ANNUAL BLUEGRASS EMERGENCE FROM FRAZE MOWED FAIRWAY SYSTEMS FUMIGATED WITH DAZOMET

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ABSTRACT

ANNUAL BLUEGRASS EMERGENCE FROM
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In the summers of 2018-19, two trials were conducted at the Hancock Turfgrass Research Center in East Lansing, MI to evaluate the viability of fraze mowing cultivation and dazomet fumigation for cool-season fairway renovations. Both trials were conducted on native and sand topdressed (TDS) blocks. In Trial 1 (Rate Study), plots were stripped with fraze mowing cultivation and dazomet was applied either; once at rates of 0, 293.7 , or 588.7 kg ha^{-1} or twice at rates of 146.8 or 293.7 kg ha^{-1}. Plots of Trial 2 (Disturbance Study) were subjected to 0, 15, 50 or 100% fraze mowing surface disturbance and uniformly fumigated with dazomet at 293.7 kg ha^{-1}. Dazomet was incorporated mechanically in either Trial via Tillage or Solid-Tine (ST) cultivation and followed procedures consistent with the fumigant label. 5-days after fumigation, all plots were seeded with creeping bentgrass (*Agrostis stolonifera* L.) [CBG]. In the Rate Study, interval treatments provided the most consistent control of ABG emergence across seasons. Only treatments applied once at 293.7 kg ha^{-1} failed to yield greater CBG cover than the control. In the Disturbance Study, plots fraze mowed to 100% and cultivated by tillage achieved the greatest ABG control but poorest CBG cover. Across trials, no single treatment provided complete or acceptable control of ABG and fraze mowing cultivation impeded CBG establishment. Fraze mowing cultivation simplified the removal of surface material but did not provide acceptable ABG control at any level of surface disturbance or dazomet treatment applied.

Dedicated to friends at the English Gardens nursery and the late George Dawes, who was my first mentor of agronomy. Dedicated to my late Grandpapa Lyle Bearss and Grandpa Gene, I know there's a special place in heaven for you guys. Dedicated to my Mom Libby, my Dad Chris, Luna Isabella, my best friend and little Sister Natalie, my big Sister Bridgette, my Brother Bob, and my little Nieces and Nephews Chloie, Cha-cha, Abigail, Chris and Josh. I also dedicate this to the ones who said I couldn't because without you I couldn't have.

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THE COMPETITIVE NATURE OF ANNUAL BLUEGRASS SPECIES

Description

Annual bluegrass (ABG) is an invasive, C3, cool-season, weedy grass species, and considered to be one of the most diverse plant species in the world today (Cross et al., 2015). Although it can spread vegetatively by its weak, stoloniferous growth habit, the ubiquity of ABG species are strongly associated to their fecundity and dense seedbank (Shem-Tov et al., 2003; Vargas et al., 2004). Many accept the idea that ABG exist as both a perennial (*Poa annua* L. f. *reptans* (Hasskn.) T. Koyama) [ABGP] and annual (*Poa annua* L. *annua*) [ABGA] variety (Gibeault, 1971; Mitich, 1998; Tutin, 1957), however, this is often still debated. Today, a majority of literature agrees that ABG species are an allotetraploid hybrid between *P. supina* Schrad. and *P. infirma* Kunth. (Chen et al., 2016; Huff et al., 2003; Mao et al., 2012). The *success* of either variety is highly dependent upon the habitat and climate in which they are grown (McElroy et al., 2002; Rudak et al., 2019). Both sub-species are well adapted to their environments and are widely distributed across the globe, with populations spanning from Sub-Antarctic to Texas and most any temperate climates in between. Previous research has demonstrated one way these species adapt so quickly is through maternal traits/effects inherited from prior generations (Johnson et al., 1998; Laossi et al., 2010). Generally speaking, ABGA is characterized as a bunch-type grass (Huff et al., 2003) most abundant in Southern climates while ABGP is weakly stoloniferous and common in the North. Some speculate sub-species can also be differentiated by seasonal emergence patterns, where ABGA peaks in Fall and ABGP, in late-Spring to early Summer (Yelverton, 2000). Although these differences can vary within sub-species and region, Calhoun (2010), Danneberger et al., (1984) and others offer evidence that emergence and seed production of either can be estimated by tracking the accumulation of

Growing Degree Days (GDD). ABG species serve the biggest threat to managed turfgrass systems for many reasons. As of 2015, ABG species were projected to be the third most widely distributed turfgrass species on US golf courses (EIFG, 2017)—this in spite of being a non-cultivated species. Today, turfgrass managers faced with ABG infestations have two options, manage it or *try* to eliminate it.

Reproduction

Poa annua reproduction varies by bio-type. ABGA is thought to exclusively reproduces sexually, though the reproduction of ABGP is often a point of contention. A majority of research revolving around ABG sub-species reproduction suggests that ABGA exclusively reproduces sexually (Koshy, 1969; Ruemmele, 1989; Vargas et al., 2004; Ellis, 1973). ABGP on the other hand is apomixic, also reproducing asexually through short stolons produced (Beard et al., 1978; Johnson et al., 1993; Timm, 1965). Ruemmele's research in the reproductive biology of ABG, however, refutes this claim with her observations, stating if ABG were an apomixic species, seed set would be expected to be similar between the two kinds of selfed inflorescences.Other evidence refuting apomixic reproduction in ABG includes; differences in seed set following self and outcrossed pollination and phenotypic differences among progeny produced from open pollination—all suggesting no clonal propagation, evidence refuting asexual reproduction of ABGP bio-types (Ruemmele, 1989). Flowers of both ABG sub-species are monoclinous/hermaphroditic, with apical florets of each spikelet typically being female (Ruemmele, 1989), however, morphology can vary by growth type (Johnson et al., 1993).
One of the first scientists to elucidate ABG taxonomy and origin was Tutin, whose primary focus was on reproductive capabilities among ABG sub-species. For both bio-types (ABGA and ABGP), Tutin observed; high frequency of selfing (Hackel, 1904; La Mantia et al., 2011; Ellis,

1973), which may account for up to 85% of pollination, the rare occurrence of cross-pollination, as well as facultative cleistogamy (the self-fertilization within the floret), protogyny (the ability for a female to become hermaphroditic) and vivipary (germination of seed while still attached to plant) (Tutin, 1957). It would later be determined that outcrossing and apomixic reproduction both increase under stress from plant density, humidity and temperature (Chen et al., 2003; Johnson et al., 1993; Mengistu, 1998). Tutin's observation of cleistogamy were corroborated by Hackel amongst others, but refuted by Koshy, who in his study found no evidence of pollen liberation within the floret suggesting cleistogamy did not occur (Hackel, 1904; Tutin, 1957; Ellis, 1973).

The genetic variability within the ABG sub-species and bio-types is clear—it's not easy to classify in any way, shape or form as the genetic variability that exists within ABG species is too diverse. Tutin lends reason to ABG's high genetic and phenotypic variability to the sub-species ability to: flower and fruit (pending ABGA or ABGP) continuously throughout a season, germinate rapidly, small seed size, ability to disperse mechanically and naturally, as well as self-pollinate.

The Seedbank

"The persistence of a given seed population in any environment depends on its resistance to exiting the seed bank *via* germination or death, and on its exposure to environmental conditions that are conducive to those fates" (Long et al., 2015). If the above sufficiently characterizes a persistent weedy species, then annual bluegrass species of cool-season turfgrass systems fit the bill. It can be generalized that ABGA seed is transient in nature and ABGP, persistent. ABGA and ABGP sub-species can produce up to 2,250 to 13,000 seeds per plant respectively, which can be dispersed by a number of vectors and remain dormant for 1 day to 6 years (Lush, 1988;

Roberts et al., 1973; Roberts, 1986). In the seedbank, counts of 30,000-35,550 seeds m^{-2} are not uncommon (Bond et al., 2005; Gibeault, 1971). These traits make managing ABG species a formidable opponent, particularly in turf systems (Cordukes, 1977; Holm et al., 1997). As mentioned, the genetic diversity of both weeds enables them to adapt quickly as needed, thus "there is a transient and persistent component" to *Poa annua* spp. seedbanks and persistence (Wells et al., 1974). Seedbank persistence of both sub-species are dynamic, largely in part to maternal effects inherited from the mother plant, which enables their seedbanks to exist as types I and II transient, and type III persistent. Although most ABG species seed are transient (ABGP type II germinating in spring and ABGA, type I, germinating in fall), studies have suggested that both sub-species transient seedbanks can become persistent (types III and IV) following cultivation or burial of the seed, causing a consistent flush of seedheads to be produced all season long (Kaminski et al., 2007; Lush, 1988). A niche characteristic of these species and further complicating the predictability of emergence

Seedbank Dormancy

As research has shown, ABG seedbanks are extremely diverse. Similarly, so are the mechanisms that govern ABG seed dormancy. Harris classifies ABG species as demonstrating secondary dormancy in soils, specifically, when the seeds become buried following seed dispersal from the plant (Harris, 1961; Lush, 1988). Conversely, Naylor suggested ABG seed is subject to primary dormancy, due to the high variability of germination within the species (Naylor, 2002). Seeds from the same plant either germinated within days or remained dormant for months to years—attributed to inherited environmental maternal effect. It has been suggested that a vernalization period may be needed for *some* fraction of ABGA seeds of a generation to "break-dormancy"—a potential indication of a required "after-ripening" period. This can be observed in southern climates where peak ABGA germination occurs in the Fall (as temperatures fall), following the seeds dispersal the season prior (Kaminski et al., 2007; Standifer et al., 1988). These references, amongst others discussed, all indicate ABG species *are* subject to dormancy cycling. Other studies have shown increased photosynthesis and overall seedling response in 2nd generation progeny, when "mother plants" and the succeeding generations were exposed to high CO2 concentrations—further driving home the overarching premise that ABG species are strongly influenced by maternal effects and once more, are capable of quickly adapting to environmental changes as needed (Bezemer et al., 2012).

Predation and Dispersal of the Seedbank

ABG seed is ubiquitous in the dung of vertebrate species and highly subject to dispersal by mechanisms of anthropogenic activity, water, and wind (Clifford, 1956; Ruemmele, 1989; Warwick, 1979; Wu et al., 1987). In a national park study, ABG made up 67% of all seed species retained in horse dung (Weaver et al., 1996). A study that investigated the viability of the Canadian goose as a potential ABG seed vector found ABG germination to be low. Despite ABG being amongst the most common seed in goose feces, of 127 fecal samples planted, only 4 germinated. This suggests pre-dispersal by geese is likely, but the digestive tract of the bird damages the seed too much to allow for it to germinate (Ayers et al., 2010).

In another study, ABG seed pre-dispersal and germination was assessed in grouse, sheep, and cattle populations. Cover and germination of ABG seed from dung was significantly lower in field conditions when compared to the greenhouse, and maximum cover was achieved through vegetative deposition of ABG plant parts (stolons) versus ABG seed alone (Welch, 1985). These and other findings seem to suggest, ABG seed viability from vertebrate pre-dispersal predation varies amongst vertebrate species, however such animals can serve as important vectors for pre-dispersal of *vegetative* ABG parts. Seed of ABG species appear to be more prone to post-dispersal predation, specifically as a function of invertebrate predation. Comparing seed cards to seed trays for seed predation studies, researchers found variability between species of seed predation from cards vs. trays. When placed in trays and enclosure trays, it was determined that vertebrates and invertebrates shared equal roles of post- and pre-dispersal (Saska et al., 2014). During trials which assessed weed-cover and predation of several species in cereals, a direct correlation between the "frequency and density of *Poa annua* L." and carabid beetle populations was observed (Speight et al., 1976). Other trials have shown ABG seed to be a preferred food source of carabid beetles. In treatments containing only granivorous carabid species and ABG and chickweed seed, daily ABG consumption was 54.3 seeds per day (and only 14.3 chickweed). When the same seeds were added to a mixed population of granivorous and carnivorous carabids, post-dispersal predation was significantly lower (46.6 seeds per day) but still relatively speaking, high.

Competetive ability

ABG's ability to compete is most strongly influenced by its seedbank and belowground population. The species themselves have no unique methods for competing with other plants like allelopathy, although studies have shown them to be influenced by *some* allelochemicals (Wu et al., 1998). So how do ABG species compete? Competition within mixed communities is complex for many reasons and can most simply be characterized by direct interference and resource competition (Vargas et al., 2004) . In support of this argument, the competitive ability of a species is most largely influenced by how it is managed (particularly for ABG species). Differences in gradients of; fertility (Dest et al., 1981; Goss et al., 1976; Guertal et al., 2018; Kohlmeier et al., 1983; Kuo, 1993; Varco et al., 1986), pH (Kuo, 1993), water (Beard, 1970;

Beard et al., 1978; Haes, 1956), environmental conditions (Juhren et al., 1957; Morgan et al., 1965; Sprague et al., 1937; Youngner, 1959), cultivation (Youngner, 1965, 1967), light and stimuli that effect growth (Bogart et al., 1973; Warwick et al., 1978) can all be manipulated to favor or disfavor or favor ABGs ability to compete (let alone survive) and ultimately, influence subsequent generations that follow. Similarly, factors that cannot always be controlled like light and temperature may serve an equally important role on ABG competition.

Barriers to sustainable management

All sustainably managed systems share three overarching characteristics. They are (i) resource conservative, and, to an extent, (ii) self-reliant (Robertson, 2015) and (iii) the embodiment of usufruct (Chambers et al., 1986)—that is, the use of resources today in a way that doesn't jeopardize their use tomorrow (O'Neill, 2019). A system threatened by a weed whose seedbank grows exponentially cannot be managed sustainably (Norsworthy et al., 2012). Therefore, when ABG species invade golf course systems they become anything but sustainable, immediately inviting the potential for evolved herbicide resistance and infestation of species-specific pests which must be managed by anthropic inputs of water, fertility and chemical strategies. Furthermore, ABG has poor tolerance to stressors relative to CBG including temperature (Beard, 1969; Bond et al., 2005; Cordukes, 1977; Dionne et al., 2010; Froud-Williams, 1985; Vargas et al., 2004), moisture (Hutchinson et al., 1982; Laskowski, 2017; Mitich, 1998; Springer et al., 2016; Warwick, 1979), light (Bond et al., 2005; Buhler, 1997; Danneberger et al., 1984; Gibeault, 1971; Grime et al., 1974; Johnson et al., 1997; Sprague et al., 1937; Vargas et al., 2004) and fertility (Beard et al., 2001; Bond et al., 2005; Gibeault, 1971; Grime et al., 1974; Nam-Il et al., 2001; Schlossberg et al., 2007; Snaydon et al., 1986). Moreover, if ABG proliferates as a function of its seedbank and the seedbank is a function of its aboveground production, returning sustainable properties of a system contaminated with ABG infestations requires an exponential depletion or elimination of the seedbank.

Herbicide Resistance

The size of a seedbank prior to its exposure to herbicides is often labeled a key contributing factor to evolved herbicide resistance by weed species (Neve et al., 2011). Today, ABG sub-species have reported herbicide resistance to eight sites of action worldwide—five cases in the US. In 2017, ABG species were ranked the third most important weed resistance species worldwide (Heap, 2019). Some of the most significant products that no longer control ABG where resistant (R) types exist include: broad spectrum herbicides like; Glyphosate (EPSP synthase inhibitor) and atrazine (PSII inhibitor), pre-emergent, microtubule inhibitors like; dithiopyr, pendimethalin, and prodiamine, and selective post-emergent herbicides like; foramsulfuron and rimsulfuron (ALS inhibitors), simazine (PSII Inhibitor), and DCMU (PSII immobile). So far in the U.S., only Tennessee has reported multiple herbicide site-resistance in ABG to ALS and PSII inhibitors. The major driving principles behind these rapidly developing resistances in ABG species is the increased selection and use of such herbicides and the dense way ABG populations grow. In 2003, researchers responded to reports of developed ABG resistance to simazine in a sod farm (first ABG resistance reported in sod production). Brosnan et al. (2017) conducted a series of tests to confirm the report. In greenhouse trials, known (R) and susceptible (S) ABG bio-types were treated with simazine at maximum label rates. While 100% control of the known S-ABG was achieved, control peaked at only 33% for suspected R types. In field trials, simazine control of the R type ABG was <3%. Using sequencing, researchers confirmed developed ABG target-site resistance (TSR) to simazine by mutation of the D1 protein (Brosnan et al., 2017). Another study showed increased production of seed by R types under increased ALS herbicide selection (Cross et al., 2015). Developed herbicide resistance in ABG species has left (and continues to leave) turfgrass managers with fewer tools they once relied on for ABG eradication. Managing the weedy species is becoming their only option.

Diseases and Insects

Although bluegrass (*Poa* spp.) species are more prone to species specific pests, infection of ABG populations in golf course systems by diseases like anthracnose (*Colletotrichum* spp.), Summer patch (*Magnaporthe poae*), and bacterial infections like *Xanthomonas translucens* pv. *Poae* and *Xanthomonas capestris* pv.*poannua* are all too common. Unlike the former two, the latter two cannot be successfully managed without anti-biotics which are not commercially available and expensive to produce. Elimination of the disease from the soil is only possible through soil sterilization (Vargas et al., 2004). Effective chemical management strategies for anthracnose are limited due to the rapid development of resistance by sensitive strains to common modes of action including benzimidazoles (Detweiler et al., 1989), DMIs (Wong, 2007), and most recently QoIs (Young et al., 2010). Despite this, research has demonstrated alternative management strategies like early and frequent sand topdressing (Wang et al., 2018), increased fertility (Hempfling et al., 2017; Inguagiato et al., 2016) and mitigation of summer stress with irrigation (Roberts et al., 2011) are effective measures for control.

Another emerging threat to ABG systems is the annual bluegrass weevil (*Listronotus maculicollis*) (ABGW), which is devastating to golf course managed turf system. Although it is not host-specific to ABG parse, it is the insects primary host. Populations of the pest have been reported in Southeastern Canada (Simard et al., 2007) northeastern US (McGraw et al., 2009). As is the case of many once effective herbicides and fungicides for control of and pest management within the ABG species, in 2009 ABGW resistance was reported to pyrethroid insecticides (Ramoutar et al., 2009). Even non-chemical management strategies come with tradeoffs. Reduced mowing heights for instance, effectively reduce ABGW oviposition and populations (Czyzewski et al., 2017) but increase ABG heat stress and susceptibility to anthracnose infection—both of which may improve at the expense of increased N fertility and supplemental irrigation.

Limitations of non-chemical alternatives for ABG management

As regulations push to eliminate chemical control in intensively managed systems like turf and options become limited, now more than ever, practitioners must begin exploring alternative strategies. Unfortunately, many of these options which have been assessed extensively and are significantly limited by their scalability and other interacting factors. The following are a few such options and some of their limitations.

Xanthomonas campestris for instance, is a relatively effective biological control for ABG, but requires applications 3x/week and must be applied continuously throughout the season for it to be effective (Bargona et al., 1992; Zhou et al., 1995). In addition, timing and placement of this treatment is critical, as it must be applied immediately following mowing to enter the plant and is highly susceptible to UV damage in full sun conditions. Other biocides like *Pseudomonas fluorescens* which produce ABG growth suppressing chemicals have also been proven effective (Kennedy, 2016), but are limited by similar factors. Moreover, biocides fail to address the ABG soil seedbank.

Some cultural approaches that take the seedbank into account include soil steaming and solarization. Steaming effectively reduced ABG emergence between 80-98% however, steam machines require copious amounts of fuel, eliminating any sustainable aspects to this approach. Steam is also reportedly, and extremely slow process, sterilizing soils at a rate of 70-100 hours per hectare (Ascard et al., 2007). Yet another highly effective non-chemical approach is solarization, which is proven to be effective against the ABG seedbank. Peachey et al., (2001) reduced survival by 89-100% in the top 5 cm with solarization, but left seed buried deeper, unharmed. As is the case for all of these methods, perhaps the biggest barrier to solarization is scale—solarizing vast acreage of a fairway would be a laborious task and highly impractical.

FRAZE MOWING CULTIVATION

In 1996, Ko Rodenburg, a Dutch parks and grounds manager in Rotterdam, Holland began his search for an all-encompassing cultivation machine: a system that could smooth the playing surface, remove organic matter, and deplete the annual bluegrass (*Poa annua* L.) soil seedbank. His idea lead to the development of both the fraise/fraize/fraze mowing system and the "Dutch method" of cultivation. As a practice, *fraise* mowing cultivation is used to (i) remove shallow-rooted weeds, accumulated thatch and surface debris at a given depth, leaving the crown of deeper-rooted plants for their subsequent regrowth, or (ii) remove all herbage and soil for new establishment or re-sod. As a machine, fraise mowing systems consists of several blades attached to a Power Take-Off (PTO) driven rotor which discards of said material via a conveyor belt (Campey-Imants, 2009; Pass, 2000). The first fraise mower, the FieldTopMaker (FTM), was manufactured by GKB machines in cooperation with Ko Rodenburg, and marketed by Van der Pols International as the KORO (aptly named after its inventor). In its original form, the FTM featured L-shaped blades which were extremely aggressive, often causing initial concern to groundskeepers who used it. Upon its release, Ground Managers were reluctant to use it due to its aggressive nature and their uncertainty of turf recovery and grow-in time needed following cultivation. In fact, the FTM (and fraise mowing in general) did not come into vogue until 3-4 years after its release, with its earliest and most widespread success in the UK—this, largely thanks to Engineer, Richard Campey, his team, and success stories which quickly spread across the UK and eventually Europe. With any success, dispute arose over ownership and distribution rights in the early 2000s between Ko Rodenburg and GKB. Settled in court, Ko Rodenburg parted ways with GKB and was given rights to the Koro and FTM name. After litigations, Rodenburg joined forces with Dutch manufacturer, Imants for continued production of the Koro, and with English company, Campey Turfcare for its further distribution.

Fraize mowing: the Universe Rotor

By 2011, the demand for a more versatile, accurate and hygienic fraise mowing system peaked, and was threatened by the popularization of hybrid systems like, Grassmaster, which slowly became commonplace in performance turf systems and pitches in the mid-2010s. Though highly successful in conventional turf systems, the L-shaped blades of the FTM rotor were ineffective at fraising and cleaning material that accumulated in hybrid systems and had high potential for damaging their synthetic fibers when set incorrectly. Carl Pass, Director of Premier Pitches Limited, and Steve Braddock, Grounds Manager of Arsenal FC became the major driving forces to finding a solution. After two prototypes failed tests on Grassmaster systems at Arsenal's, Colney Training Facility, the future of fraise mowing was at stake. A solution finally emerged thanks to ideas of former Campey Product Director, Simon Gumbrill. His idea—change the design AND action of the FTM. By configuring teeth on rotors in a spiral configuration, he thought, material could be "combed" from, rather than "shoveled" into the system and further, be un-destructive to synthetic fibers. Thus, the Universe Rotor, and *Fraize* mowing cultivation was born—fraise mowing cultivation for hybrid turf systems (Bearss et al., 2019; Pass, 2012). In 2011, the Universe rotor made its debut at Reebok Stadium in Bolton, England—a Desso Grassmaster hybrid pitch. With widespread success across Europe, in 2011, Richard Campey invested in promotion and marketing of his companies' machine to the US where it quickly reached the ears of several prominent US groundskeepers.

Fraze Mowing in the US

With the help of Gumbrill, two US groundskeepers played instrumental roles in the adoption of fraise mowing cultivation in the US; Allen Reid, Groundskeeper at FC Dallas Park, Dallas, TX and Jerad Minnick of Growing Innovations then, Groundskeeper at SoccerPlex, Baltimore, MD (Bearss et al., 2019; Minnick et al., 2013). Fraise mowing first debuted in the US at the Baltimore SoccerPlex for a project consisting of organic matter and annual bluegrass seed removal, and reseeding of Kentucky Bluegrass (*Poa pratensis* L.). Prior to project initiation, Gumbrill invited contractors from the area, Academics and Groundsmen to the demonstration and challenged the audience with the question; "who believes the field will (could) be back in playing condition in 33 days, after seeding?" With responses ranging from "impossible" to "only if you sod", Minnick successfully completed the project with the FTM in only 33 days. Today, fraise and fraize mowing is widely used in the US. In recent years, fraise mowing has found its place in Bermudagrass (*Cynodon dactylon* L.) systems where the surface is stripped to the crown, and stoloniferous growth is stimulated with quick recovery and rejuvenation of the playing surface. This technique is called Fraze mowing. Although fraze mowing cultivation in the US is primarily used in sports turf systems, several warm-season golf courses across the world have also adapted fraze mowing for their fairways.

Fraze Mowing Systems

Today there are three prominent brands of fraze mowers available on the market. All three models have a working depth of 5.08 cm and utilize a conveyor belt to remove the material. Each system has at least one feature that distinguishes it from its competitors. The Redexim Turf

Stripper 1200 utilizes the original L-shaped fraise mowing blades which are easily interchanged with proprietary Verticut knives. In addition, this system has the lowest number of cutting blades (14) of the three for easy maintenance. The GKB combinator, which is most similar to the preferred KORO FTM, also offers a system with interchangeable blades (56-92, pending model), and is available at four working widths. The KORO FTM, is by far the most dynamic of the three, with three rotors (Standard, Universe and Terraplane), and working widths ranging from 1.2-2.5m, and Universe rotor blades and configurations that allow the operator to cultivate 15, 25, 30, 50 or 100% surface area at a given depth. Regardless of how its used, fraise, fraze, fraize mowing cultivation has become a worldwide standard for high-quality turf management, which is demonstrated by the continuous development and improvement of the practice/systems. As of 2019, Gumbrill has begun investigating new rotors which have the capability of fraise mowing warm-season systems and further improving fraize mowing practices of hybrid systems.

Fraze Mowing Research

The current body of literature behind fraze mowing cultivation is limited, and refereed papers on the topic are sparse, with only three published paper to date. In the earliest published fraze mowing trials, Baker et al., (2005) evaluated perennial ryegrass (*Lolium perenne* L.) establishment and annual bluegrass (*Poa annua* L.) [ABG] control in plots lightly scarified with a Koro FTM, fraise mowed to 18 mm, or not cultivated at all. After seeding, plots were subjected to varying moisture regimes and chemical treatments and assessed based on botanical composition, several playing quality metrics and ground cover of perennial ryegrass over three seasons. Across seasons, Koro effects on playing quality were significant, achieving the greatest surface hardness with scarifying treatments and greater ball rebound for either fraise mowing treatment than the control. Researchers also noted fraise mowing cultivation yielded ABG populations lower than the control across all three seasons, with the greatest reduction in ABG populations when plots were fraze mowed to 18 mm. Such findings seem to demonstrate and support fraze mowings potential as a chemical alternative for pest suppression. Other studies, however, seem to suggest pest management with fraze mowing is most effective when it is used with other management tools. Preliminary results from an on-going 2017 study, reported a 26% reduction of ABG in Zoysiagrass (*Zoysia japonica* 'Meyer') plots fraze mowed to 2.54 cm (Brosnan et al., 2017), and speculate enhanced ABG control to be possible when fraze mowing is combined with a chemical program. Researchers concluded similarly in another study which evaluated fraze mowing for control of Spring dead spot (SDS) [*Ophiosphaerella herpotricha*] of bermudagrass. Although SDS reductions were significantly less in fraze mowing plots than those only treated with fungicide, severity was lowest when fungicides were combined with fraze mowing cultivation (Miller et al., 2017). While such studies demonstrate potential benefits of fraze mowing, results from others have been less promising. In a 2017 bermudagrass trial conducted at two locations, fraze mowing cultivation at three depths was compared with vertical mowing cultivation for its effectiveness as a preplant method during perennial ryegrass overseeding. Turf cover was not comparable with the control and vertical mowing cultivation in fraze mowed plots until 2-3 weeks after cultivation. By the end of trials, researchers concluded fraze mowing preplant cultivation yielded comparatively thinner turf cover than other treatments, and thus, was an ineffective practice during overseeding (Munshaw et al., 2017).

DAZOMET FUMIGATION

Phase-out of methyl bromide and soil fumigant background

Until 2005, Methyl bromide (MB) was the preferred fumigant for controlling soil borne fungi, nematodes, and weeds in a variety of annual and perennial crops (Fraedrich and Dwinell, 2003; Martin, 2003; Simpson et al., 2010). In 1993, MB was the third most commonly used pesticide in the U.S. (22 to 26 million kg), but now applications have been significantly reduced to 1-3 million kg (Aspelin, 1997; Atwood and Paisley-Jones, 2017). The decline was due to MB being classified as a Class I ozone-depleting substance under the Montreal Protocol and the subsequent phase-out (UNEP, 2012). This is a multifaceted issue, and currently, economically viable alternatives haven't been identified for various production systems. In 2000, California and Florida utilized 75% of the MB applied in the U.S. In total, tomatoes, strawberries and peppers accounted for 30, 19, and 14% of MB applied, respectively (USDA & ERS, 2000). Colorless, odorless and lethal, MB not only harms the ozone, but is also harmful to humans (EPA, 2008). Since 2005, MB has been systematically phased out from agricultural use with limited Critical Use Exemptions (CUE) available for cropping systems (EPA, 2016).

Description of Dazomet and MITC fumigants

Today, only six soil fumigants registered by the U.S. Environmental Protection Agency, all of which are considered Restricted Use Pesticides (RUP) (EPA, 2016). Further, only dazomet, metam-sodium, and metam-potassium have been shown to provide adequate control of fungi, nematodes, and weeds (EPA, 2008). Together, these fumigants share two characteristics. First, they are non-halogenated fumigants, and therefore, do not deplete the ozone. Second, they emit the same active biocide agent, methyl isothiocyanate (MITC). Similarities between fumigants end there. While both forms of metam are liquid by nature, dazomet (tetrahydro-3, 5-dimethyl-2H-1,3,3-thiadiazine-2-thione) is granular, the only RUP fumigant currently labeled to control ABG (*Poa annua* L.) seed germination in soils, and the only RUP fumigant labeled for turfgrass systems.

First registered in the United states in 1967, dazomet was initially used as an algaecide, bacteriostat and microbicide, before being re-registered with the EPA in 1980 for pre-plant use in ag systems (EPA, 2008). Sold today under the tradename Basamid G (AMVAC), its label extends use in ornamental sites, field nurseries, turf sites, greenhouses, non-bearing crops, and for sterilization of soil media. Dazomet can effectively *eliminate* most weed and seed populations of a soil, and *control* nematodes and various soil-borne fungi and bacteria. Activated through hydrolysis in water its efficacy is a function of wind, incorporation depth, target organism, irrigation, ambient and soil temperatures, and duration of gas containment within the soil profile (Fritsch et al., 1995).

Of all factors which influence the activity of dazomet and MITC, perhaps none have greater effect on MITC activity than irrigation and temperature . One major environmental concern of MITC is its high mobility in the soil which is directly related to the irrigation is the potential for groundwater contamination of soils with a shallow water table (Zhang et al., 2007). Moreover, irrigation is directly related to the off-gassing rate of MITC, which can be significantly reduced when 2.54 cm of water is used to seal the soil surface immediately after the fumigant is applied (Simpson et al., 2010). In addition, microbial degradation of dazomet in soil is slowed with excessively high soil moisture content but enhanced when temperatures exceed 30°C (Gan et al., 1999). With no irrigation, more than 60% of applied dazomet can be lost to volatilization in the atmosphere, however, with adequate irrigation for 5-days following application, less than 1% of hydrolyzed material is lost to the atmosphere (Zhang et al., 2007)—demonstrating the critical nature of irrigation on fumigation efficiency.

MITC fumigants have an interesting effect on soil nitrogen mineralization. For dazomet specifically, it is enhanced following its application in some soil types (Gasser et al., 1964). A likely influencing factor for enhanced N-mineralization may be from ammonia and ammonium which combined, make up 34% of dazomet volatiles during degradation (Fritsch et al., 1995). More likely, enhanced mineralization is a function N released following the lysing of soil microbes from fumigation (Chabrol et al., 1988). Other dazomet by-products in soils include, CO_2, sulfate, hydrogen sulfide, carbon disulfide, formaldehyde and methylamine. Although the majority of MITC is degraded from soils in only hours following hydrolysis, significant quantities of some of these compounds may remain for as long as 3-20 days (Ruzo, 2006). Moreover, and possibly attributing to, microbial activity is compounded in soils where MITC fumigants in general have been applied within 5-50 days prior (Smelt et al., 1989)

Renovating turf systems with dazomet

Dazomet is the most effective and currently only fumigant labeled for use in turfgrass systems. Two observations which are consistently reported in fumigant trials are; (i) an increased efficacy of fumigant under tarp cover and (ii) enhanced growth of propagated grasses corresponding with higher dazomet rates. Benefits of fumigation under tarp cover include; increased duration of soil to gas exposure, synergistic solarization of the soil, reduced seepage from point of application, and increased efficacy at lower rates (Eitel, 1995). Unfortunately, in systems as large as golf course fairways, tarp cover in not always a practical option. Some of the earliest dazomet fumigation studies in turf systems to demonstrate the critical nature of tarp fumigation were conducted by Park and Landschoot. In their first study, cultivated bentgrass plots maintained as a fairway system, were fumigated with one of four rates of dazomet and then tarped or left uncovered. Across fumigant rates and trial seasons, ABG populations were reduced by 98% in tarped plots. For uncovered plots, only those fumigated at the highest rates obtained comparable ABG reductions in either year, but never matched the level of efficacy observed in tarped plots (Landschoot et al., 2003). In a subsequent study, Park and Landschoot's research was replicated in putting green managed systems. Across research seasons, all applied rated resulted in complete control of ABG emergence under tarp cover, however in uncovered plots, no treatment provided comparable control (Landschoot et al., 2004). In addition to their similar observations in either trial (fairway and putting green), Park and Landschoot also found enhanced growth in creeping bentgrass with higher fumigation rates and reduced intervals of seeding after fumigation. These studies laid the groundwork for many of the studies to follow. Branham et al., (2004) began a new path of dazomet research, exploring the most effective rates of dazomet for ABG control without tarp cover using various soil preparation methods and bentgrass seeding intervals and how these variables influence ABG seed viability with depth. In their studies, timing of dazomet application in respect to incorporation (before vs. after) made no difference on ABG emergence. Like Park and Landschoot's fairway studies, no single rate completely controlled the ABG emergence, and only the highest rates were effective. Through regression analysis, Branham et al. (2004) also demonstrated a common principle across weed science studies—reducing the interval of seeding time after fumigation/chemical control subsequently reduces the emergence of competing weeds. One of the most critical pieces of data to come from this study, however, was the conclusion that 80% of viable ABG seed resides in the upper 1.23 cm of soil. In addition, Branham et al. reported optimum bentgrass establishment is possible when seed is propagated 1-3 days after fumigation. Corroborating with Park and Landschoot, seeding at a reduced interval after fumigation may; provide increased competition with ABG emergence, and enhance bentgrass establishment by utilizing mineralized nitrogen present shortly after fumigation. In some of the most recent dazomet fumigation work, Bravo et al., (2018) evaluated tillage and incorporation effects with and without tarp cover in cool-season climates. In addition to evaluating incorporation methods, Bravo et al. also assessed Branham et al. claims of ABG seed viability with depth by removing soil removal prior to fumigation. He also evaluated the efficacy of split applications of fumigant. In support of tarping and Branham's work, the greatest control of ABG was observed in plots fumigated at the highest rates without tarp cover, and where sod was removed with or without tarp cover for all rates except the control. Split applications yielded results neither greater nor lesser than all treatments. Furthermore, tillage seemed to have comparable effects on ABG emergence across treatments when compared with those tarped. Although all these studies were conducted in cool-season turf systems, many of these principles also extend into other species and warmer climates. In bermudagrass control trials conducted by Jeffries et al., (2017) fumigant efficacy was equivalent to tarped treatments when high-rate dazomet fumigation was incorporated via tillage.

DATA COLLECTION METHODS

Digital Image Analysis (DIA)

A significant shortcoming of visual estimations of cover, quality, etc. is the subjectivity of data—they are no more than estimations. In the past 30 years Digital Image Analysis (DIA) has become one of the most widely used methods for overcoming this boundary, turning subjective data into objective data. DIA generally refers to the software quantification of several metrics like quality or cover, from digital images based on their pixilation, distribution of red, green and blue (RGB) coloration, hue (0-360°), saturation (0-100% color) and brightness (or intensity of light scaled 0%-white to 100% black) or together, HSB (Karcher et al., 2013). Because such image characteristics are highly affected by light, controlled and consistent light conditions are critical for obtaining accurate results. This is commonly achieved through with a "light-box", a simple structure equipped with light fixtures that emulates daylight. In addition, consistency of images are largely a function of camera quality, shutter speed, aperture, ISO and white balance (Karcher et al., 2013).

Creating macros within analysis software is often a laborious task convoluted with extensive coding programmed for each analysis. The two software most commonly used for DIA are SigmaScan Pro (Systat Software, Chicago, IL) which is no longer made, and the opensource program, Image J (National Institutes of Health USA]). Douglas E. Karcher and Michael D. Richardson (2005), regarded as pioneers of this method in turfgrass research, streamlined this process and developed a macro program for SigmaScan enabling researchers to analyze images under setting tailored specifically to turfgrass. In 2017, (Zhang et al., 2017) developed a similar macro for use in ImageJ. In 2018, Karcher took it a step further and developed the subscription Java Applet TurfAnalyzer, which as its name implies, is coded specifically for turfgrass image analysis and conducts analysis at a much faster rate than competing software.

In the TurfAnalyzer applet, HSD threshold settings from a single image are manipulated by the user, and then applied to all images to quantify values of Color and Cover amongst other values. Color, which is quantified as a value of Dark Green Color Index (DGCI) uses the selected threshold to determine the average color of green pixels at that range within each image. Cover is assessed from the number of green pixels in each image at the specified threshold, divided by the total number of pixels within each image (Richardson et al., 2001). After each analysis is complete, corresponding values for each metric quantified from each image are automatically sorted into an excel spreadsheet.

INTRODUCTION: THE COMBINED EFFECTS OF DAZOMET FUMIGATION AND FRAZE MOWING CULTIVATION ON ANNUAL BLUEGRASS EMERGENCE

Although the defining attributes of a sustainable system varies, literature most commonly characterizes them to be resource conservative and have greater reliance on internal “eco-services” than anthropic inputs (Robertson, 2015). In recent years, sustainability has become a buzzword in the turf industry and the objective of many U.S. golf course practitioners. Since 2005, median maintained golf course acreage has declined (Gelernter et al., 2017), resulting in significant reductions of irrigation (Gelernter et al., 2015) and fertility. Despite these strides, fungicide and herbicide use continues to rise (Gelernter et al., 2016).

A plausible culprit for this contradictory trend and target of many chemical applications is annual bluegrass [ABG] (*Poa annua* L.)—the third most common species found in golf course systems.(Gelernter et al., 2017). In part, the ubiquity and success of ABG is a function of the species fecundity. Of the thousands of seeds each plant can produce annually (Holm et al., 1997), a majority of those viable reside in frequently disturbed soil depths between 1.27-2.54 cm (Branham et al., 2004; Green et al., 2019). One of the most important aspects of controlling ABG expansion is seedbank management. When an exponentially growing seedbank of fecund species is left unmanaged, implementing sustainable management practices can be become a challenge (Norsworthy et al., 2012). Seedbank size prior to herbicide exposure is also amongst the most critical factors for managing the rate in which herbicide resistance evolves within a weed species (Neve et al., 2011).

As of 2019, only two weed species were resistant to more herbicide sites of action than ABG, globally (Heap, 2019). The dependence on chemical control strategies has become evident in managed turf systems along the transition zone and Southern US, where heavy selective herbicide pressure has led to evolved herbicide resistance in ABG populations at six sites of action domestically (four in golf courses) and several cases of multiple site resistance. When the aboveground population can no longer be controlled, deposits to the seedbank only proliferate. Old and new post-emergent chemistries like bispyribac-sodium and methiazolin (respectively), which are effective against aboveground populations (Brosnan et al., 2017; Brosnan et al., 2013), fail to address the seedbank. Alternative chemical strategies like Plant Growth Regulators (PGRs) are effective at suppressing seed production, however, they fail to provide complete seedhead control (Jeffries et al., 2013; McCullough et al., 2005; McCullough et al., 2013). Moreover, such methods are not sustainable options. With recent reports of evolved ABG resistance to seedbank targeting pre-emergent herbicides like prodiamine (Breeden et al., 2017), effective ABG control options have become limited. It is critical non-chemical ABG management strategies be evaluated for golf courses.

The most common method for addressing the ABG seedbank on golf courses is through renovation. Since 2006, more than 1,200 golf courses have undergone major renovations (NGF, 2019). Beyond the aesthetics and enhanced playability, a renovation provides, removal of the ABG seedbank allows practitioners to use their resources more efficiently thereby permitting more sustainable management practices (Rogers III., 2018). During renovation, soils contaminated with ABG are typically sterilized, removed or both. The efficacy, practicality and subsequent cost of either method is limited by spatial constraints and therefore, confined to smaller areas like putting greens.

The only sterilant currently labeled for golf courses today is dazomet, sold under the tradename Basamid G. Granular by nature, it is activated by water, has a short soil half-life and quickly hydrolyzes to emit the noxious gas, Methyl isothiocyanate (MITC) (Smelt & Leistra, 1974). Like its predecessor methyl bromide, the efficacy of dazomet is significantly enhanced when gases are contained via tarp cover. Research suggests the loss of MITC gas can be significantly reduced in uncovered tilled systems by creating a surface water seal (Neumann et al., 1983). The percolation, diffusivity and degradation of dazomet and MITC are also strongly influenced by soil texture, moisture and temperature (Eitel, 1995; Fang et al., 2018; Gan et al., 1999; Gerstl et al., 1977; Zheng et al., 2006).

As it's label currently mandates, dazomet rates are restricted by how it is incorporated and the systems to which it is applied. On golf course fairways for instance, dazomet can be applied at rates of 293.7-588.4 kg·ha^{-1} when mechanically incorporated (ie. tillage or other cultivation), or at 73-293.7 kg·ha^{-1} when surface applied. Under tarp cover, Landschoot et al., (2003) observed 98% reductions in ABG emergence from fairways dazomet fumigated at 194 kg ha^{-1}. Without cover reductions were still appreciable, but only at maximum labeled rates.

More recent evidence suggests removing a depth of contaminated soil could offset the need for tarp cover during fumigation (Branham et al., 2004; Green et al., 2019). Bravo et al., (2018) observed reductions of 91-97% ABG from untarped fairway systems after removing the upper 3.8 cm of soil, fumigating at maximum label rates and mechanically incorporating. Short of sod cutting, no efficient methods for soil removal from large systems have been evaluated.

One option commonly used for seedbank and thatch management in sports turf systems and bermudagrass (*Cynodon dactylon* L.) re-establishment in southern climates is Fraze mowing cultivation. Functioning similar to a flail mower, a PTO driven rotor spins at a given depth removing cultivated material from the surface before disposing of it via a conveyor belt. The most popular fraze mower today is the Campey-Imants KORO FieldTopMaker (FTM) (KORO

FieldTopMaker 1.2; Campey Turf Care Systems, Cheshire, UK), which can be manipulated to affect 100%, 50%, 30%, 25% and 15% surface area of material per depth.

To assess the potential of Fraze mowing cultivation for cool-season fairway renovation, two studies were conducted evaluating its effects on ABG emergence and CBG establishment, when combined with Basamid fumigation. In Chapter 1, ABG emergence and CBG establishment are assessed as a function of fraze mowing surface disturbance, and in Chapter 2, as a function of dazomet rate and interval. Both studies shared three overarching objectives- (i) Evaluate the suitability of Fraze mowing cultivation in fairway renovation settings; (ii) Evaluate the combined effects of fraze mowing cultivation and dazomet fumigation; and (iii) Assess how efficacy of treatments is affected by fumigant incorporation and soil type. The primary objectives of the Chapter 1 Study were: (i) to assess ABG emergence from fraze mowed plots fumigated at varying rates; and (ii) evaluate CBG establishment at corresponding dazomet rates and intervals. In Chapter 2, objectives include: (i) evaluate varying levels of surface disturbance on ABG control and CBG establishment; and (ii) quantify the volume of material removed by various fraze mowing rotor configurations can remove at a set depth.

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CHAPTER 1: ANNUAL BLUEGRASS EMERGENCE AS AFFECTED BY DAZOMET FUMIGATION APPLIED TO FRAZE MOWED SYSTEMS AT VARYING RATES AND INTERVALS

ABSTRACT

The efficacy of renovation strategies which control annual bluegrass [*Poa annua* L. (ABG)] populations in golf course systems are limited by spatial constraints. Fraze mowing cultivation may help to overcome some of these spatial boundaries and offer a more efficient method for seedbank removal during fairway renovation. In the Summers of 2018-19, research was conducted to evaluate the efficacy of dazomet [Tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione] fumigation on ABG emergence and creeping bentgrass [*Agrostis stolonifera* L.] (CBG) establishment when applied to fraze mowed surfaces. Blocks of Topdressed (TDS) and native soils were sprayed with a 2.0% glyphosate solution and scalped. 1.9 cm of soil was removed from plots via fraze mowing cultivation, before dazomet was applied at one of five rates and two intervals [0, 293.7, 588.4, 146.8 +10-d and 293.7 + 10-d $kg \cdot ha^{-1}$] and incorporated with tillage or Solid-Tine (ST) cultivation. 5-d after interval treatments, P and 'Pure Select' CBG seed were applied at 48.8 $kg \cdot ha^{-1}$. Split applications of 293.7 $kg \cdot ha^{-1}$ provided the most consistent control of ABG emergence across seasons; however, comparable ABG control was also achieved by single applications of 293.7 and 588.4 in 2018 and split applications of 146.8 in 2019. With exception to single applications of 293.7 in 2018, all dazomet treatments provided CBG cover that was greater than the control. Effects of incorporation were inconsistent across seasons, although disturbance from ST cultivation was indistinguishable by the end of the study. Fraze mowing cultivation simplified the removal of surface material but did not provide acceptable ABG control for any rate or interval of dazomet applied.

MATERIALS AND METHODS

Site description and maintenance

The study was conducted on a Capac loam, (Fine-loamy, mixed, active, mesic, Aquic Glossudalfs), creeping bentgrass [*Agrostis stolonifera* (L.)] (CBG) and annual bluegrass [*Poa annua* (L.)] (ABG) mixed species site, managed as a golf course fairway, located at Michigan State University Hancock Turfgrass Research Center (HTRC), East Lansing, MI. In 2011, the site was divided into six 502 m^2 quadrants. Three were randomly chosen and topdressed until 2015, accumulating a total of 3.8 cm of sand. The remaining three quadrants were left as native soil. ABG populations, which were measured using digital image analysis in 2019, accounted for 53% and 66% of the species composition on topdressed and native quadrants, respectively. Mowing was conducted three times per week with a Toro fairway mower (Reelmaster 5400-D; The Toro Company, Bloomington, MN) and managed at 1.1 cm. The site was foliar-fed bi-weekly with CoRon (28-0-0) (Helena Agri-Enterprises, LLC., Collierville, TN) at a rate of 0.49 $kg \cdot m^{-2}$. Irrigation was automatically applied as needed, which averaged 1.1 cm wk^{-1}.

Experimental Design

The experiment was arranged as a 5 x 2 x 2 full-factorial, split plot design with two runs between 2018-2019. Six blocks which measured 3 x 8.5 m were spread across the site, three nested in each soil condition. Blocks were split into ten, 1.2 x 1.8 m plots which were separated longitudinally and latitudinally by 0.6m buffers. All plots were fraze mowed to a consistent depth, fumigated at one of five levels and two intervals of dazomet [0, 293.6, 588.4, 146.8 + 10-d, 293.7 + 10-d $kg \cdot ha^{-1}$] and then incorporated by solid-tine [ST] or tillage [Till] cultivation.

Experimental Initiation

In June of 2018 and 2019, 2.0% glyphosate solution was applied to blocks at a rate of 44 dL glyphosate ha^{-1}, using a CO_2 propelled backpack boom-sprayer (R&D Sprayers, Bellspray, Inc., Opelousas, LA). 10-d after spraying, blocks were scalped to 0.50 cm (Toro Greensmaster 800 fixed-head series; The Toro Company, Bloomington, MN). 11-d after spraying, plots were fraze mowed to a uniform depth of 1.91 cm [KORO FieldTopMaker (FTM) 1.2; Campey Turf Care Systems, Cheshire, UK)] using the Universe rotor (10 mm blades) in a 4-spiral rotor configuration for disturbance of 100% surface area. 12-d after spraying, dazomet [Basamid Granular; AMVAC Chemical Corporation, Los Angeles, CA (tetrahydro-3,5-dimethyl-2*H*-1,3,5-thiadiazine-2-thione)] was hand-applied at respective rates to plots using shaker bottles inside of a mobile box constructed to reduce wind drift. For ST incorporated plots, cultivation was conducted before fumigant was applied (Toro ProCore 648; The Toro Company, Bloomington, MN) [1.3 cm solid tines, 3.91 cm depth, 5.1 x 5.1 cm spacing, 4.9% surface disruption]. In Till plots, fumigant was incorporated from three passes with a tiller (Honda FRC 800 rear-tine tiller; American Honda Power Equipment Division, Alpharetta, GA) after fumigant was applied. Immediately following the application and cultivation of dazomet, plots were hand-watered with 57-L (2.5 cm) to activate the fumigant and create a water-seal at the surface with a custom watering-wand fitted with a flowmeter (GPI®/FLOMEC TM-150N; GPI Meters, Sparta, NJ) to ensure consistent volumes of water were delivered to each plot. For 3-d following, the volume of water applied to each plot declined by half each day (d-2= 28.4L, d-3=14.2L, d-4= 7.1L). Cultivation, fumigation and hand-watering was repeated for plots fumigated twice. 15-d following initial fumigation (5-d after interval treatments were applied), plots were hand-rolled with a steel-drum roller and fertilized with Triple Phosphate (0-46-0) at 49 kg P·ha^{-1}. A tire-dimpling device was rolled over each plot and seeded with ‘Pure Select’ CBG seed at 48.8 kg seed·ha^{-1}. Fertilizer and seed were applied by hand using shaker bottles. To maximize seed-to-soil contact for seed establishment, plots were raked gently in two directions. Automatic overhead irrigation was applied at a rate of 0.25 cm· d^{-1} until 10-d after seeding. In 2018, only half of the plots were seeded. In 2019, protocols were changed to evaluate treatment effects after the entire plot was seeded.

Trial Maintenance

CBG establishment protocols were minimal as the primary objective of this research was to evaluate treatment effects on ABG emergence. Plots were reel-mowed bi-weekly at 0.64 cm (Toro 800 fixed-head series; The Toro Company, Bloomington, MN), beginning 2 weeks after seeding (WAS). At this frequency, we aimed to minimize ABG seed dispersal between plots and promote growth of CBG. Urea (46-0-0) was melted and applied to blocks at 14.7 kg N·ha^{-1} using a CO_2 backpack sprayer and weekly at 4.9 kg N·ha^{-1} from 3-8 WAS. Irrigation was applied on an “as needed” basis but generally, received 1.3 cm weekly during the season. All weeds (excluding ABG) were pulled 3x·week^{-1} until 4 WAS. As a safeguard for development of *Pythium* spp., Mefenoxam [Subdue GR; Syngenta, Greensboro, NC; (R,S)-2-[(2,6-dimethylphenyl)-methoxyacetylamino]-propionic acid methyl ester) was applied to plots by hand at 42.7 kg·ha^{-1}. Quinclorac was also applied at 23.7 fl oz·ha^{-1} using a CO_2 backpack sprayer [Drive XLR8; BASF Corporation, Research Triangle Park, NC; (3,7-dichloro-8-quinolinecarboxylic acid) for additional weed control.

Data Collection

Annual bluegrass emergence

ABG emergence was evaluated based on ABG cover and grid count measurements which were taken 6 and 8 WAS. Visual estimates were determined as the proportion of total cover in each plot, on a scale of 0-100%. Emergence was determined from grid counts using the line-transect method (Bravo et al., 2018; Gaussoin et al., 1989). Two 0.10 m^2 grids containing 144 intersections every 6.5 cm^2, were randomly placed in each plot and the average number of intersections containing ABG plant parts was tallied. Estimations and counts were also conducted in 2018 on unseeded portions of plots which are discussed separately.

Digital Image Analysis (DIA)

Beginning 2 WAS, single images were captured bi-weekly from the center of each plot using a Canon® PowerShot SX710 HS digital camera (Canon U.S.A., Inc., Melville, NY). Images were taken inside of a custom, 2.5’ x 2’ x 2’ lightbox, which provided consistent lighting between dates. Camera settings were fixed [manual, F-stop=3.5, exposure=1/20, ISO=1600, Macro] across measuring periods and corresponded with lightbox conditions. Images were analyzed for turfgrass cover using the Java™ applet TurfAnalyzer® (Karcher et al., 2017). Before analysis Hue, Saturation and Brightness (HSB) levels were set as a threshold for green pixels [H=45-140°, S=10-100%, B=0-100%]. In the applet, turfgrass cover was quantified as the quotient of green pixels in each image and the total number of pixels in each image (Karcher et al., 2013). Given hand-weeding through 4 WAS and the lack of ABG emergence until 6 WAS, DIA measurements from 2-4 WAS reflect pure CBG establishment. Thereafter, weeds were only pulled if they obstructed DIA images, however, cover from 6-8 WAS may also reflect ABG emergence. In 2019, a final reading evaluating ABG cover was made 10 WAS, 2 weeks following the application of sethoxydim, applied 8 WAS to blocks at a rate of 110 $mL \cdot ha^{-1}$ using a CO2 backpack sprayer (44 $dL \cdot ha^{-1}$).

Clipping yield

The mass of oven-dried clippings collected by mowing was determined 4 WAS, following similar methods to those described by Baldwin (Baldwin et al., 2009). To improve accuracy, precision and eliminate potential sampler error, one swath-widths' pass was made around the perimeter of sub-plots at 0.64 cm and clippings were emptied from the basket. After, three passes were made over each plot and clippings were emptied into pre-labeled paper bags before being oven-dried at 65.6°C for 4-d. The oven-dried mass of clippings collected from each sub-plot was recorded. In 2019, considerably less clippings were removed from each plot by 4 WAS, resulting in collection of soil. To isolate clippings from debris, a floatation technique used (Kreuser et al., 2011; Stier et al., 2003). Samples were first oven dried and then emptied into a plastic tub filled with warm water, agitated, and left to settle. While the clippings floated the debris sank. Clippings were skimmed from the surface, placed in aluminum loaf pans and then subjected a final drying cycle, where after, their mass was recorded.

Statistical Analysis

All data was analyzed in JMP Pro 13 by year as a 5 x 2 x 2 full-factorial, nested, split-plot design. Blocks were treated as random effects with soils nested in each. Fixed effects of Basamid rate, soil type and method of incorporation were considered significant when p-values exceeded an alpha of 0.05. Means were compared using Fisher's LSD.

RESULTS AND DISCUSSION

Annual bluegrass emergence

ABG counts and estimated cover were significantly affected by dazomet rate in both 2018 and 2019 (Tables 1-6). All rates and intervals resulted in less ABG emergence and cover than the control. Plots fumigated twice at 293.7 $kg \cdot ha^{-1}$ achieved the lowest emergence across measuring periods. Plots fumigated once with 588.4 $kg \cdot ha^{-1}$ had comparable effects on counts in 2018. Native soil counts taken 6 WAS in 2018 control plots had 220% more ABG than TDS control plots (Figure 1). In 2019, estimated cover 10 WAS was lowest in TDS plots where fumigant was incorporated by tillage and greatest in native plots ST cultivated (Figure 2). Despite the similar timeline of protocols between seasons, nearly 4x more ABG was observed in 2019 control plots than in 2018. This massive disparity in ABG emergence may be the result of several factors. First, Microbial degradation of MITC is slowed and dazomet, enhanced, under excessively moist conditions (Gan et al., 1999; Zhang et al., 2005). In 2018, 0.64 cm of precipitation fell on the site the day following fumigation and an additional 0.64 cm over 4-d after fumigation 2 (Figure 3). Moreover, the site was subjected to 7.8 cm more precipitation in 2018 than it was in 2019. It is plausible that these events slowed MITC losses from the system. Second, unpublished research conducted on the same site of our study observed peak ABG Spring flowering to occur between 800-1300 GDD (Calhoun, 2010). Danneberger et al., (1984) who conducted similar work in Michigan, observed a decline in flowering after 363-433 GDD had accumulated. In 2018, nearly 1000 GDD had accumulated by June 26 (the day fumigant was first applied). By the same time in 2019, only 700 GDD had accumulated (Figure 4). Under Calhoun’s model, this would imply greater seed flush may have occurred following treatments in 2019, and in part, allowed for enhanced seed dispersal and recruitment between blocks during routine maintenance.

Table 1. An ANOVA showing significance of dazomet rate, incorporation method and soil type on annual bluegrass grid counts and estimated cover measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	Annual bluegrass grid counts[b]		Estimated annual bluegrass cover (%)[c]	
	6 WAS	8 WAS	6 WAS	8 WAS
Dazomet Rate (R)	***	***	**	***
Incorporation (I)	NS	NS	NS	NS
Soil Type (S)	NS	NS	NS	NS
R x I	NS	NS	NS	NS
R x S	*	NS	NS	NS
I x S	NS	NS	NS	NS
R x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July, 2018.
[b] Average number of annual bluegrass parts touching intersections spaced $6.5cm^2$ from two randomly place $0.10m^2$ grids.
[c] Estimated proportion of annual bluegrass cover in $2.2m^2$ plots
[NS, *, **, ***]Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 2. The effects of dazomet rate, incorporation method and soil type on annual bluegrass grid counts measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Application rate** (kg·ha^{-1})	**# of intersections containing annual bluegrass**[b]	
		6 WAS	8 WAS
Dazomet Rate (R)	0	4.1a[d]	6.0a
	293.7	0.6b	0.9bc
	588.4	0.7b	0.7c
	293.7 + 10-d[c]	0.5b	0.8c
	146.8 + 10-d	0.7b	1.7b
	LSD (*P*=0.05)	1.4	0.8
Incorporation Method (I)	Solid-Tine	1.0	1.5
	Till	0.9	1.3
	LSD (*P*=0.05)	NS[e]	NS
Soil Type (S)	Topdressed	0.9	0.9
	Native	1.0	2.1
	LSD (*P*=0.05)	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July 2018.
[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.
[c] (+ 10-d) signifies second application of dazomet, 10 days following the first
[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05
[e] Nonsignificant or significant at *P*=0.05

Table 3. The effects of dazomet rate, incorporation method and soil type on estimated (%) annual bluegrass cover, measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Application rate** ($kg \cdot ha^{-1}$)	**Estimated annual bluegrass cover** (%)[b]	
		6 WAS	8 WAS
Dazomet Rate (R)	0	10.9a[d]	27.8a
	293.7	4.2b	11.3b
	588.4	3.3bc	7.9bc
	293.7 + 10-d[c]	1.3c	5.3c
	146.8 + 10-d	1.7bc	10.4b
	LSD (*P*=0.05)	1.1	2.5
Incorporation Method (I)	Solid-Tine	3.7	11.9
	Till	4.9	13.2
	LSD (*P*=0.05)	NS[e]	NS
Soil Type (S)	Topdressed	3.2	10.1
	Native	5.3	15.0
	LSD (*P*=0.05)	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July 2018.

[b] Estimated proportion of annual bluegrass cover in 2.2 m^2 plots.

[c] (+ 10-d) signifies second application of dazomet, 10 days following the first

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Table 4. An ANOVA showing significance of dazomet rate, incorporation method and soil type on annual bluegrass grid counts and estimated cover measured 6, 8 & 10 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Annual bluegrass grid counts**[b]		**Estimated annual bluegrass cover (%)**[c]		
	6 WAS	8 WAS	6 WAS	8 WAS	10 WAS
Dazomet Rate (R)	**	***	**	***	***
Incorporation Method (I)	NS	NS	NS	NS	NS
Soil Type (S)	NS	NS	NS	NS	NS
R x I	NS	NS	NS	NS	NS
R x S	NS	NS	NS	NS	NS
I x S	NS	NS	NS	NS	*
R x I x S	NS	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 12 July 2019.
[b] Average number of annual bluegrass parts touching intersections spaced 6.5cm^2 from two randomly place 0.10 m^2 grids.
[c] Estimated proportion of annual bluegrass cover in 2.2 m^2 plots
[NS, *, **, ***] Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 5. The effects of dazomet rate, incorporation method and soil type on annual bluegrass grid counts measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Application rate** (kg·ha^{-1})	**# of intersections containing annual bluegrass**[b]	
		6 WAS	8 WAS
Dazomet Rate (R)	0	20.7a[d]	26.6a
	293.7	12.3ab	16.1b
	588.4	9.7bc	11.1bc
	293.7 + 10-d[c]	3.0c	4.0d
	146.8 + 10-d	6.9bc	8.3cd
	LSD (*P*=0.05)	7.5	6.2
Incorporation Method (I)	Solid-Tine	11.8	11.8
	Till	9.5	12.3
	LSD (*P*=0.05)	NS[e]	NS
Soil Type (S)	Topdressed	10.3	11.1
	Native	11.0	14.6
	LSD (*P*=0.05)	NS	NS

[a] WAS=Weeks after seeding; plots seeded 12 July 2019.
[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.
[c] (+ 10-d) signifies second application of dazomet, 10 days following the first. In 2019, weather delays caused the split application to be applied 13-d after initial fumigation.
[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05
[e] Nonsignificant or significant at *P*=0.05

Table 6. The effects of dazomet rate, incorporation method and soil type on estimated (%) annual bluegrass cover, measured 6, 8 & 10 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Application rate** (kg·ha^{-1})	**Estimated annual bluegrass plot cover** (%)[b]		
		6 WAS	8 WAS	10 WAS
Dazomet Rate (R)	0	17.1a[d]	23.8a	25.8a
	293.7	12.5ab	12.5b	17.1b
	588.4	8.8bc	12.0b	15.0b
	293.7 + 10-d[c]	5.4c	5.8c	8.3c
	146.8 + 10-d	9.6bc	9.6bc	10.7bc
	LSD (*P*=0.05)	4.7	4.8	4.8
Incorporation Method (I)	Solid-Tine	12.1	13	16.5
	Till	8.9	12.5	14.7
	LSD (*P*=0.05)	NS[e]	NS	NS
Soil Type (S)	Topdressed	9.6	10.8	13.7
	Native	11.4	14.7	17.5
	LSD (*P*=0.05)	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 12 July 2019.

[b] Estimated proportion of annual bluegrass cover in 2.2 m^2 plots.

[c] (+ 10-d) signifies second application of dazomet, 10 days following the first

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Figure 1. Annual bluegrass grid counts as affected by dazomet fumigation rate and soil type measured 6 weeks after seeding from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

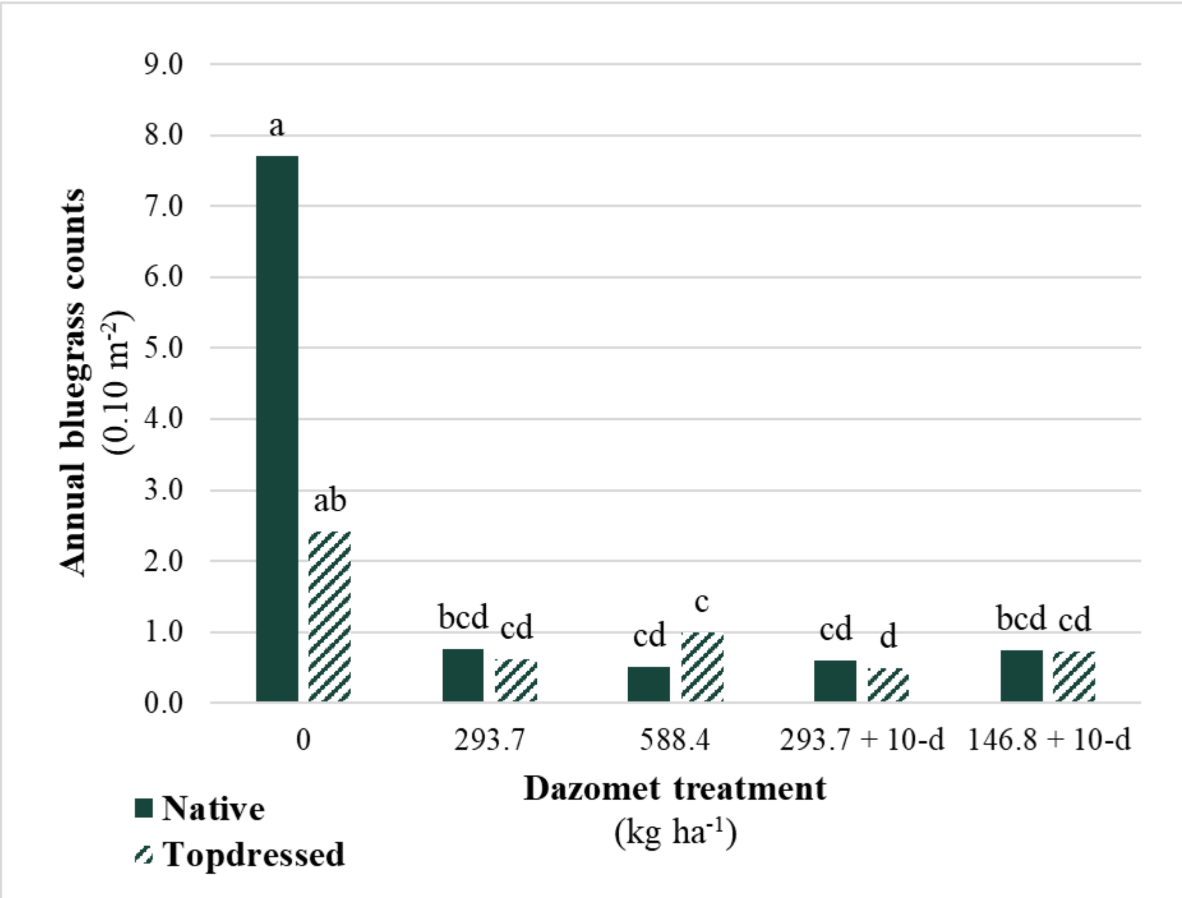


Figure 2. Annual bluegrass cover as affected by fumigant incorporation method and soil type, measured 10 weeks after seeding from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

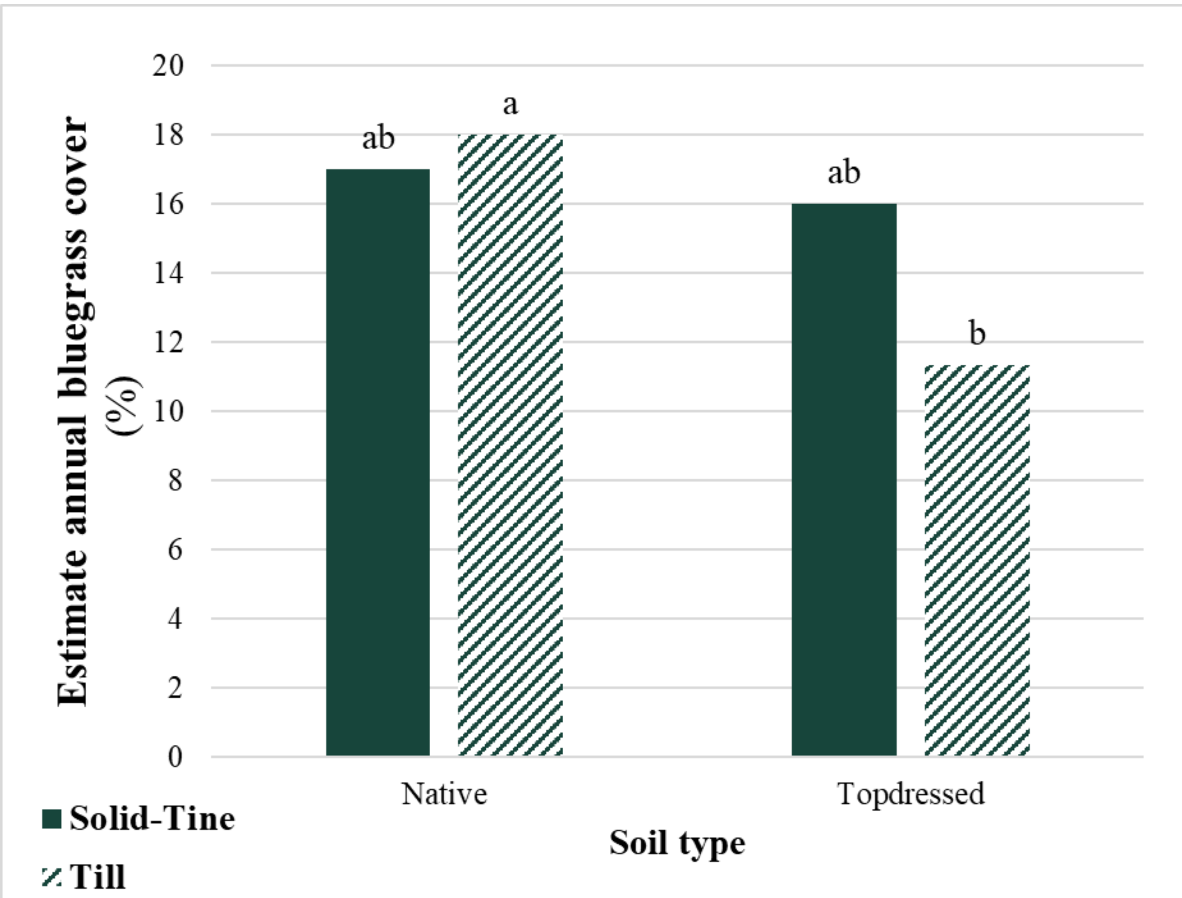


Figure 3. Precipitation events at the Hancock Turfgrass Research Center, East Lansing, MI, Summers 2018-2019.

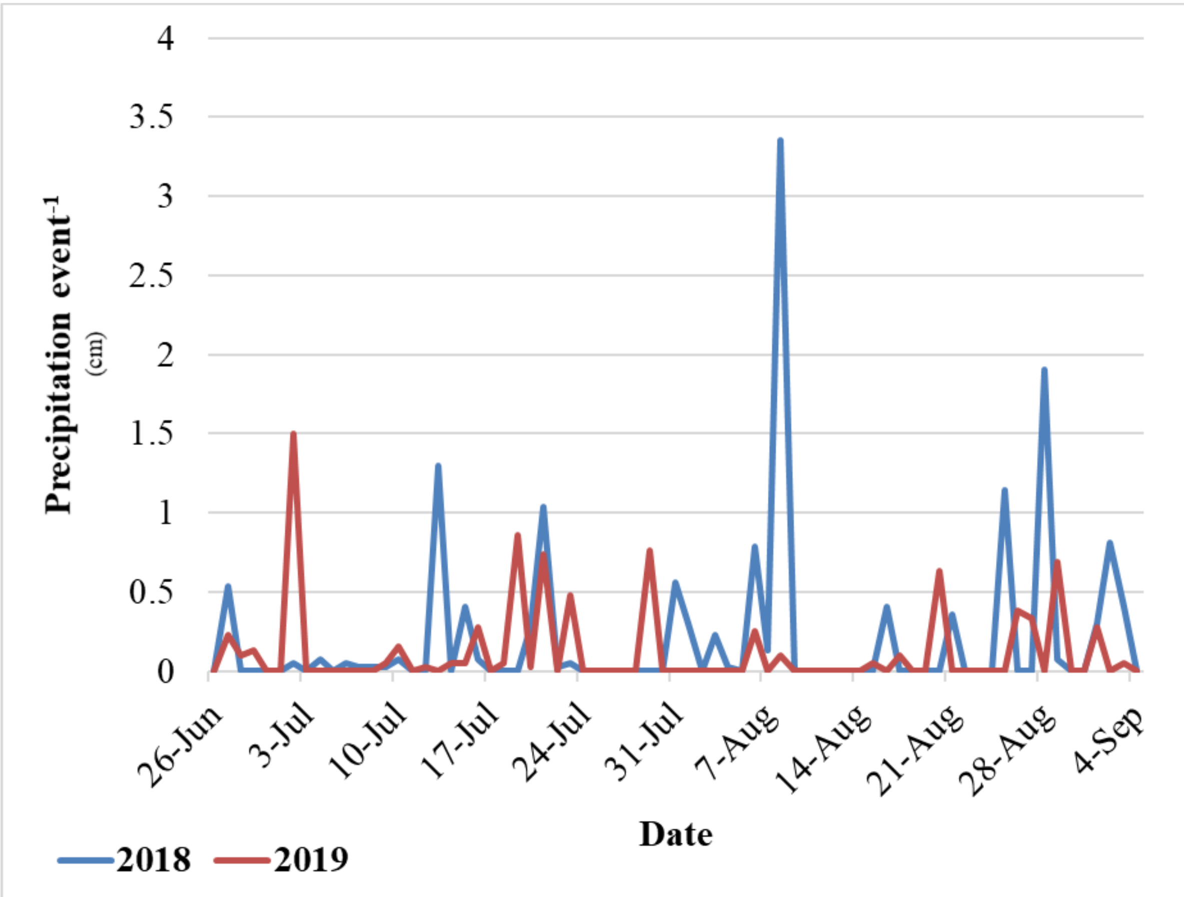
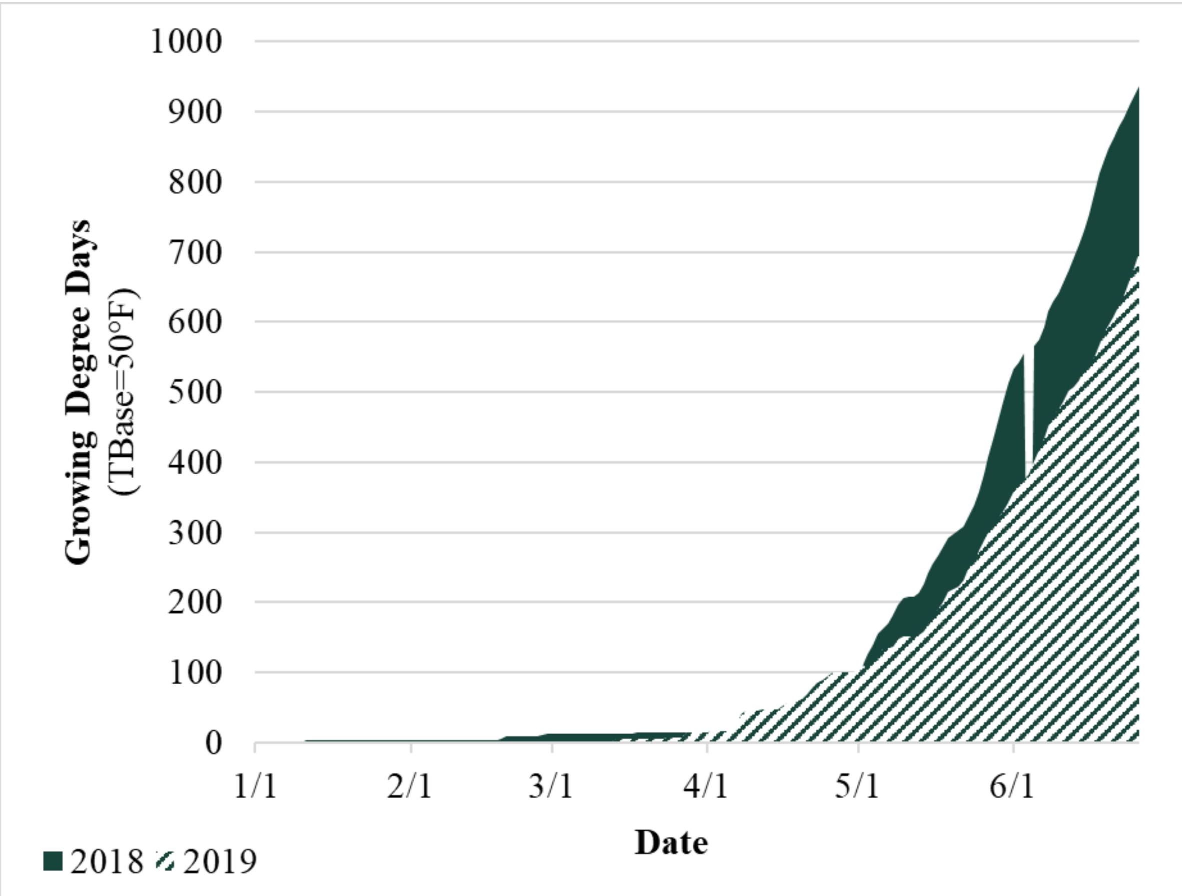


Figure 4. Accumulated Growing Degree Days at T_{Base}=50°F from 1 January-26 June, 2018 & 2019 at fairway renovation site located at the Hancock Turfgrass Research Center, East Lansing, MI, Summers 2018-2019.



A third possible explanation for the differences between years is the faster CBG establishment that occurred in 2018. In general, establishment of a given species prior to the emergence of a competing species allows the former to outcompete the latter.

Digital Image Analysis: Creeping bentgrass cover

In 2018, CBG cover was influenced by incorporation and rate effects (Table 7-8). Incorporation effects were observed only once, where CBG cover was greatest in tilled plots 2 WAS. Except 293.7 $kg \cdot ha^{-1}$ plots at 8 WAS, all dazomet rates and intervals yielded greater cover than the control from 4-8 WAS. In 2019, rate effects were not observed, however; solid-tine incorporated plots consistently yielded the greatest cover across measuring periods (Table 9-10). In 2019, cover was also affected by a significant Rate x Soil interaction observed from 4-8 WAS **(**Figures 5-7**)**. From 4-6 WAS cover was generally greater in TDS plots. The most notable exception was in native plots, 4 WAS fumigated twice at 293 $kg \cdot ha^{-1}$, which achieved the greatest cover across soils and treatments. In this study, there was some correspondence between greater dazomet rates and increased cover. Increased flushes of crop growth following dazomet fumigation has occurred in previous reports in correspondence with reduced seeding intervals relative the time and rate that dazomet was applied (Altman, 1970; Branham et al., 2004; Jenkinson et al., 1972; Landschoot et al., 2003, 2004). It is possible that increased growth following fumigation could be due to nitrogen released following the lysing of microbial population (Chabrol et al., 1988). Factors like soil moisture and soil texture, which affect degradation of MITC and dazomet, may also indirectly affect the quantity of N mineralized. When MITC is released and degrades in the soil system it also deposits numerous by-products, including ammonia (Fritsch et al., 1995), formaldehyde and hydrogen sulfide (Ruzo, 2006). In some soils, dazomet has enhanced microbial activity (Smelt et al., 1989) and the mineralization

Table 7. An ANOVA showing significance of dazomet rate, incorporation method and soil type on creeping bentgrass cover 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Creeping bentgrass cover** (%)[b]			
	2 WAS	4 WAS	6 WAS	8 WAS
Dazomet Rate (R)	NS	***	**	**
Incorporation Method (I)	*	NS	NS	NS
Soil Type (S)	NS	NS	NS	NS
R x I	NS	NS	NS	NS
R x S	NS	NS	NS	NS
I x S	NS	NS	NS	NS
R x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July 2018.
[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period. % Cover = (# of Green Pixels) / (Total Pixels).
[NS, *, **, ***] Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 8. The effects of dazomet rate, incorporation method and soil type on creeping bentgrass cover measured 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Application rate** (kg·ha^{-1})	**Creeping bentgrass cover** (%)[b] 2 WAS	4 WAS	6 WAS	8 WAS
Dazomet Rate (R)	0	24	39c[d]	62b	78b
	293.7	30	54b	80a	83b
	588.4	27	63ba	90a	96a
	293.7 + 10-d[c]	38	68a	86a	96a
	146.8 + 10-d	28	71a	88a	95a
	LSD (*P*=0.05)	NS[e]	1.4	12.7	9.2
Incorporation Method (I)	Solid-Tine	26b	61	84	92
	Till	33a	58	79	87
	LSD (*P*=0.05)	1.5	NS	NS	NS
Soil Type (S)	Topdressed	33	66	87	92
	Native	26	53	76	88
	LSD (*P*=0.05)	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July 2018.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.

% Cover = (# of Green Pixels) / (Total Pixels).

[c] (+ 10-d) signifies second application of dazomet, 10-d following the first.

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Table 9. An ANOVA showing significance of dazomet rate, incorporation method and soil type on creeping bentgrass cover 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	Creeping bentgrass cover (%)[b]			
	2 WAS	4 WAS	6 WAS	8 WAS
Dazomet Rate (R)	NS	NS	NS	NS
Incorporation Method (I)	*	*	**	**
Soil Type (S)	NS	NS	NS	NS
R x I	NS	NS	NS	NS
R x S	NS	*	*	*
I x S	NS	NS	NS	NS
R x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 12 July 2019.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.

% Cover = (# of Green Pixels) / (Total Pixels).

[NS, *, **, ***]Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 10. The effects of dazomet rate, incorporation method and soil type on creeping bentgrass cover measured 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Application rate** (kg·ha^{-1})	**Creeping bentgrass cover** (%)[b]			
		2 WAS	4 WAS	6 WAS	8 WAS
Dazomet Rate	0	51	84	93	87
	293.7	47	80	92	88
	588.4	48	82	92	86
	293.7 + 10-d[c]	56	91	81	89
	146.8 + 10-d	44	79	90	89
	LSD (*P*=0.05)	NS[d]	NS	NS	NS
Incorporation Method (I)	Solid-Tine	55b[e]	88a	95a	92a
	Till	43a	78b	88b	87b
	LSD (*P*=0.05)	10.4	7.0	3.2	3.8
Soil Type (S)	Topdressed	45	84	93	91
	Native	53	82	90	85
	LSD (*P*=0.05)	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 12 July 2019.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.

% Cover = (# of Green Pixels) / (Total Pixels).

[c] (+ 10-d) signifies second application of dazomet, 10 days following the first

[d] Nonsignificant or significant at *P*=0.05

[e] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

Figure 5. Creeping bentgrass cover as affected by dazomet fumigation rate and soil type, 4 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

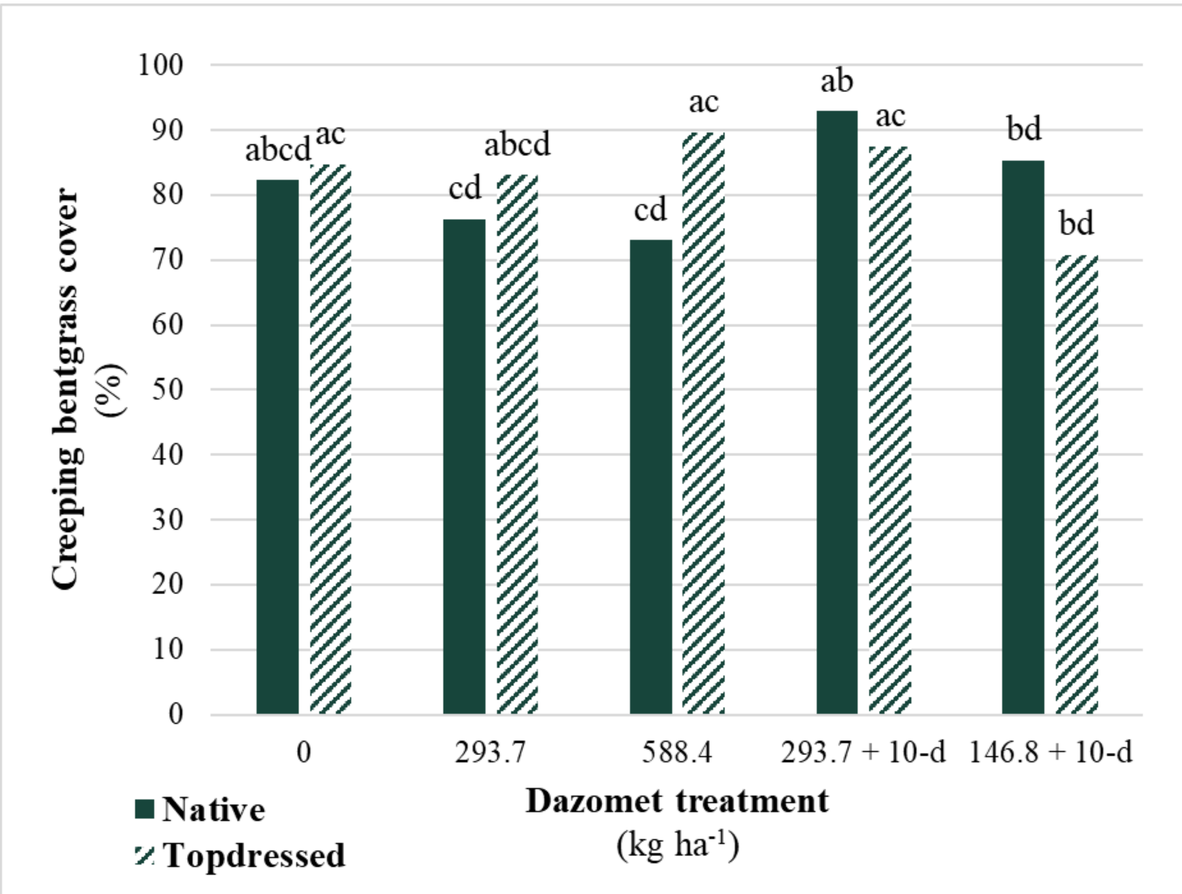


Figure 6. Creeping bentgrass cover as affected by dazomet fumigation rate and soil type, 6 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

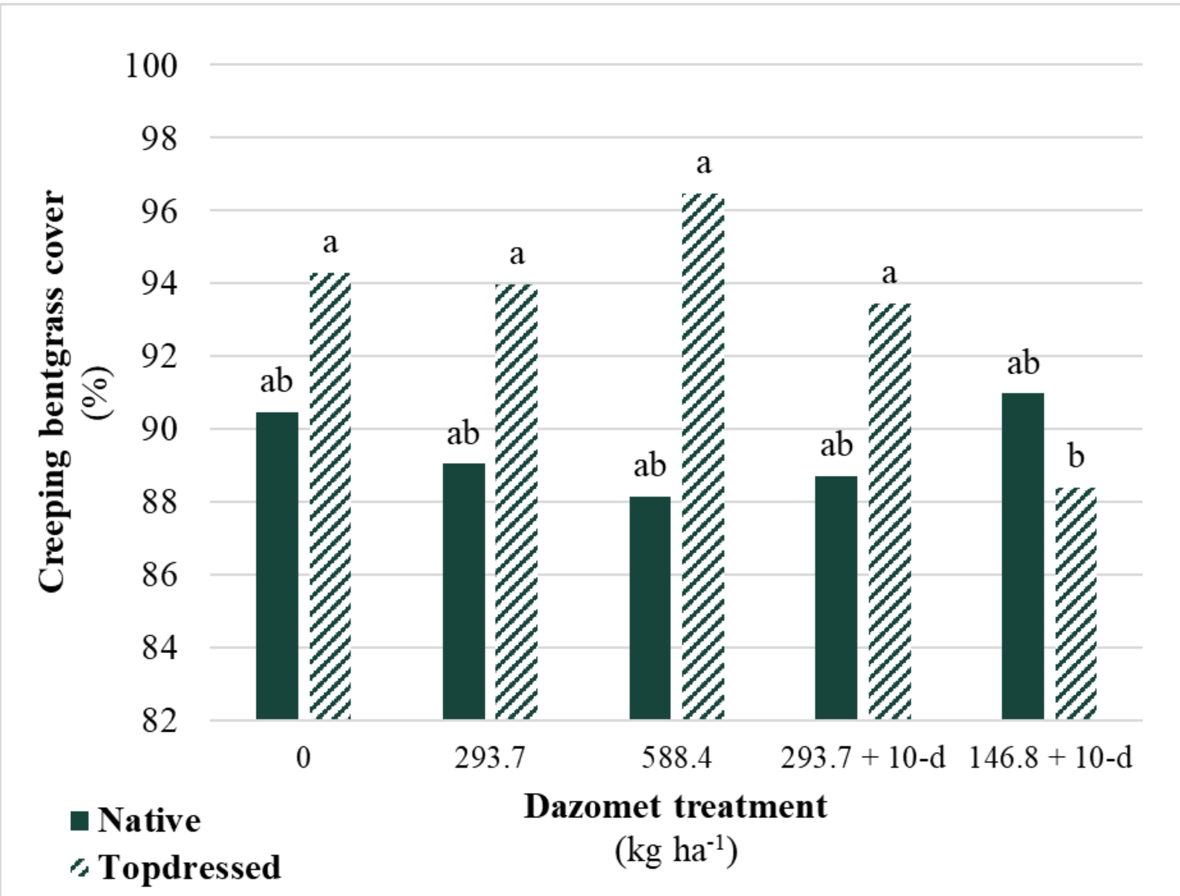
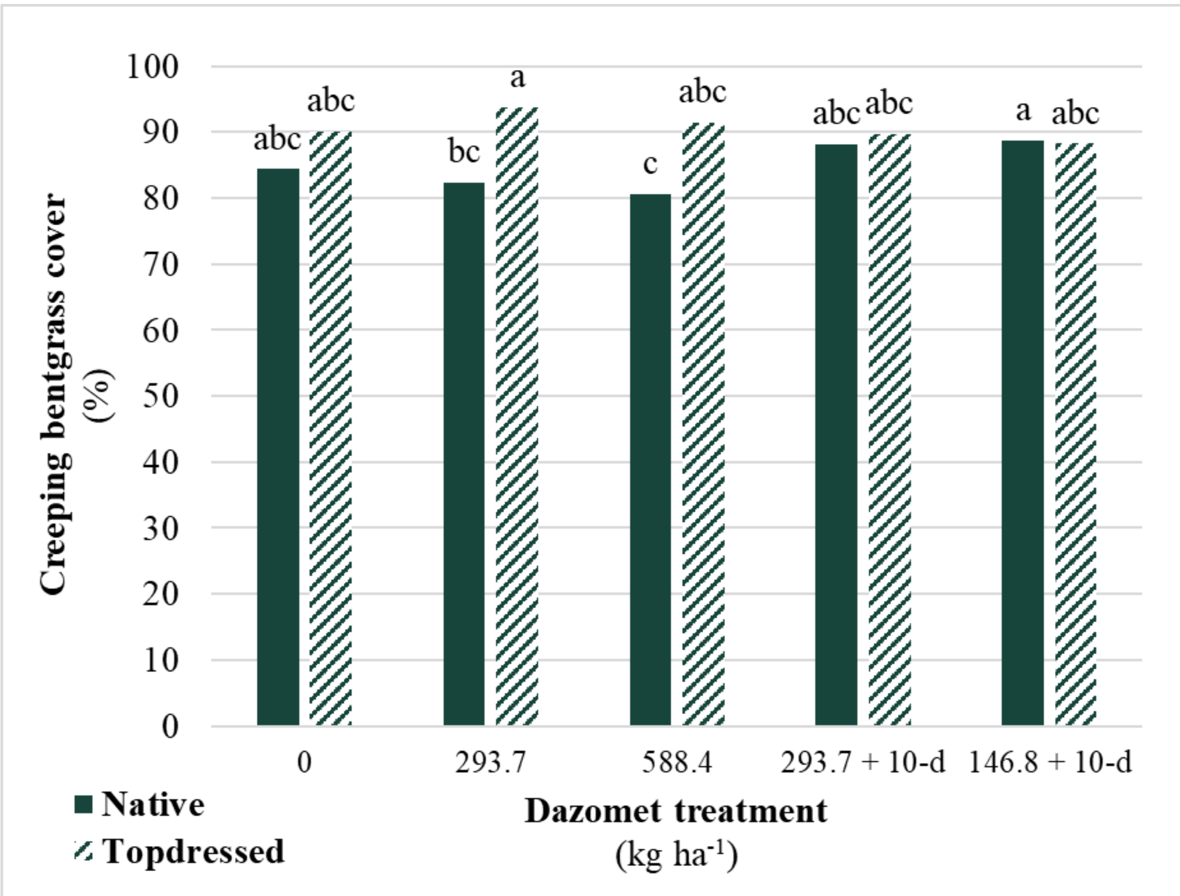


Figure 7. Creeping bentgrass cover as affected by dazomet fumigation rate and soil type, 8 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.



of soil N (Gasser et al., 1964). Given the length of time and extent to which these products and processes take place are highly dependent on soil moisture conditions, temperature, and gas containment in general. Such temporal differences between 2018 and 2019 could explain why similar effects in growth were not observed across seasons.

Clipping collection

By 4 WAS in either year of trials, ABG emergence in plots was minimal or non-existent at all. Therefore, yield measurements are reflective of non-contaminated CBG. In 2018, CBG yield was significantly affected by fumigant rate, where all rates and intervals of applied fumigant produced a greater yield than the control (Table 11-12). Plots fumigated twice at 293.7 yielded the greatest clipping yield of all treatments. These results were similar to those of Landschoot et al. (2003, 2004), but did not necessarily statistically correspond with reduced seeding intervals relative to fumigation. In the 2019 season, fumigant treatments had no effect on clipping yield, and was only affected by soil type. TDS blocks achieved nearly twice the mass of clipping yields as those collected from native blocks. Although literature suggests MITC may degrade faster in coarser textured soils, it also has demonstrated the enhanced diffusivity of MITC gases through the profile (Gerstl et al., 1977; Lembright, 1990; Thomason et al., 1974). In part, this would imply greater N mineralization potential in the TDS vs. native soil, possibly explaining the difference. That said, only 1.9 cm of the coarser textured sand would have been present in these plots after fraze mowing. It is unknown why differences between soils were not observed consistently across seasons but is likely related to temporal differences between seasons.

Table 11. An ANOVA showing significance of dazomet rate, incorporation method and soil type on creeping bentgrass clipping yield, measured 4 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summers 2018-2019.

Treatment	**Creeping bentgrass yield**[b]	
	2018	2019
Dazomet Rate (R)	**	NS
Incorporation Method (I)	NS	NS
Soil Type (S)	NS	*
R x I	NS	NS
R x S	NS	NS
I x S	NS	NS
R x I x S	NS	NS

[a] WAS=Weeks after seeding; plots seeded 10 July 2018 and 12 July 2019.
[b] Mass of creeping bentgrass removed from mowing.
NS, *, **, ***Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 12. The effects of dazomet rate, incorporation method and soil type on creeping bentgrass yield, measured 4 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summers 2018-2019.

Treatment	**Application rate** (kg·ha^{-1})	**Creeping bentgrass yield** (g)[b]	
		2018	2019
Dazomet Rate (R)	0	1.7c[d]	6.4
	293.7	6.7bc	7.3
	588.4	12.9ab	8.8
	293.7 + 10-d[c]	19.3a	10.6
	146.8 + 10-d	10.1ab	7.7
	LSD (*P*=0.05)	6.1	NS
Incorporation Method (I)	Solid-Tine	7.3	7
	Till	11.0	9.3
	LSD (*P*=0.05)	NS[e]	NS
Soil Type (S)	Topdressed	10.6	11.1a
	Native	7.6	5.9b
	LSD (*P*=0.05)	NS	3.3

[a] WAS=Weeks after seeding; plots seeded 10 July 2018 and 12 July 2019.
[b] Mass (g) of creeping bentgrass removed from mowing.
[c] (+ 10-d) signifies second application of dazomet, 10 days following the first. In 2019, weather delays caused the split application to be applied 13-d after initial fumigation.
[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05
[e] Nonsignificant or significant at *P*=0.05

CONCLUSIONS

No single dazomet treatment achieved complete control of ABG, though control and CBG establishment were enhanced by increased rates. Fraze mowing cultivation was an effective method for soil removal, but alone, failed to provide acceptable levels of ABG control or CBG establishment. Dazomet applications applied twice at 293.7 kg ha-1 provided the most consistent control, though comparable control was achieved from single applications of 293.7 and 588.4 kg ha-1 in 2018 and split applications of 146.8 kg ha-1 in 2019. In a practical setting a practitioner would have to decide if the minimal gained benefits of split applications would outweigh prolonged golf course closure. The inconsistency of rate effects may be explained by extreme differences in precipitation between seasons which could have affected the activity of the fumigant. Therefore, practitioners should also consider the seasonality and weather patterns in relation to their renovation projects. Tillage was assessed as a method for dazomet incorporation methods to evaluate current Basamid G label practices. Tillage had no influence ABG emergence, failed to achieve acceptable levels of CBG cover and resulted in an unaesthetically pleasing surface. Conversely, the less invasive ST cultivation which had not previously been evaluated as a dazomet incorporation method, yielded significantly greater CBG cover in 2019, acceptable levels of cover across seasons and was unnoticeable by 8 WAS. These finding may have impact on future Basamid G label methods.

Future research should consider investigating efficacy of fraze mowing cultivation and dazomet fumigation when CBG is seeded at reduced intervals and when fraze mowing is conducted relative to accumulated GDD.

CHAPTER 2: THE EFFECTS OF FRAZE MOWING SURFACE DISTURBANCE AND DAZOMET FUMIGATION ON ANNUAL BLUEGRASS EMERGENCE

ABSTRACT

The most opportune time to remove the annual bluegrass (*Poa annua* L.) [ABG] seedbank from golf course systems is during renovation. Effective methods for large areas like fairways have not been identified. In the summers of 2018-19, research was conducted at Michigan State University to assess the application of fraze mowing cultivation for cool-season fairway renovation. The 4 x 2 x 2 full factorial, nested, split-plot design consisted of three factors; four levels of fraze mowing surface disturbance (0, 15, 50, 100%), two soil types [native vs. sand topdressed (TDS)], and two methods of incorporation [Solid Tine (ST) vs. Tillage]. Three blocks of each soil were sprayed with 2.0% glyphosate solution and scalped. 11-d after, plots were fraze mowed to a depth of 1.9 cm at one of four levels of disturbance, and then fumigated with dazomet at a fixed rate of 293.7 $kg \cdot ha^{-1}$. ST plots were fumigated following cultivation and tilled plots, cultivated after fumigation. Plots were hand-watered for four days following fumigation, and 5-d later, fertilized with elemental P and seeded with ‘Pure Select’ creeping bentgrass [CBG] seed at rates of 48.8 $kg \cdot ha^{-1}$. Surface disturbance effects were inconsistent across years. In 2018, estimated ABG control was enhanced by tillage and surface disturbance which in 2019, yielded poorer CBG cover. The results of this trial suggest a potential tradeoff between CBG establishment and ABG control when tillage is combined with fraze mowing disturbance. Fraze mowing cultivation proved useful for the removal of surface material, however, its combined effects with low-rate dazomet fumigation were ineffective at controlling ABG emergence and impeded CBG establishment.

MATERIALS AND METHODS

Site Description and Maintenance

The study was conducted on a Capac loam, (Fine-loamy, mixed, active, mesic, Aquic Glossudalfs), creeping bentgrass [*Agrostis stolonifera* L.] (CBG) and annual bluegrass [*Poa annua* (L.)] (ABG) mixed species site, managed as a golf course fairway, located at Michigan State University Hancock Turfgrass Research Center (HTRC), East Lansing, MI. In 2011, the site was divided into six 502 m^2 quadrants. Three were randomly chosen and topdressed until 2015, accumulating a total of 3.8 cm of sand. The remaining three quadrants were left undisturbed. In 2019, the species composition of the site was quantified using digital image analysis conducted 2 weeks after sethoxydim was applied around the site at 110 mL ha^{-1} using a CO2 backpack sprayer calibrated to deliver 44 dL·ha^{-1}. DIA revealed ABG populations accounted for 53% and 66% of turfgrass cover on topdressed and native quadrants, respectively. Mowing was conducted three times per week with a Toro fairway mower (Reelmaster 5400-D; The Toro Company, Bloomington, MN) and managed at 1.1 cm. The site was foliar-fed bi-weekly with CoRon (28-0-0) (Helena Agri-Enterprises, LLC., Collierville, TN).Irrigation system was automatically applied as needed, which averaged 1.1 cm $week^{-1}$.

Experimental Design and Site Maintenance

Trials followed a 4 x 2 x 2 full-factorial, split plot design, where blocks were treated as random effects and nested within each soil type. Trial factors included; four levels of fraze mowing surface disturbance [0, 15, 50, 100%], two soil types [Topdressed (TDS) vs. native] and two methods of fumigant incorporation [Solid-Tine (ST) vs. Till]. Three blocks were nested on each soil type and divided into four, 1.2 x 4.3 m whole plots. A 0.60 m buffer was used to latitudinally divide split plot factors of each whole plot and further longitudinally separate each whole plot.

Experimental Initiation

In June of 2018-2019, blocks were sprayed with 2.0% glyphosate solution at a rate of 44 $dL \cdot ha^{-1}$, using a CO_2 propelled, backpack boom-sprayer (R&D Sprayers, Bellspray, Inc., Opelousas, LA). Blocks were scalped 10-d after spraying (Toro Greensmaster 800 fixed-head series; The Toro Company, Bloomington, MN) to 0.50 cm.

11-d after spraying, plots were fraze mowed at respective levels, to a depth of -1.91 cm [KORO FieldTopMaker (FTM) 1.2; Campey Turf Care Systems, Cheshire, UK)]. 15% surface disturbance treatments were cultivated with 3 mm blades and a two-spiral rotor configuration. 50-100% treatments were cultivated with 10 mm blades and a two and four-spiral rotor configuration, respectively. Fraze material was collected by a cart (Toro Workman 3200; The Toro Company, Bloomington, MN) which traveled alongside each plot. 12-d after spraying, plots were fumigated with dazomet [Basamid Granular; AMVAC Chemical Corporation, Los Angeles, CA (tetrahydro-3,5-dimethyl-2*H*-1,3,5-thiadiazine-2-thione)] by hand at 292.7 $kg \cdot ha^{-1}$ using shaker bottles, inside of a mobile wooden box constructed to reduce wind-drift. ST plots were cultivated [Toro ProCore 648; The Toro Company, Bloomington, MN (1.3 cm solid tines, spaced 5.1 x 5.1cm, 4.9% surface disturbance)] before dazomet was applied, and tilled plots were cultivated after dazomet was applied. Dazomet was incorporated into tilled plots using a Honda FRC 800 rear-tine tiller (American Honda Power Equipment Division, Alpharetta, GA). Immediately following the application and cultivation of dazomet, plots were hand-watered to activate the fumigant and create a water-seal at the surface. A custom watering-wand with a flowmeter (GPI®/FLOMEC TM-150N; GPI Meters, Sparta, NJ) was built to ensure consistent volumes of water were delivered to each plot. Water was applied from the day of fumigation to 3-d following, declining by half each day following (d-1= 57L, d-2= 28.4L, d-3=14.2L, d-4= 7.1L). 5-d after fumigant was applied, plots were hand-rolled with a steel-drum roller and fertilized with Triple Phosphate (0-46-0) at 49 kg P·ha^{-1}. A tire-dimpling device was rolled over each plot and seeded with creeping bentgrass seed [Agrostis stolonifera cv. 'Pure Select' (CBG)] seed at 48.8 kg seed·ha^{-1}. Fertilizer and seed were applied by hand using shaker bottles. To maximize seed-to-soil contact for seed establishment, plots were raked gently in two directions.

Trial Maintenance

Automatic irrigation was applied at 0.25 cm·d^{-1} until germination and applied on an "as-needed" basis, thereafter. Plots were reel-mowed bi-weekly at 0.64 cm. 2 weeks after seeding (WAS), urea (46-0-0) was melted and applied to blocks at 14.7 kg N·ha^{-1} using a CO_2 backpack sprayer and weekly at 4.9 kg N·ha^{-1} 3-8 WAS. All weeds (excluding ABG) were pulled 3x week^{-1} until 4 WAS. Mefenoxam [Subdue GR; Syngenta, Greensboro, NC; (R,S)-2-[(2,6-dimethylphenyl)-methoxyacetylamino]-propionic acid methyl ester) was applied to plots by hand 13 July 2018-19 at 42.7 kg·ha^{-1} as a safeguard against *Pythium* spp. infection. On 26 July 2019 quinclorac was applied at 23.7 fl oz·ha^{-1} using a CO_2 backpack sprayer [Drive XLR8; BASF Corporation, Research Triangle Park, NC; (3,7-dichloro-8-quinolinecarboxylic acid) for additional weed control.

Data Collection

Annual bluegrass emergence

Annual bluegrass cover was estimated on a scale of 0-100% and determined as the proportion of total plot area it consumed. ABG grid counts were conducted using the line-transect method, similar to that described by Bravo et al., (2018) and Gaussoin et al., (1989).

Counts were determined from the average of two, 0.10 m^2 grids containing 144 intersections every 6.5 cm^2, placed randomly in each plot. A "hit" was counted when any portion of an ABG plant touched one of these intersections.

Digital Image Analysis

Beginning 2 WAS, single images were captured bi-weekly from the center of each plot using a Canon® PowerShot SX710 HS digital camera (Canon U.S.A., Inc., Melville, NY). Images were taken inside of a custom, 2.5' x 2' x 2' lightbox, which provided consistent lighting between dates. Camera settings were fixed [manual, F-stop=3.5, exposure=1/20, ISO=1600, Macro] across measuring periods and corresponded with lightbox conditions. Images were analyzed for turfgrass cover using the Java™ applet TurfAnalyzer® (Karcher et al., 2017). Before analysis Hue, Saturation and Brightness (HSB) levels were set as a threshold for green pixels [H=45-140°, S=10-100%, B=0-100%]. In the applet, turfgrass cover was quantified as the quotient of green pixels in each image and the total number of pixels in each image (Karcher et al., 2013). Given hand-weeding through 4 WAS and the lack of ABG emergence until 6 WAS, DIA measurements from 2-4 WAS reflect pure CBG establishment. Thereafter, weeds were only pulled if they obstructed DIA images, however, cover from 6-8 WAS may also reflect ABG emergence.

Fraze material removed

On the day fraze material weight and volume was measured, 0.25 cm irrigation was applied across the site and the average Volumetric Water Content [%VWC] of three measures from each of three soil quadrants was recorded (TDR 350 FieldScout, Spectrum Technologies, Inc., Aurora, IL). Material was collected from three, 0.04 m^3 passes at each KORO rotor configuration evaluated and bagged in 0.11 m^3 paper lawn refuse bags. Immediately following, bags were weighed and the volume and mass in each bag was used to quantify the volume and weight of collected material from each 0.04 m^3 pass on each soil type. These values were used for extrapolations of $kg \cdot ha^{-1}$ and $m^3 \cdot ha^{-1}$ estimates.

Statistical Analysis

All statistical analysis was conducted in JMP Pro 13 (JMP® Pro, Version *13.* SAS Institute Inc., Cary, NC, 1989-2019). Data was analyzed by year as a 4 x 2 x 2 full-factorial, nested, split-plot design. Blocks were treated as random effects and soils were nested within each. To satisfy ANOVA assumptions of heterogeneous variances, ABG counts were square root transformed. Backtranformed means are presented. Fixed effects of KORO Surface Disturbance, Method of fumigant Incorporation and Soil type were considered significant when p-values exceeded an alpha of 0.05. All means were compared using Fisher's LSD.

RESULTS AND DISCUSSION

Annual bluegrass emergence

In 2018, ABG counts and estimated cover differed only by Soil type, 6 WAS, with lowest observed emergence in TDS plots (Tables 13-15). The greater ABG control observed in TDS plots may be explained by it's greater macroporosity, attributing to enhanced diffusivity of MITC gases through the profile of the coarser textured soil as many have previously reported (Gan et al., 1999; Gerstl et al., 1977; Lembright, 1990; Thomason et al., 1974; Zheng et al., 2006). In separate but related experiments, Landschoot et al., (2004) attributed improved MITC efficacy on ABG control to coarser textured soils. The significant D x I interaction observed 8 WAS, suggests that estimated cover was more influenced by till rather than ST incorporation (Figure 8). That is, control plots tilled had the greatest estimated cover while those subjected to 100% disturbance had the least. In 2019, ABG counts were consistently greater in ST

Table 13. An ANOVA showing significance of fraze mowing surface disturbance, incorporation method and soil type on annual bluegrass grid counts and estimated cover measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Annual bluegrass grid counts[b]**		**Estimated annual bluegrass cover (%)[c]**	
	6 WAS	8 WAS	6 WAS	8 WAS
Disturbance (D)[d]	NS	NS	NS	NS
Incorporation Method (I)	NS	NS	NS	NS
Soil Type (S)	*	NS	**	NS
D x I	NS	NS	NS	*
D x S	NS	NS	NS	NS
I x S	NS	NS	NS	NS
D x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 2 July 2018.
[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.
[c] Estimated proportion of annual bluegrass cover in 2.2 m^2 plots.
[d] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.
[NS, *, **, ***] Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 14. The effects of fraze mowing surface disturbance, incorporation method, and soil type on annual bluegrass grid counts measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Level**	**# of intersections containing annual bluegrass[b]**	
		6 WAS	8 WAS
Disturbance (D)[c]	0	1.4	5.9
	15	1.6	0.5
	50	<1.0	3.1
	100	<1.0	3.8
	LSD (*P*=0.05)	NS[e]	NS
Incorporation Method (I)	Solid-Tine	<1.0	3.0
	Till	1.0	2.8
	LSD (*P*=0.05)	NS	NS
Soil Type (S)	Topdressed	<1.0b[d]	2.0
	Native	2.3a	3.9
	LSD (*P*=0.05)	1.1	NS

[a] WAS=Weeks after seeding; plots seeded 2 July 2018.

[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05.

Table 15. The effects of fraze mowing surface disturbance, incorporation method, and soil type on estimated (%) annual bluegrass cover, measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Level**	**Estimated annual bluegrass cover (%)[b]**	
		6 WAS	8 WAS
Disturbance (D)[c]	0	7.1	9.6
	15	3.8	5.8
	50	3.8	6.7
	100	2.9	7.5
	LSD (*P*=0.05)	NS[e]	NS
Incorporation Method (I)	Solid-Tine	4.2	7.3
	Till	4.6	7.5
	LSD (*P*=0.05)	NS	NS
Soil Type (S)	Topdressed	2.3b	7.1
	Native	6.5a[d]	7.7
	LSD (*P*=0.05)	2.1	NS

[a] WAS=Weeks after seeding; plots seeded 2 July 2018.

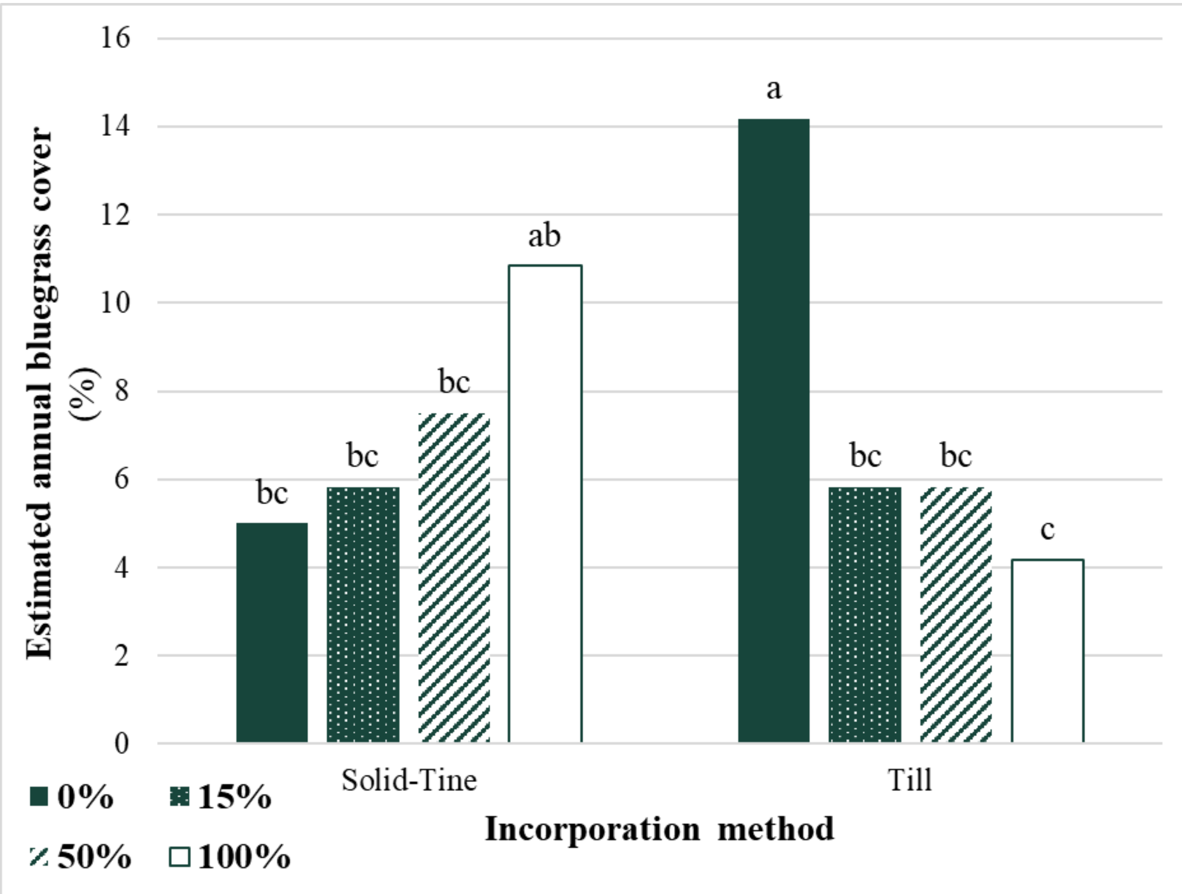
[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Figure 8. Estimated annual bluegrass cover (%) as affected by fraze mowing disturbance and fumigant incorporation method, 8 weeks after seeding from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.



incorporated plots across measurements (Tables 16-17), supporting significant differences in cover estimates made 6 WAS (Table 18). The higher ABG counts in tilled plots are similar to count data reported by Bravo et al., (2018) in a previous study conducted at the same site. It is possible the tillage disrupted soil structure, interfering with percolation of dazomet and the diffusivity of MITC gasses into the profile. Between periods, cover was lowest in plots fraze mowed at 50 and 100% disturbance, and was affected by D x I interactions, 6 and 8 WAS (Figures 9-10). In both interactions estimated cover was greatest in TDS control plots. Across factors, ABG counts in 2019 were much greater than in 2018. Differences in emergence between seasons could be explained by differences in accumulated Growing-Degree Days (GDD) relative to timing of treatments and seeding. In other research conducted at the site of the present experiment, Calhoun, (2010), observed peak Spring ABG seed flush to occur between 800-1000 GDD. By the time dazomet was applied in 2018 more than 900 GDD had already accumulated. By the same time in 2019, only 650 GDD had accumulated if more seed had already been exhausted from the system by the time 2018 trials were mowed, there may have been a lower likelihood for seed recruitment and dispersal between blocks.

Digital Image Analysis: Creeping bentgrass cover

In 2018, CBG cover was influenced by main effects of surface disturbance and incorporation and significant S x I, D x I and D x S interactions. Plots fraze mowed to 50 and 100% surface disturbance 2-8 WAS, and those subjected to ST incorporation 2 WAS yielded the lowest CBG cover (Table 19-20). In the S x I interaction 2 WAS, no difference in cover was observed on tilled plots across soils, but cover was lowest in ST cultivated, TDS plots (Figure 11). By 4 WAS the D x I interaction seems to contrast what was estimated in cover 8 WAS, where cover was more influenced by ST incorporation relative to till incorporation (Figure 12).

Table 16. An ANOVA showing significance of fraze mowing surface disturbance, incorporation method and soil type on annual bluegrass grid counts and estimated cover measured 6, 8 & 10 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Annual bluegrass grid counts[b]**		**Estimated annual bluegrass cover (%)[c]**		
	6 WAS	8 WAS	6 WAS	8 WAS	10 WAS
Disturbance (D)[d]	NS	NS	*	NS	**
Incorporation Method (I)	*	**	**	NS	NS
Soil Type (S)	NS	NS	NS	NS	NS
D x I	NS	NS	NS	NS	NS
Dx S	NS	NS	**	NS	*
I x S	NS	NS	NS	NS	NS
D x I x S	NS	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 29 June 2019

[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.

[c] Estimated proportion of annual bluegrass cover in 2.2 m^2 plots.

[d] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[NS, *, **, ***]Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 17. The effects of fraze mowing surface disturbance, incorporation method, and soil type on annual bluegrass grid counts measured 6 & 8 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	Level	# of intersections containing annual bluegrass[b]	
		6 WAS	8 WAS
Disturbance (D)[c]	0	13.1	30.9
	15	13.3	19.7
	50	10.8	21.8
	100	9.9	22.8
	LSD (*P*=0.05)	NS[d]	NS
Incorporation Method (I)	Solid-Tine	13.9a[e]	28.7a
	Till	9.6b	18.9b
	LSD (*P*=0.05)	3.7	6.4
Soil Type (S)	Topdressed	10.0	28.8
	Native	13.6	21.8
	LSD (*P*=0.05)	NS	NS

[a] WAS=Weeks after seeding; plots seeded 29 June 2019.

[b] Average number of annual bluegrass parts touching intersections spaced 6.5 cm^2 from two randomly place 0.10 m^2 grids.

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Nonsignificant or significant at P=0.05

[e] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05 .

Table 18. The effects of fraze mowing surface disturbance, incorporation method and soil type on estimated (%) annual bluegrass cover, measured 6, 8 & 10 weeks after seeding[a] from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Level**	**Estimated annual bluegrass plot cover (%)[b]**		
		6 WAS	8 WAS	10 WAS
Disturbance (D)[c]	0	16.3ab[d]	19.2	47.9a
	15	18.3a	17.1	40.8a
	50	13.8b	17.1	21.3b
	100	15.0b	18.8	27.9b
	LSD (*P*=0.05)	5.0	NS	12.8
Incorporation Method (I)	Solid-Tine	19.0a	19.4	36.3
	Till	12.7b	16.7	32.7
	LSD (*P*=0.05)	4.4	NS	NS
Soil Type (S)	Topdressed	16.9	17.9	39.4
	Native	14.8	18.1	29.6
	LSD (*P*=0.05)	NS[e]	NS	NS

[a] WAS=Weeks after seeding; plots seeded 29 June 2019.

[b] Average number of annual bluegrass parts touching intersections spaced $6.5cm^2$ from two randomly place $0.10m^2$ grids.

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Figure 9. Estimated annual bluegrass cover (%) as affected by fraze mowing disturbance and soil type, 6 weeks after seeding from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

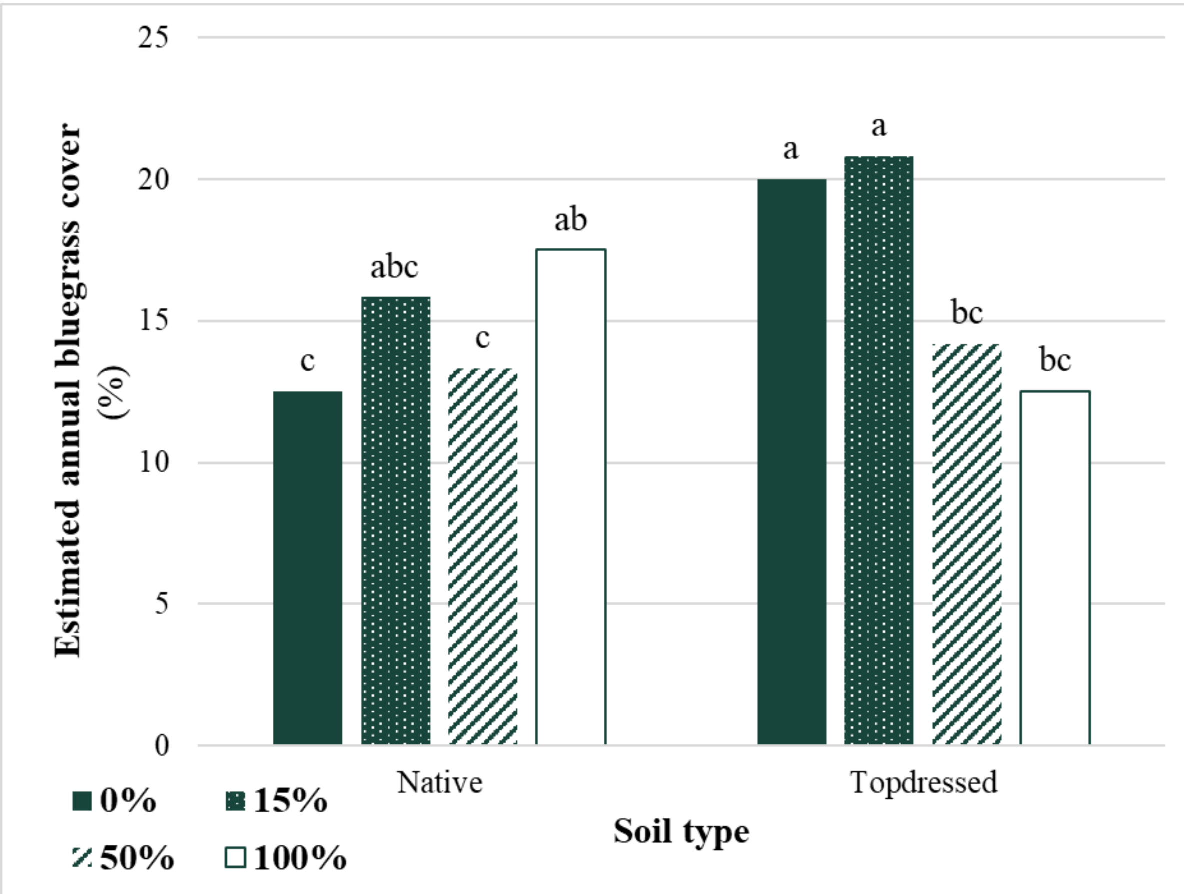


Figure 10. Estimated annual bluegrass cover (%) as affected by fraze mowing disturbance and soil type, 8 weeks after seeding from plots seeded with creeping bentgrass at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

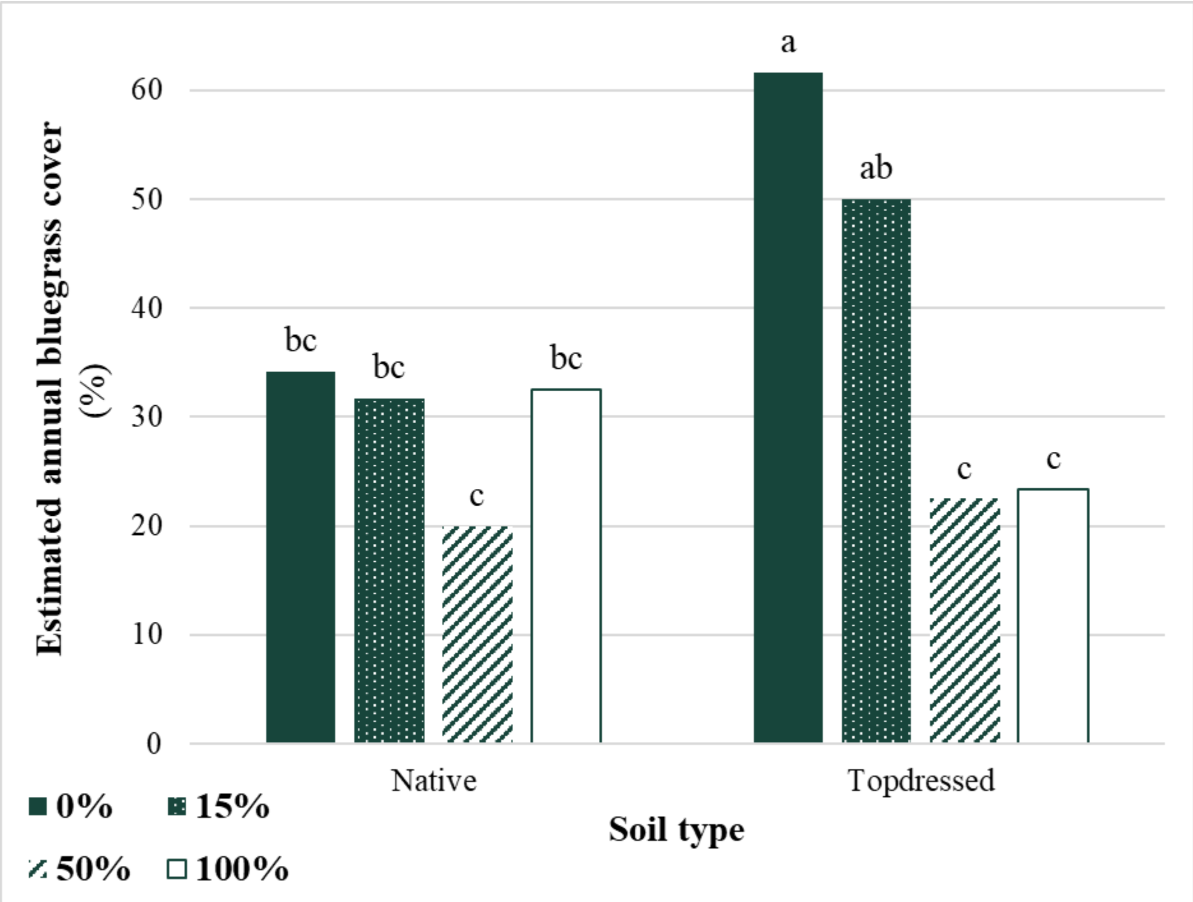


Table 19. An ANOVA showing significance of fraze mowing surface disturbance, incorporation method and soil type on creeping bentgrass cover 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	Creeping bentgrass cover (%)[b]			
	2 WAS	4 WAS	6 WAS	8 WAS
Disturbance (D)[c]	**	***	**	**
Incorporation Method (I)	*	NS	NS	NS
Soil Type (S)	NS	NS	NS	NS
D x I	NS	*	NS	NS
D x S	NS	*	*	**
I x S	**	NS	NS	NS
D x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 2 July 2018.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.
% Cover = (# of Green Pixels) / (Total Pixels).

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[NS, *, **, ***] Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 20. The effects of fraze mowing surface disturbance, incorporation method and soil type on creeping bentgrass cover measured 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

Treatment	**Level**	**Creeping bentgrass cover** (%)[b]			
		2 WAS	4 WAS	6 WAS	8 WAS
Disturbance (D)[c]	0	28a[d]	72a	81ab	96a
	15	25a	71a	87a	94a
	50	8b	46b	71bc	87b
	100	6b	36b	65c	87b
	LSD (*P*=0.05)	10	18	15	1
Incorporation Method (I)	Solid-Tine	16b	46	96	93
	Till	18a	56	88	88
	LSD (*P*=0.05)	1	NS	NS	NS
Soil Type (S)	Topdressed	12	28	54	95
	Native	12	42	49	87
	LSD (*P*=0.05)	NS[e]	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 2 July 2018.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.

% Cover = (# of Green Pixels) / (Total Pixels).

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

[e] Nonsignificant or significant at *P*=0.05

Figure 11. Creeping bentgrass cover as affected by fumigant incorporation method and soil type, 2 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

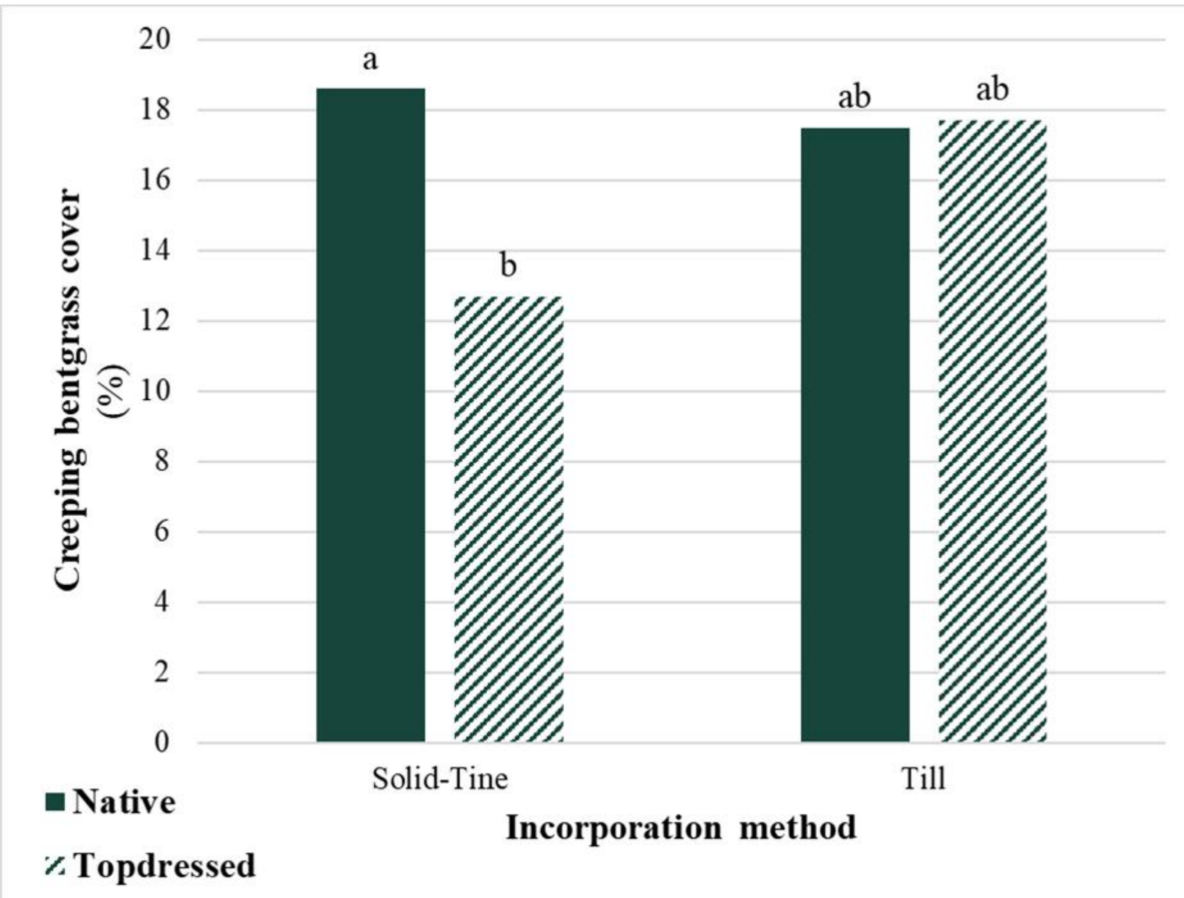
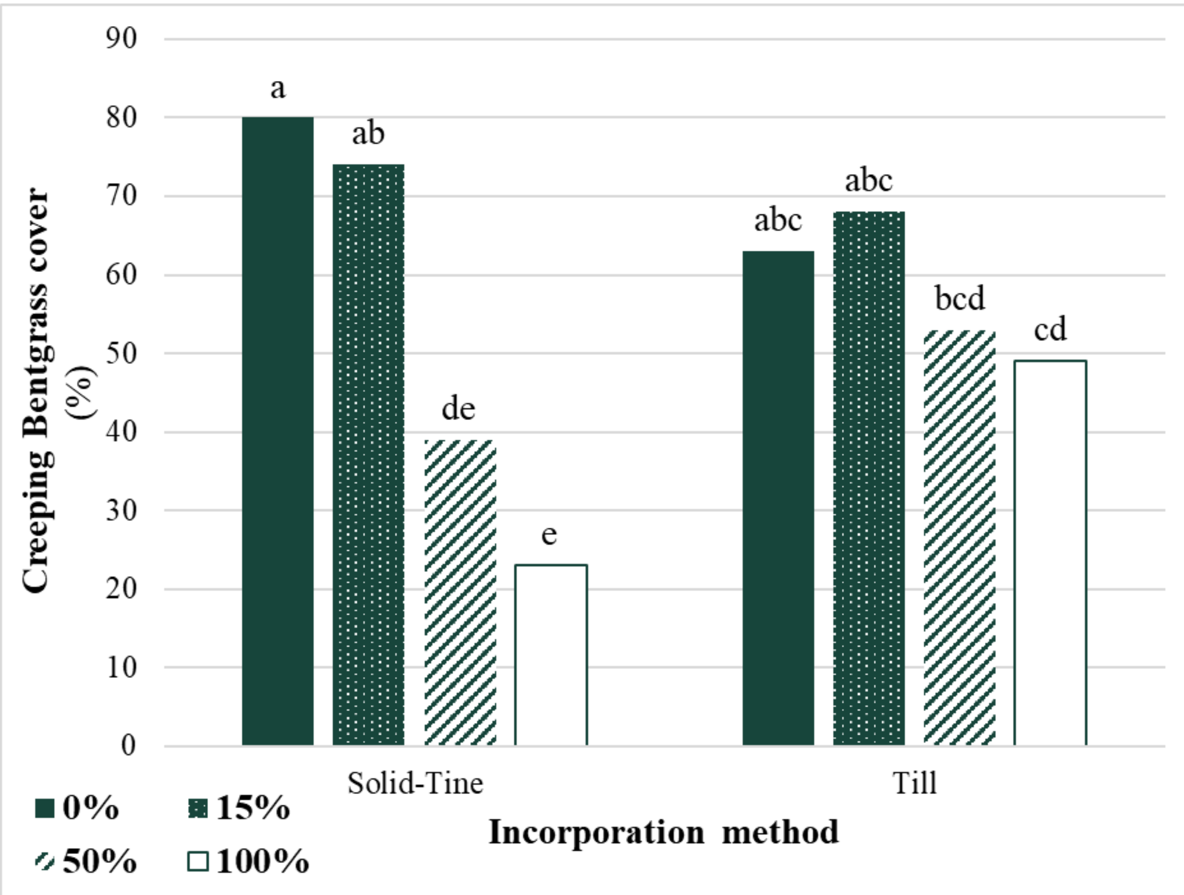


Figure 12. Creeping bentgrass cover as affected by fumigant incorporation method and fraze mowing disturbance, 4 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.



Across D x S interactions which were significant 4-8 WAS, cover in native soils was lower or marginally lower than the control and 15% disturbance treatments for 50 and 100% disturbance treatments and differed little between levels of disturbance in TDS plots (Figures 13-15). In 2019, CBG cover was only influenced by incorporation effects observed 8 WAS (Tables 21-22), where cover was significantly higher in ST incorporated plots than those tilled, supports observations of a separate unpublished study we conducted. Differences in CBG cover between 2018-19 were consequence of two key factors; (i) A bad seed lot of 'Pure Select' CBG planted in 2019 and (ii) an additional 7.8 cm of precipitation that fell on the site in the 2018 season. The poor seed quality used in 2019 was verified by a simple germination test. From 6-8 WAS, the D x I interaction effects on cover were relatively consistent; cover was lowest in Tilled plots cultivated with 100% disturbance and all levels of disturbance, higher than the control in ST plots **(**Figures 16-17**)**. Given the interference of poor seed on establishment in 2019 and temporal differences between seasons, we cannot say with certainty that fraze mowing disturbance is antagonistic against establishment. From an agronomic standpoint however, greater amounts of material removed leaves seed exposed to a bare surface and likely explains why 50-100% disturbance yielded poorer cover in 2018.

Fraze material removed

The volume of material removed at each level of disturbance was consistent between soil types and only differed by mass (Table 23). The volume of material removed from fraze mowing is an important factor for determining the practicality of fraze mowing in a renovation scenario. The volume of material removed can affect projected renovation costs for removal of material and may be restricted by available space for on-site disposal and recycling. To our knowledge, these metrics have not been reported previously in literature. Provided adequate space for on-site

Figure 13. Creeping bentgrass cover as affected by fraze mowing disturbance and soil type, 4 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

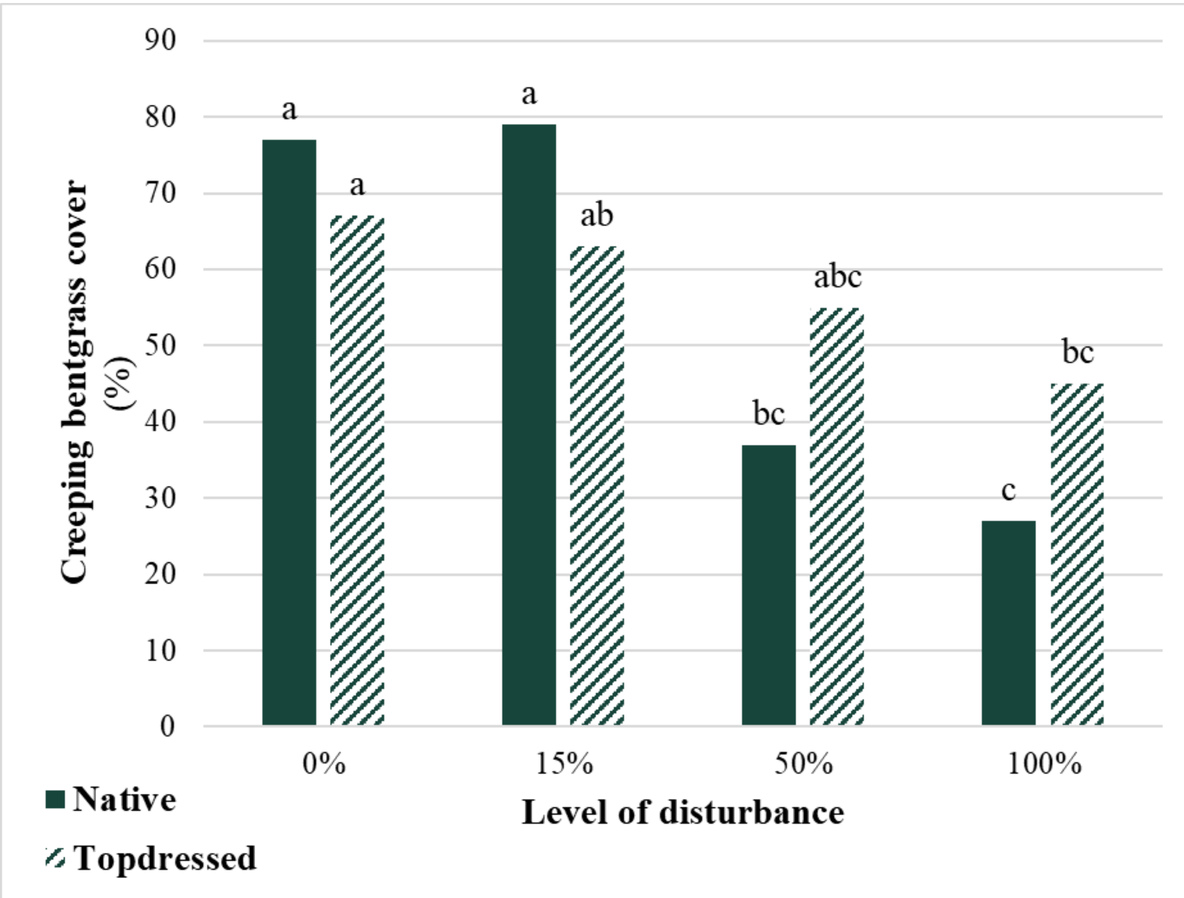


Figure 14. Creeping bentgrass cover as affected by soil type and fraze mowing disturbance, 6 weeks after seeding, from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

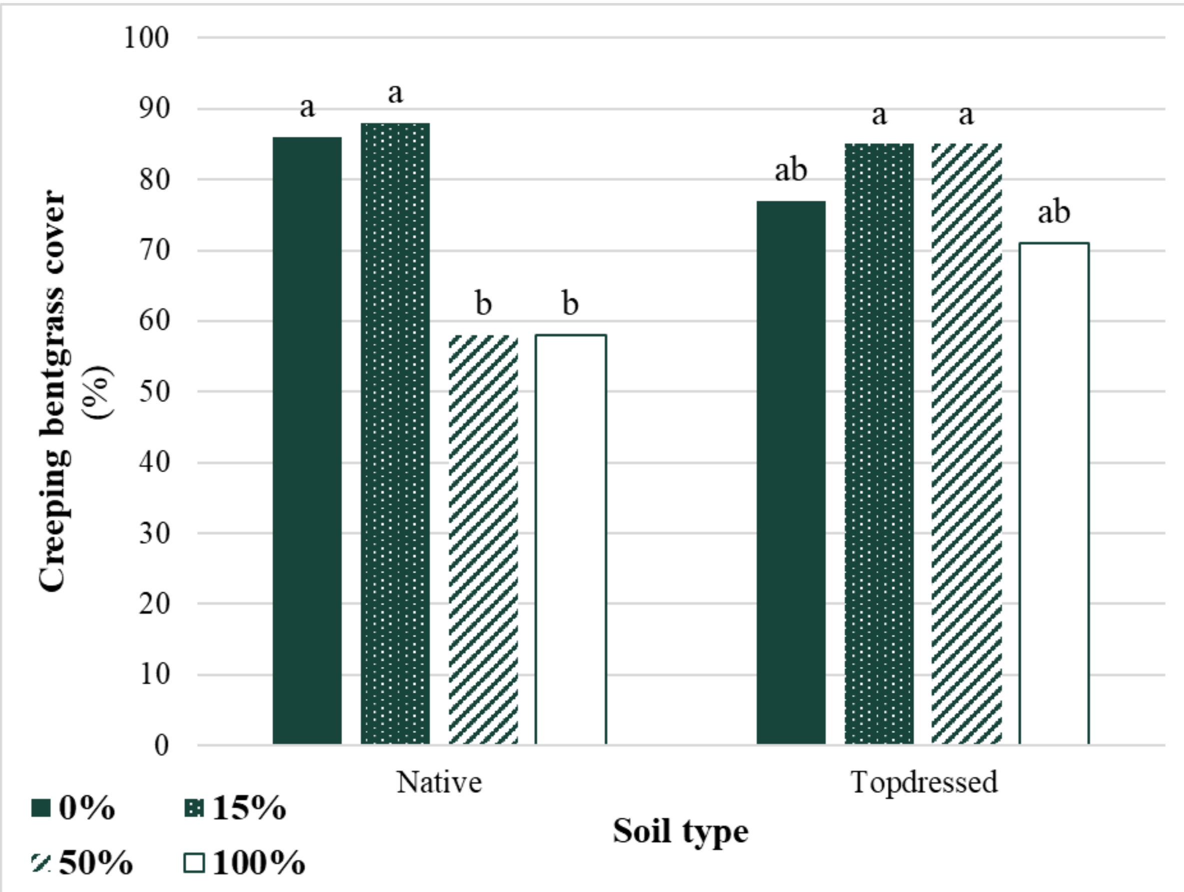


Figure 15. Creeping bentgrass cover as affected by fumigant incorporation method and fraze mowing disturbance, 8 weeks after seeding, from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

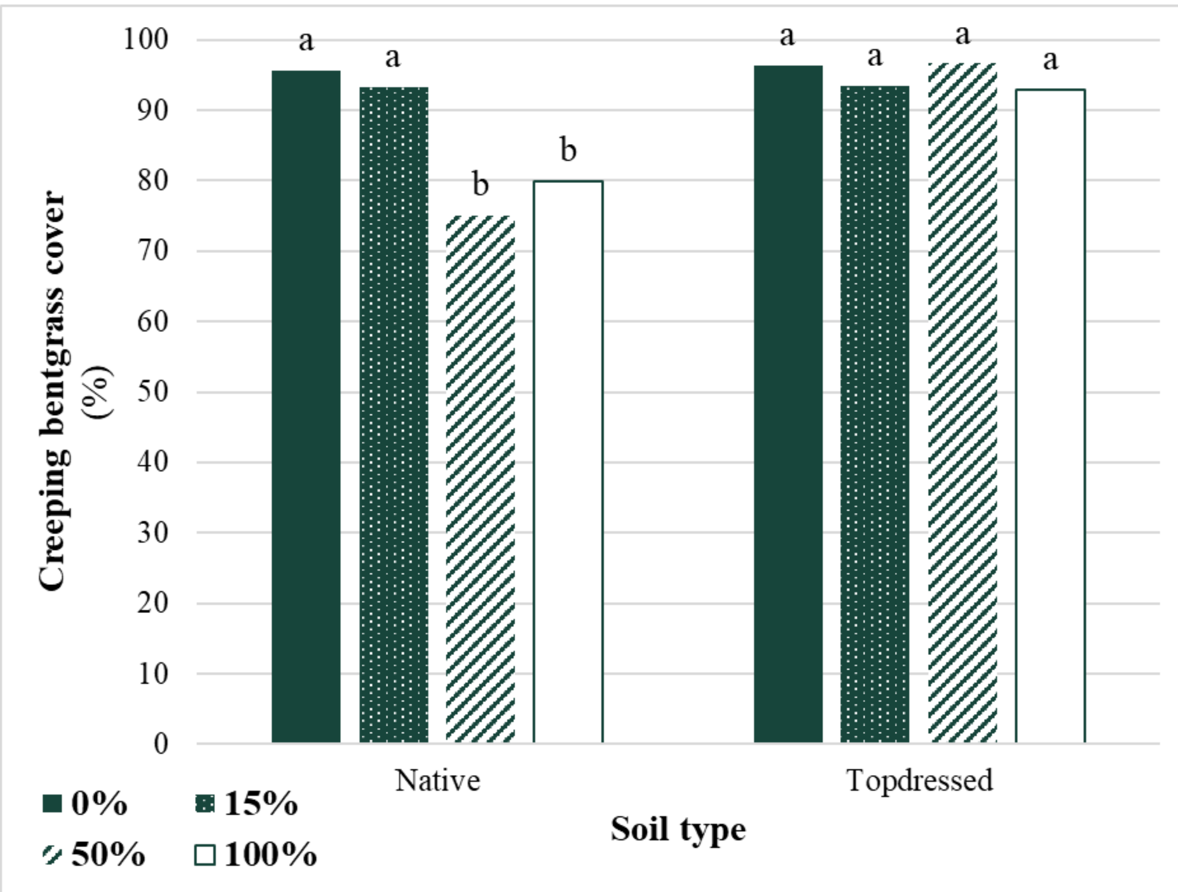


Table 21. An ANOVA showing significance of fraze mowing surface disturbance, incorporation method and soil type on creeping bentgrass cover 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	**Creeping bentgrass cover (%)[b]**			
	2 WAS	4 WAS	6 WAS	8 WAS
Disturbance (D)[c]	NS	NS	NS	NS
Incorporation Method (I)	NS	NS	NS	**
Soil Type (S)	NS	NS	NS	NS
D x I	NS	NS	**	*
D x S	NS	NS	NS	NS
I x S	NS	NS	NS	NS
D x I x S	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 29 June 2019.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period. % Cover = (# of Green Pixels) / (Total Pixels).

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[NS, *, **, ***] Nonsignificant or significant at *P*=0.05, 0.01, or 0.001, respectively.

Table 22. The effects of fraze mowing surface disturbance, incorporation method and soil type on creeping bentgrass cover measured 2-8 weeks after seeding[a] from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

Treatment	Level	**Creeping bentgrass cover** (%)[b]			
		2 WAS	4 WAS	6 WAS	8 WAS
Disturbance (D)[c]	0	6	42	72	86
	15	9	44	75	88
	50	10	51	77	87
	100	5	44	67	78
	LSD (*P*=0.05)	NS[d]	NS	NS	NS
Incorporation Method (I)	Solid-Tine	7	46	76	97a[e]
	Till	7	44	70	77b
	LSD (*P*=0.05)	NS	NS	NS	6
Soil Type (S)	Topdressed	4	36	78	86
	Native	11	54	68	83
	LSD (*P*=0.05)	NS	NS	NS	NS

[a] WAS=Weeks after seeding; plots seeded 29 June 2019.

[b] Images captured in fluorescently lit lightbox under fixed camera settings for each period.

% Cover = (# of Green Pixels) / (Total Pixels).

[c] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.

[d] Nonsignificant or significant at *P*=0.05

[e] Means followed by same letter are not significantly different at LSD according to Fisher's LSD at *P*=0.05

Figure 16. Creeping bentgrass cover as affected by fraze mowing disturbance and fumigant incorporation method, 6 weeks after seeding from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

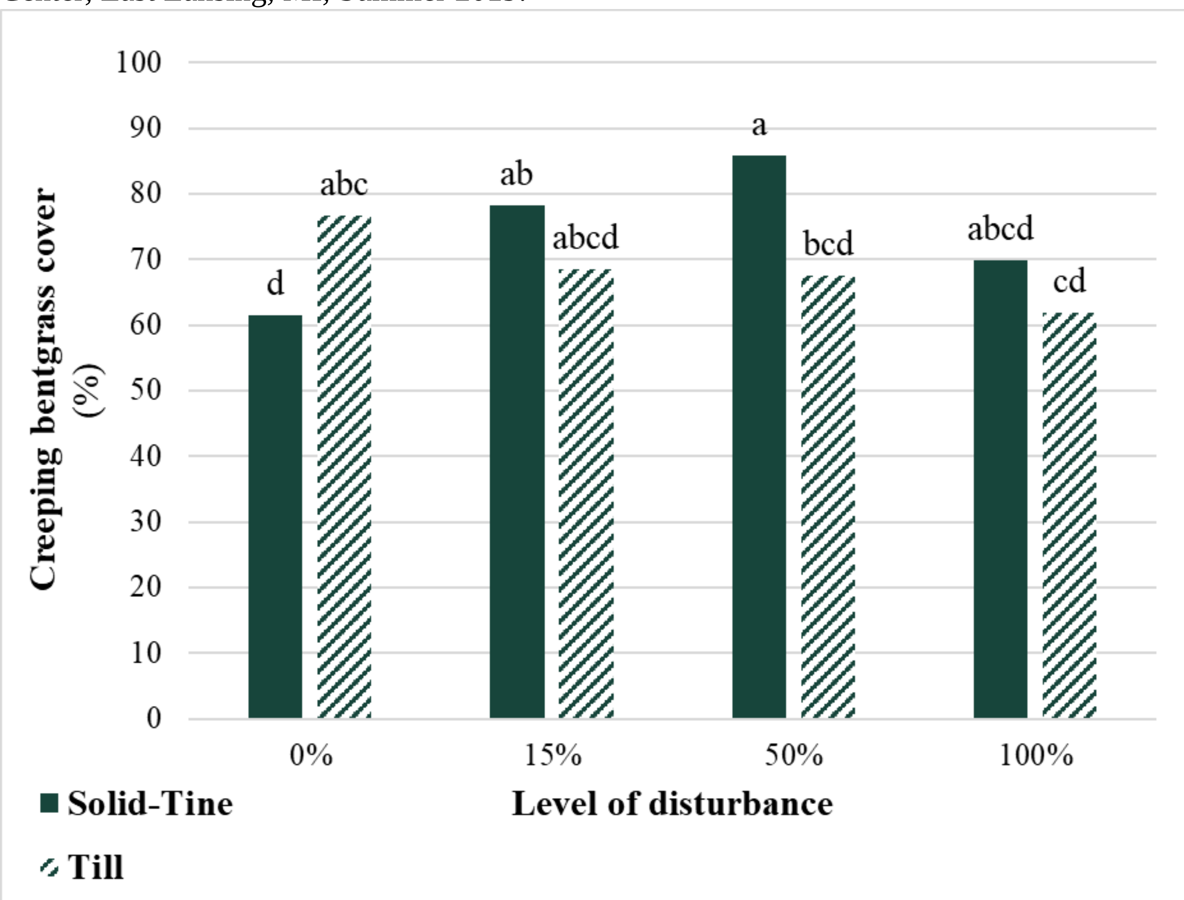


Figure 17. Creeping bentgrass cover as affected by fraze mowing disturbance and fumigant incorporation method, 8 weeks after seeding, from plots at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

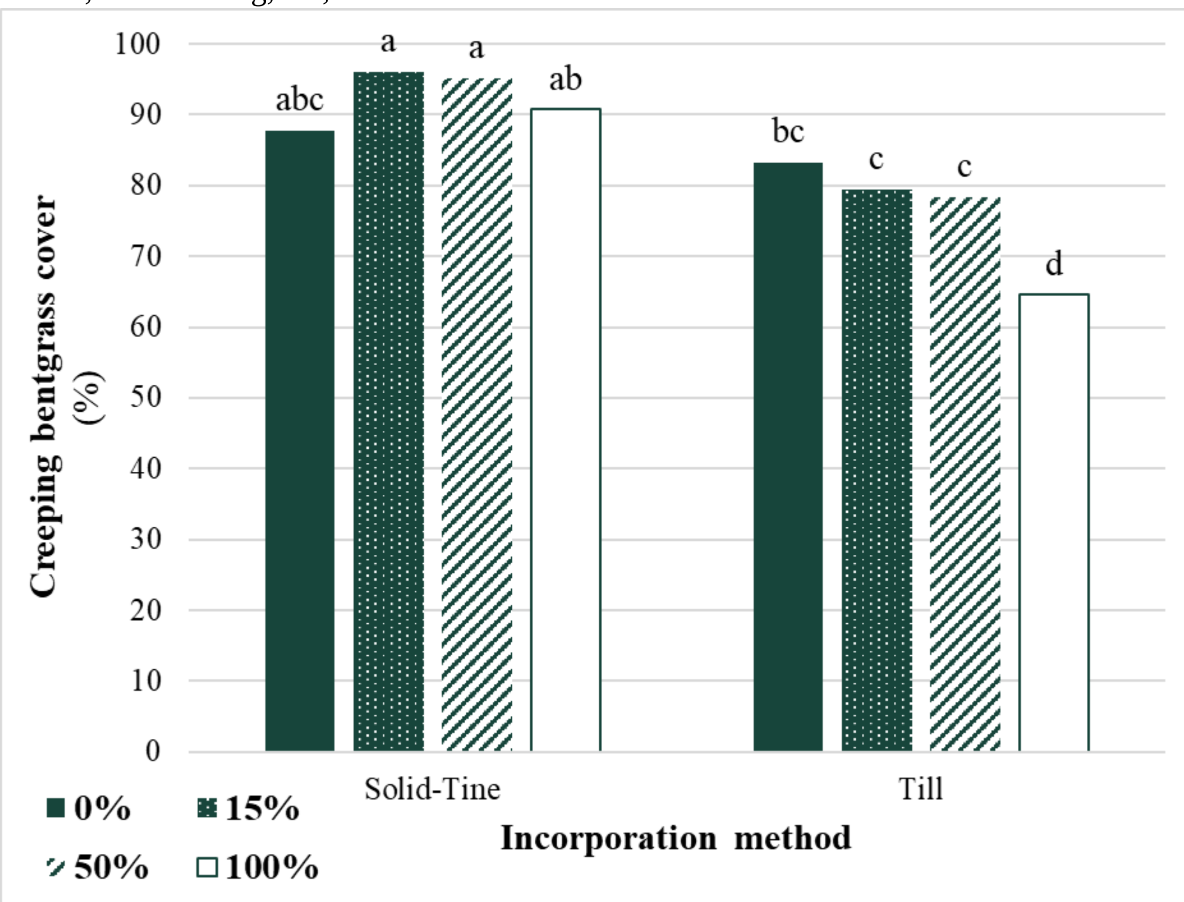


Table 23. Average volume, mass, and % volumetric water content of fraze material removed from two soil types at three levels of fraze mowing disturbance, Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

% Surface Disturbance[a]	**Topdressed**			**Native**		
	MT ha^{-1}	m^3 ha^{-1}	% Θ_{VWC}[b]	MT ha^{-1}	m^3 ha^{-1}	% Θ_{VWC}
15	9.9	80.5	34.2	15.7	80.5	35.9
50	67.3	160.6	34.8	47.8	160.6	35.2
100	111.0	179.9	36.9	100.0	179.9	32.9

[a] All plots fraze mowed to a uniform depth of 1.9 cm with varying levels of surface area disturbed (%) and removed.
[b] % Θ_{VWC}=Proportion of soil water per unit soil

disposal, it may be possible for practitioners to recycle removed material. Peachey et al., (2001), temperatures ≥ 45°C. Fernandez et al., (1994) found static compost piles are capable of reaching temperatures in excess of 45°C in as little as two days. If ABG contaminated soils could be composted adequately, refuse material has potential to be recycled. Still, even a few ABG seeds that remain viable have potential to recolonize an entire site. If future research can evaluate this theory, recycling such material can add a sustainable aspect to putting green and fairway system renovation

CONCLUSIONS

In the present study, a tradeoff was observed between the level of fraze mowing surface disturbance, CBG establishment and ABG control. ABG emergence was greatest at levels of disturbance which enhanced CBG establishment and lowest at levels of disturbance where CGB establishment was reduced. Further, significant disturbance effects on CBG establishment or ABG emergence were never observed in the same year and were inconsistent across seasons. Moreover, disturbance effects only corresponded with subjective estimated ABG cover and had significant effects on ABG counts. Therefore, in this study, fraze mowing did seem to provide additional benefits of dazomet fumigation or enhance its effects. Similarly, main effects of soil type and incorporation method did significantly influence ABG emergence and CBG establishment, however, their effects were inconsistent across seasons. The wetter 2018 season and the poor seed lot used in 2019 may have exacerbated the contrast in ABG counts and cover between soils and seasons. Of the handful of dazomet fumigation experiments conducted, none have achieved complete ABG control without tarp cover (Branham et al., 2004; Bravo et al., 2018; Landschoot et al., 2003, 2004).

An important factor that should be considered when interpreting results of this study is the difference in initial ABG populations between the site of this experiment and the site of similar studies. The ABG density in control plots of Landschoot et al., (2003) fairway dazomet trials for instance, were reported at 3,914 plants $2.2m^{-2}$ or an equivalent 177.9 plants $0.1m^{-2}$. The highest ABG density in control plots in either year of the present study peaked at 30.9 ABG plants $0.1m^{-2}$ or an extrapolated equivalent of 679.8 ABG plants $2.2\ m^{-2}$. Future research should consider evaluating fraze mowing effects for ABG control in pure ABG systems. It may also be practical to evaluate treatment effects when dazomet is either; (i) applied at higher labeled rates or (ii) applied in split intervals. Research might also consider fraze mowing contaminated soils to greater or varying depths and evaluating the recycling and composting potential of contaminated fraze material.

APPENDIX

Table 24. Schedule of 2018 protocols for Dazomet fumigation Rate trial conducted at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

DATE	PROCEDURE
06.15.2018	2.0% Glyphosate solution applied @ 44 dL ha^{-1}
06.24.2018	Scalped blocks to 0.50cm
06.25.2018	All plots fraze mowed to 1.9 cm @ 100% surface disturbance
06.26.2018	Initial fumigation treatments applied. Watered-in until 06.29.2018
07.05.2018	Dazomet applied to respective split fumigation plots and watered-in until 07.09.2018
07.10.2018	Plots hand-rolled, fertilized and seeded with 'Pure Select' @ 48.8 kg ha^{-1}
07.13.2018	Subdue GR applied at 42.7kg ha^{-1} and irrigated with 1.3cm
07.24.2018	First foliar fertilization applied @ 14.7kg N ha^{-1} 44dL ha^{-1}
09.01.2018	Sterilized SureMix + Sand soil mix at 88°C until 09.06.2018
09.06.2018	Filled 8.9cm wide square plastic pots with sterilized soil and placed in growth chamber. Extracted five, 1.9cm soil cores from Rate study plots @ 5.0cm depth, placed in paper bags and left to air-dry until 09.11.2018
09.11.2018	Weighed dried cores and topdressed half of the mass onto surface of pots in growth chamber. Remaining mass placed in cooler @ 1.1°C until 10.31.2018. Growth chamber set to 14/10-h diurnal light and temperature cycle at 65% RH, 22°C Day, 20°C Night
10.31.2018	Remaining mass of core samples sprinkled over pots and kept moist until 12.20.2019 for final assessment of emergence
12.20.2019	Pots removed from growth chamber and assessed for emergence

Table 25. Schedule of 2019 protocols for Dazomet fumigation Rate trial conducted at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

DATE	PROCEDURE
06.14.2019	2.0% Glyphosate solution applied @ 44 dL ha^{-1} with CO2 backpack sprayer
06.24.2019	Scalped blocks to 0.50cm. All plots fraze mowed to depth of 1.9 cm @ 100% surface disturbance
06.26.2019	Rate study plots fumigated. Watered-in until 06.29.2019
07.08.2019	Due to rain delays, split fumigation treatments delayed to 13-d after initial fumigation. Fumigation applied to respective Rate study plots and watered-in until 07.11.2019
07.12.2019	Plots hand-rolled, fertilized and seeded with 'Pure Select' @ 48.8 kg ha^{-1}
07.26.2019	First foliar fertilization applied @ 14.7kg N ha^{-1} 44dL ha^{-1}
07.29.2019	Applied Subdue GR by hand at 42.7kg ha^{-1} and irrigated with 1.3cm
08.03.2019	Sprayed quinclorac on both studies with CO2 backpack sprayer @ 0.22fl/oz/M
09.06.2019	Sprayed Sethoxydim with CO2 backpack sprayer @ 0.19mL m^{-2}

Table 26. Weed species observed in plots following fraze mowing cultivation at 1.9 cm depth, dazomet fumigation and dazomet incorporation across soil types, Hancock Turfgrass Research Center, East Lansing, MI, Summers 2018-19.

Weed Species	**Common Name**	**Family**
Annual Bluegrass	*Poa annua* L.	Poaceae
Barnyardgrass	*Echinochloa crus-gallis*	Poaceae
Broadleaf Plantain	*Plantago major*	Plantaginaceae
Canadian Thistle	*Cirsium arvense*	Asteraceae
Catchweed Bedstraw	*Galium aparine*	Rubiaceae
Common Dandelion	*Taraxacum officinale*	Asteraceae
Common Lambsquarters	*Chenopodium album*	Chenopodiaceae
Common Purslane	*Portulaca oleracea*	Portulacaceae
Fall Panicum	*Panicum dichotomiflorum*	Poaceae
Goosegrass	*Eleusine indica* L.	Poaceae
Large Crabgrass	*Digitaria sanguinalis*	Poaceae
Nettleleaf Goosefoot	*Chenopodium murale*	Chenopodiaceae
Prickly Lettuce	*Lactuca serriola*	Asteraceae
Prostrate Knotweed	*Polygonum aviculare*	Polygonaceae
Purple Henbit	*Lamium purpeum*	Lamiaceae
Purple Lovegrass	*Eragrostis spectabilis*	Poaceae
Smooth Crabgrass	*Digitaria ischaemum*	Poaceae
Spotted Spurge	*Euphorbia maculata*	Euphorbiaceae
Witchgrass	*Panicum capillare*	Poaceae
Yellow Nutsedge	*Cyperus esculentus*	Cyperaceae

Table 27. Schedule of protocols for Surface Disturbance trials conducted at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2018.

DATE	PROCEDURE
06.15.2018	2.0% Glyphosate solution applied @ 44 dL ha^{-1}
06.24.2018	Scalped blocks to 0.50cm
06.25.2018	Respective plots fraze mowed to 1.9 cm @ 100% and 50% disturbance.
06.26.2018	Respective plots fraze mowed to 1.9 cm @ 15% disturbance.
06.29.2018	Plots fumigated with dazomet at a uniform rate of 293.7 kg ha^{-1} and watered-in until 07.02.2018.
07.03.2018	Plots hand-rolled, fertilized and seeded with 'Pure Select' @ 48.8 kg ha^{-1}.
07.13.2018	Applied Subdue GR by hand at 42.7kg ha^{-1} and irrigated with 1.3cm
07.17.2018	First foliar fertilization applied @ 14.7 kg N ha^{-1} @ 44dL ha^{-1}
07.24.2018	Foliar fertilized Rate study with 14.7kg N ha^{-1} 44dL ha^{-1}

Table 28. Schedule of 2019 protocols Surface Disturbance trials conducted at the Hancock Turfgrass Research Center, East Lansing, MI, Summer 2019.

DATE	PROCEDURE
06.14.2019	2.0% Glyphosate solution applied @ 44 dL ha^{-1} with CO2 backpack sprayer
06.24.2019	Scalped blocks to 0.50cm. All plots fraze mowed @ respective levels of disturbance
06.25.2019	Plots fumigated with dazomet at a uniform rate of 293.7 kg ha^{-1} and watered-in until 07.02.2018.
06.29.2019	Plots hand-rolled, fertilized and seeded with 'Pure Select' @ 48.8 kg ha^{-1}.
07.13.2019	First foliar fertilization applied @ 14.7 kg N ha^{-1} @ 44dL ha^{-1}
07.29.2019	Applied Subdue GR by hand at 42.7kg ha^{-1} and irrigated with 1.3cm
08.03.2019	Sprayed quinclorac on both studies with CO2 backpack sprayer @ 0.22fl/oz/M
08.24.2019	Sprayed Sethoxydim on Disturbance study with CO2 backpack sprayer @ 0.19mL m^{-2}

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