 2015). Walnut shells have a high C:N ratio, 168:1, which has been reported to immobilize nitrogen (Sikora and Szmidt, 2001; Nicolardot et al., 2001; Hadas et al., 2004). Previous studies using walnut shell grit have not determined its effect on nitrogen mineralization. If it is to be used as a grit for weeding, the influence of walnut shells on soil nitrogen and plant uptake should be studied to determine influences nitrogen availability.

The use of abrasive grits to control weeds and provide supplemental nitrogen to the crop will depend on the biology of plants. Mitchell and Tu (2005) reported that poultry litter was a viable option as a primary fertilizer in organic corn and cotton, whereas when poultry litter was applied as a primary fertilizer in wheat the response was lower than synthetic nitrogen because of a less efficient nitrogen uptake from the poultry litter when compared to urea-N uptake in wheat (Slaton et al., 2008). Velvetleaf has exhibited a positive growth response when amended with turkey litter (Barker et al., 2006; Little et al., 2015), and when velvetleaf emerged early in the growing season it decreased corn yield (Barker et al., 2006). Braun (2017) amended soil with turkey litter and reported an increase in fresh yield, dry weight and leaves harvested from red russian kale. The growth response of corn, wheat, velvetleaf and red russian kale have not been reported when amended with walnut shells or corn cob meal. The high C:N ratio grits like walnut shells and corn cob meal had C:N ratios of 168:1 and 95:1, respectively, could immobilize nitrogen in the soil and slow plant growth, which could be detrimental to the crop. Studying the growth response of selected plants with soil amended with organic amendments at rates used in the field for propelled abrasive grits could help producers understand the affect on crop and weed growth when applied in a field setting.

The rate of nitrogen mineralization from Phytaboost Plant Food has not been previously reported. The nitrogen mineralization of turkey litter has been reported to differ depending on soil type (Sistani et al., 2008; Gordillo and Cabrera, 1997) but the nitrogen mineralization Sustane-® has not been documented. The rate of nitrogen mineralization in soil amended with Agra Grit or corn cob meal has not been documented. The plant response from soil amended with abrasive grits such as Sustane 8-2-4, Agra Grit, and corn cob meal have not been documented.

A soil incubation study was performed to determine the nitrogen mineralization rates from grits applied at several rates to soil used in air-propelled abrasive grits in laboratory conditions. A greenhouse study was performed to determine growth response of selected plants to grits applied in the soil. The hypothesis of the soil incubation study is that the nitrogen mineralization will be similar regardless of type and amount of grit used. The hypothesis of the greenhouse study is that the plant response will be similar regardless of type of grit used within a species.

3.3 Materials and Methods.

Soil Incubation.

Two studies were performed. In the first, N mineralization from Sustane 8-2-4 (i.e.: 8-2-4, N-P-K), which was used in field weed control experiments, was examined in a 112-d incubation experiment adapted after Sistani et al. (2008). In a second study, multiple grits were used in 183 d study. A Brandt silty clay loam soil was used for the first study. Soil was collected from the 0- to 3-cm depth before planting in 2015 from the

Aurora Research Farm Station in Aurora, South Dakota (Chapter 2). A Egan silty clay loam soil was used for the second study. Soil was collected from the 0- to 3-cm depth before planting in 2015 from the Southeast Research Farm in Beresford, South Dakota (Chapter 2).

The grit used in the first study was a high-nitrogen turkey litter product (Sustane 8-2-4) described in chapter 2 and a no-grit control. The grits studied in the second study also included an additional nutrient ratio of turkey litter (Sustane 4-6-4), pelletized and crushed soybean meal (Phytaboost Plant Food 7-1-2), crushed walnut shells (Agra Grit), corn cob meal and a no-grit control (Table 3.1). To determine the nitrogen composition of the grits, each grit was ground in a Cyclone Sample Mill (UDY, Colorado) to pass through a 1-mm sieve. Total N, $\delta^{15}N$, and $\delta^{13}C$ were quantified in 1 mg sample (four replications) using a Sercon 20-20 continuous flow ratio mass spectrometer (Sercon Ltd, UK) (Clay et al., 2005a).

The studies were established as a completely randomized repeated measure design. The amount of grit applied to the soil comprised individual treatments in the first study (Table 3.2). In the second study the main factor was the type of grit applied, the and the subfactors were the amount and time of grit added (Table 3.3). The first study had 3 replications of each treatment, and the second study had 4 replications of each treatment.

Table 3.1. Description of grits used in both nitrogen mineralization and release incubation studies. These grits have been previously used as grits for propelled abrasive grit management weed control.

Grit	C:N	Description
Agra Grit	168	Crushed walnut shells
Corn Cob Meal	91	Crushed corn cob meal
Phytaboost Plant Food 7-1-2	5	Crushed and pelletized soybean meal, a certified organic fertilizer with 7, 1, 2% N, P, K, content.
Sustane 8-2-4	6	Aerobically composted turkey litter, a certified organic slow release fertilizer with 8, 2, 4 or 4, 6, 4 % N, P, K.
Sustane 4-6-4	5	

In the first study 250 g of dry soil were put into 1 L beakers, whose tops were 90% covered with parafilm. The Sustane 8-2-4 grit was applied at day 0 at a base rate of 3.6 g kg^{-1} (1X) with additional 1/3X (1.2 g grit), 2X (7.2 g grit), and 4X (14.4 g grit) rates. The amount of nitrogen added to the soil from the different rates of Sustane 8-2-4 can be found in Table 3.3. The rates of grit applied correspond with the amount of grit applied to control weeds in the field, where the 1/3X represents 270 kg ha^{-1} used at the University of Illinois, and the 1X represents 800 kg ha^{-1} used at SDSU in field trials. After grit addition, soil was mixed well and deionized water was added to the beakers to achieve 30 g water to 100 g soil moisture content. Moisture content of the beakers was checked every two days on a weight basis and water was added to maintain the 30% content. The incubation was kept at 25°C in an enclosed dark room.

For the second study, 250 g of soil was placed into 1-L plastic bags. Grits were applied at day 0 at a base rate of 3.6 g kg^{-1} of soil on 0 day (X, and 1/3X), 0 and 10 d (X+X), and 0, 10 and 20 d (X+X+X) after study initiation to mimic field application timings as seen in past field studies of air-propelled abrasive grit management. The amount of nitrogen added from each grit treatment can be found in Table 3.4. After grit addition, soil was mixed well and deionized water was added to the plastic bags to achieve 30 g water to 100 g soil moisture content. The incubation was kept at 25°C in an enclosed dark room.

Soil was sampled six times from 0 to 112 d for both experiments, sampling dates provided in (Table 3.2). Two additional samplings were done at 142 and 183 d for the second experiment. At each sampling time 16 g of wet soil were removed, were dried at 38°C, and ground to pass through a 2-mm sieve. A 10 g (± 0.02) dry sample was weighed into an Erlenmeyer flask. Soil nitrogen was extracted by adding 100 ml of 1*M* KCl solution. The slurry was shaken for one hour on a reciprocal shaker. The slurry was filtered through paper filters by gravity. The filtrates were stored at 3°C and analyzed on an ASTORIA-PACIFIC Micro-Segmented Analyzer (Clackamas, Oregon), which analyzed NO_3-N and NH_4-N. The filtrates were compared with blanks for controls and standards ranging from 0.2 to 10 μg ml^{-1} of nitrogen per 100 ml of 1*M* KCl.

Table 3.2. Soil Sampling dates after study initiation during both the first and second nitrogen mineralization and release incubation studies.

Soil sampling day
0
7
14
28
56
112
142 [1]
183 [1]

[1] Soil samples at these dates are only included in the second incubation study.

Nitrogen Release and Uptake by Indicator Plants

Greenhouse experiments were modified from Wortman (2015) to determine the effect of nitrogen release from grits on early stage plant growth. Three experiments were performed from December 2016 to April 2017. The greenhouse conditions were 16 h day/8 h night, with a day temperature of 25°C and a night temperature of 15°C.

Pots were filled with sand that had been acid washed and rinsed with deionized water until a neutral pH. A layer of 2 cm of Brandt soil was placed on top of the sand. Grits used in this experiment were Agra Grit, corn cob meal, and Sustane 8-2-4. Grit was added at a rate of 3.6 g grit to kg^{-1} soil. The nitrogen added to the pots were 3.4, 5.7, 86.2

mg for Agra Grit, corn cob meal, and Sustane 8-2-4, respectively. The sand-soil mixture was allowed to incubate for a week.

Seeds of corn (*Zea mays*), wheat (*Triticum aestivum*), red russian kale (*Brassica napus pabluaria*) and scarified velvetleaf (*Abutilon theophrasti*) were planted into each pot. Corn, wheat, red russian kale, and scarfied velvetleaf were planted at depths of 3, 0.5, 1 and 1 cm, respectively. Velvetleaf seeds were scarified by boiling for 20 seconds and dowsing with cold water just before planting. The corn hybrid planted was Dekalb 49-72RIB, spring wheat was ‘Brick’, red russian kale was ‘Seedz’, and the velvetleaf originated from a local population in Brookings County, SD. Seeds were planted 7 d after initiation of the study, and plants were thinned two weeks after emergence to 1, 3, 5 and 5 plants pot^{-1} of corn, kale, wheat, and velvetleaf, respectively.

Plant height measurements started 14 d after study initiation. Thereafter, heights were measured every two days up to day 28 and final height measurements recorded 34 d after study initiation. Relative greenness of the newest full leaf of the plants were measured at 34 d using a Konica Minolta SPAD-meter (Japan) in the second and third experiments. Shoots were harvested and fresh weight biomass was recorded. Samples were dried at 60°C and weights recorded. Plants were harvested 34 d after study initiation as the laboratory soil incubation determined that 50% of nitrogen mineralization occurred within 30 days of application.

Statistical Analysis

Soil Incubation

Data from each grit and timing application were fitted to an exponential rise to maximum three parameter model:

$$f = y_0 + N_a(1 - e^{-bx})$$

where f is the estimated organic nitrogen mineralized at a given time, y_0 is the initial nitrogen found in the soil at time zero, N_a is the available nitrogen in the active pool, b is the rate of nitrogen mineralization in the slow release pool which is a more stable nitrogen in the soil, and *x* is a specified time. The data were analyzed using SigmaPlot 13 (Systat Software Inc., 2017) to determine the regression constants, of which an analysis of variance (ANOVA) was performed.

Nitrogen Release and Uptake by Indicator Plants

The treatments were replicated four times within an experiment, and experiments were conducted three times from December of 2016 through April of 2017. The experiment had a factorial arrangement with four factors (plant species), and four levels (grit types). An analysis of covariance (ANCOVA) was used to examine the plant height response (mm day^{-1}) of each species. The linear statistical model (Kuehl, 2000) with separate regressions for each treatment is;

$$y_{ij} = \mu_i + \beta_i(x_{ij} - \bar{x}_i) + e_{ij}$$

$$i = 1, \ldots, 4 \qquad j = 1, \ldots, 4$$

where y_{ij} is the response variable of growth (mm day^{-1}), μ_i is the treatment mean, β_i is the coefficient for the linear regression of y_{ij} on x_{ij} for the *i*th term and where e_{ij} is the normally distributed random error. The fixed variables are μ_i and x_{ij}, and the random variables are y_{ij} and β_i. The ANCOVA was analyzed using the "lm" function in base R (R Core Team, 2017). The mean squares for each variable were estimated using an analysis of variance (ANOVA) to determine if the slopes of the growth rates were significant. The ANOVA was completed using the library agricolae (de Mendiburu, 2009) in R (R Core Team, 2017).

Relative fresh weight and relative dry biomass were calculated by assigning the heaviest weight within an experiment and species a value of "1", and then the other weights were a proportion of the heaviest weighted plant. Relative fresh weight and relative dry biomass were used to be able to compare plant responses among all experiments.

ANOVA was used to analyze the data for relative fresh weight, and relative dry weight per plant, and relative greenness. The linear statistical model of the completely randomized factorial design (Kuehl, 2000) is:

$$y_{ijk} = \mu + A_i + B_{ij} + AB_{ij} + e_{ijk}$$

where y_{ijk} is the mean observation of the A_i grit and B_{ij} species, μ is the overall mean, A_i is the species type effect, B_{ij} is the grit type effect, AB_{ij} is the interaction of the grit:species effect, e_{ijk} is the random error. The A_i species and B_{ij} grit effects are fixed, and the AB_{ij} grit:species interaction and e_{ijk} are random. To estimate the mean squares for each variable an ANOVA was completed using the library agricolae (de Mendiburu, 2017) in R (R Core Team, 2017).

3.4. Results and Discussion.

Mineralization of nitrogen from soil amended with organic grits

Study 1. Total nitrogen added to the Brandt silty clay loam soil ranged from 0 to 1148 μg N g^{-1} soil (Table 3.3). The nitrogen baseline (y_0) averaged 112 μg N g^{-1} soil at day 0. The estimated available nitrogen (N_a) of the control treatment was 203 μg N g^{-1} soil, and was similar among the 1/3X, 1X and 2X Sustane 8-2-4 treatments. The estimated available nitrogen (N_a) differed only in the 4X rate. (Table 3.3). The ranking is consistent with the total nitrogen added to the soil. The estimated nitrogen mineralization rate of the slow release nitrogen pool (b) was similar for the 1/3X, 1X, and 2X rates and averaged 0.13 μg N g^{-1} soil day^{-1}. This rate was faster than the control and 4X treatments (0.03 μg N g^{-1} soil day^{-1}), which were similar (Figure 3.1, and Table 3.3).

The percent of nitrogen released from the Sustane 8-2-4 treatments within 56 d of the start of the incubation ranged from 36% (4X) to 86% (1/3X) and was inversely related to the amount of nitrogen added to the soil with 1/3X > 1X > 2X > 4X (Table 3.4). The low percent of nitrogen released from the 4X treatment may indicate that soil microbes had limited capacities to mineralize increasingly higher amounts of organically bound nitrogen.

The differences in the amount of available nitrogen (N_a) among the Sustane 8-2-4 treatments reflects the amount of nitrogen added to the soil with each treatment. The estimated nitrogen mineralization rate (b) of the slowly available pool of N among the Sustane treatments should have been similar as the grit was the same among treatments. However, the 4X treatment had a slower nitrogen mineralization rate (Table 3.3). The amount of nitrogen available from the high application may have overwhelmed microbial activity (Dinnes et al., 2002). The percent of nitrogen released from the Sustane treatments was similar to the amount released by other organic poultry litters under aerobic soil incubations which ranged from 25 to 77% for after 35 to 120 d of incubation (Castellanos and Pratt, 1981; Hadas et al., 1983; Cabrera et al., 1993).

Table 3.3. In the Brandt silty clay loam soil total nitrogen added, estimated available nitrogen, soil nitrogen mineralization rate, R2 value, and P-value from the equation $f = y_0 + N_a(1 - e^{-bx})$ and percent (%) nitrogen released within the first 56 d of the incubation from each amount of Sustane added and the no-grit control treatment. The y_0 value averaged 112 µg N g^{-1} soil among all amounts added to the soil. Values in brackets are standard error.

Amount of grit added	Total nitrogen added	Available nitrogen (N_a)	Slow pool nitrogen mineralization rate (b)	R^2	P-value	Percent nitrogen released in 56 d
g grit kg^{-1} soil	ug N g^{-1} soil		ug N g^{-1} soil day^{-1}			- % -
0 (control)	-	203 [57]	0.03 [0.02]	0.54	0.003	-
1.2 (1/3X)	96	123 [19]	0.11 [0.04]	0.73	0.0001	86[1.3]
3.6 (1X)	287	168 [29]	0.16 [0.07]	0.70	0.0001	72 [2.5]
7.2 (2X)	575	240 [37]	0.16 [0.06]	0.74	0.0001	51 [2.2]
14.4 (4X)	1148	366 [47]	0.06 [0.02]	0.80	0.001	36 [4.1]

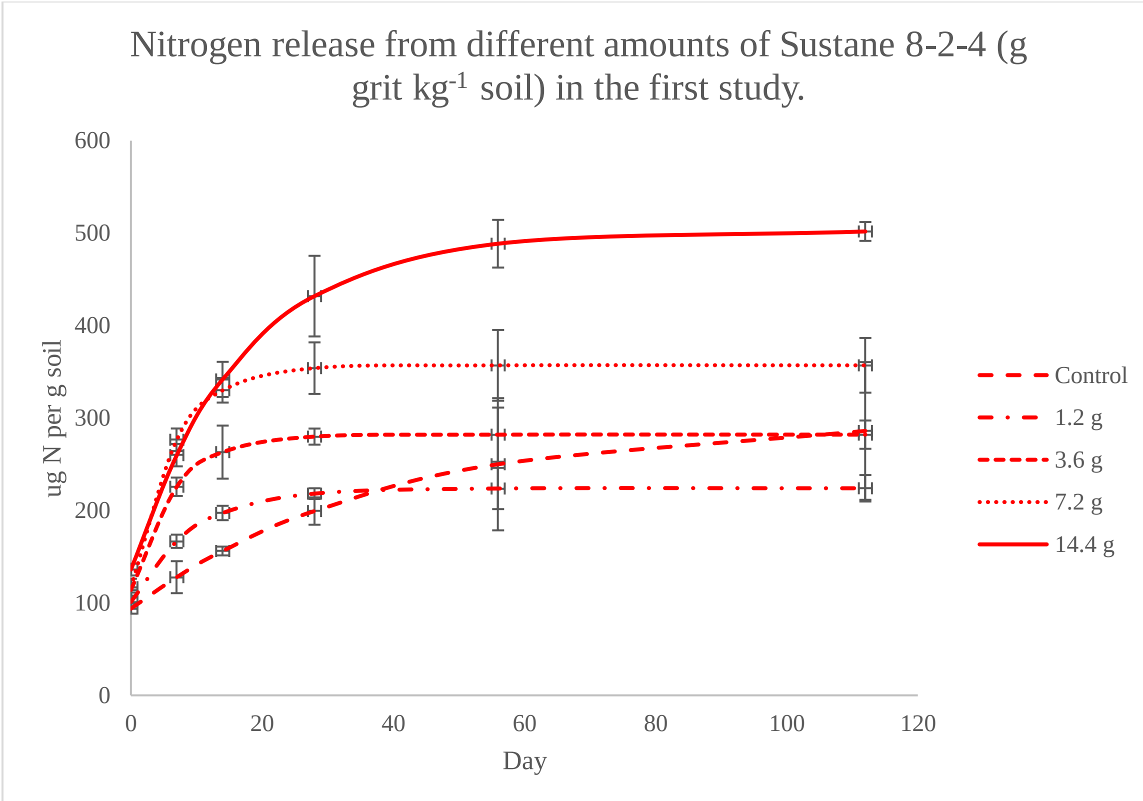

Figure 3.1. Nitrogen release (µg N g^{-1} soil day $^{-1}$) of different rates of Sustane 8-2-4 to different amounts of grit in a Brandt silty loam soil using the model

$f = y_0 + N_a(1 - e^{-bx})$.

Study 2. Before treatment, the baseline of nitrogen (y_0) in soil averaged 46 µg N g^{-1} soil at day 0. Total nitrogen added ranged from 4 to 969 µg N g^{-1} soil depending on grit type and amount added (Table 3.4). The no-grit control treatment had 121 µg N g^{-1} soil mineralized at 56 d N_a, which was similar to the 1/3X Agra Grit, and1/3X and 1X amounts of corn cob meal and Sustane 4-6-4 (Table 3.4). The estimated available nitrogen (N_a) among the amounts of Agra Grit applied to the soil was inversely related to the amount of nitrogen applied, with 1/3X > 1X > X+X = X+X+X (Table 3.4). The 1/3X and 1X corn cob meal grit treatments' estimated N_a amounts were similar with 125 and 152 µg N g^{-1} soil, in the X+X and X+X+X the estimated N_a amounts were 90 and 75 µg

N g^{-1} soil. The estimated N_a amount from Phytaboost Plant Food 7-1-2 increased with increasing amounts of grit applied to the soil, and ranged from 173 (1/3X) to 719 (X+X+X) μg N g^{-1} soil. The estimated N_a amounts for both Sustane 8-2-4 and 4-6-4 also increased with increasing amounts of nitrogen applied to the soil and ranged from 177 (1/3X) to 527(X+X+X) μg N g^{-1} soil for Sustane 8-2-4 and 146 (1/3X) to 282 (X+X+X) μg N g^{-1} soil for Sustane 4-6-4. The estimated nitrogen mineralization rate of the slow release nitrogen pool (*b*) was similar averaging 0.038 ±0.002 μg N g^{-1} soil day^{-1}, except corn cob meal. The slow release N pool from corn cob meal 1X, 1/3X, X+X, X+X+X was estimated to be 0.010, 0.021, 2.6E-05, and 1.0E-06 μg N g^{-1} soil day^{-1}, respectively. The modified exponential rise to maximum model for the nitrogen mineralization and release rate for the no-grit control, Agra Grit, Phytaboost Plant Food 7-1-2, Sustane 8-2-4 and Sustane 4-6-4 fit the data well, with R^2 values from 0.37 to 0.88 with p-values < 0.0001 (Table 3.4; Figures 3.2, 3.3, 3.4, 3.5). Modeling the mineralization of nitrogen in soil amended with corn cob meal using the exponential rise to maximum value did not fit the same pattern, with decreases in available N after the first few sampling intervals showing immobilization.

The percent of nitrogen mineralized or released from the grits in the first 56 days varied depending on the type and amount of grit applied (Table 3.4). The amount of nitrogen mineralized from the different amounts of Agra Grit and corn cob meal applied were compared to the no-grit control because of the immobilization of nitrogen at the first few samplings. The percent of nitrogen mineralized from 1/3X Agra Grit treatment compared to the no-grit control was 104%, whereas the 1X, X+X and X+X+X had an average mineralization of 70% compared to nitrogen mineralized from the no-grit control (Table 3.4). The percent of nitrogen mineralized from the soil amended with corn cob meal compared to the no-grit control ranged from 13 to 80% and was inversely related to the amount of grit applied with 1/3X > 1X > X+X > X+X+X (Table 3.4). The percent of nitrogen released from Phytaboost Plant Food 7-1-2 averaged 70% of the amount applied from the 1/3X, 1X and X+X+X treatments, whereas the X+X treatment released 80% of nitrogen applied (Table 3.5). The Sustane 4-6-4 1/3X treatment released 82% of nitrogen applied, whereas the 1X, X+X and X+X+X released on average 57% of the nitrogen applied (Table 3.4). The Sustane 8-2-4 1/3X and 1X treatments released on average 72% of nitrogen applied, whereas the larger amounts, X+X and X+X+X, released on average 50% of nitrogen applied (Table 3.4).

Table 3.4. In the Egan silty clay loam soil the C:N ratio of the grit, amount of grit added, total nitrogen added, available nitrogen, and R^2 estimated from this equation: $f = y_0 + N_a(1 - e^{-bx})$ and percent nitrogen released in the first 56 d from each grit type. The y_0 value averaged 46 ug N g^{-1} soil, and b value averaged 0.038 ±0.002 ug N g^{-1} soil day^{-1} among all grits and amount added to the soil. Values in brackets are standard error. X = 3.6 g grit kg^{-1} soil.

Grit	Timing of grit applied	Amount of grit applied	Total nitrogen added	Available nitrogen (N_a)	R^2	Percent nitrogen released in 56 d[1]
		g grit kg^{-1} soil	------ug N g^{-1} soil------			- % -
Control			-	121 [12.3]	77	-
Agra Grit	1/3X	1.2	4	122 [14.1]	73	104 [5.1]
	1X	3.6	11	92 [14.0]	60	79 [6.8]]
	X+X	7.2	22	66 [14.5]	43	67 [6.2]
	X+X+X	10.8	34	65 [16.4]	37	73 [4.7]
Corn cob meal	1/3X	1.2	6	125 [16.3]	69	80 [2.1]
	1X	3.6	19	152 [38.2]	74	50 [3.1]
	X+X	7.2	38	90[2]	75	37 [4.7]
	X+X+X	10.8	57	75[2]	67	13 [1.1]
Phytaboost Plant Food 7-1-2	1/3X	1.2	108	173 [22.6]	67	68 [3.6]
	1X	3.6	323	317 [46.0]	65	72 [2.8]
	X+X	7.2	646	506 [41.6]	85	81 [1.7]
	X+X+X	10.8	969	719 [68.3]	81	71 [2.2]
Sustane 4-6-4	1/3X	1.2	54	146 [4.1]	79	82 [5.2]
	1X	3.6	163	149 [23.1]	61	59 [3.1]
	X+X	7.2	326	199 [28.9]	63	60 [4.1]
	X+X+X	10.8	489	282 [22.9]	85	51 [6.2]
Sustane 8-2-4	1/3X	1.2	96	177 [34.5]	80	76 [5.1]
	1X	3.6	287	194 [26.3]	66	67 [6.1]
	X+X	7.2	575	302 [38.6]	69	47 [4.1]
	X+X+X	10.8	862	527 [36.5]	88	52 [4.3]

[1] Agra Grit and corn cob meal are the percent of nitrogen mineralized from the soil compared to the total nitrogen mineralized from the no-grit control.

[2] Based off of estimation without the first two samplings.

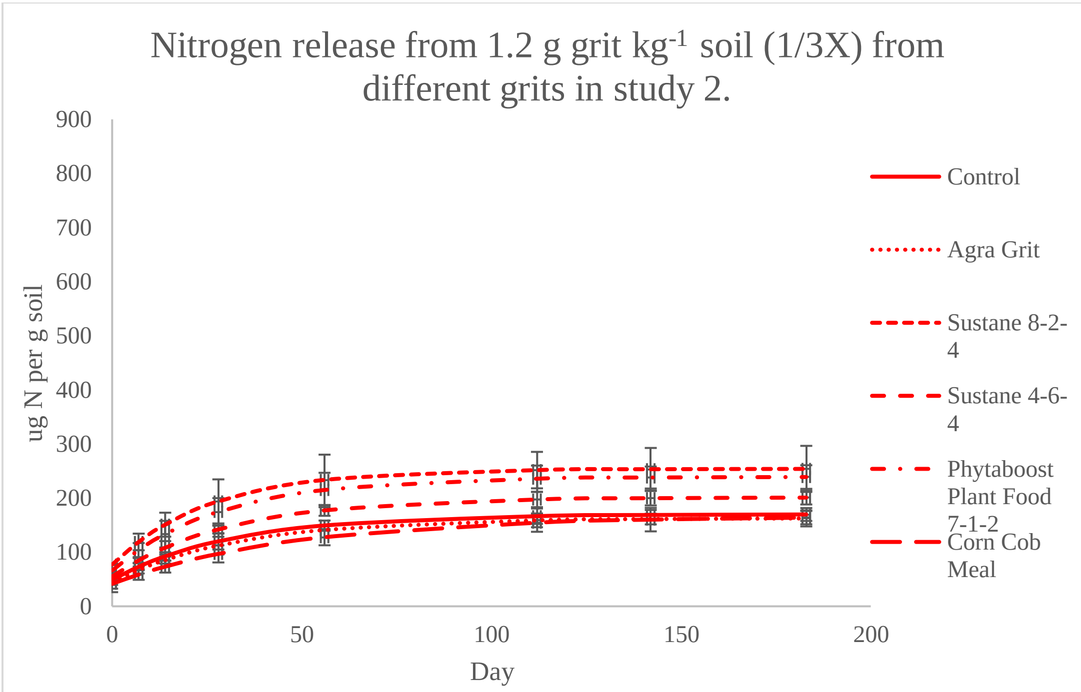

Figure 3.2. Nitrogen release (µg N g^{-1} soil day $^{-1}$) of 1.2 g grit per kg soil (1/3X) in an Egan silty clay loam soil using the model $f = y_0 + N_a(1 - e^{-bx})$.

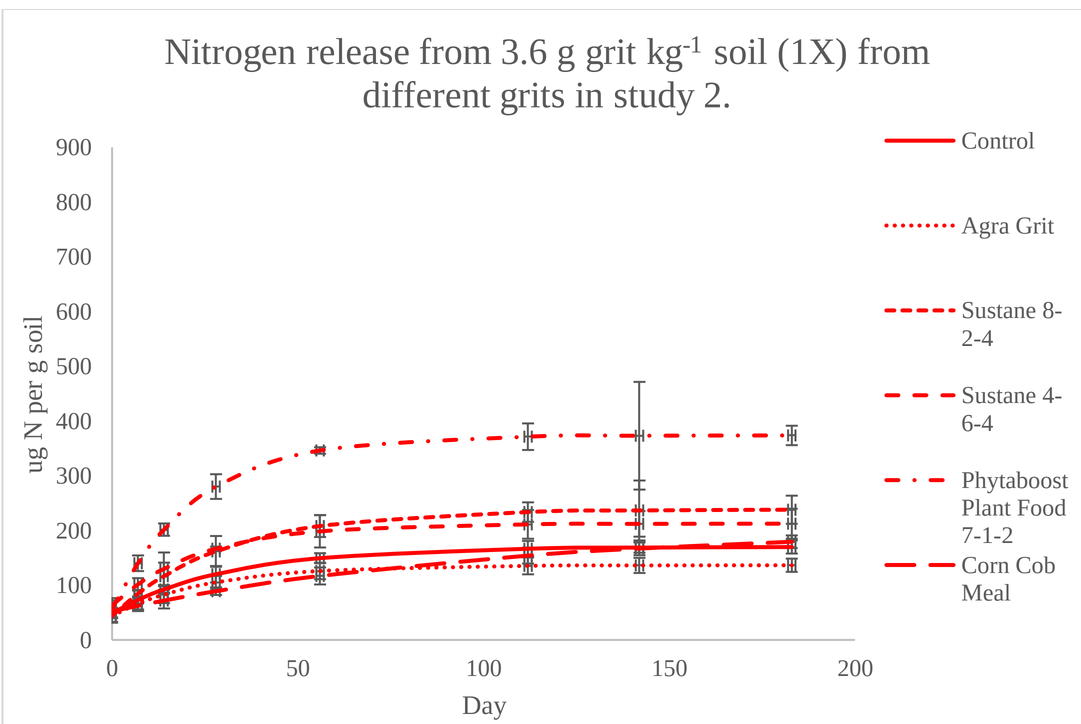

Figure 3.3. Nitrogen release (µg N g^{-1} soil day $^{-1}$) of 3.6 g grit per kg soil (1X) in an Egan silty clay loam soil using the model $f = y_0 + N_a(1 - e^{-bx})$.

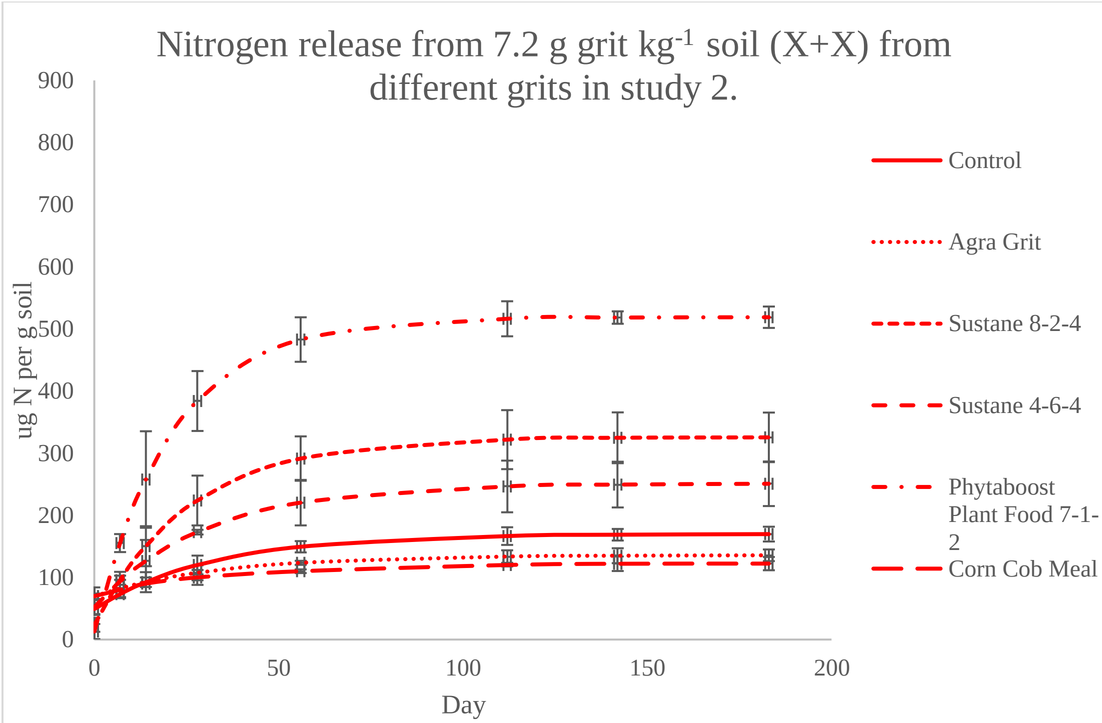

Figure 3.4. Nitrogen release (μg N g^{-1} soil day^{-1}) of 7.2 g grit per kg soil (X+X) in an Egan silty clay loam soil using the model $f = y_0 + N_a(1 - e^{-bx})$.

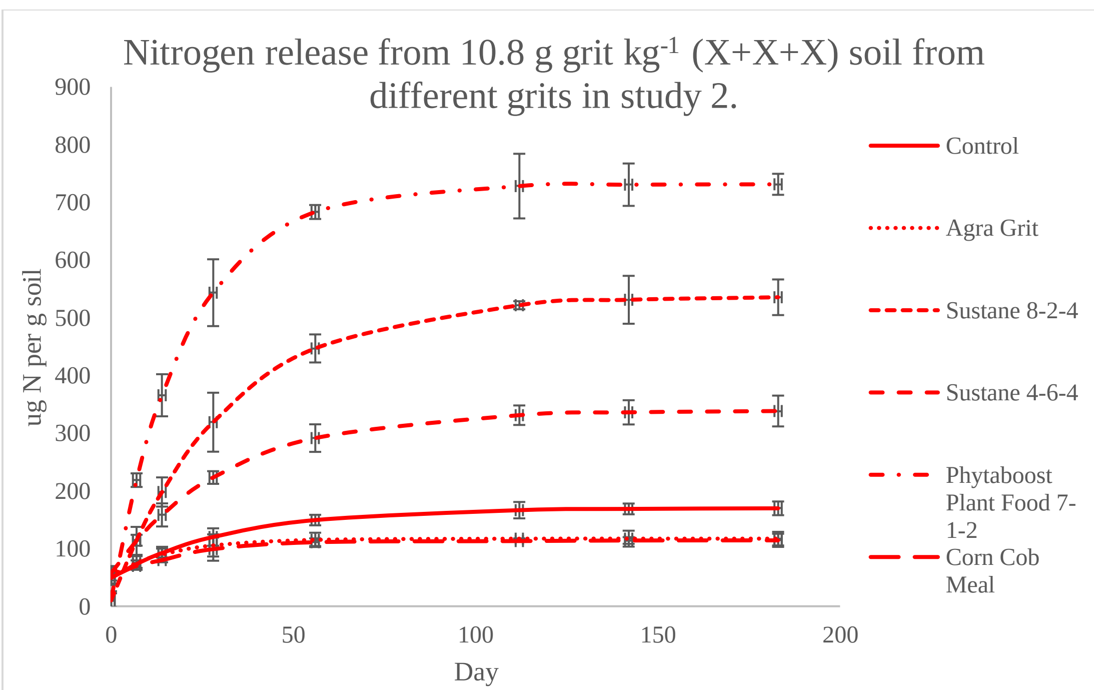

Figure 3.5. Nitrogen release (μg N g^{-1} soil day^{-1}) of 10.8 g grit per kg soil (X+X+X) in an Egan silty clay loam soil using the model $f = y_0 + N_a(1 - e^{-bx})$.

The differences in the estimated available nitrogen (N_a) values among the grits could be due to the total nitrogen content and type of grit (Spargo et al., 2016; Agehara and Warnacke, 2006). The smaller estimated available nitrogen (N_a) values from amounts larger than 1.2 g grit kg^{-1} soil of Agra Grit applied could be due to the high C:N ratio (168:1) (Table 3.5), as ratios higher than 25:1 will increase nitrogen immobilization (Paul and Clark, 1989; Flavel and Murphy, 2006). The lack of estimated available nitrogen (N_a) values from the 7.2 and 10.8 g grit kg^{-1} soil corn cob meal treatments also could be attributed to the high C:N ratio, as the model only fit these data after the first few sample dates were estimated from the Agra Grit models (Figure 3.4, 3.5). The total nitrogen of Phytaboost Plant Food 7-1-2 was the largest, 8.97 ug g^{-1} (Table 3.5), and had the largest estimated available nitrogen (N_a) values when compared among the Sustane nitrogen fertilizers (Table 3.6, 3.7). The estimated available nitrogen (N_a) values among the organic fertilizers (Phytaboost Plant Food 7-1-2, Sustane 8-2-4 and 4-6-4) were positively related to the amount of grit, and nitrogen applied to the soil. The similarity of the estimated nitrogen release rate from the slow pool (*b*) among Agra Grit, Phytaboost Plant Food 7-1-2, Sustane 8-2-4 and Sustane 4-6-4 and no-grit control could be that the nitrogen was mineralizing from the soil organic matter rather than from the grits in this pool of nitrogen. Gordillo and Cabrera (1997) reported that the mineralization rate of the slow nitrogen did not differ among different turkey litters, and Hartz and Johnstone (2006) reported that after two weeks, nitrogen release from organic amendments mimicked the nitrogen mineralization from soil organic matter.

Table 3.5. Total nitrogen and carbon (ug g^{-1}), and C:N ratio of grits studied in soil incubation and greenhouse experiments. Values in brackets are standard error.

Grit	Nitrogen	Carbon	C:N
	ug g^{-1}		
Agra Grit	0.31 [0.03]	51.2 [1.7]	168 [13.4]
Corn Cob Meal	0.53 [0.06]	46.8 [0.20]	91 [10.7]
Phytaboost Plant Food 7-1-2 [1]	8.97 [0.08]	44.8 [0.04]	5.0 [0.04]
Sustane 4-6-4 [1]	4.53 [0.04]	28.5 [0.57]	6.3 [0.15]
Sustane 8-2-4	7.98 [0.20]	40.2 [0.12]	5.0 [0.12]

The high R^2 values among the different amounts of Agra Grit, Phytaboost Plant Food 7-1-2, Sustane 4-6-4 and Sustane 8-2-4, and the no-grit control would mean that the exponential rise to maximum model fit the data well and can describe the mineralization and release of nitrogen from these grits. The R^2 values among the different amounts of corn cob meal applied were high, even though SigmaPlot had a difficult time modeling these data, as both the 7.2 and 10.8 g grit per kg soil mineralized less than 40% of what the no-grit control treatment mineralized.

The percent nitrogen mineralized from Agra Grit would be expected to be lower than that of the corn cob meal amended soil because of the higher C:N ratio (Paul and Clark, 1989; Flavel and Murphy, 2006). The larger particle size of corn cob meal, 2 mm, compared to Agra Grit, 1mm, might have increased the carbon decomposition and nitrogen immobilization (Angers and Recous, 1996; Ambus and Jensen, 1997). The percent of nitrogen released from Phytaboost Plant Food 7-1-2 is similar to the value reported by Sexton and Jemison (2011), who reported that 75% of the N in soybean meal was released into an organic potato field within three months of the application. The percent of nitrogen released from Sustane 4-6-4 and 8-2-4 over 56 d is similar to previously reported values of nitrogen release from organic fertilizers. Organic poultry litter released 25 to 77% of its nitrogen from 25 to 120 d (Castellanos and Pratt 1981; Hadas et al., 1983; Cabrera et al., 1993; Gordillo and Cabrera, 1997). High nitrogen containing organic fertilizers (> 10% nitrogen), like feather meal and seabird guano, have been reported to release 60 to 80% of nitrogen applied from 4 to 8 weeks (Hadas and Kutusky et al., 2004; Hartz and Johnstone, 2006). The application of high C:N grits as propelled abrasive grits could immobilize nitrogen in the field, whereas the use of organic fertilizers could provide supplemental nitrogen for crop growth.

Comparison of the no-grit control and Sustane 8-2-4 treatments between study 1 and study 2.

The first and second studies had distinct differences between incubation conditions. The first incubations used beakers with 10% of the area exposed to air, whereas the second study was in sealed plastic bags. Polyethylene (plastic) bags are a suitable replacement for exposed beakers to maintain aerobic conditions, and reduce

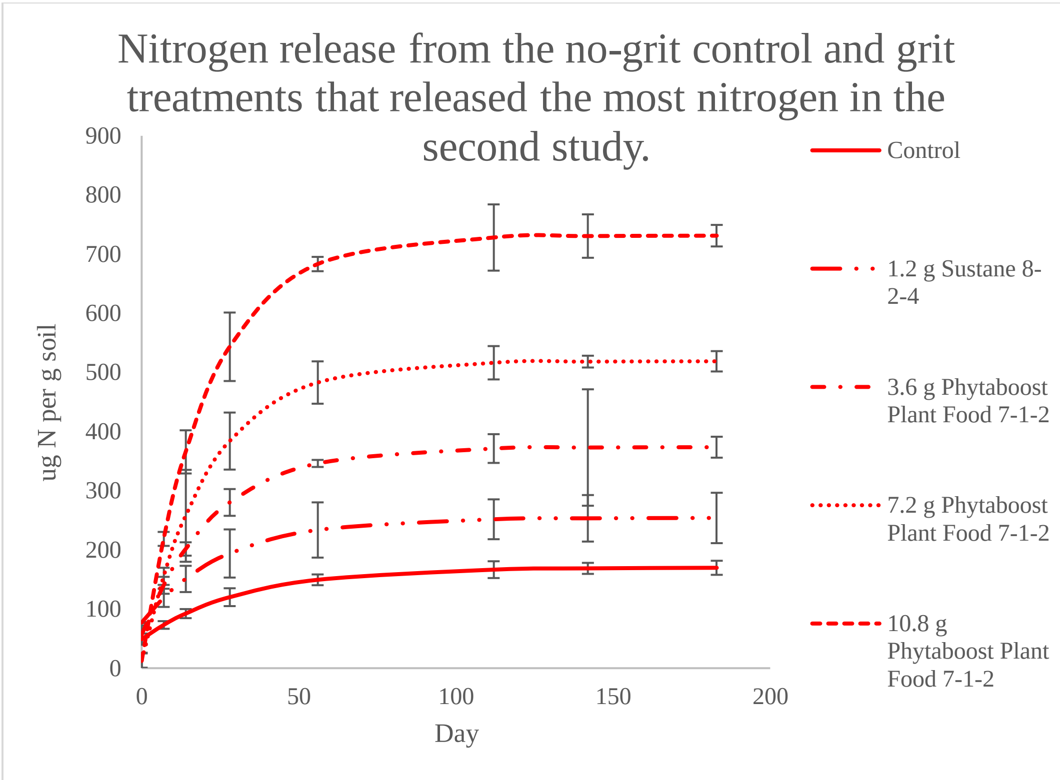

Figure 3.6. Nitrogen release (µg N g^{-1} soil day^{-1}) of no-grit control, 1.2 g grit kg^{-1} soil (1/3X) Sustane 8-2-4, 3.6 (1X), 7.2 (X+X), and 10.8 (X+X+X) g grit kg^{-1} soil in an Egan silty clay loam soil using the model $f = y_0 + N_a(1 - e^{-bx})$. These grits were the grits that released the most nitrogen at each rate.

moisture loss (Eno, 1960; Finzi et al., 1998; Compton and Boone, 2000; Contosta et al., 2011). The major differences in nitrogen release can be attributed to the different soils used in each study. The baseline nitrogen values between the studies was different, as the Brandt silty clay loam in the first study had and average baseline nitrogen of 112 µg N g^{-1} soil which was more than double the average baseline nitrogen of the Egan silty clay loam, 46 µg N g^{-1} soil. The estimated available nitrogen in the no-grit control in the first study, 203 µg N g^{-1} soil, was almost twice as large as the value in the second study, 112 µg N g^{-1} soil. At 56 d after the start of the experiments, the exponential rise to maximum estimated that the amount of nitrogen mineralized from the control treatments in the Egan and Brandt soils were 277 and 153 μg N g^{-1} soil. Stanford and Smith (1972) and Reich et al. (1997) reported that soil nitrogen mineralization differs among soils, whereas in the current experiments the slow pool nitrogen mineralization was similar between both no-grit control treatments.

The estimated available nitrogen and nitrogen release of 1.2 (1/3X) and 3.6 g (1X) of Sustane 8-2-4 kg^{-1} soil differed between soils. The Egan silty clay loam had lower estimated available nitrogen values than the Brandt silty clay loam when amended with Sustane 8-2-4. The larger N_a from the Brandt soil compared to the Egan soil is similar to what Hadas et al. (1983) reported. They indicated that soils with higher sand contents had higher N mineralization. The Egan soil had smaller available nitrogen (N_a) than the Brandt soil which may have been because of the higher silt and clay content, as Gordillo and Cabrera (1997) and Sistani et al. (2008) reported that higher silt and clay content had less available nitrogen. The Egan soil had been under organic N management, while the Brandt soil had previously been in a conventionally managed soil where synthetic nitrogen fertilizer applications were used to replace crop N uptake. The nitrogen mineralization rates in the Brandt soil were twice as large as the nitrogen mineralization rates in the Egan soil when amended with Sustane 8-2-4. The larger percent of nitrogen released in the Brandt silty clay loam soil can be attributed to the larger sand content in the soil (Gordillo and Cabrera, 1997; Sistani et al., 2008). The highest amount (X+X+X, 10.8 g grit kg^{-1} soil) of Sustane 8-2-4 in the Egan soil did not overwhelm the microbes in the soil which differed from the highest rate in the Brandt soil (4X, 14.4 g grit kg^{-1} soil) which had a slower mineralization rate than the other rates of Sustane 8-2-4. At 56 d after the start of the experiments, the exponential rise to maximum model estimated that the amount of nitrogen released from the Sustane 1/3X and 1X treatments in the Brandt soil were 235 and 280 μg N g^{-1} soil which were only numerically different, whereas in the Egan soil the values were lower at 202 and 217 μg N g^{-1} soil which were only numerically different. In both soils, the exponential rise to maximum model fit the data of the no-grit controls and both rates of Sustane 8-2-4, as the R^2 values ranged from 0.54 to 0.80. The R^2 values in both soils with the Sustane 8-2-4 and no-grit control treatments would mean that the exponential rise to maximum model fit the data and can be used to describe the parameters. The percent of nitrogen released from Sustane 8-2-4 decreased as amount of nitrogen increased in both soils.

Nitrogen release and uptake by indicator plants

Corn response.

Height response. The height response was similar among experiments ($p = 0.24$) whereas the height response differed among treatments ($p = 0.001$) and therefore the data was combined among all experiments. The height response of the Sustane 8-2-4 treatment was 2.55 mm day^{-1} and higher than the other treatments (Table 3.6). The Agra Grit, corn cob meal and no-grit control treatments had similar, 2.25 mm day^{-1}which was slower than Sustane 8-2-4 treatment (Table 3.6).

Table 3.6. The corn height response (mm day^{-1}), relative fresh weight and relative dry biomass ($plant^{-1}$) for each grit. The height response, relative fresh weight and relative dry biomass were similar among experiments. Letters denote significant difference at level $\alpha = 0.05$.

Grit	Height response	Relative fresh weight	Relative dry biomass
	mm day^{-1}	----- $plant^{-1}$ -----	
Agra Grit	2.22 b	0.58 b	0.63
Corn cob meal	2.29 b	0.64 ab	0.71
Sustane 8-2-4	2.55 a	0.79 a	0.80
Control	2.24 b	0.57 b	0.62
P-value	0.001	0.05	0.14

Relative Greenness. The relative greenness differed between the second and third experiments ($p = 0.012$). In the second experiment the relative greenness differed among grits ($p = 0.056$). The Sustane 8-2-4 treatment had the highest numerical relative greenness, 38.0 SPAD, but was similar to the corn cob meal and no-grit treatments in the second experiment. The Agra Grit treatment had the lowest relative greenness, 30.8 SPAD, in the second experiment and was similar to both the corn cob meal and no-grit treatments (Table 3.7). The relative greenness in the third experiment was lower than the second experiment and similar among all grit treatments ($p = 0.19$) and averaged 30.5 SPAD.

Table 3.7. The relative greenness (SPAD) for each grit in corn in experiments 2 and 3 as they differed (p = 0.012). Relative greenness was not measured in experiment 1. Letters denote significant difference at level $\alpha = 0.05$.

	Experiment	
Grit	2	3
	--SPAD --	
Agra Grit	30.8 b	26.7
Corn cob meal	34.1 ab	-
Sustane 8-2-4	38.0 a	34.2
Control	34.0 ab	29.4
P-value	0.056	0.19

Fresh Weight. The relative fresh weight was similar among experiments (p = 0.26) and differed among grit treatments (p = 0.05). The Sustane 8-2-4 had the highest relative fresh weight, 0.79 plant^{-1}, and was similar to corn cob meal, 0.64 plant^{-1}, and higher than both the Agra Grit and no-grit control treatments (Table 3.7). The Agra Grit and no-grit control treatments were similar and averaged 0.58 plant^{-1} and were similar to corn cob meal.

Dry Biomass. The relative dry biomass was similar among experiments (p = 0.45) and among treatments (p = 0.14) and averaged 0.69 plant^{-1}.

Wheat response.

Height Response. The height response of the wheat was similar among experiments (p = 0.24), whereas the height response differed among grit treatments (P < 0.10). The

Sustane 8-2-4 had the fastest height response, 1.26 mm day^{-1}, than the Agra Grit, corn cob meal, and no-grit control treatments which were similar and had an average height response of 1.08 mm day^{-1}.

Table 3.8. The wheat height response (mm day^{-1}), relative fresh weight and relative dry biomass (plant^{-1}) for each grit. The height response, relative fresh weight and relative dry biomass were similar among experiments. Letters denote significant difference at level $\alpha = 0.05$.

Grit	Height response	Relative fresh weight	Relative dry weight
	mm day^{-1}	----- plant^{-1} -----	
Agra Grit	1.13 b	0.48 b	0.56 b
Corn cob meal	1.04 b	0.43 b	0.49 b
Sustane 8-2-4	1.26 a	0.86 a	0.89 a
Control	1.06 b	0.48 b	0.55 b
P-value	<0.001	2.87E-11	1.98E-11

Relative Greenness. The relative greenness of wheat differed between the second and third experiments ($p = 0.0002$). The relative greenness in the second experiment was similar among grit treatments ($p = 0.31$) and averaged 37.2 SPAD. The Sustane 8-2-4 treatment had the highest relative greenness, 36.2, in the third experiment, whereas the Agra Grit, corn cob meal and no-grit control had lower and similar relative greenness and averaged 20 SPAD.

Table 3.9. The relative greenness (SPAD) for each grit in wheat in experiments 2 and 3 as they differed ($p = 0.0002$). Relative greenness was not measured in experiment 1. Letters denote significant difference at level $\alpha = 0.05$.

	Experiment	
Grit	2	3
	--SPAD --	
Agra Grit	32.1	23.5 b
Corn cob meal	38.5	14.4 b
Sustane 8-2-4	44.1	36.2 a
Control	34.1	22.1 b
P-value	0.31	0.003

Fresh Weight. The relative fresh weight of wheat was similar among experiments ($p = 0.12$) whereas the relative fresh weight of grit treatments differed ($p < 0.001$). The Sustane 8-2-4 treatment had the highest relative fresh weight, 0.86 $plant^{-1}$, whereas the Agra Grit, corn cob meal and no-grit control had similar relative fresh weight, 0.46 $plant^{-1}$, and lower than the Sustane 8-2-4 treatment.

Dry Biomass. The relative dry biomass of wheat was similar among experiments ($p = 0.32$) whereas the relative dry biomass differed among grit treatments ($p < 0.001$). The Sustane 8-2-4 treatment had a higher relative dry biomass, 0.89 $plant^{-1}$, than the Agra Grit, corn cob meal, and no-grit control treatments which had an average relative dry biomass of 0.53 $plant^{-1}$.

Red Russian Kale.

Height Response. The height response of red russian kale was similar among grit treatments within the first and third experiments. The height response averaged 0.528 mm day^{-1} among all grit treatments in the first and third experiments. The height response in the second experiment was slower than the first and third experiments and the Sustane 8-2-4 treatment differed from the Agra Grit, corn cob meal and no-grit control treatments. The Sustane 8-2-4 height response was 0.411 mm day^{-1}, whereas the Agra Grit, corn cob meal and no-grit control had a slower and similar height response of 0.289 mm day^{-1} (Table 3.10).

Relative Greenness. The relative greenness of red russian kale was similar between both the second and third experiments and among treatments ($p = 0.59$) and averaged 39.3 SPAD.

Fresh Weight. The relative fresh weight of red russian kale was similar among experiments ($p = 0.23$) whereas the relative fresh weight differed among treatments ($p = 0.002$). The Sustane 8-2-4 treatment had a higher relative fresh weight, 0.87 $plant^{-1}$, than the other treatments, whereas the Agra Grit, corn cob meal, and no-grit control treatment were similar and had average relative fresh weight of 0.55 $plant^{-1}$.

Dry Biomass. The relative dry biomass of red russian kale was similar among experiments ($p = 0.24$), whereas the relative dry biomass differed among treatments ($p = 0.00012$). The Sustane 8-2-4 treatment had the highest relative dry biomass, 0.95 $plant^{-1}$, than the Agra Grit, corn cob meal, and no-grit treatments which had similar relative dry biomass and averaged 0.52 $plant^{-1}$.

Table 3.10. The red russian kale height response (mm day^{-1}), relative greenness (SPAD), relative fresh weight ($plant^{-1}$), and relative dry biomass ($plant^{-1}$) for each grit among all experiments. Relative greenness, fresh weight and dry biomass were similar among experiments ($p > 0.25$). Letters denote significant difference at level $\alpha = 0.05$.

Grit	Height response [1]	Relative greenness [2]	Relative fresh weight	Relative Dry biomass
	mm day^{-1}	SPAD	---- $plant^{-1}$----	
Agra Grit	0.293	41.1	0.59 b	0.54 b
Corn cob meal	0.280	37.8	0.49 b	0.48 b
Sustane 8-2-4	0.411	40.0	0.87 a	0.95 a
Control	0.294	37.7	0.56 b	0.54 b
P-value	<0.10	0.59	0.002	0.00012

[1] Height response displayed here is the second experiment because of the difference among grit treatments and from the first and third experiments.

[2] Relative greenness was only measured in the second and third experiments.

Velvetleaf response.

Height response. Velvetleaf had an average height response of 0.178 mm day^{-1} among all experiments and did not differ among treatments.

Relative greenness. The relative greenness of velvetleaf was similar between both the second and third experiments, and among all treatments and averaged 34.4 SPAD.

Fresh Weight. The relative fresh weight of velvetleaf was similar among experiments (P = 0.24). The Sustane 8-2-4 had the highest relative fresh weight, 0.75 $plant^{-1}$, and similar to the relative fresh weight of the no-grit control treatment, 0.62 $plant^{-1}$ (Table 3.11). The Agra Grit and corn-cob meal treatments had similar relative fresh weight, and averaged 0.53, and were lower than the Sustane 8-2-4 treatment, whereas they were similar to the no-grit control (Table 3.11).

Dry biomass. The dry biomass of velvetleaf was similar among experiments (p = 0.11), whereas the dry biomass differed among treatments (p = 0.025). Velvetleaf had the highest dry biomass when amended with Sustane 8-2-4, averaged 0.071 g $plant^{-1}$, whereas the Agra Grit, corn cob meal and control treatments had similar dry biomass and averaged 0.036 g $plant^{-1}$.

Table 3.11. The velvetleaf height response (mm day^{-1}), relative greenness (SPAD), relative fresh weight ($plant^{-1}$), and dry biomass (g $plant^{-1}$) for each grit among all experiments. All measurements were similar among experiments ($p > 0.15$). Letters denote significant difference at level $\alpha = 0.05$.

Grit	Height response	Relative greenness [1]	Relative fresh weight	Dry biomass
	mm day^{-1}	SPAD	$plant^{-1}$	g $plant^{-1}$
Agra Grit	0.180	35.1	0.55 b	0.041 b
Corn cob meal	0.159	33.5	0.50 b	0.034 b
Sustane 8-2-4	0.196	33.4	0.75 a	0.071 a
Control	0.178	35.6	0.62 ab	0.041 b
P-value	0.12	0.33	0.03	0.03

[1] Relative greenness was only measured in the second and third experiments.

Discussion among grits and species

Height response. Corn and wheat amended with Sustane 8-2-4 exhibited a faster height response than when these species were amended with Agra Grit, corn cob meal, or the no-grit control in all experiments. In one experiment of red russian kale there was a faster height response from Sustane 8-2-4 when compared to the Agra Grit, corn cob meal or no-grit control treatments. The faster height response could be from the added nitrogen from Sustane 8-2-4 compared to the other grits as data from the soil incubation reported that Sustane 8-2-4 increased the soil available N, and lack of nitrogen has been reported to slow growth of plants (Zhao et al., 2005). The height response was consistent among all grit treatments and experiments in velvetleaf. These data contradict Lindquist et al. (2007) who reported that velvetleaf had a greater response to nitrogen than corn when in a field setting. The high C:N ratio grits (Agra Grit and corn cob meal) did not have a reduction in plant height response compared to the no-grit control. The height response of wheat, red russian kale and velvetleaf were 50 to 90% slower than the height response of corn on average among all grits and experiments, which could be due to plant development. The faster height response of Sustane 8-2-4 in plants could be beneficial for corn growth, but also for other plants, such as weeds in the field. The similar height response of plants to Agra Grit, or corn cob meal when compared with the no-grit control treatment could mean that when these grits are used as a weed control measure they might not spur additional growth of weeds.

Relative Greenness. Relative greenness is a relative measure of nitrogen content and provides a measure of nitrogen uptake from grit treatments (Schepers et al., 1992; Bullock and Anderson, 1998). Only one experiment in both corn and wheat exhibited a higher relative greenness with Sustane 8-2-4 compared to the other grit treatments, whereas both velvetleaf and red russian kale had similar relative greenness values among all grits and experiments. Blackmer and Schepers (1995) reported that when corn relative greenness was measured at or before the V6 growth stage the observations have a limited potential as a tool for predicting corn response to nitrogen because environmental conditions need to be considered at this stage. In field settings with red russian kale, there was no difference in relative greenness between walnut shells and turkey litter (Braun, 2017), which is similar to results presented here. The lack of difference of velvetleaf relative greenness could mean that this early season nitrogen might not affect velvetleaf seedling growth stages. Relative greenness in wheat after tillering did not show differences to different nitrogen fertilization rates when compared to wheat yield (Spaner et al., 2005; Debaeke et al., 2004), whereas in this present study the relative greenness might have been measured too early to be able to detect a difference in nitrogen fertilization from the grit treatments.

Fresh Weight. The corn, wheat and velvetleaf relative fresh weights were higher when these species were treated with Sustane 8-2-4 compared to the Agra Grit, corn cob meal and no-grit control treatments. The higher fresh weight could be due to the added nitrogen from the grits, as the other grits added very little nitrogen to the system. The Agra Grit and corn cob meal treatments did not reduce relative fresh weight when compared to the no-grit control treatment. The similarity of relative fresh weight of the Agra Grit, corn cob meal and no-grit control could be because the potting system did not have a large amount of nitrogen for these grits to immobilize, which has been reported in the laboratory soil incubation. The red russian kale relative fresh weight was similar among all grit treatments which differs from what Braun (2017) reported that the fresh wet of red russian kale was greater when treated with turkey litter than walnut shells.

Dry biomass. The response of wheat, red russian kale, and velvetleaf when amended with Sustane, a nitrogen fertilizer, is similar to the strong growth response of certain weeds to conventional nitrogen fertilizer sources (Andreasen et al., 2006; Blackshaw et al., 2003; Blackshaw and Brandt, 2008; Hoveland et al., 1976), and differs from the lack of response of common lambsquarters, Powell amaranth, and giant foxtail to blood meal, a high nitrogen content organic fertilizer (Little et al., 2015). The larger relative dry biomass of velvetleaf with Sustane 8-2-4 is similar to what Little et al. (2015) and Bonifas (2005) reported that velvetleaf positively responded to both conventional and organic fertilizer sources. The corn did not have a larger dry biomass with Sustane 8-2-4 which is the different than what would have been expected (Lindquist et al., 2007).

3.5. Conclusion.

The release of nitrogen from organic fertilizers could have varied effects on weed and crop growth as the percent of nitrogen released from the Sustane grits was inversely related to the amount of nitrogen applied, and lower than the nitrogen released from Phytaboost Plant Food 7-1-2. In the soil incubations, the high C:N ratio grits immobilized soil nitrogen, but did not have an adverse effect on plant growth in the greenhouse study when compared to the no-grit control. The faster height response, higher relative greenness, and higher relative dry biomass of these selected plants from soil amended with Sustane 8-2-4, than soil amended with Agra Grit, corn cob meal or the no-grit control, could mean that Sustane could increase plant growth from a single application of grit within the growing season. Thus, if attempts at grit-weeding were not successful, the application of Sustane 8-2-4 could help provide additional nitrogen to weeds, as Poffenbarger et al. (2015) reported that smooth pigweed in well-fertilized organic soils competed against corn better than when grown in conventional soil conditions. The increased weed interference can be detrimental to corn and soybean yields if the weeds are present during the critical weed free period (Van Acker and Swanton, 1993; Hall et al., 1992). The use of Agra Grit, or corn cob meal to control weeds in the air-propelled abrasive weed management systems might not increase weed or crop growth, but might immobilize nitrogen in the soil, which could decrease crop yield. Grits used for propelled abrasive weed management affect weed growth and have differing rates of nitrogen release and mineralization in different soils, and with differing amounts applied to the soil.

CHAPTER 4

General Conclusions and Future Research.

4.1 General Conclusions.

Organic nitrogen fertilizers were able to reduce weeds with a height of 3 cm or less and increase crop yields higher than the season-long weedy check. In the corn field studies, the Phytaboost Plant Food 7-1-2 and Sustane 8-2-4 organic nitrogen fertilizers grits increased crop yields higher than the season-long weed-free check when two applications of these grits reduced weed densities during the critical weed free period. Peak in-row weed biomass was higher in organic nitrogen fertilizer treatments than with non-fertilizer grits. The increased corn yield and in-row weed biomass from two grit applications of organic nitrogen fertilizers could be from the increase in soil available nitrogen which also increased the plant growth response in greenhouse settings.

The relative greenness of corn in the field studies was increased when organic nitrogen fertilizers were used as abrasive grits. The increase in soil available nitrogen from the organic fertilizer grits also increased the relative greenness in corn in the greenhouse plant nitrogen uptake studies.

In field studies, the Agra Grit grit treatment had lower yields than the organic nitrogen fertilizers, because of the immobilization of the soil available nitrogen. The soil incubations determined that non-fertilizer grits, corn cob meal and Agra Grit, immobilized soil available nitrogen. The peak in-row weed biomass of the Agra Grit treatment was similar to the organic nitrogen fertilizer grits. In greenhouse settings the plants treated with Agra Grit had similar plant growth response compared to the no-grit control treatment. If non-fertilizer grits, like Agra Grit or corn cob meal, do not control in-row weeds the soil nitrogen may be immobilized and decreased corn yield, while depending on the weed population there may be no differences in weed growth or biomass.

4.2. Future Research.

The information from these corn and soybean field studies can be used to further improve the use of air-propelled abrasive weed management to control weeds in organic cropping systems. New organic fertilizer and non-fertilizer grits should be studied to determine the effects on weed control, crop yield and nutrient dynamics in the field. The use of abrasive grit management should continue trying research methods to make this new method of weed control possible for additional crops, such as sunflowers, carrots or tree fruits. The nitrogen dynamics in field settings should be studied when organic nitrogen fertilizers are used as organic nitrogen fertilizer grits increased soil available nitrogen, while non-fertilizer grits decreased soil available nitrogen.

The same nozzle design has been used in all abrasive weed management studies and when used with the PAGMan has not had consistent weed control throughout all treatments and locations. A new nozzle design should be investigated to determine how the design effects weed control and the amount of grit applied to the soil. A new design of an abrasive grit management machine should be studied to improve control of weeds while reducing the cost of grit applications.

Abrasive grit management controls weeds when they are 3 cm or smaller, aipplying grit based off of weed seedling stages, rather than crop growth stages, could improve weed control using abrasive grits. Research should be conducted when grit applications are focused around weed seedling stages rather than crop growth stages when using a large commercial abrasive grit management system. These potential research opportunities could help improve the use of abrasive weed management to control weeds in organic cropping systems.

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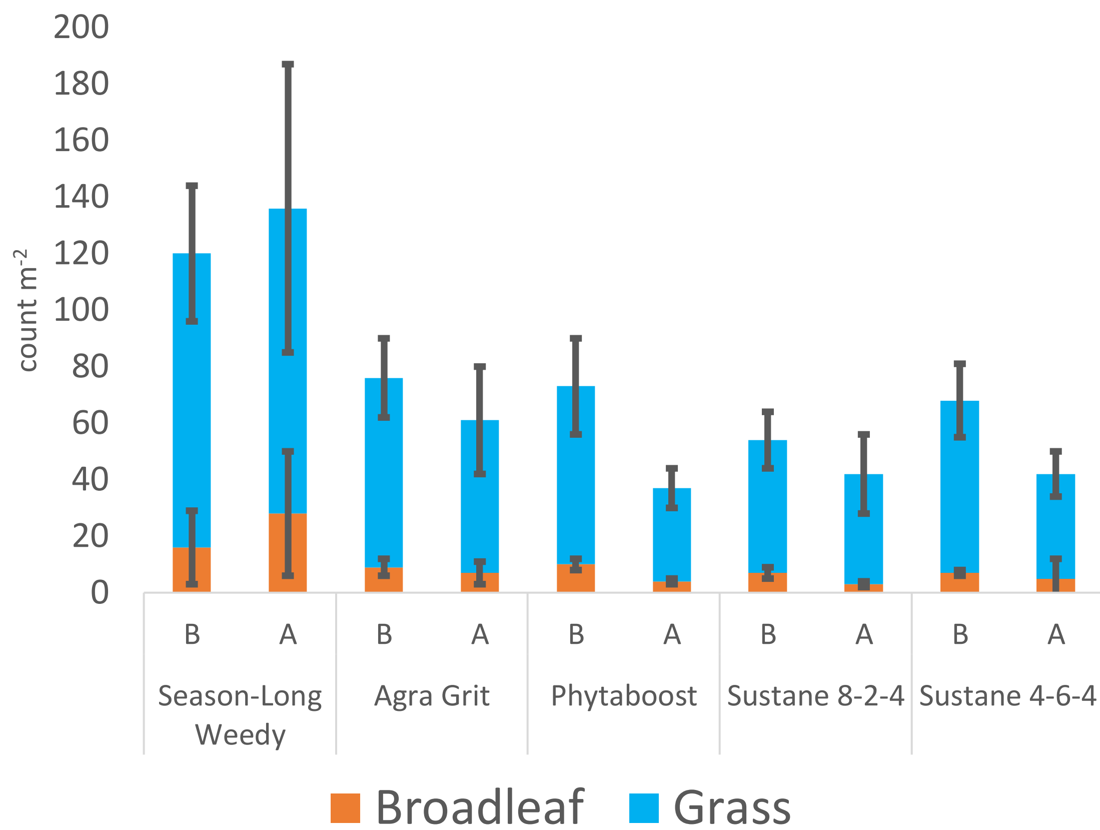
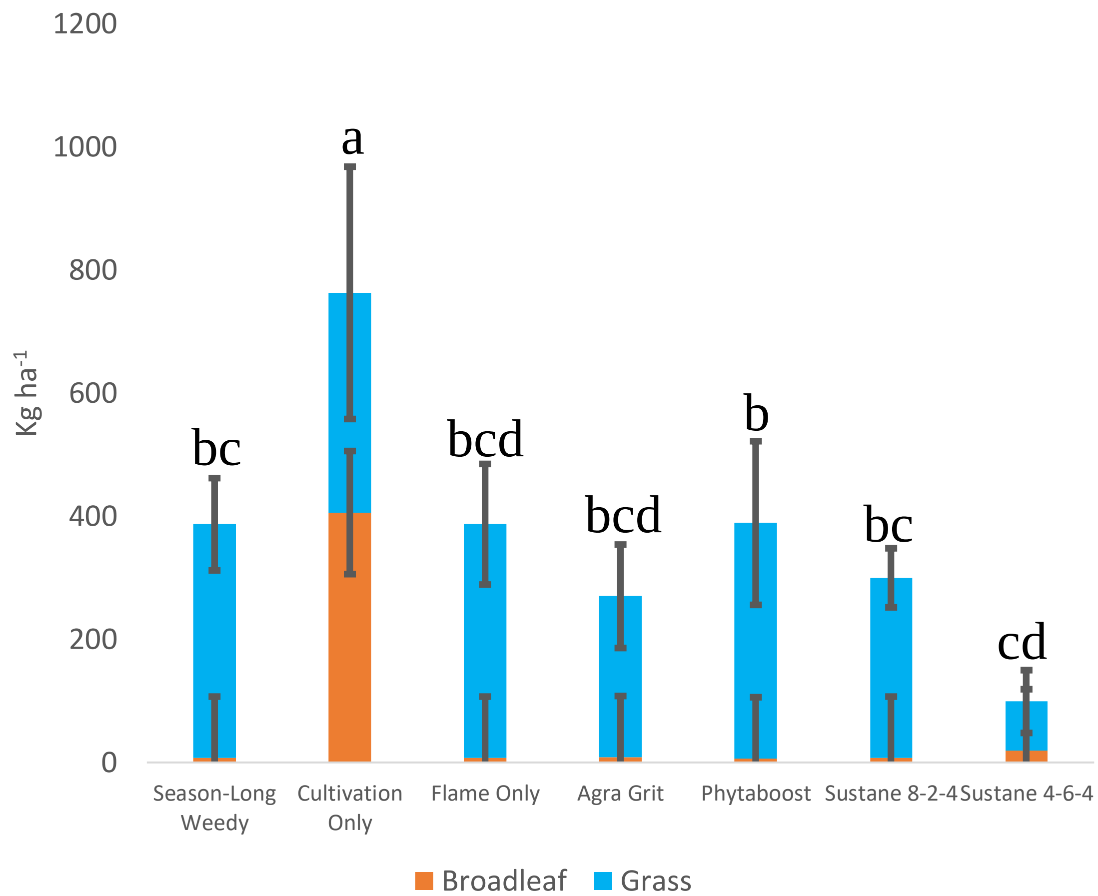
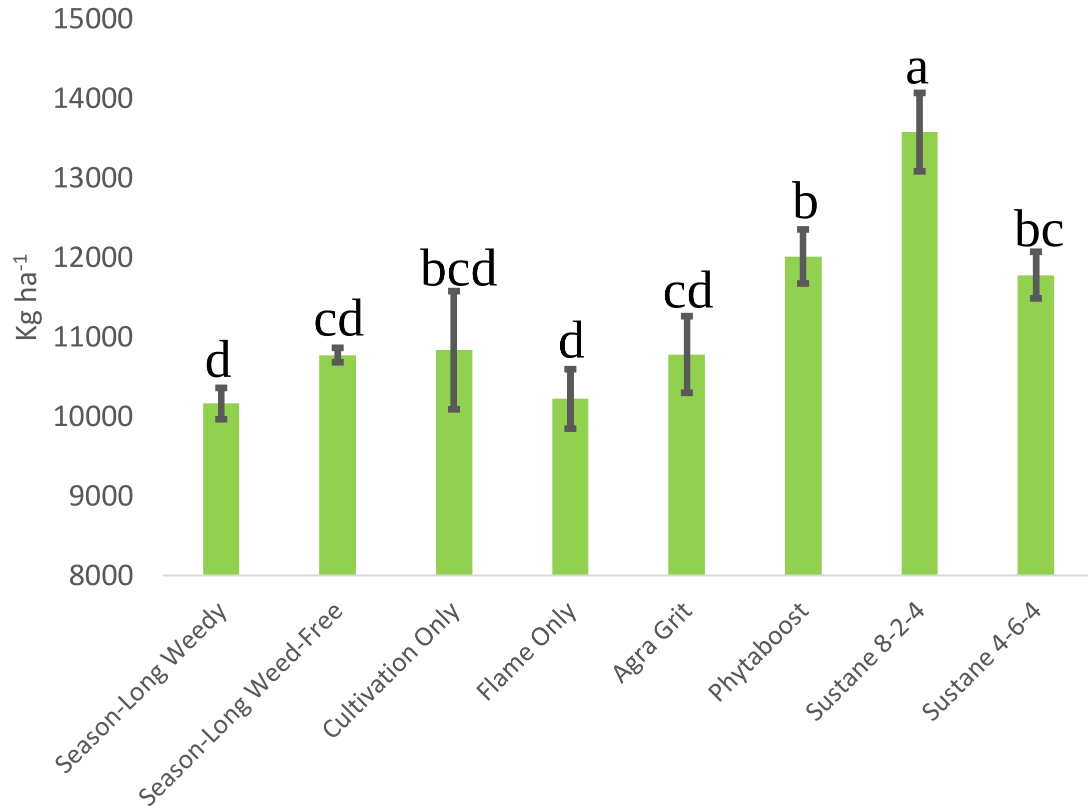
APPENDIX



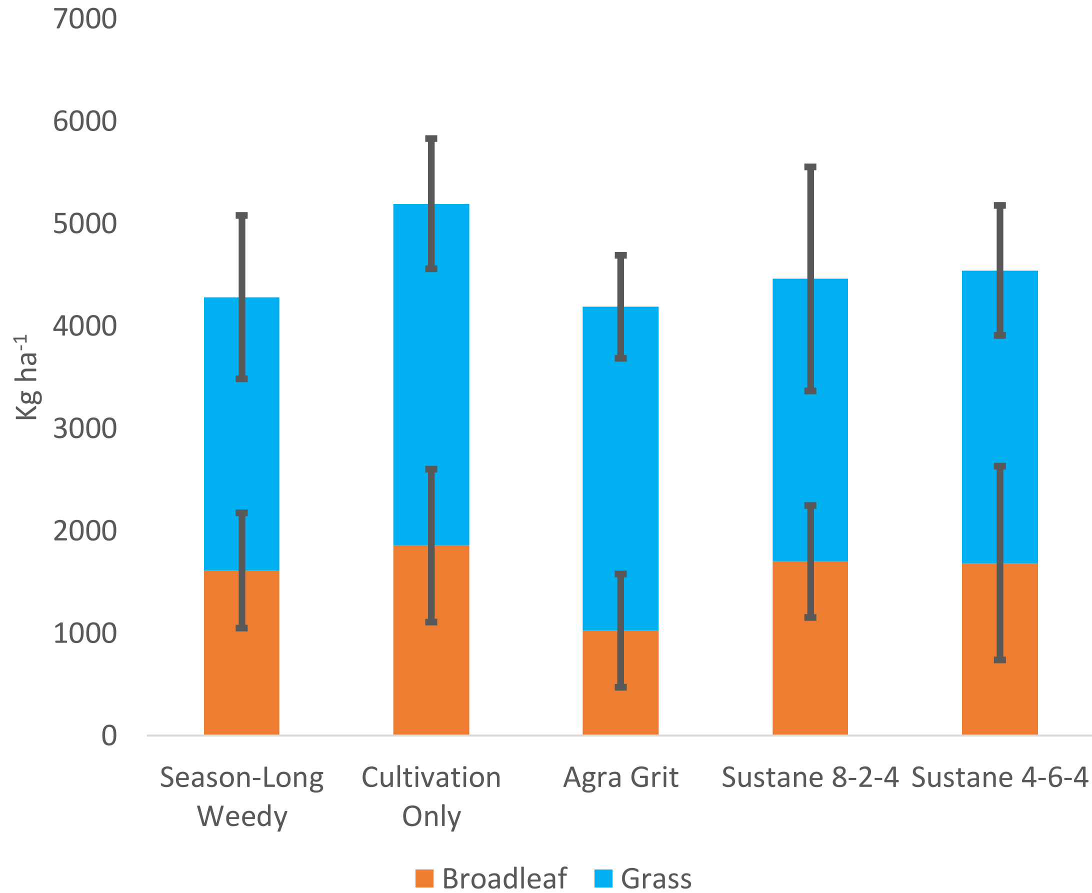
Supplemental Figure 1. The before (B) and after (A) in-row weed densities (count m^{-2}) of the season-long weedy check and all grit treatments in corn in Aurora in 2016. The orange part of the bar is the broadleaf in-row weed density, and the blue part of the bar is the grass in-row weed density.



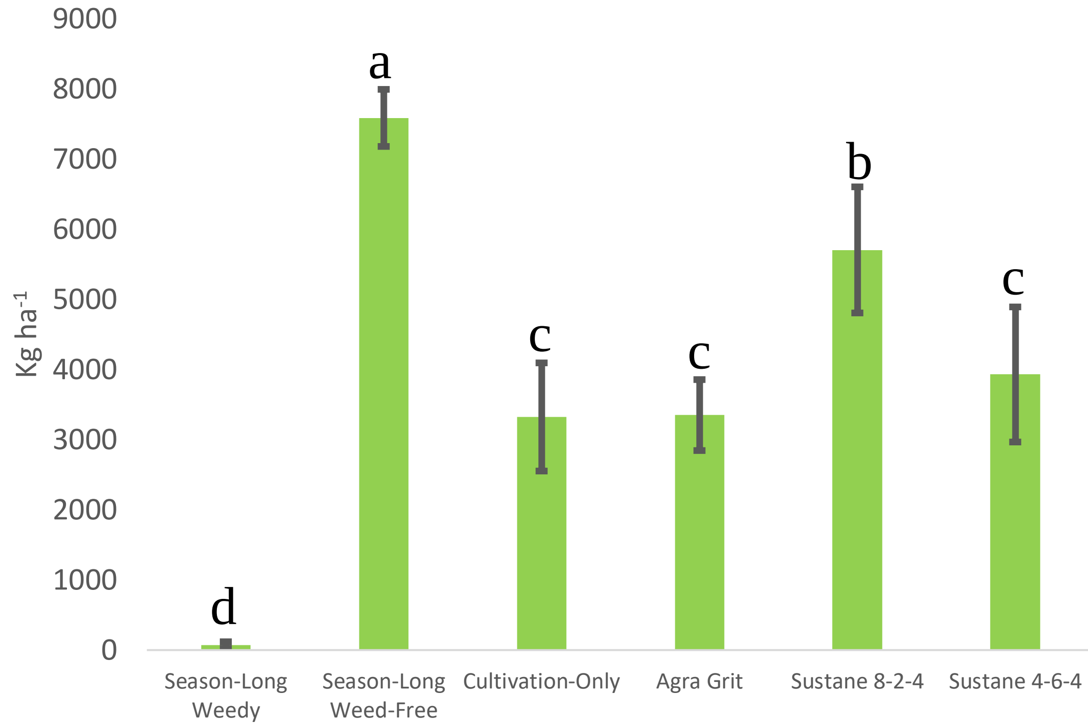
Supplemental Figure 2. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation- and flame-only treatments and all grit treatments in corn in Aurora in 2016. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass. Letters denote significant differences at level $\alpha = 0.05$ for total in-row weed biomass.



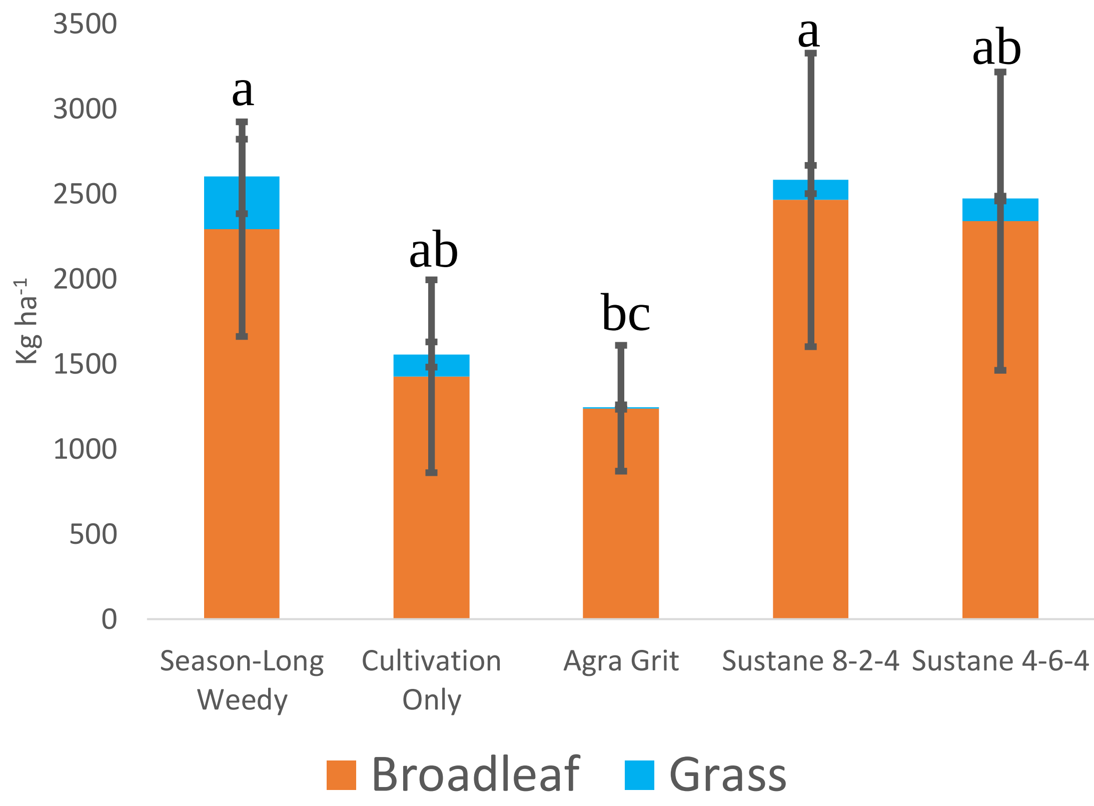
Supplemental Figure 3. The corn grain yield (kg ha^{-1}) of all treatments in Aurora in 2016. Letters denote significant differences at level $\alpha = 0.05$.



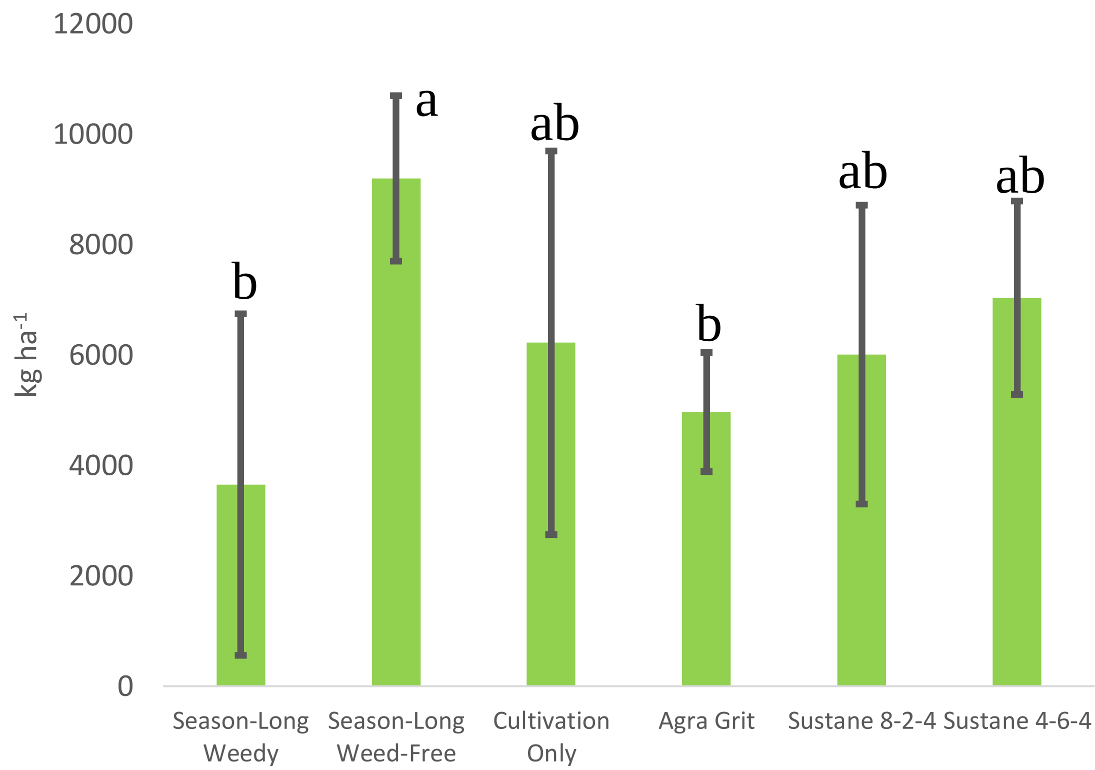
Supplemental Figure 4. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only and grit treatments in corn in Aurora in 2017. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass.



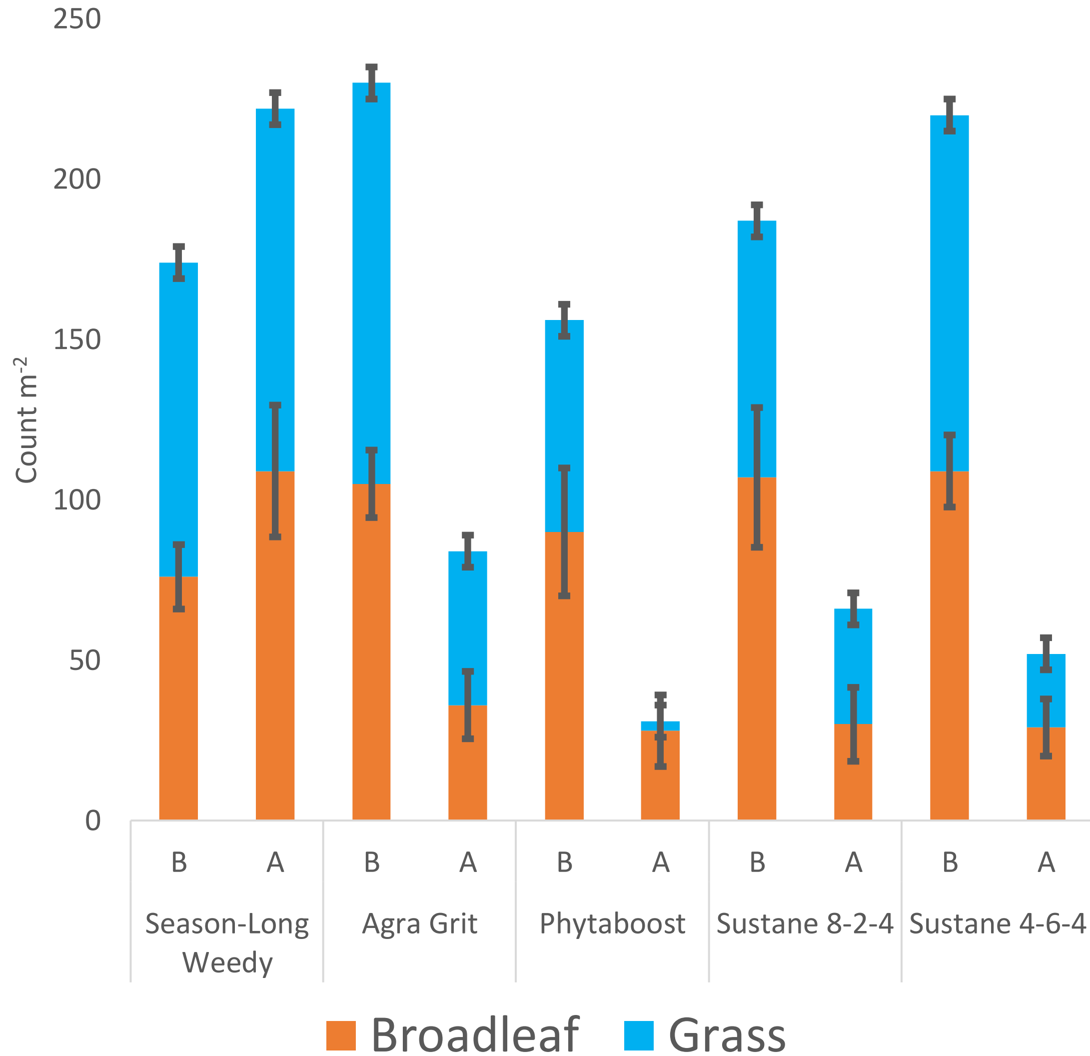
Supplemental Figure 5. The corn grain yield (kg ha^{-1}) of all treatments in Aurora in 2017. Letters denote significant differences at level $\alpha = 0.05$.



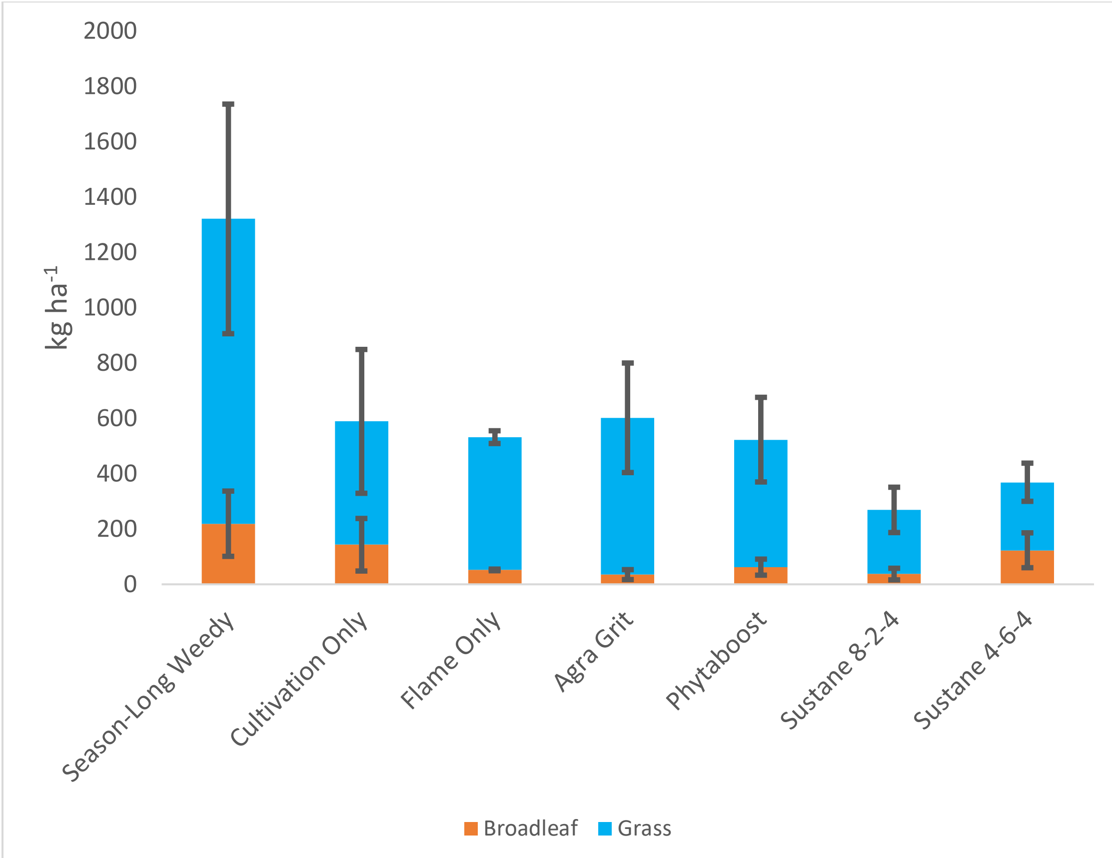
Supplemental Figure 6. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only, and grit treatments in corn in Morris in 2017. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass. Letters denote significant differences at level $\alpha = 0.05$ for total in-row weed biomass.



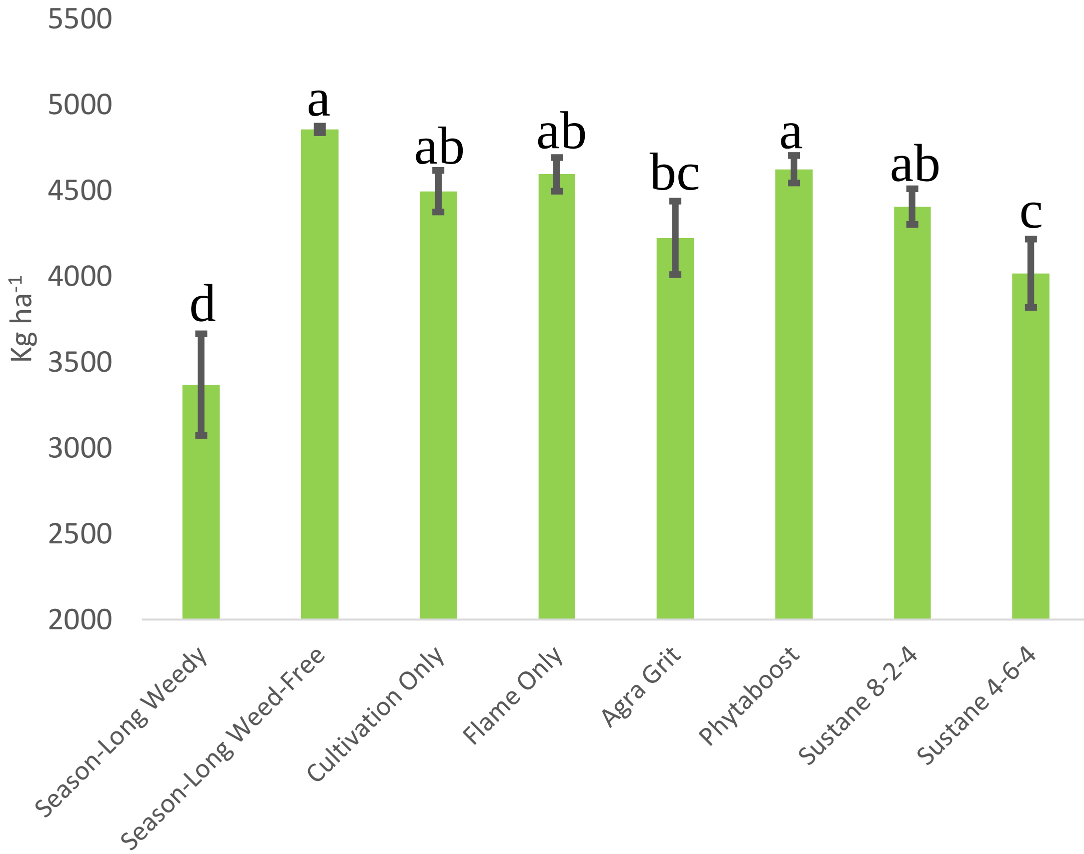
Supplemental Figure 7. The corn grain yield (kg ha^{-1}) of all treatments in Morris in 2017. Letters denote significant differences at level $\alpha = 0.05$.



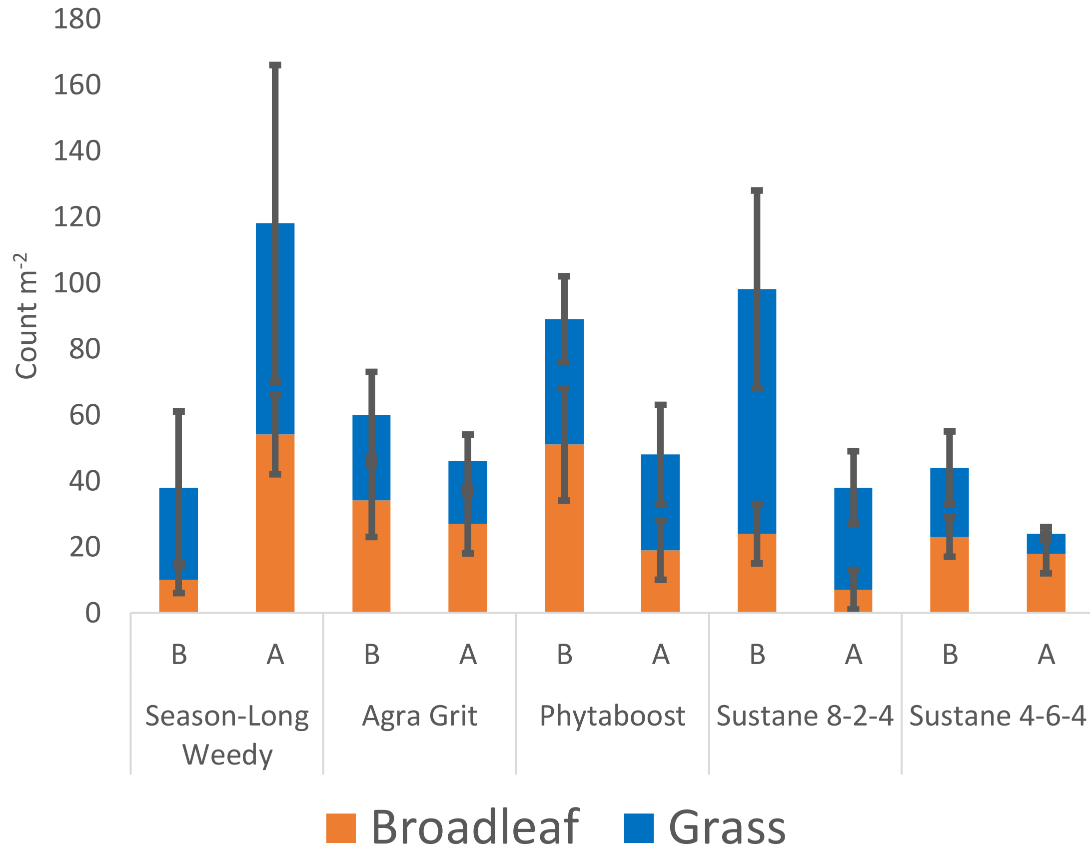
Supplemental Figure 8. The before (B) and after (A) in-row weed densities (count m^{-2}) of the season-long weedy check and all grit treatments in soybean in Aurora in 2016. The orange part of the bar is the broadleaf in-row weed density, and the blue part of the bar is the grass in-row weed density.



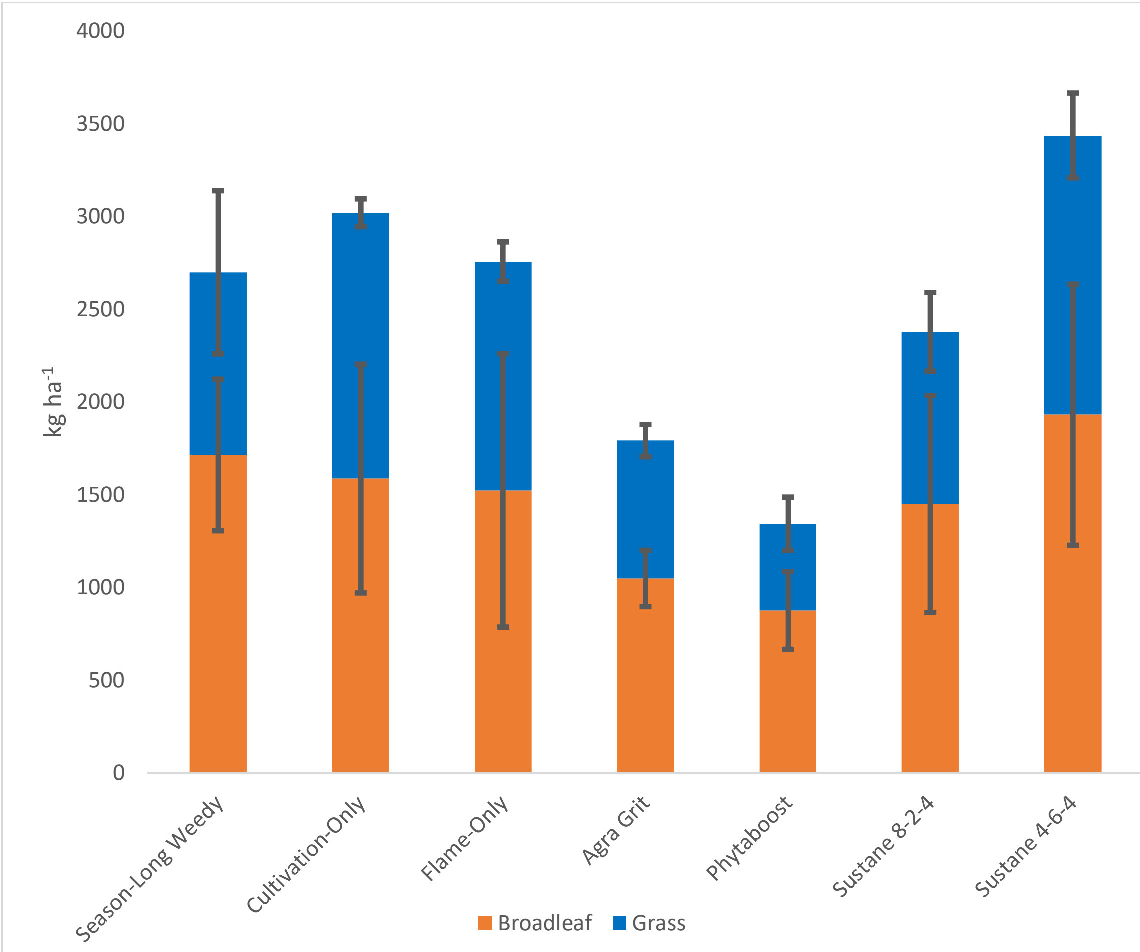
Supplemental Figure 9. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only, and grit treatments in soybean in Aurora in 2016. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass.



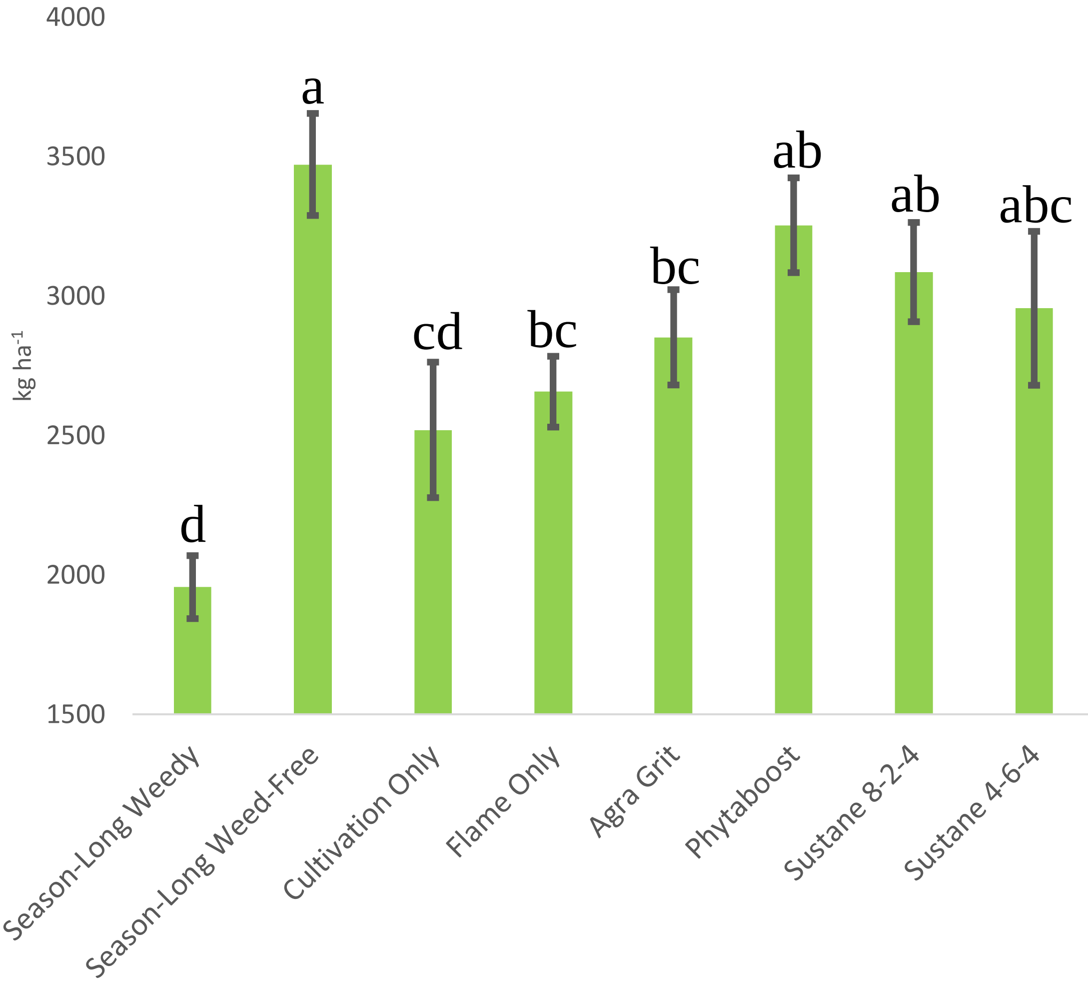
Supplemental Figure 10. The soybean grain yield (kg ha^{-1}) of all treatments in Aurora in 2016. Letters denote significant differences at level $\alpha = 0.05$.



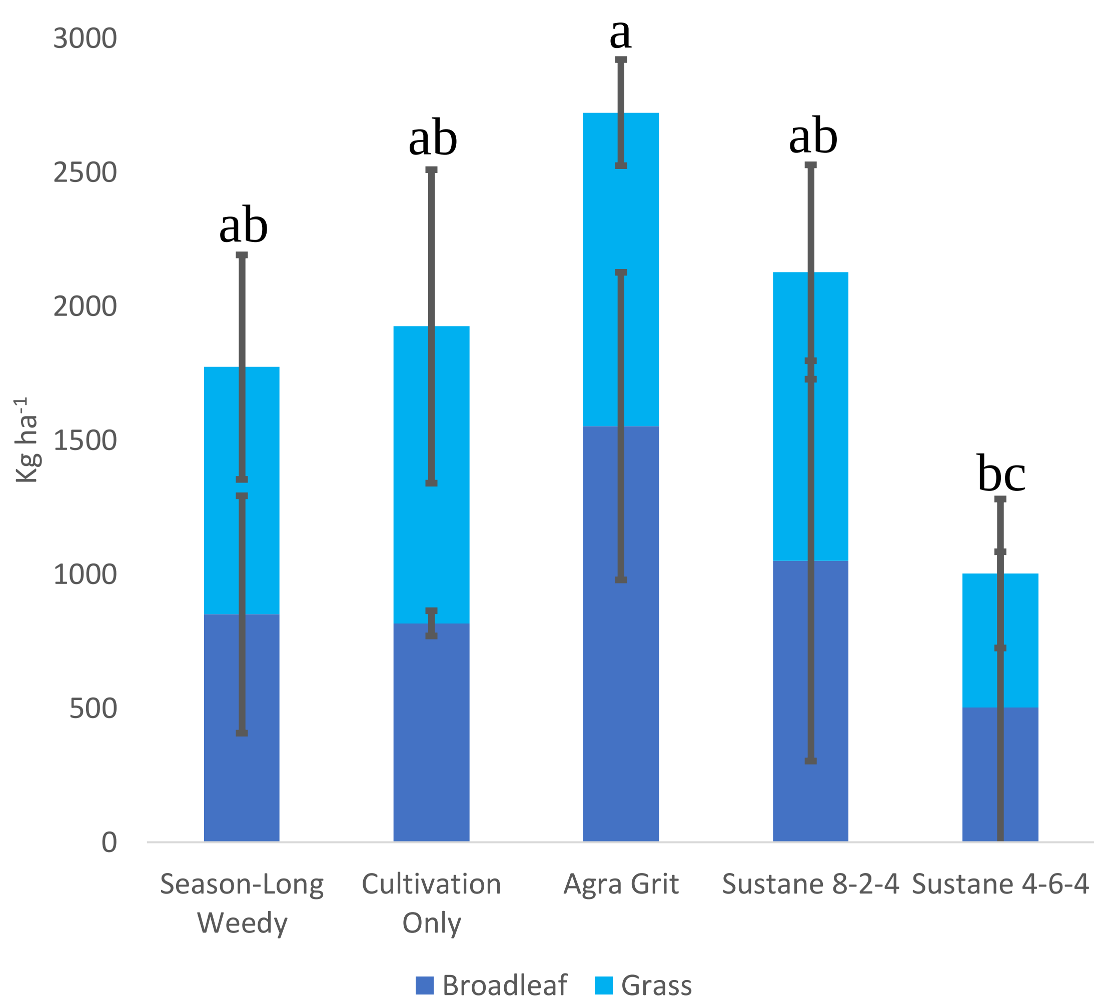
Supplemental Figure 11. The before (B) and after (A) in-row weed densities (count m^{-2}) of the season-long weedy check and all grit treatments in soybean in Morris in 2016. The orange part of the bar is the broadleaf in-row weed density, and the blue part of the bar is the grass in-row weed density.



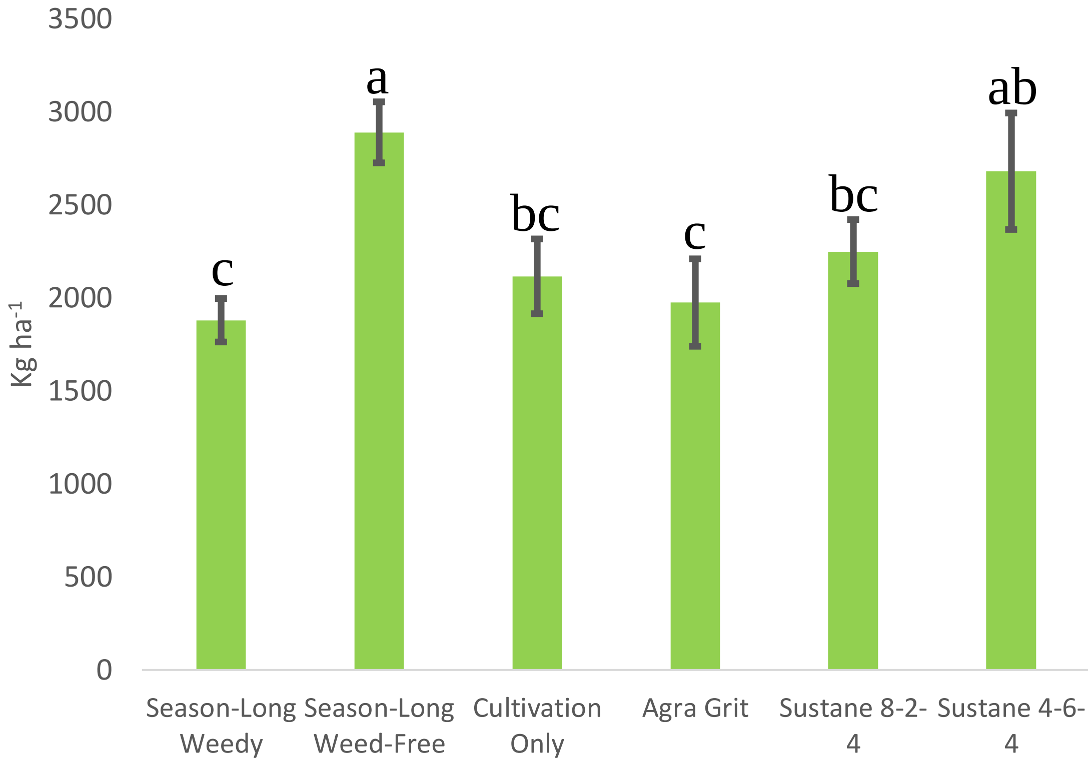
Supplemental Figure 12. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only, and grit treatments in soybean in Morris in 2016. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass.



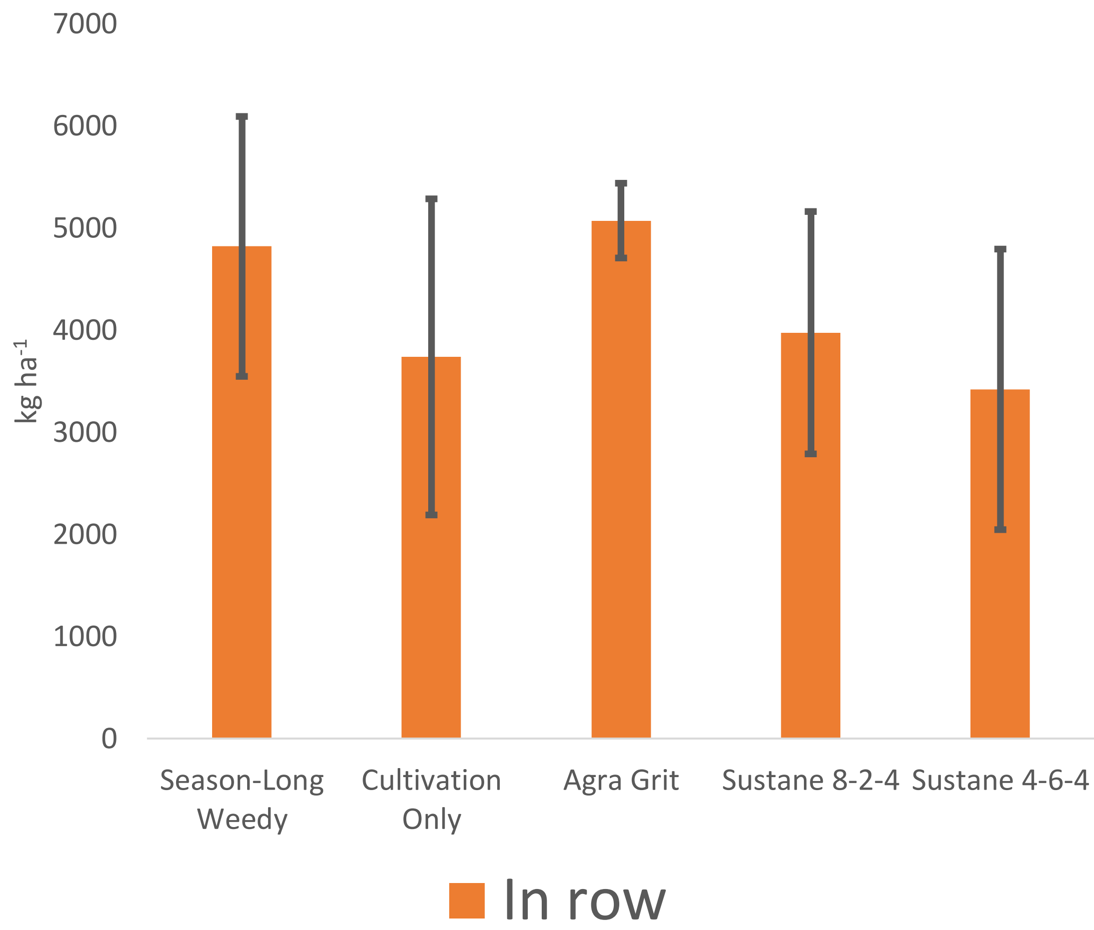
Supplemental Figure 13. The soybean grain yield (kg ha^{-1}) of all treatments in Morris in 2016. Letters denote significant differences at level $\alpha = 0.05$.



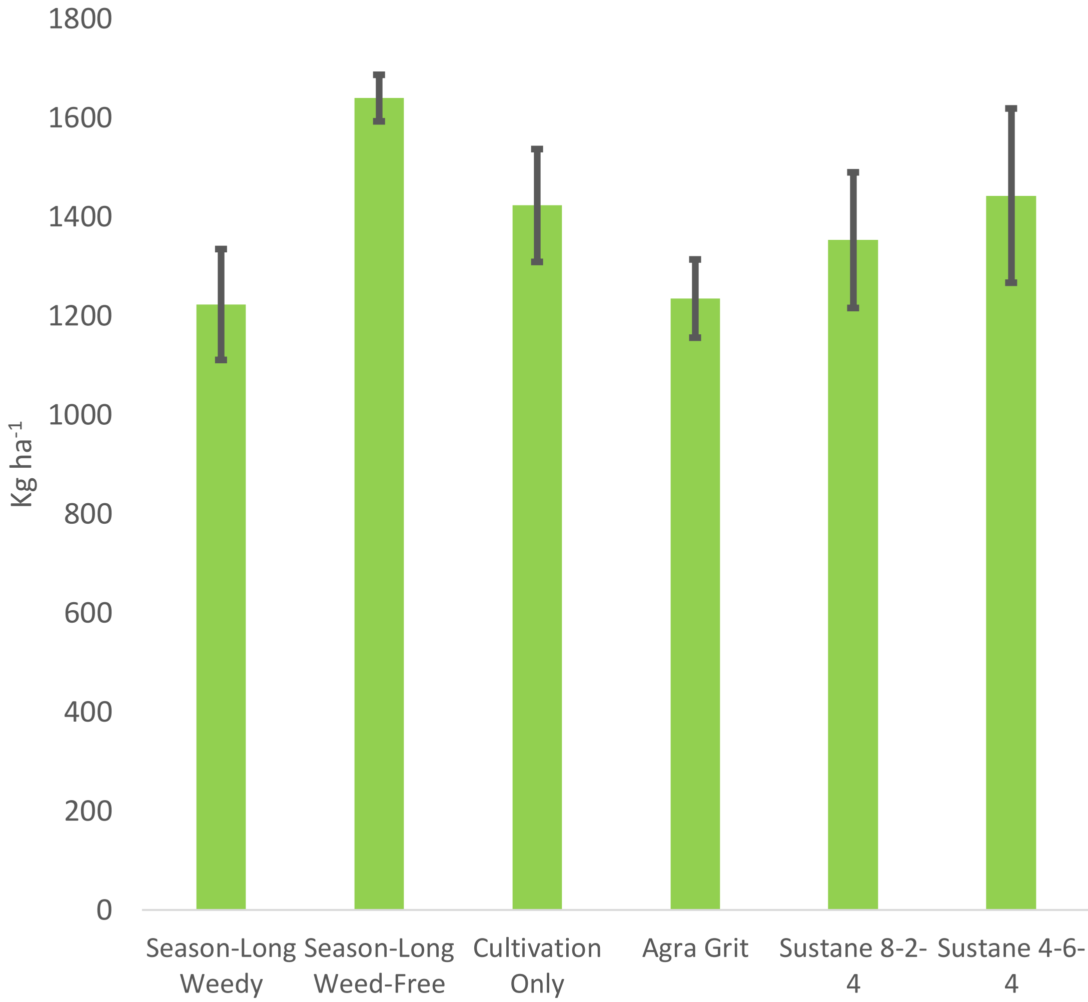
Supplemental Figure 14. The in-row weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only, and grit treatments in soybean in Aurora in 2017. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The orange part of the bar is the broadleaf in-row weed biomass, and the blue part of the bar is the grass in-row weed biomass. Letters denote significant differences at level $\alpha = 0.05$ for total in-row weed biomass.



Supplemental Figure 15. The soybean grain yield (kg ha^{-1}) of all treatments in Aurora in 2017. Letters denote significant differences at level α = 0.05.



Supplemental Figure 16. The in-row broadleaf weed biomass (kg ha^{-1}) of the season-long weedy check, cultivation-only, and grit treatments in soybean in Beresford in 2017. The season-long weed-free in-row weed biomass was 0 kg ha^{-1}. The in-row grass weed biomass among all treatments was 0 kg ha^{-1}.



Supplemental Figure 17. The soybean grain yield (kg ha^{-1}) of all treatments in Beresford in 2017.