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Corncob Grit Application as an Alternative to Control Weeds in Two Crop Production Systems

Mauricio Erazo-Barradas
South Dakota State University

CORNCOB GRIT APPLICATION AS AN ALTERNATIVE TO CONTROL WEEDS IN TWO CROP PRODUCTION SYSTEMS

BY

MAURICIO ERAZO-BARRADAS

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This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Sharon ~~A. Clay, Ph.D.~~ Date
Major Advisor

David Wright, Ph.D. Date
Head, Department of Plant Science

Graduate School, Dean Date

This dissertation is dedicated to my parents,

Félix Erazo Domínguez and Lucina Barradas Lagunes.

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ABSTRACT

CORNCOB GRIT APPLICATION AS AN ALTERNATIVE TO CONTROL WEEDS IN TWO CROP PRODUCTION SYSTEMS

MAURICIO ERAZO-BARRADAS

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Weed management is one of the most challenging production problems in organic cropping systems because of limited weed control methods. Grits, derived from agricultural residues, have been demonstrated to control weed seedlings selectively in corn. This research examined weed efficacy and crop yield of an integrated air-propelled abrasive corncob grit (for in-row weed control) at varying timings and frequencies and flame-weeding or cultivation (for between-row weed control) system in two corn production systems. In the first study efficacy of weed control was assessed with this approach in an organic corn silage production system established in Morris, MN in 2013 and 2014. The second study examined efficacy of weed control with this method in a transitioning corn production system established in Aurora, SD in 2013 and 2014. A third study compared efficacy of weed control in both production systems. Measurements included: weed identification, weed density by species, weed biomass (total, broadleaf, grass, in-row, and between-row), plant height, and corn yield (silage and grain). Early applications of abrasive corncob grit resulted in the decrease of 68% and 52% of the total weed biomass in two years of evaluation, and it increased corn silage yield up 26 % when compared to the season long weed control. Late application of corncob grit at the V7 corn growth stage resulted in less weed control. One application at V1 increased corn yield. Additional treatments with or after the V1 treatment improved weed control and may increase yield. Waiting until V5 for grit application resulted in 80% in-row weed biomass reduction, however, there was no positive effect on corn yield. In the second study, in-row weed control resulted in the decrease of 61% of total weed biomass in the transitioning corn production system. Between-row weed control reduced total weed biomass up to 31% for cultivation and 51% for flaming. Even though the application of corncob grit as well as cultivation and flaming at the V5 corn growth stage reduced the total weed biomass, an application of these treatment-combinations at early stages of corn development may potentially achieve better weed control. A treatment combination of in-row weed control and between-row weed control reduced grass biomass. Between-row weed control treatments alone reduced grass weed biomass up to 68% and 61% with flaming treatments. Application of abrasive corncob grit increased corn yield up to 9% compared to the season long weed control. The comparison of these two systems determined that abrasive corncob grit for in-row weed control can reduce weed biomass in both weed control systems and increase silage and corn grain yield.

CHAPTER 1

General background: A review on organic agriculture and row weed management

1.1 Organic agriculture and weed control

In the United States, the area under organic crop production is increasing rapidly mainly due to growing consumer demand for chemical-free food and an attractive income potential for organic producers (Derksen *et al*., 2002). This cropland area has increased more than 500% from 1995 to 2011, as the total organic cropland grew from 370,200 ha in 1995 to 2,178,000 ha in 2011 (Greene, 2013). However, even with this increase, the current certified organic hectares account for only about 0.5% of the total U.S. farmland production (Greene, 2013).

In 2006, the Midwest area of the U.S. was ranked ninth nationally in certified organic crop hectares where wheat (*Triticum aestivum* L.) was the top ranked certified organic crop followed by corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) (Parsons, 2008). In 2008, South Dakota and Minnesota had 53,400 ha and 49,500 ha of certified organic land respectively (USDA, 2008a). In the U.S., Minnesota ranked third and second, whereas South Dakota ranked 13th and 11th, in certified organic land for corn for grain and silage, respectively (USDA, 2008b). High remunerative prices and reduced cost of inputs relative to horticultural vegetable crops have motivated growers to increase the area under organic row-crop production.

Estimated sales of organic products grew 20% each year from 1990-2000, which made the organic food industry the fastest growing segment of U.S. agriculture (Dimitri and Greene, 2002). According to Greene (2014), U.S. sales of organic products were an estimated $28.4 billion in 2012 –over 4% of total food sales- and it reached an estimated $35 billion in 2014. This rapid rate of growth easily justifies increased research efforts centered on organic production.

For both conventional and organic crop production systems, weeds are one of the major problems and responsible for severe grain yield quantity and quality losses (Stopes and Millington, 1991; Bridges, 1992, Bond and Grundy, 2001). Production losses from weed competition remain a top management concern, greatest barrier to production, and highest research priority among organic farmers (Baker and Smith, 1987; Walz, 1999; Walz, 2004). The ability to control weeds also is considered a major limiting factor for farmers wishing to transition to organic production systems (Bond and Grundy, 2001; Walz, 2004). Based on historic (pre-herbicide methods), organic farmers still rely heavily on mechanical cultivation and hand weeding for weed management. However, repeated cultivation can accelerate loss of soil organic matter, destroys soil aggregates, increases the chances for soil erosion, and promotes emergence of new weed flushes (Harper, 2015). In addition, the labor required for hand weeding is expensive, time consuming, and difficult to organize (McErlich and Boydston, 2013).

Controlling weeds in organic farming is challenging because synthetic chemical herbicides are not used to control weeds (Liebman and Davis, 2009) and requires the use of many techniques and strategies to achieve economically acceptable weed control and crop yields (Walz, 1999). Therefore, controlling weeds without synthetic herbicides under the certification procedures of organic agriculture is difficult to achieve (Kruidhof *et al*., 2008). There are very few herbicides approved for use in organic production, and they are costly and often non-selective, thus can injure crops (Webber *et al*., 2009). The most widely used organic amendment that provides some weed control is corn gluten meal, a by-product of cornstarch production (Stier, 1999; Webber III and Shrefler, 2007). Corn gluten is a natural substance that can be used as an organic fertilizer and has an average nutrient content of 9% N, 0 % P, and 0 % K (CSU, 2013). Use as an herbicide on organic farms (Webber *et al*., 2010; Christians, 1993) is at a rate of 1000 kg ha^{-1} (Stier, 1999). Corn gluten meal can be applied as pre-emergence herbicide, however, the time of application is extremely important, as the gluten must be present when weed seeds germinate to inhibit root formation (Webber *et al*., 2010; Christians, 1993). Broadleaf species are generally more susceptible than grasses to corn gluten meal. In field studies, weed cover has been reduced up to 84% when corn gluten meal was incorporated prior to planting (McDade and Christians, 2000). Researchers do not recommend incorporating corn gluten meal prior to direct seeding crops but by shallow cultivation, rather than being left on the soil surface, as crop seedling survival is reduced in the presence of this broad-spectrum herbicide. Weeds affected by corn gluten meal include redroot pigweed (*Amaranthus retroflexus* L.), black nightshade (*Solanum nigrum* L.), common lambsquarters (*Chenopodium album* L.), curly dock (*Rumex crispus* L.), creeping bentgrass (*Agrostis palustris* Huds.), common purslane (*Portulaca oleracea* L.), common dandelion (*Taraxacum officinale* Weber), and smooth crabgrass (*Digitaria ischaemum*

Schreb. ex Muhl.). Of weeds that have been tested, barnyardgrass (*Echinochloa crus-galli* [L.] Beauv.) and velvetleaf (*Abutilon theoprasti* Medikus) are the least susceptible to corn gluten meal (Bingaman and Christians, 1995).

Corn gluten meal also can be used as an abrasive grit to control weeds. Wortman (2014) evaluated corn gluten meal in a series of abrasive grit experiments in the greenhouse and reported that one blast of this material applied at a rate of 0.47 g cm^{-3} with a pressure of 517 kPa at one leaf stage in Palmer amaranth (*Amaranthus palmeri* S.Wats.) reduced seedling biomass by 95%. Earlier, Forcella et al. (2011) found that corn gluten meal applied to seedlings of yellow foxtail (*Setaria pumila* [Poir] Roem. & Schult.) retarded growth sufficiently to eliminate competition with adjacent corn plants. These results suggested corn gluten meal, an approved organic herbicide, can be used effectively as an abrasive grit in some crops and may provide weed suppression as well as supplemental crop nutrition.

1.2 Troublesome weeds in corn

Numerous studies have shown that weed control early in the growing season is necessary to reduce yield losses in corn. Corn yield loss is generally proportional to the amount of weeds present and while the ratio is not always one-to-one, some studies suggest that for every pound of weed dry matter, there is a reduction of approximately one pound of corn dry matter (grain, cobs, stalks and leaves) (Gianessi *et al*., 2002). Since the light, nutrients, and moisture resources that go into weeds cannot simultaneously go into the crop, crop yield is reduced proportionately (Rajcan and Swanton, 2001).

The literature reports examples of weed species present in corn and the level of yield loss. Among the broadleaf weed species, pigweeds (*Amaranthus* spp.) are troublesome and widespread, infesting corn fields throughout the United States, including the Upper Midwest (Bridges, 1992; Knezevic *et al.* 1994, 1997; Shoup *et al.*, 2003). Knezevic *et al.* (1994) reported that a density of 0.5 plants of redroot pigweed per meter of row in corn can reduce corn yield by 5%. Common waterhemp (*Amaranthus rudis* Sauer) populations of 11 plants m^{-2} have been reported to reduce corn yield by 56% (Bensch *et al*., 2003). Density of 1 plant m^{-1} row for redroot pigweed and velvetleaf has been reported to have minimal (<5%) impact on corn yield (Dielman *et al*., 1995; Scholes *et al*., 1995). However, velvetleaf interference in corn has been reported to reduce corn yield by 10% (Clay *et al*., 2005).

Species such as giant green foxtail (*Setaria viridis* [L.] Beauv.) can cause as much as 35% yield reduction in corn and soybean with more than 8 weeks of competition (Harris and Ritter, 1987). Barnyardgrass competition can reduce corn yield by as much as 30% (Clay *et al.*, 2005) or 82% (Bosnic and Swanton, 1997) depending on the time of weed and corn emergence, weed density, and how long the weed is competing with the crop for nutrients, water, and light.

In addition to common weeds reducing yield, herbicide resistant weeds are problematic. For example, biotypes of field bindweed (*Convolvulus arvensis* L.) have always been tolerant to glyphosate and other herbicides (DeGennaro and Weller 1984).

Glyphosate-resistant weeds that are becoming more common in South Dakota include kochia (*Kochia scoparia* [L.] Schrad.), common ragweed (*Ambrosia artemisiifolia* L.), horseweed or marestail (*Conyza Canadensis* [L.] Cronq.), and common waterhemp (Moechnig *et al*., 2013). The development of glyphosate resistance in weeds and the subsequent expansion of areas infested with these weeds underlie the importance of alternative weed control methods, not just for organic production.

1.3 Critical period for weed control (CPWC) in corn

Weeds negatively affect crop production efficiency in several ways, including reducing yields, reducing harvest efficiency, contaminating grain and silage, and contributing to future problems through weed seed production (Hartzler, 2003). Weeds that emerge with the crop have the greatest potential to affect yields, and the yield loss associated with this group of weeds is strongly influenced by how long they are allowed to remain in the field.

The critical period of weed control (CPWC) is defined as an estimate of the duration weed control must be effective to prevent weed interference from reducing yields (Hall *et al*., 1992). During the first few weeks after crop emergence, resources present in the environment are generally sufficient to support both weed and crop growth. With continued and increasing demand on resources in limited supply, interference between weeds and crops becomes firmly established such that the weeds are no longer tolerated due to negative effects on the crop, thereby marking the beginning of the CPWC

(Norsworthy and Oliveira, 2004). Conversely, the maximum time the crop must be kept free of weeds to prevent yield loss is the end of the critical weed-free period.

In studies evaluating corn established under tillage and no-tillage conditions by Halford *et al*. (2001), it was concluded that the beginning of the CPWC was stable, usually beginning when six leaves had emerged from the whorl (20 days after seedling emergence) with the end of the CPWC being more variable, ranging from when nine to 13 leaves had emerged from the whorl (~30-40 days after emergence). The critical period for corn under no-till conditions tended to start and end earlier than under conventional tillage practices. In the Midwestern United States, the beginning of the CPWC ranged from emergence to the seven-leaf stage of corn (V7), with the end of the CPWC ranging from the five-leaf stage to anthesis (Evans *et al*., 2003).

In a two-year study conducted at South Dakota State University, weed interference with corn growth was evaluated by comparing growth and yield responses of corn to nitrogen, low light (shade), and weed stresses. Shade, present until V2, reduced biomass and leaf area more than 50% at V2, and recovering plants remained smaller than non-stressed plants at V12. Grain yields of shade-stressed and non-stressed plants were similar, unless shade remained until V8. Weed stress reduced corn growth and yield in 2008 when weeds remained until V6. In 2009, weed stress until V2 reduced corn vegetative growth, but yield reductions occurred only if weed stress remained until V6 or later (Moriles *et al*., 2012).

1.4 Row weed management

Corn is a row crop that normally requires a high level of weed control to avoid significant yield losses (silage and grain) and reduction in quality from weed competition. In addition, weed management improves harvest operations, and avoids weed seed dispersal promoting the buildup of the weed seed bank and subsequent future weed populations. Even though most row crops have low competitive abilities against weeds, there are differences that may determine the weed control level needed as well as the critical period during which a certain level of weed control is required. Row crops, such as corn and soybean that reach canopy closure can suppress late emerging weeds typically from mid-season and onward (Clay *et al*., 2005). In contrast, some crops never reach canopy closure, such as onion (*Allium cepa* L.) and leek (*Allium ampeloprasum* L.) (Baumann *et al.,* 1993) and require almost complete weed control throughout the entire growing season and are, therefore, the most demanding crops, technically and economically, to maintain weed free. Hence, time consumption for hand-weeding varies according to crop, planting arrangement (narrow vs. wide rows), weed density and the success of preceding weed control measures. Earthbound Farms, the largest organic farm in North America, reported their weed control operations cost up to $1,000 an acre to keep weeds under control (Earthbound Organic, 2006). Hand weeding used in organic sweet corn was reported to be 5 hr ha^{-1} (Grubinger, 1999), and organic tomatoes required from 3 to 5 cultivations to manage weeds (Klonsky *et al*., 1993). Poor weed control is often cited as a major reason for lower yields in organic production. A 20-year study in Iowa indicated that corn yields were 34% higher in the conventional vs. the organic operations. Multiyear studies in Nebraska and South Dakota reported that conventional corn yields were 17 to 20% higher than organic corn yields (Welsh, 1999).

1.5 Between-row weed control

Cultivation practices can be a means to reduce herbicide use in corn production by using mechanical methods to effectively control weed populations. Between-row cultivation had been used regularly both in conventional and organic row crops, but in many cases has been replaced by synthetic chemical weed control in conventional crops such as corn.

Mechanical methods that only work the between-row space usually are successful in most situations, mainly because the crop plants are not directly affected by the weeding tools and, moreover, the crops can be shielded in different ways (Mattsson *et al*., 1990). Hoes with blades configured as a ‘‘duck foot’’ shape (Melander *et al*., 2003) mounted on shanks are often used for inter-row cultivation, but other cultivators such as rotary hoes, rolling cultivators, and power take-off (PTO)-driven cultivators are also used (Bowman, 1997). These techniques involve movement and disturbance of the soil. In contrast, flaming and steaming do not involve any soil disturbance, and these techniques have been proven to successfully control weeds.

Flame cultivation, or simply “flaming,” is used in some vegetable crops and corn (Diver, 2002). Flaming before crop emergence has been the predominant thermal weed control method in slow-germinating row crops such as onion, leek, carrot, and corn. Pre-emergence flaming is only of limited value in fast emerging crops such as kale (*B.*

oleracea L. var. *acephala* DC.) because the crop may emerge before most weeds, making a broadcast application of flaming useless (Melander, 1998a). The advantages of flame weeding are that it leaves no chemical residue in the soil and does not disturb soil, but it has disadvantages in its high consumption of costly fossil fuels (Ascard, 1998; Lampkin, 1997).

Flaming creates a temperature high enough to dehydrate or rupture the plant cells so that weed death occurs. Flaming kills weeds that have emerged before the crop, mainly by rupturing the cell membranes and the indirect effect of subsequent desiccation (Bertram, 1994; Ellwanger *et al.,* 1973a, 1973b). The effect of flame weeding varies with plant size (Ascard 1994, 1995, 1998); plants at 4 to 12 leaves required two- to four-fold higher energy rates for control than those at the zero- to four-leaf stage. Flaming effectively controls most broadleaf weeds, especially those that are less than five centimeters tall.

According to Finney and Creamer (2005a), there are three types of flame cultivation – parallel flaming, cross flaming, and middle flaming. Parallel flaming involves directing burners to the rear so that the flame patterns run parallel with the crop row. Parallel flaming is used when crops lack tolerance to flaming or because a crop commonly tolerant to flaming is in a susceptible stage (Ulloa *et al*., 2011). Cross flaming can be done by directing the burners so that the flame patterns are across the crop row from each other, but not directly across (Knezevic *et al*., 2012). Burners set directly across from each other can create turbulence and cause flames to damage crop leaves (Diver, 2002). Cross flaming can be accomplished when the crop is in a tolerant stage of growth - when the crop is taller than the weeds, has a woody stem, or both. To increase crop tolerance, a sprayer can be fitted on the flamer to spray water on the crop just above the burners. Middle flaming uses burners located beneath a hood over the row middle (Knezevic *et al*., 2012). The hood directs the flame to the row middles but protects the crop. Infrared weeders are similar in principle to flame weeders. With infrared weeders, however, the flame is directed to a ceramic element or steel plate that radiates heat at 1,800 to 2,000°F (Diver, 2002).

Soil steaming can potentially lead to almost complete weed control for long periods. Steaming is used to kill weed seeds as an alternative to the use of pre-emergence herbicides. In this process, steam is mixed with air and injected into the soil to heat it to 82°C (Baker and Smith, 1987). Length of time and temperature are critical if weed seeds are to be controlled. Addition of compounds such as CaO or KOH can further increase weed control by boosting and maintaining soil heating, reaching peak temperatures of 80°C at 150 mm depth for a longer period of time through exothermic reaction compared to only the application of steam (Peruzzi *et al.,* 2002). Experiments carried out in Italy showed that addition of KOH at 4,000 kg ha^{-1} reduced the total weed seedbank by 76% compared with steaming alone and that the rate of seedling emergence decline for a 100 kg increase in KOH rate was 58 seedlings m^{-2} (Moonen *et al.,* 2002). However, an extremely high consumption of fossil energy and low work rates (slow driving application) are major disadvantages of current soil steaming technology (Pinel *et al.,* 1999). This has led to the idea of band-steaming where only a limited soil volume is steamed corresponding to the intra-row area (Melander *et al.,* 2002). Band-steaming is currently under investigation and more results are required to judge the potential for practical use.

1.6 In-row weed control

Hand-weeding in-row weeds (i.e., weeds growing between the crop plants in the rows), is an appreciable financial burden in organic crop production systems and where herbicide effectiveness is insufficient in conventional cropping systems. Mechanization of the in-row weed control would not only lower the direct costs for hand-weeding but also release time and labor to be used elsewhere in the production operation by enhancing the possibilities for growing more profitable organic crops and thereby improving growers' income (Melander, 1998b; Finney and Creamer, 2005b).

Several mechanical methods have application for in-row weed control, primarily controlling weeds by uprooting or burying, or both (Kurstjens and Kropff, 2001; Kurstjens and Perdok, 2000; Terpstra and Kouwenhoven, 1981). As with most other mechanical weeding implements, operator skill, experience, and knowledge are critical to success. Drawbacks to mechanical in-row methods include poor seedbed preparation resulting in soils difficult to till, low work rates, delays due to wet conditions, and the subsequent risk of weed control failure as weeds become larger. Weed harrowing with spring-tine, chain, or drag harrows may be used (Lampkin, 1997), but the spring-tine harrow with flexible tines is probably the most preferred one with the widest range of applications. It can either be used before crop emergence or post-emergence, and it involves weeding the whole crop.

Torsion weeders, with pairs of tines set on either side of the crop row and lowered 20 to 30 mm into the soil (Bowman, 1997), offer more precise intra-row control but steering becomes crucial, normally including a second operator to specifically steer the implement. Finger weeders, with flexible rubber tines on ground driven–cone wheels, were also developed specifically for in-row weed control (Bowman, 1997). Vertical brush weeding, with brushes rotating around vertical axes and placed in pairs to cultivate either side of the crop row, is a method that emerged in the early 1990s (Melander, 1997). The torsion weeder, finger weeder, and brush weeder are all mainly developed for postemergence use in high-value vegetable crops because of their low working capacity. However, their application for sugar beets (*Beta vulgaris* L.), including weed harrowing, have been studied in a series of experiments in southern Sweden, and the torsion weeder generally performed better than the other three methods both in terms of weeding and cost effectiveness (Ascard *et al.*, 1995), but the weed harrow had higher work rates and required no particular attention on steering.

Attempts have been made to use technology to guide weeding tools to selectively remove the weeds without touching the crop plants (Blasco *et al.,* 2002; Bontsema *et al.*,1998; Søgaard and Heisel, 2002). Results with mechanical weed control have been particularly good in transplanted row crops such as cabbage (*Brassica oleracea* L.), celery (*Apium graveolens* L.), leek (*Allium porrum* L.) and sugar beet (Melander, 2000; Melander *et al.*, 1999), where transplanting itself creates very favorable conditions for mechanical weeding because large crop plants are established in a newly cultivated soil. Provided that the crop plants are well anchored, they can withstand mechanical effects even a few days after transplanting where the first flushes of weed seedlings normally are emerging and need to be controlled. Transplanted crops also gain a competitive advantage over the weeds as compared with sowing the crop, which gives a better suppression of weeds that may have escaped control.

Mechanical intra-row methods generally operate with low selectivity, especially in drilled row crops having slow emergence and low initial growth rates, such as carrots, onion, and leek. The same applies to silage corn under cool U.S. Midwest growing conditions where cool and wet weather may often slow crop growth in the beginning of the season. Low selectivity means that a high weed control level might be associated with severe crop injuries, particularly if large weeds are to be controlled satisfactorily (Kurstjens and Bleeker, 2000). It is essential that the crop has a size advantage over the weeds to achieve sufficient control. For example, sugar beets need to have developed four to six true leaves (Ascard and Bellinder, 1996; Ascard *et al*., 1995), onions a height of more than 10 cm (Ascard and Bellinder,1996; Melander and Hartvig, 1995), and corn from emergence up to 20 cm (Gunsolus *et al*., 2010) before they can tolerate direct contact with mechanical weeders.

Although organically-compatible forms of weed control are available, such as flaming, steaming, crop rotation, and inhibitory natural products; weeds remain a persistent issue for crop management and a need for successful weed management is imperative in organic crop systems. Most organic farmers still rely on repeated soil tillage for weed control (Greene 2013; van der Schans *et al.,* 2006) as a substitute for herbicides; unfortunately, tillage can generate soil and environmental problems, and if done at the wrong time, it can increase soil erosion or decrease water infiltration. Therefore, strong motivation exists for weed researchers to develop new weed management techniques that do not involve soil tillage, thereby reducing concerns with regard to soil degradation, and that do not depend upon synthetic herbicides, thus satisfying the philosophies of organic advocates. Even though the aforementioned techniques (i.e., flaming, steaming, crop rotation, and inhibitory natural products) have shown promising weed control, none of them has been particularly successful in crops. More organically-compatible techniques are needed.

A novel technique based on the sand blaster principle has been considered to control post emergence weed in agronomic crops. This technique differs from the Pneumat system (Lütkemeyer, 2000), which uses subsoil nozzles to blow compressed air upward to remove the roots of weeds. Instead, a sand blaster uses grit as abrasive particles, propelled from nozzles above the soil surface to strip and kill plants. Nørremark *et al.* (2006) were the first ones to coin this idea, however; they did not test it experimentally. Previous research has demonstrated that grits derived from agricultural residues could be used to control small broadleaf and grass weed seedlings selectively in corn (Forcella, 2009a, 2009b; Forcella et al., 2011). Wortman (2014) evaluated corn gluten meal in a series of experiments in the greenhouse and field and found that one blast of this material at the one-leaf stage in Palmer amaranth can reduce seedling biomass by 95%. These results suggested that corn gluten meal, an organically approved herbicide and fertilizer, can be effectively used as abrasive grits in vegetable crops, simultaneously providing weed suppression and supplemental crop nutrition. In several crops, in-row weed control alternatives may include the use of abrasive grit materials such as biochar and nitrogen-rich seed meals (crop residues) complemented with weed flaming operations as a between-row management. New weed control techniques that do not involve soil disturbance may be embraced more readily by organic growers.

1.7 Hypothesis and Research objectives

The hypothesis proposed in this study was that the use of abrasive corncob grit in organic corn applied at different corn growth stages and times (frequency) to control post-emergence weeds will increase crop yield and decrease weed interference.

The overall objective of this study was to test the efficacy of a post-emergence (POST) weed control system in two production systems by integrating air-propelled abrasive corncob grit (in-row control) at varying times and frequencies augmented by a single flame-weeding or cultivation (between-row weed control). The novelties in this research include the combination of two tested forms of between-row weed control (flaming and cultivation) with a new in-row weed control (application of abrasive corncob grit) to improve weed control and subsequently obtain higher yields in organic corn. Therefore, in the chapters that follow, we assessed the evaluation of this POST weed control system in an organic corn silage production system (Chapter 2) and in a transitional corn production system (i.e., transitioning from conventional to organic system) (Chapter 3), as well the differences and similarities of both systems (Chapter 4).

CHAPTER 2

Corncob grit application for weed management in an organic corn silage production system

2.1 Abstract

Management and weed control of weeds in organic farming is challenging because synthetic chemical herbicides are not used. Thus, weed control in organic fields requires the use of many techniques and strategies to accomplish economically acceptable weed control and crop yields. A two-year field study examined efficacy of air-propelled abrasive grits for in-row weed control and resulting corn silage yield. Grit was applied one, two, or three times at several leaf stages of corn (V leaf stages and frequencies) followed by flame-weeding or cultivation for between-row weed control. Application of grit decreased in-row weed biomass as much as 80% and 99% in two years of evaluation. In-row corncob grit application treatments increased corn silage yield up to 256 % when compared against a season-long untreated control. One grit application at V1 increased silage yield, and additional treatments with or after the V1 treatment improved weed control and some increased yield. Waiting until V5 for grit application resulted in 80% in-row weed biomass reduction.

2.2 Introduction

The interest for organic crop production is increasing quickly mostly as a result of growing consumer demand for chemical-free food and an attractive income potential for organic producers (Derksen *et al.,* 2002). In the USA, the price markup of organic plant products is substantial. For instance, of the 15 plant products listed by Falguera *et al.* (2012), the markup averaged 1.9 (± 0.14) times that of their conventional counterparts. Estimated sales of organic products grew 20% each year from 1990-2000, which made the organic food industry the fastest growing segment of the U.S. agriculture (Dimitri and Greene, 2002). In organic crop production systems, weeds have been cited as one of the major problems and responsible for severe grain yield quantity and quality losses (Stopes and Millington, 1991). Production losses from weed competition are among the most important crop management concerns for organic crop farmers, and the ability to control weeds is considered a major limiting factor for farmers wishing to transition to organic production systems (Bond and Grundy, 2001; Walz, 2004). Organic crop farmers have historically cited weeds as one of the greatest barriers to organic production and rank weed management as their number one research priority (Baker and Smith, 1987; Walz, 1999; Walz, 2004).

Controlling weeds in organic farming is challenging because synthetic chemical herbicides, which are formulated to have high efficacy, are not used to control weeds (Liebman and Davis, 2009). Instead, organic farming requires the use of many techniques and strategies to achieve economically acceptable weed control and crop yields (Walz, 1999). Therefore, controlling weeds without synthetic herbicides under the rules of organic agriculture often is difficult to achieve (Kruidhof *et al*., 2008). Weed control in organic crop systems rely on hand-weeding and mechanical methods (McErlich and Boydston, 2013), however, high labor costs are associated with hand-weeding, and repeated soil tillage destroys soil quality, increases the chance of soil erosion, and promotes emergence of new flushes of weeds (Harper, 2015). Despite the availability of other weed control techniques such as crop rotation, cover crops, biological herbicides (i.e. corn gluten meal), steaming, and flaming, weeds are a persistent problem for crop management without herbicides. As a consequence, there is a need for weed scientists to develop new and organically-acceptable weed management techniques that do not involve soil tillage. To date, weed control research has focused largely on the implementation of integrated approaches (Liebman and Davis, 2009) and updating existing integrated eed management techniques (Cloutier *et al*., 2007; Van Der Weide *et al*., 2008) to improve weed control in organic agriculture rather than developing entirely new methods.

Previous research has suggested that abrasive grits may be used to control weeds (Nørremark *et al.,* 2006), and ongoing research has demonstrated that granulated walnut shells can be used to control small lambsquarters seedlings (Forcella, 2009a). Trial and error tests of this concept in greenhouse (Forcella, 2009b) and field experiments (Forcella, 2012) demonstrated that split-second blasts of corncob grit delivered from a sand blaster at a 517 kPa pressure was enough to achieve up to 85% mortality of common lambsquarters at the five-leaf stage of corn. Field studies showed that two applications using hand-held equipment and air-propelled corncob grit, combined with inter-row cultivation, can successfully reduce the presence of weeds in corn and the subsequent weed-induced reduction in corn yield (Forcella, 2012).

Flaming can be used in some vegetable crops and corn that are suited to this weed control practice after they are planted. Dose-response studies reported by Ascard (1994, 1995, 1998) indicted that a single dose of 10-40 kg of propane ha^{-1} was required to achieve 95% control of sensitive species, such as common lambsquarters with 0- to 4-leaves, whereas plants with 4- to 12-leaves required 40-150 kg propane ha^{-1}. These results suggested that flaming is most effective on sensitive weed species at an early growth stage. Abrasive weed control in combination with other weed control techniques may be used as a system for integrated crop and weed management. For instance, weed control was achieved with the use of post-emergence in-row application of corncob grit to reduce the presence of weeds and therefore the competition with the crop, which was supplemented with flaming operations for between-row weed management (Forcella, 2012). Despite the weed control achieved by flaming or cultivation alone, there is not enough evidence that suggests how effective these two techniques can be if they are applied together with the application of abrasive corncob grit.

The objectives of this two-year field experiment were: 1) to assess the efficacy of POST weed control system in an organic corn silage production system by integrating air-propelled abrasive corncob grit (for in-row control) at different timings and frequencies with either flame-weeding or cultivation (for between-row weed control, one time), and 2) to quantify the effects of corncob grit application, flaming, cultivation, and the combination of these treatments on corn silage yield.

2.3 Materials and Methods

Field experiment. Field corn was planted in certified organic fields on May 26, 2013 and May 21, 2014 at about 95,600 and 73,000 plants ha^{-1}, respectively, in rows spaced 0.76 m apart at the West Central Research and Outreach Center (WCROC) of the University of Minnesota in Morris (Stevens County, MN). The corn hybrids planted in 2013 and 2014 were Viking 79-96N (V79-96N) and Blue River 33L90 (BR-33L90), respectively. The soil types were McIntosh silt loam (fine-silty, mixed, superactive, frigid Aquic Calciudoll) and McIntosh/Tara (fine-silty, mixed, superactive, frigid, Aquic Hapludoll) silt loam complex for 2013 and 2014 experiments. Both types of soil are very deep, moderately well drained calcareous soils that formed in a silty mantle of glacial lacustrine sediments or loess over loamy glacial till on glacial lake plains and moraines. Water permeability is moderate or moderately slow. Slopes range from 0 to 3 percent. The major difference between these soils is that the Tara series soils do not have calcic horizons in the upper part of the solum whereas the McIntosh silt loam does. Mean annual precipitation is about 56 cm, and mean annual air temperature is about 5°C. (https://soilseries.sc.egov.usda.gov/OSD_Docs/M/MCINTOSH.html).

In both years, the experiments consisted of 16 treatments (see Table 2-1), including two grit-free checks (season-long weedy, SLWC; and hand-weeded, HWC), which were evaluated and monitored for weed control and influence on corn silage yield. Single, double, or triple applications of grit were applied each year. The three- (V3) and five- (V5) leaf stage of corn (Ritchie *et al*., 1997) were common application times in both years, whereas V1 was the first application time in 2013 and V7 was the last application time in 2014 (Table 2-1). The differences between years were due to weather-related delays in 2014 for the initial grit application.

The selected treatments were established in a randomized complete block design with four replications in plots measuring 3 m long by 3.05 m wide consisting of 4 planted rows. In each plot, corncob grit was applied along the rows for in-row weed control at different corn growth stages/grit application times. For between-row weed control, cultivation or flaming was performed in four rows for each treatment. Alongside the rows where grit was applied, four rows remained grit-free with the same cultivation and flaming setting as described for the grit treatments. These rows were used to perform matched paired t-tests to compare the efficacy of the grit application on weed control and the effect on corn yield.

Abrasion of weeds was performed using grit (Green Products Company, Conrad, IA) derived from corncobs with a commercial standard particle size of the grit of 20-40 mesh (0.5 mm diameter) (Forcella, 2009b). A four-row grit applicator constructed by the South Dakota State University (SDSU) Agricultural Engineering Department in 2012 (Lanoue, 2012) was mounted on the three-point hitch (hydraulic system, attaching points, the lifting arms, and the stabilizers) of a John Deere® 7810 tractor (Figure 2-1). The four-row grit applicator consisted of an air compressor unit, two tanks, a hollow 20 x 20 cm steel bar, eight cylindrical nozzles, and high-strength hoses. Compressed air was pumped from the air compressor unit into the hollow bar (for even distribution of air pressure). The bar was pressurized at 700 kPa. Air then flowed through the high-strength hoses at high velocity to the eight cylindrical nozzles. Grit was fed into the tips of the nozzles and entrained by the pressurized air. (Separate hoses carried grit from the holding tanks to the nozzle tips *via* gravity and vacuums created by the nozzles.)

One nozzle along each side of the crop row was aimed at the crop row within 10 to 15 cm from the base of corn plants and at an angle of about 30° from the horizontal (soil surface) and 60° from the vertical (upright corn plants) (Forcella, 2012). The eight-nozzle applicator applied grit at a rate of 480 kg ha^{-1} with a pressure of 690 kPa at a ground speed of 2.5 km hr^{-1}.

Table 2-1. Treatment combinations of leaf stage of corn (based on Ritchie *et al*., 1997) at grit application + between-row weed control established in Morris, MN in 2013 and 2014.

2013	2014
Grit V1 Flaming	Grit V3 Flaming
Grit V1 Cultivation	Grit V3 Cultivation
Grit V3 Flaming	Grit V5 Flaming
Grit V3 Cultivation	Grit V5 Cultivation
Grit V5 Flaming	Grit V7 Flaming
Grit V5 Cultivation	Grit V7 Cultivation
Grit V1+V3 Flaming	Grit V3+V5 Flaming
Grit V1+V3 Cultivation	Grit V3+V5 Cultivation
Grit V1+V5 Flaming	Grit V3+V7 Flaming
Grit V1+V5 Cultivation	Grit V3+V7 Cultivation
Grit V3+V5 Flaming	Grit V5+V7 Flaming
Grit V3+V5 Cultivation	Grit V5+V7 Cultivation
Grit V1+V3+V5 Flaming	Grit V3+V5+V7 Flaming
Grit V1+V3+V5 Cultivation	Grit V3+V5+V7 Cultivation
Season Long Weedy Check	Season Long Weedy Check
Hand-Weedy Check	Hand-Weedy Check

The between-row operation was completed only once, early at V5 in 2013 and V7 in 2014.

Flaming was applied in one of the between-row weed control treatments at the five- and seven-leaf stage of corn (July 2, 2013 and July 7, 2014, respectively) utilizing a custom-built handheld flame weeder. The flamer provided open flames using propane as a source for combustion. This equipment consisted of a cane, with the propane supply tank (4.5 kg tank) carried in a backpack and a flamer with five burners mounted 15-cm apart. Burners were positioned 18-cm above soil surface beneath a hood over the row middle and angled back at 30˚ to the soil. Flaming treatment was applied at a constant speed of 3.1 km hr^{-1} delivering a propane dose of approximately 50 kg ha^{-1}.

For the other between-row treatment, cultivation was performed using a John Deere® 886 cultivator mounted on the three-point hitch (hydraulic system, attaching points, the lifting arms, and the stabilizers) of a John Deere® 7610 tractor driven at 5 km hr^{-1}on July 1, 2013 and July 7, 2014, at the five- and seven-leaf stage of corn, respectively.

Measurements to evaluate effectiveness of the treatments included: weed identification, weed density by species, and weed biomass, which were collected in a 40 cm x 15 cm areas in-row and between-rows of each plot. In- and between-row weed identification and weed density were collected one day before and three days after grit application, flaming, and cultivation in the same location. Weed biomass was collected just prior to corn silage harvesting (August 20, 2013 and September 15, 2014, respectively, at the R2 corn growth stage). Aboveground portions of weeds within these quadrats were clipped, identified, counted by species, dried at 40°C for 2 weeks, and weighed.

Height of three randomly selected corn plants from the two central rows of each plot were measured in cm from soil surface to the node of the flag leaf at the R2 corn growth stage. Silage corn yield was calculated as the total dry crop biomass of the plants harvested from one-meter long sections of the two central rows of each plot. Plants were weighed (fresh weight), chopped, dried at 40°C for two weeks, and the dry crop biomass was recorded.

Figure 2-1. In-row grit application applied in Morris, MN in 2013 and 2014 was made with a four-row applicator developed at SDSU.

Pictures courtesy of Dean Peterson

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 silage yield, and plant height. The linear statistical model for a randomized complete block design (Steel and Torrie, 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} leaf stage of corn:grit application:between-row application (cultivation or flaming) effect, μ is the overall (grand) mean, α_i is the leaf stage of corn effect of treatment i^{th} where $\sum_i \propto_i = 0$, for i = 1,…..16, β_j is the effect in block j^{th} where $\sum_j \beta_i = 0$ for j = 1,….,4, and $\epsilon_{ij} \sim iid\ \mathrm{N}(0, \sigma_e^2)$ is the random error effect.

To estimate the mean squares for each trait, data from all checks were included and an analysis of variance (ANOVA) was performed using the library agricolae (de Mendiburu, 2014) in R (R Core Team, 2014). The decision to include two controls in this experimental design was justified based on the objectives of the experiment, in the same way as any other treatment. Weeded or ''hand weed-free'' check plots are an integral part of most weed management experiments. They estimate the maximum potential yield without weed competition for a given site-year environment, however, weed-free yield varies from site to site and year to year in response to other factors such as changing weather or crop management. In this case, the controls were compared with all other treatments (Piepho *et al*., 2006), and since controls usually have a very high or very low variance with respect to all the other treatments, it is expected to detect differences among treatments and controls (Ahrens *et al*., 1990; Phelps, 1991).

2.4 Results and Discussion

Climate. The 2013 and 2014 growing seasons were very similar in terms of growing degree days and rainfall (Table 2-2). However, both 2013 and 2014 were cooler and wetter than the 30-year average. In terms of growing degree day accumulation (GDDA), the months of May, June, and August of 2013 and 2014 were similar to the 30-year average (1986-2014). July of both 2013 and 2014 were 200 GDDA lower than the 30-year average. Cumulative precipitation (CP) in May of 2013 was 25% less and 2014 was 10% less than the 30-year average. The total CP observed at the end of August, the last month of the growing season for this study, was 10% greater in 2013 and 33% greater in 2014 than the 30-year average. Overall, 2013 and 2014 were remarkably similar to one another in terms of GDD and CP than either were to the 30-year average.

These temperature differences may be important for growth and development of crops and weeds, as every single crop and weed species is associated with a distinctive set of growth and development requirements that creates both spatial and temporal variability in nutrient, water, and light availability. Variability of these resources will affect where and when the soil is favorable for seed germination. Crops with different growing seasons or growth patterns also alter the light environment of the soil. This, in turn, may influence control timing in relation to the growth stage of target weeds to obtain the best control efficacy and ultimately corn yield.

Weed Control. Weed counts before and after the application of grit (Figure 2-2) for in-row weed control showed that in 2013 (Table 2-3) weeds were more prevalent during the different leaf stages of corn than in 2014 (Table 2-4). Broadleaf weed species were the predominant species in both years. At V1, the most prevalent weed species were redroot pigweed (85%) at the two true-leaf stage and common lambsquarters (15%) at the three true leaf stage, and between V3 and V5 Pennsylvania smartweed (20%) at the three and five true-leaf stages, respectively. Broadleaf weeds were present from the one-leaf stage of corn to the time the corn was harvested for silage. Grasses were never present during the applications of grit at the different leaf stages of corn in both years. Grasses were noted at about the six- and seven-leaf stage of corn.

The soil was tilled before crop establishment in both years, and tilled soils offer better germination environments for most seeds both physically and chemically, as the soils are more aerated, warmer, and experience larger temperature fluctuations (Mohler, 2001). Perhaps these temperature fluctuations in 2013 and 2014 could have affected seed germination of broadleaf and grasses species. Many weeds require soil temperatures above a certain threshold in order to germinate, and lower average soil temperatures therefore would have delayed weed seed germination in both years. In addition, the initial state and distribution of the weed seedbank were unknown, and these two conditions may have influenced the study results. For instance, by comparing the "before" weed densities at V1 and V5 in 2013 and V3 and V7 in 2014, seedling numbers doubled in 2013 and tripled in 2014. In more normal (warmer) years, perhaps densities would be higher earlier in the season.

There were fewer weeds after the application of grit compared with weed numbers before the application (Table 2-3). In 2013, matched pairs analysis revealed that mean weed counts were lower after the application of grit than before at the V1

($prob<t=0.002$), V3 ($prob<t=0.001$), and V5 ($prob<t=0.001$) leaf stage of corn (Table 2-3). These results suggested that the use of corncob grit had a positive effect on weed control by reducing the number of weeds when corncob grit was applied. Weed control showed that one application at the V1-leaf stage of corn controlled 23% of the weeds present (Table 2-3). Weed abrasion at later stages of corn growth development (V3 and V5) showed that more weeds were present and weed control at V3 and V5 controlled weeds by 18% and 16%, respectively. Double application of grit at V1+V3 and the triple application V1+V3+V5 were as efficient as applications at the V1-leaf stage of corn to control weeds. Even though the reduction in weed density for treatments involving grit application at the V1 alone or in combination with V3 or the triple application with V3+V5 was similar, the weed numbers present before and after the treatment application showed a high variability in weed control efficacy (Table 2-3). Weed pressure was slight in 2014 (Table 2-4) and no differences among grit applications were observed.

Table 2-2. Growing degree days accumulation (GDDA) base 10°C and cumulative precipitation (CP) recorded during the length of the experiments established in Morris, MN in 2013 and 2014.

Month	2013		2014		1986-2014	
	GDDA	CP	GDDA	CP	GDDA	CP
		--cm--		--cm--		--cm--
May	144	6.1	155	7.5	154	8.1
June	401	29.8	431	28.8	400	18.5
July	753	36.3	733	32.9	970	27.8
August	1066	39.1	1043	47.6	1153	35.8
Total	2364	111.3	2362	116.8	2677	90.2

Figure 2-2. Application of corncob grit at different corn growth stages in Morris, MN 2013

Pictures courtesy of Dean Peterson, Morris, MN.

Table 2-3. Weed density (plants per m^2) before and after the application of corncob grit and matched pair t-test for in-row weed control in Morris, MN, in 2013. Values in brackets represent percent (%) weed control compared to the Season-Long Weedy Check.

	Application time					
	V1		V3		V5	
Leaf stage of corn+corncob application	Before	After	Before	After	Before	After
V1	15	13 [35]				
V3			22	18 [28]		
V5					30	25 [38]
V1+V3	17	13 [35]	15	13 [48]		
V1+V5	19	13 [35]			28	15 [63]
V3+V5			23	18 [28]	20	10 [75]
V1+V3+V5	17	13 [35]	20	17 [32]	20	13 [68]
Prob < t	0.002		0.001		0.001	
SLWC	19	20	23	25	30	40
HWC	3	3	5	7	7	8

Table 2-4. Weed density (plants per m^2) before and after the application of corncob grit for in-row weed control in Morris, MN, in 2014. Values in brackets represent percent (%) weed control compared to the Season-Long Weedy Check.

	Application time					
	V3		V5		V7	
Leaf stage of corn+corncob application	Before	After	Before	After	Before	After
V3	3	0 [100]				
V5			5	0 [100]		
V7					10	2 [69]
V3+V5	3	0 [100]	3	0 [100]		
V3+V7	4	0 [100]			3	0 [100]
V5+V7			5	0 [100]	3	0 [100]
V3+V5+V7	4	0 [100]	3	0 [100]	3	0 [100]
SLWC	5	8	6	9	11	13
HWC	2	2	2	3	3	2

Weed densities after the application of cultivation (Figure 2-3) or flaming (Figure 2-4) for between-row weed control were approximately 18 and 23 m^{-2} in 2013 (Table 2-5) and 7 and 13 m^{-2} in 2014 (Table 2-6). Compared to the SLWC treatment, these densities represented between-row weed control levels of about 55 to 72% for cultivation and 45 to 53% for flaming.

Broadleaf weed species were the most predominant species present in both years. Between-row weeds present at V1, V3 and V5 were redroot pigweed at the four and six true-leaf stages respectively, common lambsquarters at the five true-leaf stage in both years, and Pennsylvania smartweed at the six true leaf-stage in 2013. In both years, grasses were present at least 1 plant m^{-2} during the applications of cultivation or flaming.

Despite flaming not being as effective in reducing weed density as cultivation, the beneficial effect is that flaming did not involve soil disturbance. Therefore, weed seeds on or close to the soil surface can lose viability due to desiccation and harsh weather (Moyer *et al.,* 1994; Anderson, 2005). Cultivation however, induces changes in seed distribution, indirectly affecting germination of weeds present in the seedbank. These results suggested that the application of cultivation and flaming had a positive effect on weed control by reducing the number of weeds when these treatments are applied.

There is a general consensus that weed species composition will shift in response to changes in tillage. Whether the diversity of the weed community increases is less clear (Nichols *et al.,* 2015). While tillage will contribute to community shifts, the weed species present will be an expression of both management and the environment (Stevenson *et al*., 1997; Legere *et al*., 2005, Plaza *et al*., 2011; Boscutti *et al*., 2015), duration of the experiment, and long-term field history (Mohler, 2011). Tillage itself provides germination stimulus for weeds requiring light flashes, scarification, fluctuating temperatures, ambient CO_2 concentration, and/or higher nitrate concentrations to break dormancy (Benech-Arnold *et al.*, 2000). Therefore, depending on the extremity of the environment, the accumulation of seeds on un-tilled soil surfaces may increase the proportion of unviable seeds in the seedbank.

Figure 2-3. Application of corncob grit + cultivation treatment in the experiment established in Morris, MN 2013.

Between-row weed control (Cultivation)

In-row weed control (Grit application)

In-row weed control (Grit application)

Figure 2-4. Application of corncob grit + flaming treatment in the experiment established in Morris, MN 2013.

Between-row weed control (Flaming)

In-row weed control (Grit application)

In-row weed control (Grit application)

Table 2-5. Between-row weed density (plants per m^2) before and after the application of cultivation or flaming and matched pair t-test for between-row weed control in Morris, MN, in 2013. Values in brackets represent percent (%) weed control in comparison to Season-Long Weedy Check.

	Evaluation timing					
	V1	V3	V5 Cultivation		V5 Flaming	
Leaf stage of corn+corncob application			Before	After	Before	After
V1	20	24	33	17 [58]	34	25 [40]
V3	21	24	35	18 [55]	33	24 [43]
V5	19	25	34	18 [55]	35	25 [40]
V1+V3	21	24	35	19 [53]	34	24 [43]
V1+V5	21	25	33	18 [55]	35	22 [48]
V3+V5	20	26	36	19 [53]	33	23 [45]
V1+V3+V5	22	25	35	19 [53]	35	22 [48]
Prob < t			0.00023		0.0001	
SLWC	22	25	36	40	37	42
HWC	3	3	5	7	7	7

SLWC, Season-Long Weedy Check; HWC, Hand-Weeded Check

Table 2-6. Weed density (plants per m^2) before and after the application of cultivation or flaming and matched pair t-test for between-row weed control in Morris, MN, in 2014. Values in brackets represent percent (%) weed control in comparison to Season-Long Weedy Check.

	Evaluation timing					
	V3	V5	V7 Cultivation		V7 Flaming	
Leaf stage of corn+corncob application			Before	After	Before	After
V3	10	13	22	8 [71]	24	12 [59]
V5	10	12	24	8 [71]	23	14 [52]
V7	12	14	23	7 [75]	22	13 [55]
V3+V5	12	14	22	7 [75]	22	14 [52]
V3+V7	10	12	24	7 [75]	22	14 [52]
V5+V7	11	14	25	8 [71]	24	14 [52]
V3+V5+V7	12	14	24	8 [71]	21	14 [52]
Prob < t			0.001		0.0012	
SLWC	12	13	25	28	25	29
HWC	0	0	0	0	0	0

SLWC, Season-Long Weedy Check; HWC, Hand-Weeded Check

Total weed biomass. For total weed biomass, the combined effect of abrasive grit applied at different leaf stages of corn and the application of flaming or cultivation was significant in 2013 ($p=0.000151$) and 2014 ($p=0.00525$) (Tables 2-7 and 2-8). This indicated that total weed biomass changed depending on the combined effect of the number and timing of grit application (one, two, or three in-row weed control applications) plus the use of between-row weed control (flaming or cultivation).

In both years, the combined application of abrasive corncob grit at different leaf stages of corn plus either flaming or cultivation, substantially reduced the total (In-row + Between-row) weed biomass. Total weed biomass was reduced up to 89% in both years by the treatments evaluated in the field. (Table 2-9). In 2013 and 2014, because of high variability in weed density, 12 (86%) and 10 (71%) of the treatments were statistically equal to the hand-weeded check (Figure 2-5) respectively; and all the six (43%) common treatments evaluated in both years had less weed biomass than the season-long weedy check (Figure 2-6).

On average, total weed biomass was reduced when compared to the season long-weedy treatment by 61% (2013) and 78% (2014) when flaming was performed whereas 71% and 86% of total biomass reductions were observed when cultivation was performed in 2013 and 2014, respectively, for the between-row weed control. In contrast, a single application of abrasive corncob grit provided on average 83% (at the one-, three-, and five-leaf stage of corn) and 63% (at the three-, five-, or seven-leaf stage of corn) weed control in 2013 and 2014, respectively, when compared with the season-long weedy check. A single application of abrasive corncob grit at the five-leaf stage of corn reduced weed biomass at the end of the season by 89% (2013) and 83% (2014), suggesting that abrasion events at or near the five-leaf stage of corn may be more critical for reducing total weed dry biomass than earlier events (Forcella, 2012).

Two applications of abrasive corncob grit achieved about 79% (at the one- and three-, one- and five-, and three- and five-leaf stages of corn) and 68% (at the three- and five-, three- and seven-, and five- and seven-corn growth stages) weed biomass reduction in 2013 and 2014, respectively, compared with the season-long weedy check. Under these circumstances, season-long weed control was as high as 89% in both years and as low as 71% (2013) and 49% (2014). Application of grit at the one- and five- and three- and five-leaf stages of corn resulted in weed biomass reductions at the end of the season of 80% in 2013, whereas application of grit at the three- and seven-leaf stages of corn achieved 85% weed control in 2014.

A triple application of abrasive grit delivered on average 80% (at the one-, three-, and five-leaf stage of corn) and 69% (at the three-, five-, and seven-leaf stage of corn) in 2013 and 2014, respectively, when compared with the season-long weedy check. The triple application of abrasive corncob grit in 2013 had similar biomass as a single treatment, therefore, additional applications did not improve season-long weed control beyond that achieved with any single application at the one-, three, or five-leaf stage of corn.

Table 2-7. Analysis of variance for the variable total weed biomass collected in Morris, MN 2013.

		Total weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	12963333	4321111	5.546	0.251110
Treatment	15	82469747	5497983	7.056	0.000151***
Error	45	35063003	779178		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-8. Analysis of variance for the variable total weed biomass collected in Morris, MN 2014.

		Total weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	7667177	2555726	1.272	0.29544
Treatment	15	81133363	5408891	2.692	0.00525**
Error	45	90425436	2009454		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-9. Mean total weed biomass of the combined in-row and between-row weed control treatments established in Morris, MN in 2013 and 2014.

Treatment	Total weed biomass		Control	Treatment	Total weed biomass		Control
	-----kg ha^{-1}----		--%--		-----kg ha^{-1}----		--%--
Season-Long Weedy Check	5465	a	0	Season-Long Weedy Check	5017	a	0
Grit V1+V3 Flaming	1583	b	71	Grit V7 Flaming	3016	abc	40
Grit V1+V3+V5 Flaming	1282	b	77	Grit V5+V7 Flaming	2561	bc	49
Grit V3 Flaming	1207	bc	78	Grit V5+V7 Cultivation	2312	bcd	54
Grit V1+V5 Cultivation	1170	bc	79	Grit V3+V5+V7 Flaming	2160	bcd	57
Grit V3+V5 Flaming	1121	bc	79	Grit V3 Cultivation	2012	bcd	60
Grit V3 Cultivation	1111	bc	80	Grit V3+V5 Cultivation	1804	bcde	64
Grit V1+V5 Flaming	1086	bc	80	Grit V7 Cultivation	1787	bcde	64
Grit V5 Flaming	1083	bc	80	Grit V5 Flaming	1704	bcde	66
Grit V3+V5 Cultivation	1013	bc	81	Grit V3 Flaming	1689	bcce	66
Grit V1 Flaming	966	bc	82	Grit V3+V5 Flaming	1677	bcde	67
Grit V1+V3+V5 Cultivation	932	bc	83	Grit V3+V5+V7 Cultivation	898	cde	82
Grit V1+V3 Cultivation	918	bc	83	Grit V5 Cultivation	868	cde	83
Grit V1 Cultivation	681	bc	88	Grit V3+V7 Flaming	858	cde	83
Grit V5 Cultivation	611	bc	89	Grit V3+V7 Cultivation	536	de	89
Hand-Weeded Check	0	c	100	Hand-Weeded Check	0	e	100
	$LSD_{(0.05)}$=1257				$LSD_{(0.05)}$=2018		

Figure 2-5. Hand Weeded Check (HWC) in the experiment established in Morris, MN 2013.

Between-row and in-row hand weed control

In-row hand weed control

Between-row hand weed control

Figure 2-6. Season Long Weedy Check (SLWC) in the experiment established in Morris, MN 2013.

Between-row no weed control

In-row no weed control

In-row no weed control

Broadleaf weed biomass. For broadleaf weed biomass, the combined effect of abrasive corncob grit at different leaf stages of corn and the application of flaming or cultivation was significant in 2013 ($p= 0.000318$) and 2014 ($p=0.00543$) (Tables 2-10 and 2-11). This indicated that the season long weed control of broadleaf weed biomass changed depending on the combined effect of the levels of corncob grit timing application (one-, two, or three-in row-weed control applications) plus the use of between-row weed control (flaming or cultivation).

Because broadleaf weeds were the most prevalent species in both years, a similar pattern to the one observed for season long total weed biomass control was observed for broadleaf weed biomass control. In both years, the combined application of abrasive grit at different leaf stages of corn plus either flaming or cultivation, considerably reduced the combined broadleaf (In-row + Between-row) weed biomass. Compared to the season-long weedy check, broadleaf weed biomass was reduced 88% in 2013 and 89% by the treatments evaluated in the field (Table 2-12).

In 2013 and 2014, 13 (93%) and 9 (69%) of the treatments were statistically equal to the hand-weeded check respectively; and all the six common treatments evaluated in both years were statistically different from the season-long weedy check.

When compared to the season-long weedy check, application of flaming reduced broadleaf weed biomass on average by 85% and 63% in 2013 and 2014 whereas 85% and 71% average broadleaf weed biomass reduction were achieved in 2013 and 2014, respectively, for the between-row weed control. For in-row weed control, a single application of abrasive grit resulted in about 85% (at the one-, three-, and five-leaf stages of corn) and 65% (at the three-, five-, and seven-leaf stages of corn) weed control in 2013 and 2014, respectively, when compared with the season-long weedy check. One application of abrasive grit at the five-leaf stage of corn achieved season-long weed control between 83% (2014) and 89% (2013), indicating that an abrasive grit application at this corn growth stage plays a more critical role for reducing broadleaf weed biomass than early corn growth stages.

All six two-applications of abrasive grit achieved in average 85% and 86% (at the three- and seven-leaf stages of corn) of broadleaf weed biomass control in 2013 and 2014, respectively, when compared with the season-long weedy check. Two applications of abrasive grit achieved a season-long weed control as high as 89% in both years and as low as 44% (2014) and 83% (2013). Application of abrasive corncob grit at the one- and five-leaf stages of corn resulted in season-long broadleaf weed control of 88% in 2013, whereas application of abrasion corncob grit at the three- and seven-leaf stages of corn delivered 86% weed control in 2014.

Similar results were obtained with the triple application of abrasive corncob grit delivering in average 86% (at the one-, three-, and five-leaf stages of corn) and 69% (at the three-, five-, and seven-leaf stages of corn) in 2013 and 2014, respectively, when compared with the season-long weedy check. The triple application of abrasive grit in 2013 was as effective as the single application at one-, three-, or five-lea stages of corn and additional applications did not improve season-long weed control beyond that achieved with those corn growth stages. In 2014 an additional application after the three-leaf stage of corn was necessary to achieve broadleaf weed control as effective as the triple application. Albeit cultivation and flaming were performed approximately one week after the last grit application (V7) in 2014 and therefore most of the broadleaf weeds were almost as tall as the corn plants, treatments where grit was applied at V3+V7 plus flaming or cultivation were as effective as the triple application to reduce broadleaf weed biomass.

Table 2-10. Analysis of variance for the variable broadleaf weed biomass collected in Morris, MN 2013.

		Broadleaf weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	2018353	2018353	4.959	0.465715
Treatment	15	4962889	4962889	12.194	0.000318***
Error	45	406991	406991		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-11 Analysis of variance for the variable broadleaf weed biomass collected in Morris, MN 2014.

		Broadleaf weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	8925451	2975150	1.521	0.22189
Treatment	15	78620972	5241398	2.680	0.00543**
Error	45	88003717	1955638		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-12. Mean broadleaf weed biomass of the combined in-row and between-row weed control treatments established in Morris, MN in 2013 and 2014.

Treatment	Broadleaf weed biomass		Control	Treatment	Broadleaf weed biomass		Control
	-----kg ha^{-1}----		--%--		-----kg ha^{-1}----		--%--
Season-Long Weedy Check	5073	a	0	Season-Long Weedy Check	5017	a	0
Grit V3+V5 Cultivation	942	b	81	Grit V7 Flaming	2808	b	44
Grit V1+V3 Cultivation	853	b	83	Grit V5+V7 Flaming	2393	bc	52
Grit V1+V3 Flaming	815	bc	84	Grit V5+V7 Cultivation	2312	bc	54
Grit V5+Grit Flaming	805	bc	84	Grit V3+V5+V7 Flaming	2160	bc	57
Grit V1+V5 Cultivation	759	bc	85	Grit V3 Cultivation	2012	bc	60
Grit V1 Flaming	755	bc	85	Grit V3+V5 Cultivation	1804	bcd	64
Grit V3 Cultivation	752	bc	85	Grit V7 Cultivation	1787	bcd	64
Grit V1+V3+V5 Flaming	741	bc	85	Grit V5 Flaming	1704	bcd	66
Grit V3 Flaming	736	bc	85	Grit V3+V5 Flaming	1677	bcd	67
Grit V3+V5 Flaming	710	bc	86	Grit V3 Flaming	1502	bcd	70
Grit V1 Cultivation	681	bc	87	Grit V3+V5+V7 Cultivation	898	bcd	82
Grit V1+V3+V5 Cultivation	680	bc	87	Grit V5 Cultivation	868	bcd	83
Grit V1+V5 Flaming	602	bc	88	Grit V3+V7 Flaming	858	bcd	83
Grit V5 Cultivation	585	bc	88	Grit V3+V7 Cultivation	536	cd	89
Hand-Weeded Check	0	c	100	Hand-Weeded Check	0	d	100
	$LSD_{(0.05)}$=908				$LSD_{(0.05)}$=1991		0

Grass weed biomass. In 2013 and 2014, yellow foxtail and green foxtail were too sparse across the plots that an analysis of variance was not possible to perform. A plausible explanation of the lack of grass weed species in both years could have been that when the soil was tilled before planting, the grass weed seeds present in the soil were vertically distributed near the soil surface, but since the soil was disturbed, the weed seeds could have been buried deeper in the soil profile, plus if the soil did not have temperature fluctuations some seeds would not germinate. Common tillage regimes have generalized patterns of seeds distributions (Ball, 1992; Mohler, 1993; Dorado *et al.,* 1999), and these tillage-induced changes in seed distribution therefore indirectly affect germination and seedling establishment.

In-row weed biomass. The application of abrasive grit at different leaf stages of corn was significant in 2013 (p=0.00778) and 2014 (p=0.023) (Tables 2-13 and 2-14). This indicated that the control of in-row weed biomass depended on the timing application (one-, two-, or three in-row weed control applications) of abrasive grit.

In both years, the application of abrasive grit at different leaf stages of corn significantly reduced the in-row weed biomass. In-row weed biomass made up 21% and 30% of the total weed biomass (Season-Long Weedy Check In-row weed biomass / Season-Long Weedy Check Total weed biomass) in 2013 and 2014, respectively (Table 2-15). In 2013 and 2014, 4 (57%) and 6 (86%) of the treatments were statistically equal to the hand-weeded check, respectively; and all the three (43%) common treatments evaluated in both years were statistically different from the season-long weedy check.

On average, in-row weed biomass was reduced when compared with the season-long weedy check by 74% (2013) and 79% (2014) when abrasive grit was applied. A single application of grit averaged 74% (at the one-, three-, and five-leaf stages of corn) and 73% (at the three-, five-, and seven-leaf stages of corn) in-row weed control in 2013 and 2014, respectively, when compared with the season-long weedy check. Single applications at the one- and five-leaf stages of corn in 2013 and at three- and seven-leaf stages of corn were the most effective for in-row weed control in 2013 and 2014, respectively, suggesting that corncob grit can be applied at or near these corn growth stages and achieve acceptable in-row weed control.

Two applications of abrasive corncob grit achieved on average 75% (at the one- and three-, one- and five-, and three- and five-leaf corn growth stages) and 83% (at the three- and five, three- and seven, and five- and seven-leaf stages of corn) of in-row weed control in 2013 and 2014, respectively, compared with the season-long weedy check. In-row season-long weed control with two applications of grit was as high as 88% in 2013 (at the one- and five-leaf stages of corn) and 99% in 2014 (at the three- and seven-leaf stages of corn)

A triple application of grit achieved on average 68% (at the one-, three-, and five-leaf stages of corn) and 83% (at the three-, five-, and seven-leaf stages of corn) in 2013 and 2014, respectively, when compared with the season-long weedy check. Double or triple applications of grit would have been expected to deliver a longer season-long weed control than the one achieved with any single application, however, the results here reported suggest that a single application at early or late growth stage would achieve the same weed control.

Table 2-13. Analysis of variance for the variable in-row weed biomass collected in Morris, MN 2013.

	In-row weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	1410671	470224	6.539	0.74500
Treatment	8	3746644	468330	6.512	0.00778***
Error	52	3739573	71915		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-14. Analysis of variance for the variable in-row weed biomass collected in Morris, MN 2014.

	In-row weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	600184	200061	0.456	0.714
Treatment	8	8722067	1090258	2.486	0.023*
Error	52	22801462	438490		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-15. Mean in-row weed biomass of the treatments established in Morris, MN in 2013 and 2014.

Treatment	In-row weed biomass	Control	Treatment	In-row weed biomass	Control
	-----kg ha^{-1}----	--%--		-----kg ha^{-1}----	--%--
Season-Long Weedy Check	1177 a	0	Season-Long Weedy Check	1501 a	0
V3+V5	415 b	65	V3	688 b	54
V3	370 bc	69	V5+V7	547 bc	64
V1+V3+V5	370 bc	69	V5	402 bc	73
V1+V3	320 bcd	73	V3+V5+V7	248 bc	83
V5	290 bcd	75	V3+V5	215 bc	86
V1	231 bcd	80	V7	111 bc	93
V1+V5	146 cd	88	V3+V7	5 c	100
Hand-Weeded Check	0 d	100	Hand-Weeded Check	0 c	100
	$LSD_{(0.05)}$=225			$LSD_{(0.05)}$=580	

Between-row weed biomass. The application of between-weed control was significant in 2013 (p=0.00012) and 2014 (p=0.000766) (Tables 2-16 and 2-17). This indicated that the application of either cultivation or flaming reduced the weed biomass between rows in corn.

Between-weed biomass made up 79% and 70% of the total weed biomass (Season-Long Weedy Check Between-row weed biomass / Season-Long Weedy Check Total weed biomass) in 2013 and 2014, respectively (Table 2-18). In 2013, both, flaming and cultivation reduced considerably the between-row weed biomass; the average effects of flaming (Flaming / Season-Long Weedy Check Between-row weed biomass) and cultivation (Cultivation / Season-Long Weedy Check Between-weed row weed biomass) were 81% and 84%, respectively. In 2014, flaming and cultivation reduced weed biomass by 53% and 68%, respectively. The effect of applying flaming and cultivation were 32% and 16% less in 2014, respectively, compared with the effects observed in 2013. The 2014 applications were performed after the seven-leaf corn growth stage, wherein the weeds were taller, stronger, and more tolerant of these cultural practices. In both years, the effect of applying cultivation was similar to the effect of the hand-weeded check, however, in 2013, the difference between flaming and cultivation was 3% indicating that flaming would be a more desirable cultural practice to perform because it does not promote soil disturbance and the subsequent vertical movement of weed seeds (seed distribution) to the soil surface stimulating indirectly the germination of seeds, seedling establishment, and contributing to future problems through weed seed production (seed bank), and building up new weed flush in the crop.

Table 2-16. Analysis of variance for the variable between-row weed biomass collected in Morris, MN 2013.

		Between-row weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	6539461	2179820	4.325	0.81400
Treatment	3	50762446	16920815	33.575	0.00012***
Error	57	28726591	503975		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-17. Analysis of variance for the variable between-row weed biomass collected in Morris, MN 2014.

		Between-row weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	6848639	2282880	1.492	0.226516
Treatment	8	29673012	9891004	6.463	0.000766***
Error	52	87235009	1530439		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-18. Mean between-row weed biomass of the treatments established in Morris, MN in 2013 and 2014.

Treatment	Between-row weed biomass	Control	Treatment	Between-row weed biomass	Control
	-----kg ha^{-1}----	--%--		-----kg ha^{-1}----	--%--
Season-Long Weedy Check	4287 a	0	Season-Long Weedy Check	3515 a	0
Flaming	830 b	81	Flaming	1647 b	53
Cultivation	668 bc	84	Cultivation	1115 bc	68
Hand-Weeded Check	0 c	100	Hand-Weeded Check	0 c	100
	$LSD_{(0.05)}$=170			$LSD_{(0.05)}$=1751	

Corn silage yield. Corn responded to the combined application of abrasive corncob grit at different corn growth stages and flaming or cultivation in 2013 ($p=0.000229$) and 2014 ($p=0.0413$) (Tables 2-19 and 2-20) ($P>0.05$). This indicated that corn silage yield changed depending on the combined effect of the number and timing of grit applications (one-, two, or three-in-row weed control application) plus the use of between-row weed control (flaming or cultivation).

On average, a single application of grit increased silage corn yield about 255% (at the one-, three-, and five-leaf stages of corn) and decreased by about 2% (at the three-, five-, and seven-corn growth stage) in 2013 and 2014, respectively, when compared with the season-long weedy check (Table 2-21). Corn yield treated at the five- or seven-leaf stage of corn was similar to the yield of the season-long weedy check. Single applications at the one- and three-leaf stage of corn in 2013 and three-leaf stage of corn in 2014 were the most effective to increase corn silage yield. Applications of grit at early leaf stage of corn in combination with either flaming or cultivation had a positive effect on yield because the yields are similar to the yield of the hand-weeded check (Table 2-21).

Two applications of abrasive corncob grit increased yield on average of 241% (at the one- and three-, one- and five-, and three- and five-leaf stages of corn) and 7% (at the three- and five-, three- and seven-, and five- and seven-leaf stages of corn) in 2013 and 2014, respectively. Under the same settings, corn silage yield increased up to 198% in 2013 (at the three- and five-leaf stages of corn) and 26% in 2014 (at the three- and five-leaf stages of corn) compared with the season-long weedy check.

A triple application of abrasive corncob grit increased corn silage yield on average 220% (at the one-, three-, and five-leaf stages of corn) and 8% (at the three-, five-, and seven-leaf stages of corn) in 2013 and 2014, respectively, when compared to the season-long weedy check. Average yields of the single application at the three- or double applications at the three- and five-, and three- and seven-leaf stages of corn, as well as the triple application (at three-, five-, and seven-leaf stages of corn) were similar to the yield of the hand-weeded check in 2014, whereas in 2013 single applications at the one- and three-leaf stages of corn and the double application at the one- and three-leaf stages of corn had corn silage yields similar to the yield of the hand-weeded check.

These results showed that weed control must start before the critical weed-free period, weeds reduce corn yield at early stage of growth development and they must be repeated in a timely fashion until late-emerging weeds no longer reduce yield (Oliver 1988; Radosevich *et al*. 1997; Zimdahl 1980). The critical weed-free period in this case was from emergence to the three-leaf stage of corn because weed control not initiated until after the three-leaf stage of corn had a detrimental effect on corn yield reduction. Complete season-long weed control is not necessary to achieve maximum yield because late-emerging weeds often do not reduce yield after the critical period (Cardina *et al.* 1995; Knake and Slife 1965; Oliver 1988; Radosevich *et al.* 1997). This critical period is defined by experiments varying in time of weed removal after crop emergence.

In both years yield increased with early abrasive grit applications (Table 2-21). In 2013, single grit application at the one-leaf stage of corn and double grit application at the one- and three-leaf stages of corn resulted in higher yields compared to the yield of the five-leaf stages of corn treatment. Applications of corncob grit at the one- or three-leaf stages of corn to control weed have been reported to have a beneficial effect on yield (Forcella, 2012). Silage yield of grit-treated corn at one-, three-, and one- and three-leaf stages of corn did not differ from the hand-weeded check treatment, which indicated that even two abrasive grit treatments did not injure corn sufficiently to lower yields (Forcella, 2012). Corn plants exposed to grit abrasion –in case they are damaged- at early stages of development were most likely to overcome damage and have higher yields because ear and tassel tissues are not differentiated until after the three-leaf stage of corn and the growing point is still below the soil surface so it is not injured (McWilliams *et al.*, 1999). Even though plants at different corn growth stages did not show any symptoms of being damaged by abrasion, treatments consisting of a single application at the five- or in combination with one-, three- or one- and three-leaf stages of corn had a yield statistically similar to the yield of the season-long weedy check. With three sequential grit abrasion events, according to Forcella (2012), at the one-, -three, and five-leaf stages of corn, injury to corn plants was insignificant in terms of yield losses, similar results are being reported here. Mechanical damage to corn plants early in the season possibly due to the presence of physical factors can promote the presence and incidence of diseases. Although slight leaf pitting due to grit abrasion occurred on treated corn seedlings, no diseases were observed subsequently in these experiments and no yield losses were attributed to them.

In 2013 (Table 2-22), the silage yield was 14870 and 14485 kg ha^{-1} for cultivation and flaming when averaged over in-row grit applications. Compared to the hand-weeded check (14970 kg ha^{-1}), these yields were statistically similar and much larger than the yield of the season-long weedy check (6008 kg ha^{-1}). In contrast, in 2014, the silage yield was 9395 kg ha^{-1} and 9166 kg ha^{-1} for flaming and cultivation, respectively, when averaged over grit applications. Both of these yields were similar to the season-long weedy check (Table 2-27). The relatively late interventions (grit, cultivation, and flaming) in 2014 may have allowed early weed/crop competition to occur as well as damage to older corn plants by the grit.

Table 2-19. Analysis of variance for corn silage yield collected in Morris, MN 2013.

		Corn silage yield (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	49158567	16386189	1.841	0.153313
Treatment	15	512900788	34193386	3.842	0.000229***
Error	45	4000540495	8900900		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-20. Analysis of variance for corn silage yield collected in Morris, MN 2014.

		Corn silage yield (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	6649091	2216364	1.963	0.3490
Treatment	15	58006099	3867073	1.125	0.0413*
Error	45	88652413	1970054		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-21. Mean corn silage yield of the treatment combinations involving in-row and between-row weed control established in Morris, MN in 2013 and 2014.

2013		2014	
Treatment	Yield	Treatment	Yield
	-----kg ha^{-1}----		-----kg ha^{-1}----
Grit V1+V3 Cultivation	17880 a	Hand-Weeded Check	11347 a
Grit V1+V3 Flaming	17862 abc	Grit V3+V5 Flaming	10170 ab
Grit V1 Cultivation	16970 abc	Grit V3+V7 Flaming	10110 abc
Grit V1 Flaming	16952 abc	Grit V3 Flaming	10070 abc
Grit V3 Cultivation	16027 abcd	Grit V3+V5 Cultivation	10070 abcd
Grit V3 Flaming	15660 abcd	Grit V3+V5+V7 Cultivation	9941 abcd
Hand-Weeded Check	14970 abcd	Grit V3 Cultivation	9713 abcd
Grit V1+V5 Cultivation	13615 bcd	Grit V3+V5+V7 Flaming	9562 bcd
Grit V1+V3+V5 Cultivation	13580 cd	Grit V5+V7 Cultivation	9433 cd
Grit V5 Cultivation	13407 cd	Grit V3+V7 Cultivation	9361 cd
Grit V5 Flaming	13007 cd	Grit V5 Flaming	9238 cd
Grit V1+V3+V5 Flaming	12902 cd	Season-Long Weedy Check	8971 cd
Grit V1+V5 Flaming	12802 cd	Grit V5+V7 Flaming	8847 cd
Grit V3+V5 Cultivation	12610 d	Grit V5 Cultivation	8069 d
Grit V3+V5 Flaming	12212 d	Grit V7 Flaming	7768 d
Season-Long Weedy Check	6008 e	Grit V7 Cultivation	7571 d
	$LSD_{(0.05)}$=4249		$LSD_{(0.05)}$=1998

Table 2-22. Mean between-row corn silage yield of the treatments established in Morris, MN in 2013 and 2014.

Treatment	Corn silage yield	Treatment	Corn silage yield
	-----kg ha^{-1}----		-----kg ha^{-1}----
Hand-Weeded Check	14970 a	Hand Weeded Check	11347 a
Cultivation	14870 a	Flaming	9395 b
Flaming	14485 a	Cultivation	9165 b
Season-Long Weedy Check	6008 b	Season-Long Weedy Check	8971 b
	$LSD_{(0.05)}$=4600		$LSD_{(0.05)}$=1900

Plant height. Because silage corn includes the entire aboveground portion of the plant, maintaining corn height to maximize total biomass is an important corn yield factor when controlling weeds. Prevalent weather conditions were ideal for corn plants to grow, develop, and reach a height that allowed them to express the highest silage yield, and compete with weeds. In 2013 and 2014, no differences in plant height were observed among treatments (Tables 2-23 and 2-24). Average corn plant height at harvest was 197 cm in 2013 and 246 cm in 2014.

Weed abrasion in combination with either cultivation or flaming did not have a positive or negative impact on plant height. Even though cultivation and flaming were performed after the seven-leaf stage of corn in 2014 and plants could have been damaged because of the height they had reached at the time of application, plants were not affected. It is known that cultivation too near the plant after the three-leaf stage of corn growth stage can destroy some of the brace root system, and flaming could have destroyed some of the exposed leaves by desiccation, however, these two agricultural practices could not damage the growing point below the soil surface (McWilliams et al., 1999), so damage to the corn plant above the soil surface at this time usually results in very little reduction corn silage yield. Application of flaming, cultivation and even abrasive corncob grit at the five-leaf stage of corn and beyond could not have a detriment on plant height and ultimately on corn silage yield because the roots of the second whorl now form the major part of the root system and leaf and ear shoots are being initiated, and this initiation has been completed by the five-leaf stage of corn (potential ear shoot number is determined). The results here presented agree with the ones previously reported on corn plants being able to withstand grit application (Forcella, 2009, 2012) and broadcast flaming (Knezevic *et al*., 2009) after the five-leaf stage of corn with no effect on plant height and yield.

Table 2-23. Analysis of variance for plant height collected in Morris, MN in 2013.

Source of variation	Df	SS	Plant height (m) MS	F value	Pr (>F)
Block	3	1.5151	0.5050	15.632	0.418
Treatment	15	0.5809	0.0387	1.199	0.308
Error	45	1.4538	0.0323		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 2-24. Analysis of variance for plant height collected in Morris, MN in 2014.

Source of variation	Df	SS	Plant height (m) MS	F value	Pr (>F)
Block	3	0.1120	0.03732	4.753	0.876
Treatment	15	0.2957	0.01972	2.511	0.582
Error	45	0.3534	0.00785		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

2.5 Conclusions

Application of abrasive corncob grit to control in-row weeds can be used as an effective approach to control weeds and increase organic corn silage yield. The results indicated that abrasive corncob grit for in-row weed control can substantially reduce weed biomass, with decreases of 89% and 80% of the total weed biomass in two years of evaluation. Compared to the season-long weedy check, in-row application of abrasive corncob grit increased yield up to 256 %. Late application of corncob grit at the seven-leaf stage of corn resulted in less weed control and no yield increase. These results showed the importance of applying corncob grit at earlier stages (V1 to V5) to achieve better weed control and maintain high crop yield. One application at the one-leaf stage of corn (V1) can increase corn yield, and additional treatments with or after the V1 treatment improved weed control and may increase yield. Thus, the final recommendation for the application timing of abrasive grit in silage corn is between V1 and V5.

CHAPTER 3

Corncob grit application for weed management in a transitional farming corn production system

3.1 Abstract

Effective weed control is especially challenging to farmers who are transitioning from traditional crop production into organic or more sustainable crop production, where avoidance of synthetic herbicides is mandatory. This two-year field study examined weed management and corn yield as affected by air-propelled abrasive corncob grit for in-row weed control. Grit applications were made at several times and frequencies, alone or in combination with between-row weed control through either flame-weeding or cultivation. Between-row weed control) was induced at the five-leaf stage of corn. Application of abrasive corncob grit increased corn yield up to 44%. In-row weed control resulted in the decrease of 95% of the in-row weed biomass. Between-row weed control reduced weed biomass up to 87% for cultivation and 85% for flaming of the between-row weeds. In-row weed control treatments reduced broadleaf and grass biomass up to 99% and 82%, respectively. Between-row weed control treatments reduced broadleaf and grass weed biomass up to 86% and 51%, respectively. These results indicated that abrasive corncob grit for in-row weed control supplemented with cultivation or flaming can substantially reduce weed biomass and may be an effective tool for transitioning corn production.

3.2 Introduction

Humans farmed without synthetic fertilizers, relying on organic fertilizers derived from plants and animals (Fussell, 2015) until the late 1940's. Moreover, crops and animals were protected from pests and diseases using naturally occurring materials. Weed control and management relied on mechanical practices such as hand pulling or hoeing; cultural control, especially crop rotations; and prevention measures, such as planting clean seed (Hay, 1974). However, after World War II and the discovery of auxin mimic herbicides, such as 2,4-D, agriculture began placing greater reliance on external inputs, particularly herbicides to control weeds (Vats, 2015).

Due to the increased adoption of zero or reduced tillage production systems, farmers around the world have become increasingly dependent on herbicides (Enache and Ilnicki, 1990). These chemical products accounted for the largest portion of world pesticide sales (48%), followed by insecticides (29%), fungicides (17%), and other pesticides (6%) (USEPA, 2011). According to the USEPA (2011), world pesticide costs totaled more than $36 billion in 2006 and more than $39 billion in 2007. In the U.S. alone, pesticide spending totaled $12 billion in 2006 and $13 billion in 2007, in proportions similar to those of world expenditures on herbicides. In 2007, in terms of world expenditures, U.S. farmers accounted for about 32% of total pesticides, 38% of herbicides, 39% of insecticides, 15% of fungicides, and 25% of other pesticides.

The need for alternative weed management tactics is a consequence of the continuing evolution of herbicide resistance, the lack of new herbicides registered for vegetables and grain crops, and herbicide contamination of the surface and ground water in many agricultural communities (Barbash *et al*., 1999). In addition, increasing concerns about food quality, farm worker health, rural development, and the environmental impacts of farming systems, for example, have focused the attention of policy makers, consumers, researchers and farmers on alternative productions systems, including organics (Johnson, 2004).

Effective weed control is especially challenging to farmers who are transitioning from traditional crop production into organic or more sustainable crop production, avoiding the use of herbicides (Bond and Grundy, 2001; Walz, 2004). However, controlling weeds without synthetic herbicides under the rules of organic agriculture is difficult to achieve (Kruidhof *et al*., 2008). Furthermore, the enforcement of rules by the USDA-administered Organic Food Production Act of 1990 and the National Organic Program prohibits the use of synthetic chemicals for organic-labeled produce, indicating the importance of non-pesticide crop production systems (Ngouajio *et al.*, 2003; Ploeg 1999; Wang *et al*., 2003; Hooks and Johnson 2002; Kremer and Li 2003). The Organic Farming Research Foundation (2002) ranked weed control as the top priority and hence non-herbicide based weed management options are needed, particularly for organic farming (Hutchinson and McGiffen, 2000).

Organic farmers commonly seek certification in order to promote and sell their produce as organic. When starting to produce certified organic goods, the land undergoes a required transition period. This period is called “conversion” and usually lasts between one to three years, depending on previous land use and the levels of chemical residues present at the initial inspection (USDA, 2015). After the process of “organic” conversion has been met, the need to maintain an organic land becomes important. Literature is replete with studies of weed control techniques such as crop rotation, cover crops, biological herbicides (i.e. corn gluten meal), steaming, and flaming; all of which are tools to be used for crop management without herbicides. Although various researchers have pointed out the importance and the availability of these weed control techniques, there is a clear lack of knowledge of their efficiency in an integrated weed management strategy. Therefore, weed control research needs to focus on the implementation of integrated approaches (Liebman and Davis, 2009) and updating existing integrated weed management strategies (Cloutier *et al*., 2007; Van Der Weide *et al*., 2008) towards a better weed control in transitional farming crop production as well as in certified organic agriculture.

A novel technique reported the idea of using abrasive grits to control weeds (Nørremark *et al.,* 2006), and an ongoing research has demonstrated that crop residues such as walnut shells can be used to control small weed seedlings (Forcella, 2009a). Recent field studies based on this technique have demonstrated that the application of air-propelled corncob grit combined with inter-row cultivation can successfully reduce the presence of weeds in corn and maintain corn yield (Forcella, 2012). This technique in combination with other between-row weed control techniques such as weed flaming can be used as a multifunctional tool for integrated crop and weed management in post emergence in-row application of abrasive grits to reduce the presence of weeds and, thereby, competition with the crop (Forcella, 2012).

The objectives of this two-year field experiment were to assess the efficacy of a post-emergence (POST) weed control system in a transitional corn production system by integrating air-propelled abrasive corncob grit for in-row control (1) at different timings and frequencies, (2) with either flame-weeding or cultivation (for between-row weed control, one time), and (3) to quantify the effects of these treatments on corn yield.

3.3 Materials and Methods

Field experiment. A commercially available 97-day corn hybrid was planted on May 28, 2013 and May 25, 2014 at about 79,000 plants ha^{-1} in rows spaced 0.76 m apart at the Aurora Research Field Station of the South Dakota State University (Brookings County, SD). The soil parent materials were loess over glacial outwash, and the soil series was Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludoll) (https://soilseries.sc.egov.usda.gov/OSD_DOCS/B/BRANDT.html; Clay *et al*., 2009). This type of soil has high water availability and is well drained (USDA-NRCS 2004). Field capacity (-0.03 MPa) and permanent wilting point (-1.5 MPa) of this soil are about 0.3 and 0.1 g g^{-1}, respectively.

In both years, the experiments consisted of 16 treatments (see Table 3-1), including two grit-free checks (season long weedy, SLWC, and hand-weeded, HWC), which were evaluated and monitored for weed control and corn yield. Single, double, or triple applications of grit were applied each year with timing of applications based on corn phenology. Leaf stages of corn were V1, V3, and V5 (Ritchie *et al.*, 1997) were the first, second, and third times of application (Table 3-1).

The selected treatments were established in a randomized complete block design with four replications in plots measuring 3 m long by 3.05 m wide consisting of 4 planted rows. In each plot, corncob grit was applied along the rows for in-row weed control at different corn growth stages/grit application times. For between-row weed control, cultivation or flaming was performed in four rows for each treatment. Alongside the rows where corncob grit was applied, four rows remained grit-free with the same cultivation and flaming setting as described for the grit application. These rows were used to perform matched pair t-tests to compare the efficacy of the grit application on weed control and the effect on corn yield.

Abrasion of weeds was performed using grit (Green Products Company, Conrad, IA) derived from corncobs with a commercial standard particle size of 20-40 mesh (0.5 mm diameter) (Forcella, 2009b). Weeds were blasted with a gravity-fed sand blasting unit as described by Forcella **(**2009a**)**. The blasting nozzle was aimed at the top of the weed in a downward 45° angle and weeds were approximately 30 cm from the tip of the blasting orifice. Grit was delivered in a conical pattern and aimed at the top of the weed in an effort to defoliate the plant, and in the case of dicotyledons, destroy the apical meristem. Blasting distance, angle, and pressure all influence efficacy of this technology (Forcella 2009a), so each of these factors was held constant across the trials.

Table 3-1. Treatment combinations of leaf stage of corn (based on Ritchie *et al*., 1997) at grit application + between-row weed control established in Aurora, SD in 2013 and 2014.

2013 and 2014
Grit V1 Flaming
Grit V1 Cultivation
Grit V3 Flaming
Grit V3 Cultivation
Grit V5 Flaming
Grit V5 Cultivation
Grit V1+V3 Flaming
Grit V1+V3 Cultivation
Grit V1+V5 Flaming
Grit V1+V5 Cultivation
Grit V3+V5 Flaming
Grit V3+V5 Cultivation
Grit V1+V3+V5 Flaming
Grit V1+V3+V5 Cultivation
Season Long Weedy Check
Hand-Weedy Check

At V5 between-row weed operation of flaming or Cultivation was added

Flaming was used as one of the between-row weed treatments at the five-leaf stage of corn (July 5, 2013 and July 9, 2014) utilizing a custom built handheld flame weeder. The flamer provided open flames using propane as a source for combustion. This equipment consisted of a cane, with the propane supply tank (4.5 kg tank) carried in a backpack and a flamer with five burners mounted 15-cm apart. Burners were positioned 18-cm above soil surface beneath a hood and angled back at 30˚ to the soil. Flaming treatment was applied at a constant speed of 3.1 km hr^{-1}delivering a propane dose of approximately 50 kg ha^{-1}. For the other between-row treatment, cultivation was performed using a John Deere® 886 cultivator mounted on the three-point hitch (hydraulic system, attaching points, the lifting arms, and the stabilizers) of a John Deere® 7619 tractor driven at 5 km hr^{-1} on July 6, 2013 and July 10, 2014 at the five-leaf stage of corn.

Measurements to evaluate effectiveness of the treatments included: weed identification, weed density by species, and weed biomass (in-row and between-row). Weed data were collected in a 40 cm x 15 cm areas in-row and between-rows of each sub-sub-plot. In- and between-row weed identification and weed density information was collected one day before and three days after grit application, flaming, or cultivation in the same location. Weed biomass was collected just prior to corn harvesting (October 16, 2013 and October 10, 2014, respectively, at the R6 corn growth stage). Aboveground portions of weeds within these quadrats were clipped, identified, and counted species, dried at 40°C for 2 weeks, and weighed.

Height of three randomly selected corn plants from the two central rows of each sub-sub plot were measured in cm from soil surface to the node of the leaf flag at the R6 corn growth stage. From corn plants in 1-m long sections of the two central rows of each sub-sub plot, ears were harvested, dried at 40°C for two weeks, and shelled. Grain yield was adjusted to 15% moisture content.

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 yield, and plant height. The linear statistical model for a randomized complete block design (Steel and Torrie, 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} leaf stage of corn:grit application:between-row application (cultivation or flaming) effect, μ is the overall (grand) mean, α_i is the leaf stage of corn effect of treatment i^{th} where $\sum_i \propto_i = 0$, for i = 1,…..16, β_j is the effect in block j^{th} where $\sum_j \beta_i = 0$ for j = 1,….,4, and $\epsilon_{ij} \sim iid\ \mathrm{N}(0, \sigma_e^2)$ is the random error effect.

To estimate the mean squares for each trait, data from all checks were included and an analysis of variance (ANOVA) was performed using the library agricolae (de Mendiburu, 2014) in R (R Core Team, 2014). The decision to include two controls in this experimental design was justified based on the objectives of the experiment. ‘Hand-weeded'' (i.e., weed-free) check plots are an integral part of most weed management experiments, as they estimate the maximum potential yield without weed competition for a given site-year environment. However, weed-free yield varies from site to site and year to year in response to other factors such as changing weather or crop management. In this case, the controls were compared with all other treatments (Piepho *et al*., 2006), and since controls usually have a very high or very low variance with respect to all the other treatments, it is expected to detect differences among treatments and controls (Ahrens *et al*., 1990; Phelps, 1991).

3.4 Results and Discussion

Climate. The 2013 and 2014 growing seasons were very similar in terms of growing degree days and rainfall (Table 3-2) and similar to the 30-year averages. Accumulated growing degree days (GDDA) for the months of May, June, July and August of 2013; and the months of September and October of 2014 were similar to the 30-year average (1986-2014). Precipitation for 2013 was very similar to the 30-year average. In 2014, more rainfall was observed early in the growing season. The 2013 growing season was slightly warmer and drier than 2014. Although fairly similar climates were observed between 2013 and 2014, the slight temperature and precipitation differences may be important for growth and development of crops and weeds. Every single crop and weed specie is associated with a distinctive set of growth and development requirements that creates both spatial and temporal variability in nutrient, water, and light availability. Variability of these resources will affect where and when the soil is favorable for seed germination. For example, in a water-limited environment a spring-irrigated crop will promote spring weed seed germination, while a fall-irrigated crop will promote fall weed germination. Crops with different growing seasons or growth patterns also alter the light environment of the soil. This, in turn, may influence control timing in relation to the growth stage of target weeds to obtain the best control efficacy.

Weed Control. Weed counts before and after the application of corncob grit for in-row weed control showed that weeds were present in similar number in both years during the different corn growth stages (Tables 3-3 and 3-4). In both years, broadleaf weeds were present from the V1 leaf stage of corn until corn harvest. On the other hand, grasses were noted at the V5 leaf stage of corn until harvest. Broadleaf weed species were the predominant species present in both years. At the one- and three-leaf stages of corn, redroot pigweed at the two and three true-leaf stage and common lambsquarters at the three and four true leaf stage were most prevalent. At the five-leaf stage of corn Pennsylvania smartweed at the three and five true-leaf stage and grasses were present.

In 2013 and 2014, matched pairs-analyses showed that mean counts were lower after the application of corncob grit than before at the V1 ($prob<t$=0.0001; $prob<t$=0.001), V3 ($prob<t$=0.0002; $prob<t$=0.001), and V5 ($prob<t$=0.001; $prob<t$=0.001) corn growth stages (Tables 3-3 and 3-4). These results suggested that the use of corncob grit has a positive effect on weed control by reducing the number of weeds when corncob grit was applied. Weed counts showed that a single application in either year at the V1 leaf stage of corn controlled 50% of the weeds present. Grit application at later leaf stages of corn (V3 and V5) had greater weed densities and weed

control was as efficient as at V1. Double application of corncob grit at V1+V3, V1+V5, and V3+V5 reduced more weeds than single applications at V1, V3, and V5. Triple application at V1+V3+V5 had the most effective weed control in both years. Even though the application of corncob grit at V5 can be performed late in the corn growing season, controlling weeds at such late stage can have an adverse effect on corn growth and development; during the first few weeks after crop emergence, resources present in the environment are generally sufficient to support both weed and crop growth. As crop plants and weeds continue growing and developing, an increasing demand on resources in limited supply and competition between weeds and crops becomes firmly established such that the weeds are no longer tolerated due to negative effects on the crop, marking the beginning of the critical period of weed control (Norsworthy and Oliveira, 2004). Therefore, waiting to apply corncob grit until the five-leaf stage of corn could have an adverse effect on crop production efficiency by reducing yield, reducing harvest efficiency, and contributing to future problems through weed seed production (Hartzler, 2003).

Table 3-2. Growing degree days accumulation (GDDA) base 10°C and cumulative precipitation (CP) recorded during the length of the experiments established in Aurora, SD in 2013 and 2014.

Month	2013		2014		1986-2014	
	GDDA	CP	GDDA	CP	GDDA	CP
		--cm--		--cm--		--cm--
May	152	6.6	168	7.6	140	6.4
June	419	19.1	434	26.0	390	14.7
July	774	27.2	729	32.0	750	24.8
August	1114	30.8	1048	38.7	1050	32.6
September	1385	34.3	1240	43.4	1299	39.3
October	1452	39.9	1329	44.7	1479	45.7
Total	5256	158	4948	192	5108	164

Table 3-3. Weed density (plants per m^2) before and after the application of corncob grit and matched pair t-test for in-row weed control in Aurora, SD 2013. Values in brackets represent percent (%) weed control compared to SLWC “after” densities.

	Application time					
	V1		V3		V5	
Leaf stage of corn+corncob application	Before	After	Before	After	Before	After
V1	35	18 [57]				
V3			50	25 [55]		
V5					59	18 [75]
V1+V3	35	18 [57]	18	9 [84]		
V1+V5	37	15 [64]			38	15 [79]
V3+V5			50	23 [58]	44	15 [79]
V1+V3+V5	35	17 [60]	19	9 [84]	18	9 [88]
Prob<t	0.0001		0.0002		0.001	
SLWC	35	42	50	55	60	72
HWC	5	8	10	12	16	25

Table 3-4. Weed density (plants per m^2) before and after the application of corncob grit and matched pair t-test for in-row weed control in Aurora, SD 2014. Values in brackets represent percent (%) weed control compared to SLWC “after” densities.

	Application time					
	V1		V3		V5	
Leaf stage of corn+corncob application	Before	After	Before	After	Before	After
V1	50	30 [54]				
V3			70	40 [51]		
V5					60	25 [73]
V1+V3	51	31 52]	37	20 [76]		
V1+V5	51	28 [57]			55	25 [73]
V3+V5			71	41 [50]	45	22 [76]
V1+V3+V5	51	29 [55]	38	22 [73]	25	10 [89]
Prob<t	0.001		0.001		0.001	
SLWC	52	65	70	82	88	92
HWC	8	10	15	18	25	35

Weed density before the application of cultivation (Figure 3-1) or flaming (Figure 3-2) for between-row weed control indicated higher weed densities in 2014 (Table 3-6) compared with 2013 (Table 3-5), similar number of weeds were observed across the plots regardless of corn in-row grit timing, before the application of cultivation or flaming at V5; weed density was similar among plots indicating a low variability of weeds present in the field. Broadleaf weed species were predominant in both years until V3, after the V5 leaf stage of corn, grasses started to emerge. Even though between-row weed control was performed at the V5 leaf stage of corn, between-row weeds present at V3 and V5 were redroot pigweed at the three and five true-leaf stages, respectively, and common lambsquarters at the four true-leaf stage in both years; and Pennsylvania smartweed at the four true-leaf stage in 2013 and 2014. In both years, grasses such as green foxtail and yellow foxtail were present during cultivation or flaming at the five-leaf stage of corn.

In this crop system, matched pairs analysis performed for 2013 and 2014 showed that mean weed counts in both years were lower after flaming or cultivation. A significant difference in weed control occurred before and after flaming (2013: $prob<t$=0.00015, 2014: $prob<t$=0.00021) and cultivation (2013: $prob<t$=0.00018, 2014: $prob<t$=0.0012) (Tables 3-5 and 3-6). On average, cultivation reduced weed density by 54% and 55% in 2013 and 2014, respectively. Flaming, reduced weed density by 44% and 48% in 2013 and 2014, respectively. Cultivation, provided more weed control in both years than flaming. These results suggested that the application of cultivation and flaming had a positive effect on weed control by reducing the number of weeds when these treatments are applied.

At harvest, broadleaf species such as redroot pigweed at the 6 true leaf stage (approximately 45 cm tall), common lambsquarters at the nine or ten true leaf stage (approximately 65 cm tall), and Pennsylvania smartweed were present in both years at the time the corn was harvested. Grass species such as green foxtail and yellow foxtail were the grass species present in both years (100%). Grass species were not present at early corn growth stages, however, after the five-leaf stage of corn, grass species were observed.

Figure 3.1. Application of corncob grit + cultivation treatment in the experiment stablished in Aurora, SD in 2014.

Between-row weed control (Cultivation)

In-row weed control (Grit application)

Between-row weed control (Cultivation)

In-row weed control (Grit application)

Figure 3.2. Application of corncob grit + flaming treatment in the experiment established in Aurora, SD in 2014.

Between-row weed control (Flaming)

In-row weed control (Grit application)

Between-row weed control (Flaming)

In-row weed control (Grit application)

Table 3-5. Weed density (plants per m^2) between-row before and after the application of cultivation or flaming and matched pair t-test for between-row weed control in Aurora, SD 2013. Values in brackets represent percent (%) weed control compared to SLWC “after” densities.

	Evaluation timing					
	V1	V3	V5 Cultivation		V5 Flaming	
Leaf stage of corn+corncob application			Before	After	Before	After
V1	35	43	53	23 [63]	54	28 [56]
V3	36	44	54	25 [60]	52	29 [55]
V5	36	45	52	24 [62]	51	28 [56]
V1+V3	35	46	55	25 [60]	53	31 [52]
V1+V5	36	46	54	26 [59]	50	30 [53]
V3+V5	34	45	54	25 [60]	51	28 [56]
V1+V3+V5	35	44	56	27 [57]	53	29 [55]
Prob < t			0.00018		0.00015	
SLWC	36	44	56	63	62	64
HWC	5	8	9	12	10	12

SLWC: Season-Long Weedy Check
HWC: Hand-Weeded Check

Table 3-6. Weed density (plants per m^2) between-row before and after the application of cultivation or flaming and matched pair t-test for between-row weed control in Aurora, SD 2014. Values in brackets represent percent (%) weed control compared to SLWC "after" densities.

	Evaluation timing					
	V1	V3	V5 Cultivation		V5 Flaming	
Leaf stage of corn stage+corncob application			Before	After	Before	After
V1	42	54	64	28 [58]	63	33 [51]
V3	44	52	64	28 [58]	64	34 [50]
V5	42	52	64	29 [57]	65	36 [47]
V1+V3	44	52	65	30 [55]	64	36 [47]
V1+V5	43	53	65	30 [55]	64	37 [46]
V3+V5	45	55	66	29 [57]	65	34 [50]
V1+V3+V5	46	54	64	28 [58]	66	36 [47]
Prob < t			0.00012		0.00021	
SLWC	48	55	66	67	67	68
HWC	6	0	9	9	10	10

SLWC: Season-Long Weedy Check
HWC: Hand-Weeded Check

Total weed biomass. The combined application of abrasive corncob grit at different leaf stages of corn plus flaming or cultivation reduced weed biomass at corn harvest in 2013 (p=0.000757) and 2014 (p=0.0124) (Tables 3-7 and 3-8). The reduction in total weed biomass was dependent on the combined effect of the levels of grit application timing (one, two, or three in-row weed control applications) plus the use of between-row weed control (flaming or cultivation).

The combined application of abrasive corncob grit at different leaf stages of corn plus either flaming or cultivation, noticeably reduced the total (In-row + Between-row) weed biomass up to 91% in 2013 and 87% in 2013 and 2014, respectively (Table 3-9). Total weed biomass was reduced from 56% (Grit V3+V5 Flaming) to 91% (Grit V3 Cultivation) in 2013 (Table 3-9), and from 48% (Grit V1+V3+V5 Cultivation) to 87% (Grit V1+V3 Flaming) in 2014 (Table 3-10). In 2013 and 2014, 13 (93%) and 11 (79%) of the treatments were statistically equal to the hand-weeded check (Figure 3-3), respectively, an all treatments evaluated in both years were different from the season-long weedy check (Figure 3-4).

On average, total weed biomass (broadleaf+grass) was reduced when compared with the season-long weedy check by 72% (2013) and 74% (2014) when row middles were flamed, while 75% and 70% of total biomass reductions were observed when row middles were cultivated in 2013 and 2014, respectively, for the between-row weed control. In contrast, a single application of abrasive corncob grit provided 78% and 75% (at the one-, three-, and five-leaf stages of corn) weed control in 2013 and 2014, respectively, when compared with the season-long weedy check. A single application of abrasive corncob grit at the one-, three-, and five-leaf stages of corn provided season-long control of 76%, 88%, and 70%, respectively in 2013, and 66%, 80%, and 80% in 2014. These results suggested that abrasion events at or near the five-leaf stages of corn may be more critical for reducing total weed dry biomass than earlier events (Forcella, 2012).

Two applications of abrasive corncob grit achieved on average 69% and 75% (at the one- and three-, one- and five-, and three- and five-leaf stages of corn) of weed control in 2013 and 2014, respectively, compared with the season-long weedy check. Under these circumstances, season-long weed control was as low as 56% (2013: Grit V3+V5 Flaming; 2014: Grit V1+V5 Cultivation) in both years and as high as 79% (2013: Grit V1+V5 Flaming) and 87% (2014: Grit V1+V3 Flaming). According to these results, double applications can achieve weed control of 80% when grit is applied at the one- and three- or one- and five-leaf stages of corn supplemented with the application of flaming. Early applications of grit plus an additional application of weed flaming at early leaf stages of corn development can improve weed control.

Concerning the triple application of grit, an average effect of 73% and 62% (at the one-, three-, and five-leaf stages of corn) in 2013 and 2014, respectively, were observed when compared with the season-long weedy check. In both years, the triple application of grit was not as effective as the single application, meaning that additional applications did not improve season-long weed control beyond that achieved with a single application at the one-, three, or five-leaf corn growth stages.

Previous studies used abrasive grit made from corncob to control common lambsquarters in corn (Forcella, 2009b). Results showed that timing of weed abrasion was critical, with highest levels of control corresponding to the one- and five-leaf stages of corn or the one-, three-, and five-leaf stages of corn development.

In another study, Forcella (2012) used air-propelled abrasive grit for postemergence in-row weed control in field corn. Results showed that season-long weed control of annual weeds below 65% is not sufficient to prevent yield loses in corn.

Wortman (2014) evaluated tomato and pepper in a series of thirteen greenhouse trials, which were conducted to determine the susceptibility of these crops and weeds to abrasive weed control. One blast of corn gluten meal or greensand fertilizer (both of which are approved organic fertilizers) reduced seedling biomasses of Palmer amaranth (one-leaf stage) by 95 and 100% and green foxtail (one-leaf stage) by 94 and 87%, respectively. Results suggest that organic fertilizers can be used as abrasive grits in vegetable crops providing effective weed suppression.

Table 3-7. Analysis of variance for the variable total weed biomass collected in Aurora, SD 2013.

	Total weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	937297	312432	0.276	0.842407
Treatment	15	57605898	3840393	0.392	0.000757***
Error	45	50941773	1132039		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-8. Analysis of variance for the variable total weed biomass collected in Aurora, SD 2014.

	Total weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	14338688	4779563	1.040	0.3839
Treatment	15	164507531	10967169	2.387	0.0124*
Error	45	206736559	4594146		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-9. Mean total weed biomass of the combined in-row and between-row weed control treatments established in Aurora, SD in 2013 and 2014.

Treatment	Total weed biomass		Control	Treatment	Total weed biomass		Control
	-----kg ha^{-1}----		--%--		-----kg ha^{-1}----		--%--
Season-Long Weedy Check	4643	a	0	Season-Long Weedy Check	7403	a	0
Grit V3+V5 Flaming	2032	b	56	Grit V1+V3+V5 Cultivation	3872	b	48
Grit V3+V5 Cultivation	1726	bc	63	Grit V1+V5 Cultivation	3275	b	56
Grit V5 Flaming	1630	bc	65	Grit V1 Flaming	3099	b	58
Grit V1+V3 Flaming	1373	bc	70	Grit V3+V5 Flaming	2435	bc	67
Grit V1+V3+V5 Flaming	1373	bc	70	Grit V1+V5 Flaming	2224	bc	70
Grit V1 Cultivation	1273	bc	73	Grit V3+V5 Cultivation	2007	bc	73
Grit V1+V5 Cultivation	1273	bc	73	Grit V1 Cultivation	1892	bc	74
Grit V1+V3 Cultivation	1148	bc	75	Grit V1+V3+V5 Flaming	1712	bc	77
Grit V1+V3+V5 Cultivation	1148	bc	75	Grit V1+V3 Cultivation	1704	bc	77
Grit V5 Cultivation	1135	bc	76	Grit V3 Flaming	1669	bc	77
Grit V1 Flaming	986	bc	79	Grit V5 Cultivation	1518	bc	79
Grit V1+V5 Flaming	986	bc	79	Grit V5 Flaming	1465	bc	80
Grit V3 Flaming	632	bc	86	Grit V3 Cultivation	1196	bc	84
Grit V3 Cultivation	422	c	91	Grit V1+V3 Flaming	942	bc	87
Hand-Weeded Check	298	c	94	Hand-Weeded Check	0	c	100
	$LSD_{(0.05)}$=1515				$LSD_{(0.05)}$=2018		

Figure 3-3. Hand Weeded Check (HWC) in the experiment established in Aurora, SD in 2014.

Between-row and in-row hand weed control

In-row hand weed control

In-row hand weed control

Between-row and in-row hand weed control

Figure 3-4. Season Long Weedy Check (SLWC) in the experiment established in Aurora, SD in 2014.

Between-row no weed control

Between-row no weed control

In-row no weed control

In-row no weed control

Broadleaf weed biomass: The combined effect of abrasive corncob grit at different leaf stages of corn and the application of flaming or cultivation was significant in 2013 ($p=0.000115$) (Table 3-10) but not significant ($p=0.111$) in 2014 (Table 3-11). For 2013, this indicated that, the season long weed control of broadleaf weeds changed depending on the combined effect of the levels of corncob grit timing application (one, two, or three in-row weed control applications) plus the use of between-row weed control (flaming or cultivation). The changes in broadleaf populations from one year to the next year could be the result of spatial variability of weeds at the Aurora Field Station, as the exact location of the experimental plots differed each year. Alternatively, random variations may have occurred in birth and death rates of these annual weeds, for example due to the different effects of weather or disturbance (i.e., cultural practices). This latter component tends to make weed population dynamics more unpredictable (Freckleton and Watkinson, 2002).

The combined application of abrasive corncob grit at different corn growth stages plus either flaming or cultivation, considerably reduced the broadleaf in-row + between-row weed biomass (Table 3-12). In 2013, 12 (86%) of the treatments were statistically equal to the hand-weeded check, meaning broadleaf weed biomass control was achieved with the application of the treatments in the field. When compared with the season-long weedy check, application of flaming and cultivation reduced broadleaf weed biomass on average by 84% and 86%, respectively.

For in-row weed control, a single application of abrasive corncob grit resulted in an average of 94% reduction in weed biomass (at the one-, three-, and five-leaf stages of corn) in 2013 when compared with the season-long weedy check. These three single applications of abrasive corncob grit at either one-, three-, or five-leaf stages of corn had the same effect on weed control, and their weed control effect was similar to the hand-weeded check. One application of abrasive corncob grit at the one-, three-, and five-leaf stages of corn achieved season-long weed control of 91%, 94%, and 96%, indicating that a late application of abrasive corncob grit at the five-leaf stage of corn added a mere 5% and 2% of broadleaf weed control compared to earlier applications at one- or three-leaf corn growth stages, respectively.

Two applications of abrasive corncob grit achieved on average 82% (at the one- and three-, one- and five-, and three- and five-leaf corn growth stages) reduction of broadleaf weed biomass in 2013 when compared to the season-long weedy check. Two applications of abrasive corncob grit achieved a season-long weed control as high as 99% (one- and five-leaf corn growth stages) and as low as 60% (one- and three-leaf stages of corn). Application of abrasive corncob grit at the one- and three-, one- and five-, and three- and five-leaf stages of corn resulted in season-long broadleaf weed control of 69%, 94%, and 82%, respectively, indicating that one more application of abrasive corncob grit at the five-leaf stage of corn after either one- or three-leaf stages of corn increased broadleaf weed control.

Triple application of abrasive corncob grit delivered on average 69% (at the one-, three-, and five-leaf stages of corn) season-long broadleaf weed control in 2013 when compared to the season-long weedy check. It would have been expected that a triple application of abrasive corncob grit had a higher level of season-long weed control, however, on average, triple applications were less effective than single or double application of abrasive corncob grit.

Table 3-10. Analysis of variance for the variable broadleaf weed biomass collected in Aurora, SD 2013.

		Broadleaf weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	1486095	495365	1.243	0.305207
Treatment	15	24563067	1637538	4.110	0.000115***
Error	45	17929042	398423		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-11. Analysis of variance for the variable broadleaf weed biomass collected in Aurora, SD 2014.

		Broadleaf weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	12493849	4164616	0.789	0.507
Treatment	15	127111593	8474106	1.605	0.111
Error	45	237599448	5279988		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-12. Mean broadleaf weed biomass of the combined in-row and between -row weed control treatments established in Aurora, SD 2013.

Treatment	Broadleaf weed biomass		Control
	-----kg ha^{-1}----		--%--
Season-Long Weedy Check	2575	a	0
Grit V1+V3 Flaming	1025	b	60
Grit V1+V3+V5 Flaming	1025	b	60
Grit V1+V3 Cultivation	563	bc	78
Grit V1+V3+V5 Cultivation	552	bc	79
Grit V3+V5 Flaming	469	bc	82
Grit V3+V5 Cultivation	441	bc	83
Grit V1 Cultivation	439	bc	83
Grit V1+V5 Cultivation	283	bc	89
Grit V3 Flaming	254	bc	90
Grit V5 Cultivation	170	bc	93
Hand-Weeded Check	59	c	98
Grit V3 Cultivation	55	c	98
Grit V5 Flaming	32	c	99
Grit V1 Flaming	31	c	99
Grit V1+V5 Flaming	31	c	99
	$LSD_{(0.05)}$=899		

Grass weed biomass: The combined effect of abrasive corncob grit at different leaf stages of corn and the application of flaming or cultivation on grass biomass control was significant in 2014 ($p= 0.0547$) but not significant in 2013 ($p=0.1004$) (Tables 3-14 and 3-13). Season long weed control of grass weed biomass changed depending on the combined effect of the frequency and timing of grit applications (one, two, or three in-row weed control applications) plus the use of between-row weed control applied (flaming or cultivation). As observed in broadleaf populations, grass populations were not the same from one year to the next year; fluctuations in grass populations could be the result of random variations in spatial distributions or, for example, due to the different effects of weather or disturbance (i.e. cultural practices), this latter component tends to make weed population dynamics more unpredictable (Freckleton and Watkinson, 2002).

In 2014, yellow foxtail and green foxtail were the predominant grass species that accounted for 100% of the grass biomass. Application of abrasive corncob grit at different corn growth stages plus either flaming or cultivation, considerably reduced the grass in-row + between-row weed biomass (Table 3-15). In 2014, 9 (64%) of the treatments were statistically equal to the hand-weeded check, meaning that the application of corncob grit plus either flaming or cultivation can achieve the same season-long grass weed control observed when hand-weeded control was performed, indicating that the application of abrasive corncob grit plus flaming or cultivation can be a as effectively as pulling weeds manually.

When compared to the season-long weedy check, application of flaming and cultivation reduced grass weed biomass on average by 51% and 17%, respectively. In-row grass weed control showed that, a single application of abrasive corncob grit resulted in average 41% at the five-leaf stage of corn in 2014 when compared to the season-long weedy check. One application of abrasive corncob grit at the five-leaf stage of corn achieved season-long weed control of 32%, indicating that an application of abrasive corncob grit at the five-leaf stage of corn had an acceptable level of weed control.

Two applications of abrasive corncob grit (at the V1+V5 and V5, and V3+V5 leaf stages of corn) achieved on average 22% reduction of grass weed biomass in 2014 when compared to the season-long weedy check. Two applications of abrasive corncob grit achieved a season-long weed control as low as 8% (V1+V5 leaf stages of corn). Application of abrasive corncob grit at V3+V5 leaf stages of corn resulted in season-long broadleaf weed control of 20%, indicating that one additional application of abrasive corncob grit after the three-leaf stage of corn increased grass weed control. If abrasive corncob grit is applied at the one-leaf stage of corn and a second application is done until the five-leaf stage of corn, grass weed control is not as effective (-5%) as the two applications performed at the one- and three-leaf stages of corn unless a triple application is performed.

Triple application of abrasive corncob grit delivered on average 55% (at the one-, three-, and five-leaf stages of corn) season-long broadleaf weed control in 2014 when compared to the season-long weedy check. On average, triple applications were more effective than double applications of abrasive corncob grit for grass control.

Table 3-13. Analysis of variance for the variable grass weed biomass collected in Aurora, SD 2013.

		Grass biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	3759959	1253320	2.206	0.0976
Treatment	15	14076629	938442	1.652	0.1004
Error	45	25567801	568173		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-14. Analysis of variance for the variable grass weed biomass collected in Aurora, SD 2014.

		Grass biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	1970855	656952	1.080	0.3670
Treatment	15	16989502	1132633	1.863	0.0547
Error	45	27363686	608082		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-15. Mean grass weed biomass of the combined in-row and between-row weed control treatments established in Aurora, SD 2014.

Treatment	Grass weed biomass		Control
	-----kg ha^{-1}----		--%--
V1+Grit+Cultivation	1735	a	0
V1+V5+Grit+Cultivation	1595	ab	8
Season-Long Weedy Check	1366	abc	21
V1+V5+Grit+Flaming	1346	abc	22
V3+V5+Grit+Cultivation	1299	abc	25
V5+Grit+Cultivation	1272	abcd	27
V1+V3+V5+Grit+Cultivation	945	abcde	46
V1+Grit+Flaming	907	abcde	48
V3+V5+Grit+Flaming	875	abcde	50
V1+V3+Grit+Cultivation	800	abcde	54
V5+Grit+Flaming	583	bcde	66
V1+V3+Grit+Flaming	467	cde	73
V3+Grit+Cultivation	299	cde	83
V1+V3+V5+Grit+Flaming	285	cde	84
V3+Grit+Flaming	183	de	89
Hand-Weeded Check	0	e	100
	$LSD_{(0.05)}$=1110		

In-row weed biomass. The application of abrasive corncob grit at different leaf stages of corn was significant in 2013 (p=0.000147), but not significant in 2014 p=0.222) (Tables 3-16 and 3-17). In 2013, the control of in-row weed biomass depended solely on whether grit was applied, and not on the timing or frequency of application (Table 3-18).

In 2013, the application of abrasive corncob grit at different corn growth stages significantly reduced the in-row weed biomass. In-row weed biomass made up 44% of the total weed biomass (Season-Long Weedy Check In-row weed biomass / Season-Long Weedy Check Total weed biomass) in 2013 (Table 3-18). All treatments were statistically equal to the hand-weeded check and statistically different from the season-long weedy check. On average, in-row weed biomass was reduced when compared to the season-long weedy check by 88% when abrasive corncob grit was applied.

Table 3-16. Analysis of variance for the variable in-row weed biomass collected in Aurora, SD 2013.

		In-row weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	217658	72553	0.508	0.679000
Treatment	8	20662279	2582785	18.067	0.000147***
Error	52	7433548	142953		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-17. Analysis of variance for the variable in-row weed biomass collected in Aurora, SD 2014.

		In-row weed biomass (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	12804158	4268053	1.530	0.218
Treatment	8	31097106	3887138	1.530	0.222
Error	52	145099512	2790375		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-18. Mean in-row weed biomass of the treatments established in Aurora, SD 2013.

Treatment	In-row weed biomass		Control
	-----kg ha^{-1}----		--%--
Season-Long Weedy Check	2582	a	0
V3+V5	463	b	82
V1+V+V53	450	b	83
V1	373	b	86
V1+V3	319	b	88
V1+V5	282	b	89
V3	167	b	94
V5	129	b	95
Hand-Weeded Check	59	b	98
	$LSD_{(0.05)}$=480		

Between-row weed biomass. The application of between-row weed control was significant in 2013 (p=0.0143) and 2014 (p=0.000219) (Tables 3-19 and 3-20). This indicated that the application of either cultivation or flaming had a positive effect on reducing the weed biomass between rows in corn.

Between-row weed biomass made up 56% and 43% of the total weed biomass (Season-Long Weedy Check Between-row weed biomass / Season-Long Weedy Check Total weed biomass) in 2013 and 2014, respectively (Table 3-21). Both flaming and cultivation reduced between-row weed biomass significantly and comparably in each year. The average effects of flaming (Flaming / Season-Long Weedy Check Between-row weed biomass) and cultivation (Cultivation / Season-Long Weedy Check Between-weed row weed biomass) were 50% and 62%, respectively, in 2013, and 85% and 87% in 2014. Thus, the effects of applying flaming and cultivation were 35% and 23% smaller in 2013 compared to the effects observed in 2014 even though the between-row biomass recorded in 2013 was less than that in 2014. In both years, the effect of applying cultivation and flaming were similar to the hand-weeded check, indicating that cultivation would be a more desirable cultural practice to perform, but from the standpoint of soil disturbance, flaming would be better because it does not promote soil disturbance and the subsequent vertical movement of weed seeds to the soil surface.

Table 3-19. Analysis of variance for the variable between-row weed biomass collected in Aurora, SD 2013.

	Between-row weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	329872	109957	0.159	0.9233
Treatment	3	7941475	2647158	3.835	0.0143*
Error	57	39349571	690343		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-20. Analysis of variance for the variable between-row weed biomass collected in Aurora, SD 2014.

	Between-row weed biomass (kg ha^{-1})				
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	4951923	1650641	0.952	0.422000
Treatment	3	51961843	17320614	9.986	0.000219***
Error	57	98868476	1734535		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-21. Mean between-row weed biomass of the treatments established in Aurora, SD in 2013 and 2014.

Treatment	Between-row weed biomass	Control	Treatment	Between-row weed biomass	Control
	-----kg ha^{-1}----	--%--		-----kg ha^{-1}----	--%--
Season-Long Weedy Check	2060 a	0	Season-Long Weedy Check	4222 a	0
Flaming	1039 b	50	Flaming	617 b	85
Cultivation	785 b	62	Cultivation	556 b	87
Hand-Weeded Check	238 b	88	Hand-Weeded Check	0 b	100
	$LSD_{(0.05)}$=665			$LSD_{(0.05)}$=1895	

Corn Yield. Corn responded to the combined application of abrasive corncob grit at different leaf stages of corn and flaming or cultivation in 2013 (p=0.0203) and 2014 (p=0.000437) (Tables 3-22 and 3-23). These results indicated that corn yield changed depending on the combined effect of the frequency and timing of grit applications (one, two, or three in-row weed control applications) plus the use of between-row weed control (flaming or cultivation).

Single applications at the one- or five-leaf stage of corn increased corn yield by 29% in 2013 and 44% in 2014. Applications of abrasive corncob grit at early or late corn growth stages in combination with either flaming or cultivation had a positive effect on yield because the yields were similar to the yield of the hand-weeded check (Table 3-24).

Two applications of grit increased corn yield 20% and 29% (at the one- and three-, one- and five-, and three- and five-leaf stages of corn) in 2013 and 2014, respectively, when compared to the season-long weedy check. Under these circumstances, corn yield increased 30% and 36% when abrasive corncob grit was applied at the V1+V3 leaf stages of corn in 2013 and 2014, respectively. Even though corn yield increased up to 43% when abrasive corncob grit was applied at the V3 and V5 leaf stages of corn in 2014, this treatment increased corn yield by only 9% in 2013. These data indicate that abrasive corncob application at the V1 and V3 leaf stages of corn can increase yield, and it is relatively more stable across years.

A triple application of abrasive corncob grit (V1+V3+V5) increased corn yield 31% in 2013 and 25% in 2014 when compared with the season-long weedy check. Single, double, or triple applications of abrasive corncob grit involving the V1 leaf stage of corn resulted in corn yields that were similar to the yield of the hand-weeded check in 2013. Similarly, double applications of corncob grit in combination with the V3 leaf stage of corn (either V1+V3 or V3+V5) also were similar to the yield of the hand-weeded check. These results suggested that application at or near the V3 leaf stage corn alone or in combination with another corn-growth stage can increase corn yield.

In 2013 (Table 3-25), average corn yields were 17584 and 17128 kg ha^{-1} for flaming and cultivation treatments. Compared to the hand-weeded check, these yields were similar (18388 kg ha^{-1}) and greater than the yield of the season-long weedy check (14269 kg ha^{-1}). In 2014, corn yields were 14365 kg ha^{-1} and 15248 kg ha^{-1} when averaged for cultivation and flaming, respectively, and both yields were less than the yield of the hand-weeded check (19381 kg ha^{-1}) (Table 3-25). However, flaming treatments that included grit applications at V1+V3 and V3+V5 maintained corn yields equivalent to the hand-weeded check, as also was observed in 2013.

Weed control in this experiment, where a series of factors and levels were compared simultaneously, put emphasis on the time various applications were made. These results showed that weed control must start before the critical weed-free period, weeds reduce crop yield at early stage of growth development, and they must be repeated in a timely fashion until late-emerging weeds no longer reduce yield (Oliver 1988; Radosevich *et al*. 1997; Zimdahl 1980). The critical weed-free period in this case was from emergence to V5 leaf stage corn in both years. Complete season-long weed control is not necessary to achieve maximum yield because late-emerging weeds often do not reduce yield after the critical period (Cardina *et al.* 1995; Knake and Slife 1965; Oliver 1988; Radosevich *et al.* 1997).

Table 3-22. Analysis of variance for corn yield collected in Aurora, SD 2013.

		Corn yield (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	37370137	12456712	2.933	0.0435*
Treatment	15	141071470	9404765	2.214	0.0203*
Error	45	191137757	4247506		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-23. Analysis of variance for corn yield collected in Aurora, SD 2014.

		Corn yield (kg ha^{-1})			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	23352010	7784003	1.421	0.249002
Treatment	15	295528246	19701883	3.597	0.000437***
Error	45	246470933	5477132		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-24. Mean corn yield of the treatment combinations involving in-row and between-row weed control established in Aurora, SD 2013 and 2014.

2013		2014	
Treatment	Yield	Treatment	Yield
	-----kg ha^{-1}----		-----kg ha^{-1}----
Grit V1+V3 Flaming	18947 a	Hand-Weeded Check	19381 a
Grit V1+V3+V5 Flaming	18848 a	V5+Grit+Flaming	18121 ab
Grit V1 Flaming	18835 a	V3+V5+Grit+Flaming	17904 ab
Grit V1+V3+V5 Cultivation	18455 ab	V1+V3+Grit+Flaming	16211 abc
Hand-Weeded Check	18388 ab	V3+Grit+Flaming	15678 bcd
Grit V1+V3 Cultivation	18232 ab	V1+V3+Grit+Cultivation	15105 bcde
Grit V1 Cultivation	18019 ab	V3+V5+Grit+Cultivation	14954 bcde
Grit V1+V5 Flaming	17848 abc	V5+Grit+Cultivation	14941 bcde
Grit V3 Flaming	17845 abc	V1+V3+V5+Grit+Flaming	14512 cdef
Grit V5 Cultivation	16891 abcd	V3+Grit+Cultivation	14407 cdef
Grit V1+V5 Cultivation	16857 abcd	V1+V3+V5+Grit+Cultivation	14249 cdef
Grit V3+V5 Cultivation	16421 abcd	V1+Grit+Cultivation	13709 cdef
Grit V5 Flaming	15888 bcd	V1+V5+Grit+Cultivation	13189 cdef
Grit V3 Cultivation	15019 cd	V1+Grit+Flaming	12464 def
Grit V3+V5 Flaming	14878 d	V1+V5+Grit+Flaming	11846 ef
Season-Long Weedy Check	14269 d	Season-Long Weedy Check	11492 f
	$LSD_{(0.05)}$=2935		$LSD_{(0.05)}$=3333

Table 3-25. Mean between-row corn yield of the treatments established in Aurora, SD 2013 and 2014.

Treatment	Corn yield	Treatment	Corn yield
	-----kg ha^{-1}----		-----kg ha^{-1}----
Hand-Weeded Check	18388 a	Hand-Weeded Check	19381 a
Flaming	17584 a	Flaming	15248 b
Cultivation	17128 a	Cultivation	14365 b
Season-Long Weedy Check	14269 b	Season-Long Weedy Check	11492 c
	$LSD_{(0.05)}$=2800		$LSD_{(0.05)}$=2780

Plant height: No differences in plant height were observed among treatments in 2013 and 2014 (Tables 3-26 and 3-27). Application of abrasive corncob grit in combination with either cultivation or flaming did not influence plant height, despite the fact that cultivation and flaming were performed at the five-leaf stage of corn in both years. It could perhaps be hypothesized that if flaming or cultivation was applied before the five-leaf stage of corn, an effect on plant height presumably could be observed, however, since the growing point in corn is below the soil surface (McWilliams et al., 1999), no damage to it was observed. It has been reported that corn is able to tolerate the application of abrasive corncob grit (Forcella, 2012) and flaming (Ulloa *et al*., 2011) at different corn growth stages, therefore an effect on plant height could be expected. However, application of flaming, cultivation, and even abrasive corncob grit at the five-leaf stage of corn could not have a detriment on plant height and ultimately on corn yield because the roots of the second whorl now form the major part of the root system and leaf and ear shoots are being initiated and this initiation has been completed by V5 (potential ear shoot number is determined). The results here resented here agree with the ones previously reported on corn plants being able to withstand grit application (Forcella, 2012) and broadcast flaming (Knezevic *et al*., 2009; Ulloa et al., 2011) up to the five-leaf stage of corn with no effect on plant height and yield.

Table 3-26. Analysis of variance for plant height collected in Aurora, SD 2013.

		Plant height (m)			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	0.0605	0.02015	1.296	0.287
Treatment	15	0.3525	0.02350	1.511	0.142
Error	45	0.6997	0.01555		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

Table 3-27. Analysis of variance for plant height collected in Aurora, SD in 2014.

		Plant height (m)			
Source of variation	Df	SS	MS	F value	Pr (>F)
Block	3	0.0351	0.01171	0.786	0.608
Treatment	15	0.2371	0.01581	1.061	0.417
Error	45	0.6705	0.01490		
Total	63				

Df.: Degrees of freedom, SS: Sum of Squares, MS: Mean Squares

3.5 Conclusions

Combination of in-row weed control using abrasive corncob grit and between-row weed control using flaming or cultivation can be used as an alternative to control weeds in transitioning farming systems. Application of abrasive corncob grit increased corn yield up to 44% compared to weedy checks. These results suggested the importance of applying grit before or at the five-leaf stage of corn to avoid plant stunting through weed/crop competition. In-row weed control resulted in the decrease of 95% of the in-row weed biomass. Between-row weed control had a significant impact on reducing weeds by up to 87% for cultivation and 85% for flaming of the between-row populations. Even though the application of corncob grit as well as cultivation and flaming at the five-leaf stage of corn reduced the total weed biomass, an application of these treatment combinations at early stages of corn development could potentially achieve better weed control.

In-row and between-row weed control had a significant impact on reducing weedy broadleaf and grass biomass. In-row weed control treatments reduced broadleaf and grass biomass up to 99% and 82%, respectively. Between-row weed control treatments reduced broadleaf and grass weed biomass up to 86% and 51%, respectively. These results indicated that abrasive corncob grit for in-row weed control supplemented with cultivation or flaming can substantially reduce weed biomass and help maintain high corn yields in crop production systems transitioning to organic certification.

CHAPTER 4

Comparison of corncob grit application to control weeds in two crop production systems

4.1 Abstract

Organic farming systems are assumed to be sustainable, but there are few data available about the performance of organic systems compared to traditional cropping systems over time in terms of weed densities and control. Application of in-row weed control using abrasive corncob grit in combination with between-row weed control using flaming or cultivation can manage weeds in organic and transitioning farming systems. The application of abrasive corncob in combination with either flaming or cultivation reduced total biomass, broadleaf biomass, and grass weed biomass. Application of corncob grit for in-row weed control at early corn growth stages is not as effective as late applications. However, grit application at late stage of corn growth stage can have a detrimental effect on corn silage yield or corn grain yield. These results suggested the importance of applying corncob grit before or at the V5 corn growth stage to avoid yield losses. These results indicate that abrasive corncob grit for in-row weed control can substantially reduce weed biomass and increase corn yield in an organic crop system as well as in a transitioning crop system.

4.2 Introduction

Crop systems experience gradual changes in soil properties that affect long-term productivity. Some of these changes involve the presence of unwanted plant species (weeds) that compete for light, nutrients, and space with the plants of the crop system. Weeds can cause adverse changes to a cropping system by lowering yield, quality, and profits and increasing field-time and labor.

A majority of the studies comparing efficiency between traditional crop systems and organic systems examined weather-related factors. Organic crop systems do extremely well compared to traditional crop systems in water- and climate-stress situations. A number of studies have shown that under drought conditions, crops in organically managed systems produce higher yields than comparable crops managed conventionally (Dormaar *et al*., 1988; Stanhill, 1990). This advantage can result in organic crops outyielding conventional crops by 70-90% under severe drought conditions (Lockeretz *et al*., 1981; Petersen *et al*., 1999; Wynen, 1994). A few other studies included organic crop systems comparison in which maize and tomatoes were grown in rotation and compared to conventionally produced crops (Kaffka and Koepf, 1987; Kaffka, 1985). Many assume that organic farming systems are sustainable, but there are few data available about the performance of organic systems compared to traditional cropping systems over time (Kaffka and Koepf, 1987; Kaffka, 1985; Mäder *et al*., 2002).

Organic crop systems in North America have been shown, on average, to yield approximately 90% to 95% of conventional crop systems (Lotter, 2003). Others have shown that organically managed crop systems have lower long-term yield variability, i.e., higher cropping system stability (Henning, 1994; Peters, 1994; Smolik *et al.,* 1995). Swift (1994) proposed that assessments of crop performance should include analysis of two components: yield and stability of yield from one climatic cycle to the next.

Crop production losses from weed competition are among the most important crop management concerns for organic crop farmers, and the ability to control weeds is considered a major limiting factor for farmers wishing to transition to organic production systems (Bond and Grundy, 2001; Walz, 2004). Effective weed control is especially challenging to farmers who are transitioning from traditional crop production into organic or more sustainable crop production (Baker and Smith 1987). The Organic Farming Research Foundation (2002) ranked weed control as the top priority and, hence, a non-herbicide based weed management is increasingly needed, particularly for organic and sustainable farming (Hutchinson and McGiffen 2000).

Literature has reported the availability of many weed control techniques such as crop rotation, cover crops, biological herbicides (i.e., corn gluten meal), steaming, and flaming as a tools to be used for crop management without herbicides. Although various researchers have noted the importance and the availability of these weed control techniques, there is a clear lack of knowledge of their efficiency as a multidisciplinary weed management strategy. Therefore, weed control research needs to be focusing on the implementation of integrated approaches (Liebman and Davis, 2009) and updating existing integrated weed management (Cloutier *et al*., 2007; Van Der Weide *et al*., 2008) towards better weed control in transitional crop production as well as organic agriculture.

The objective of this study was: 1) to compare the differences and similarities of a post (POST) weed control system in an organic crop production system (Chapter 2) against a transitional corn production system (Chapter 3).

4.3 Materials and Methods

The materials and methods of this section were described in chapters 2 and 3. The variables discussed were: weed control, total weed biomass, broadleaf weed biomass, grass weed biomass, corn silage yield, corn yield, and plant height.

4.4 Results and Discussion

Climate: The 2013 and 2014 growing seasons were very similar in terms of growing degree days and rainfall for Morris, MN (Table 2-2) and Aurora, SD (Table 3-2). In terms of growing degree day accumulation (GDDA), the months of May, June, and August of 2013 and 2014 were similar to their respective 30-year average (1986-2014) in Aurora while the months of May, June, July, and August of 2013, and the months of September and October of 2014 were similar to the 30-year average for Morris. In relation to cumulative precipitation (CP), while Aurora had less precipitation at the beginning of the growing season in both years, Morris in 2013 was very similar to the 30-year average, whereas in 2014 more rainfall was observed early in the growing season. Although fairly similar climates were observed between 2013 and 2014 for both locations, the slight temperature and precipitation differences were important for growth and development of crops and weeds. Grass weeds were so sparse in 2013 and 2014 for

Morris that an analysis of variance could not be performed. Whether the sparsity was due to field histories or weather variables is not known. For Aurora, the differences in GDDA and CP may have influenced the abundance of broadleaf weeds in 2014.

Weed control: For Morris, weed counts before and after the application of corncob grit for in-row weed control showed that weed densities were appreciably higher in 2013 (Table 2-3) than in 2014 (Table 2-4). On the other hand, for Aurora, weed densities were only somewhat higher in 2014 compared to 2013 (Tables 3-3 and 3-4). In both locations the most prevalent weeds species were redroot pigweed, common lambsquarters, Pennsylvania smartweed, green foxtail and yellow foxtail.

Despite the fact weed densities were higher in 2014 than 2013 in Aurora, matched pairs analyses showed that mean counts were lower after the application of corncob grit than before at the different leaf stages of corn (V). Similar results were observed for Morris in 2013 and 2014. Application of abrasive corncob grit at the one-leaf stage of corn in Aurora controlled 19% (Table 2-3) of the weeds whereas 50% (Table 3-3) of weed control was achieved for Morris. These results suggested that the use of corncob grit had a positive effect on weed control by reducing the number of weeds when abrasive corncob grit was applied.

Matched pairs analysis performed for 2013 and 2014 showed that mean weed counts in both years and locations were smaller after the application of flaming or cultivation. For Aurora, on average, across all the leaf stages, cultivation reduced weed density by 47% and 68% in 2013 and 2014, respectively. Flaming, averaged across all the leaf stages, reduced weed density by 30% and 40% in 2013 and 2014, respectively. For Morris, on average, across all the leaf stages, cultivation reduced weed density by 54% and 55% in 2013 and 2014, respectively. Flaming, averaged across all the leaf stages, reduced weed density by 44% and 48% in 2013 and 2014, respectively.

Total weed biomass: For both locations and years, the combined effect of abrasive corncob grit applied at different leaf stages of corn and the application of flaming or cultivation was significant. In Aurora, total weed biomass was reduced up to 89% in 2013 and 2014 (Table 3-9) by the treatments evaluated in the field whereas for Morris weed biomass was reduced up to 91% in 2013 and 87% in 2013 and 2014, respectively (Tables 2-9). Between-row weed control in Aurora, showed that in average, total weed biomass was reduced when compared to the season-long weedy check up to 74% when row middles were flamed while up to 75% total biomass reductions were observed when row middles were cultivated. For Morris, on average, total weed biomass was reduced when compared to the season long-weedy treatment by 78% and 86% when flaming and cultivation were performed, respectively for the between-row weed control.

A single application of abrasive corncob grit provided in average 78% and 83% of in-row weed control for Aurora and Morris, respectively when compared to the season-long weedy check. For Aurora, a single application of abrasive corncob grit at the V3 leaf stage of corn provided season-long control of 88%, whereas Morris, a single application of abrasive corncob grit at the V5 leaf stage of corn provided season-long control of 89%, suggesting that abrasion events at or near the V3 to V5 leaf stage of corn may be more critical for reducing total weed dry biomass than early events (Forcella, 2012) and enough to minimize corn yield loss due to weed competition.

In Aurora, double applications of abrasive corncob grit can achieve weed control of 80% when corncob grit is applied at the V1+V3 or V1+V5 leaf stages of corn supplemented with the application of flaming. In Morris, application of corncob grit at the V1+V5 and V3+V5 leaf stages of corn resulted in season-long weed control of 80%, whereas application of abrasion corncob grit at the V3+V7 leaf stages achieved 85% of season-long weed control, these results suggested that weed control was similar when abrasive corncob was applied at those corn growth stages.

Concerning the triple application of abrasive corncob grit, an average effect of 73% and 80% were observed for Aurora and Morris, respectively when compared to the season-long weedy check. In both locations, the triple application of abrasive corncob grit was not as effective as the single, meaning that additional applications did not improve season-long weed control beyond that achieved with a single application at the V1, V3 or V5 leaf stages.

Broadleaf weed biomass: In broadleaf weed biomass, the combined effect of abrasive corncob grit at different corn growth stages and the application of flaming or cultivation was significant in Morris (Tables 2-10 and 2-11) and Aurora (Tables 3-10 and 3-11). This indicated that the season long weed control of broadleaf weed biomass changed depending on the combined effect of the levels of corncob grit timing application plus the levels of the between-row weed control applied. Broadleaf weeds were the most prevalent species in Morris, and when compared to the season-long weedy check application of flaming and cultivation reduced broadleaf weed biomass in average 85% for the between-row weed control. For Aurora, when compared to the season-long weedy check, application of flaming and cultivation reduced broadleaf weed biomass in average 84% and 86%, respectively.

For in-row weed control, a single application of abrasive corncob grit resulted in average 85% and 94% weed control for Morris and Aurora, respectively when compared to the season-long weedy check. One application of abrasive corncob grit at the five-leaf stage of corn achieved season-long weed control between 89% and 96% for Morris and Aurora, indicating that application of abrasive corncob grit at this corn growth stage plays a more critical role for reducing broadleaf weed biomass than early corn growth stages.

Two-application of abrasive corncob grit achieved in average 86% and 82% of broadleaf weed biomass control in Morris and Aurora, respectively when compared to the season-long weedy check. Application of abrasive corncob grit at the one- and five-leaf stages of corn resulted in season-long broadleaf weed control of 88% in Morris, whereas two applications of abrasive corncob grit achieved a season-long weed control as high as 99% (V1+V5 leaf stages of corn). Two applications of abrasive corncob grit achieved a season-long weed control as high as 89% in both years and as low as 44% (2014) and 83% (2013). Application of abrasive corncob grit at the V1+V5 leaf stages of corn resulted in season-long broadleaf weed control of 88% in 2013 and 99% weed control in 2014 in Aurora. These results indicated that one more application of abrasive corncob grit at the V5 leaf stage of corn after either V1 or V3 leaf stages of corn increased broadleaf weed control.

Triple application of abrasive corncob grit delivered in average 86% and 69% season-long broadleaf weed control in 2013 when compared to the season-long weedy check for Morris and Aurora. It would have been expected that a triple application of abrasive corncob grit had a more efficient season-long weed control, however, in average, triple applications were as efficient as single or double application of abrasive corncob grit.

Grass weed biomass: For Morris, grass weeds observed, yellow foxtail and green foxtail were too sparse across the plots that an analysis of variance was not possible to perform. In Aurora, the combined effect of abrasive corncob grit at different leaf stages of corn and the application of flaming or cultivation on grass biomass control was significant in 2014 (Table 3-14). Season-long weed control of grass weed biomass changed depending on the combined effect of the levels of corncob grit timing application (one-, two-, or three-in row-weed control application) plus the levels of the between-row weed control applied (flaming or cultivation).

When compared with the season-long weedy check, application of flaming and cultivation reduced grass weed biomass an average 51% and 17%, respectively. In-row grass weed control showed that, a single application of abrasive corncob grit resulted in about 41% when compared with the season-long weedy check. Two-application of abrasive corncob grit achieved in average 22% of grass weed biomass control when compared to the season-long weedy check. Two applications of abrasive corncob grit achieved a season-long weed control as high as 66% (V1+V3 leaf stages of corn). Application of abrasive corncob grit at the one- and three-corn growth stages resulted in season-long grass weed control of 54% , indicating that one additional application of abrasive corncob grit after the one-leaf stage of corn increased grass weed control.

Triple application of abrasive corncob grit delivered in average 55% season-long broadleaf weed control when compared to the season-long weedy check. On average, triple applications were more efficient than double applications of abrasive corncob grit.

In-row weed biomass. The application of abrasive corncob grit at different leaf stages of corn was significant in 2013 and 2014 (Tables 2-13 and 2-14) for Morris and Aurora (Table 3-16). In-row weed biomass made up 305 and 44% of the total weed biomass (Season-Long Weedy Check In-row weed biomass / Season-Long Weedy Check Total weed biomass) for Morris and Aurora, respectively.

For Morris and Aurora, in average, in-row weed biomass was reduced when compared to the season-long weedy check up to 79% and 88%, respectively when abrasive corncob grit was applied. Even though all the single applications were statistically equal, single applications at the three- and five-corn growth stages were the most effective for in-row weed control, suggesting that corncob grit can be applied at or near the five-corn growth stage and achieve acceptable in-row weed control.

Two applications of abrasive corncob grit achieved in average 83% and 86% of in-row weed control in Morris and Aurora, respectively compared to the season-long weedy check. Under these circumstances, in-row season-long wee control considering two applications of abrasive corncob grit was as high as 99% and 95% for Morris and Aurora.

A triple application of abrasive corncob grit achieved in average 83% for Morris and Aurora when compared with the season-long weedy check. A double or triple applications of abrasive corncob grit would have been expected to deliver a longer season-long weed control than the one achieved with single applications, however, the results here reported suggest that a single application at early or late growth stage would achieve the same weed control.

Between-row weed biomass. The application of between-weed control was significant in 2013 for Morris (Tables 2-16 and 2-27) and Aurora (Tables 3-19 and 3-20). This indicated that the application of either cultivation or flaming had a positive effect on reducing the weed biomass between rows in corn. Between-weed biomass made up 79% and 56% of the total weed biomass (Season-Long Weedy Check Between-row weed biomass / Season-Long Weedy Check Total weed biomass) for Morris and Aurora, respectively.

The average effects of flaming (Flaming / Season-Long Weedy Check Between-row weed biomass) and cultivation (Cultivation / Season-Long Weedy Check Between-weed row weed biomass) were 81% and 84%, for Morris, and 85% and 87% for Aurora. Application of flaming would be better because it does not promote soil disturbance and the subsequent vertical movement of weed seeds (seed distribution) to the soil surface stimulating indirectly the germination of seeds, seedling establishment, and contributing to future problems through weed seed production (seed bank), and building up new weed flush in the crop.

Corn silage yield and corn yield: Corn responded to the combined application of abrasive corncob grit at different leaf stages of corn and flaming or cultivation for Morris (Tables 2-19 and 2-20) and Aurora (Tables 3-22 and 3-23). These results indicated that corn yield changed depending on the combined effect of the levels of corncob grit timing application (one-, two, or three-in-row weed control application) plus the levels of the between-row weed control applied (flaming or cultivation).

For Morris, the silage yield was 16728 and 12627 kg ha^{-1} averaged over cultivation and flaming when corncob grit was applied and for Aurora, corn yield was 17127 and 17584 kg ha^{-1} averaged over cultivation and flaming when corncob grit was applied. In average, a single application of abrasive corncob grit increased silage corn yield in average 255%, and corn yield by 29% when compared to the season-long weedy check. Single applications at the one- and three-leaf stages of corn were the most effective corn growth stages to apply abrasive corncob grit and increase corn silage yield and corn yield. Applications of abrasive corncob grit at early corn growth stages in combination with either flaming or cultivation had a positive effect on yield because the yields are similar to the yield of the hand-weeded check.

Two applications of abrasive corncob grit increased on average up to 241% and 29% corn silage yield and corn yield for Morris and Aurora, respectively, when compared with the season-long weedy check. Under the same settings, corn silage yield and corn increased up to 198% (at the V3+V5 growth stages) and 36% when abrasive corncob grit was applied at the V1+V3 leaf stages of corn for Morris and Aurora.

A triple application of abrasive corncob grit increased corn silage yield and corn yield in average up to 220% and 31% for Morris and Aurora, respectively. For Morris and Aurora, average yields of the single application at the V3 and V5 or double applications at the V3+V5, as well as the triple application (at V3+V5+V7 leaf stages of corn) were similar to the yield of the hand-weeded check. These results suggested that application at or near the V3 leaf stage of corn alone or in combination with another leaf stage of corn can increase corn yield.

Plant height: For plant height, no differences in plant height were observed among treatments in Morris and Aurora. Application of abrasive corncob grit in combination with either cultivation or flaming did not increase or decrease corn plant height.

4.5 Conclusions

A combination of in-row weed control using abrasive corncob grit and between-row weed control using flaming or cultivation can be used to control to control weeds in organic and transitioning farming systems. Application of abrasive corncob in combination with either flaming or cultivation reduced total biomass, broadleaf biomass, and grass weed biomass. Application of corncob for in-row weed control at early leaf stages of corn is not as effective as late applications, however application at late stage of corn growth stage of development can have a detrimental effect on corn silage yield or corn grain yield. These results suggested the importance of applying corncob grit before or at the five-leaf stage of corn.

These results indicate that abrasive corncob grit for in-row weed control can substantially reduce weed biomass and increase corn yield.

CHAPTER 5

General Conclusions

Application of abrasive corncob grit to control in-row weeds can be used as an effective approach to control weeds and increase corn yield in organic systems and transitioning crop systems. Application of corncob at early leaf stages of corn development achieved a better weed control in both systems by decreasing the total weed biomass in both systems. These results indicated that abrasive corncob grit for in-row weed control can substantially reduce weed biomass, more specifically broadleaf biomass. An additional applications of corncob grit at the five- in combination with one- or three-leaf stage of corn resulted in better weed control.

Future perspectives

Information from weed control using corncob grit will be used to test different weed control settings in corn as well as other crops. Some of these new settings will include the use of different grit size particles, other grits sources, application at different growth stages of development different than the ones here proposed, different angles of the nozzles, different tractor speeds, and weed control on broadleaf crops.

The findings from this study indicates that broadleaf weed control can effectively be achieved with the use of corncob grit applied at different leaf stages of corn. Even though grass species are harder than broadleaf weed species to control, grass species can be to some degree, be controlled with the use of this technique.

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