NON-CHEMICAL VEGETATION MANAGEMENT USING FRAISE MOWING IN NATURALIZED GOLF COURSE GRASSLANDS

A Thesis

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ABSTRACT

Responding to public pressure to reduce synthetic chemical use and combating the rise of herbicide resistance in amenity grasslands are challenging due to the lack of alternative options. Additionally, the changing climate is less conducive to traditional grassland species success. The ability to rapidly renovate grassland surfaces could provide solutions to both challenges by reducing weed seed pressure and establishing genetically improved, well adapted varieties. Fraise mowing is an aggressive cultivation practice designed to harvest verdure, organic matter, and soil to a depth of 5 cm while allowing turfgrass to reestablish from unharvested rhizomes or provide an advantageous seedbed for establishing via seed or sod. Given the weed seed bank accumulates near the soil surface in no-till systems, we hypothesized fraise mowing could be an effective means of weed seed bank harvest and long-term, non-chemical weed control. Field experiments were conducted from 2017 – 2019 at the Vineyard Golf Club (Edgartown, MA) in low-maintenance, naturalized fine fescue rough heavily infested with smooth crabgrass (*Digitaria ischaemum* (Schreb.) Muhl.). Three weed seed bank harvest depths and two grassland establishment rates across five timings were evaluated for preventing weed re-infestation. Prior to fraise mowing, soil cores were collected from the study area and subjected to seedbank analysis. Similarly, seedbank analysis of harvested fraise mow debris was completed to determine efficacy of weed seed harvest. Despite a substantial reduction in the smooth crabgrass weed seed bank and a significant effect of timing and harvest depth on re-infestation, smooth crabgrass surpassed thresholds (<15%) by the end of the first full growing season, indicating the need for additional follow-up treatments for commercially acceptable control.

BIOGRAPHICAL SKETCH

Christopher Sitko was born and raised in Pottstown, Pennsylvania where his family owns and operates a small Christmas tree farm. Chris's grandparents instilled an appreciation and passion for agronomy early in his life. He completed his BS in 2015 at Cornell University majoring in Agricultural Sciences, minoring in Business and Horticulture, and working summers as a turfgrass management intern at Lancaster Country Club and Saucon Valley Country Club. Upon graduation, Chris completed an internship with the USGA Green Section and worked as an assistant superintendent at Westchester Country Club in Rye, NY. He returned to Cornell in Summer 2017 as an MS Candidate in the Horticulture department.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure 11. Figure 11. Influence of surface harvest depth and timing on turf cover (%) measured on May 16, 2018. Surface harvest timings are presented as growing degree-days (base 10°C) prior to smooth crabgrass emergence in the study location. The surface harvest timing May 18 was installed after the sampling date and is not included in this figure.

LIST OF TABLES

LIST OF ABBREVIATIONS

Growing Degree Day, GDD; Harvest Weed Seed Control, HWSC; High Pressure Sodium, HPS; Preemergence, PRE; Postemergence, POST; Vineyard Golf Club, VGC.

LITERATURE REVIEW

Classifying Plants as Weeds

There are philosophical and practical definitions of weeds. For example, Ralph Waldo Emerson described *weeds as plants* whose virtues have not yet been discovered. The Weed Science Society of America defines a weed as a plant that causes economic losses or ecological damage, creates health problems for humans or animals, or is undesirable where it is growing (Weed Science Society of America 2016). In amenity grasslands, weeds are classified to facilitate control strategies and are considered by weed type, plant family, life cycle, and seasonal growth habit (McElroy and Bhowmik 2013).

Globally, weeds pose the greatest threat to crop loss (Oerke 2006). Weed interference in crop production can lower yields and quality through resource competition, reduced harvest efficiency, and contamination of harvested grain (Soltani et al. 2016). In agronomic crops, economic thresholds to optimize weed control strategy are designed to mitigate potential yield loss. However, the variety of land use associated with amenity grassland performance with metrics are not as clear as yield, various thresholds for weeds exist.

Weed thresholds in amenity grasslands comprise three distinct categories: functional, aesthetic, or biological and may change at the system scale or prove species specific (Larsen and Fisher 2005; McCarty et al. 1994). For example, low functional thresholds exist for species such as large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and white clover (*Trifolium repens* L.) on athletic fields due to reduced field durability, playability and compromised athlete safety (Brosnan et al. 2014; Larsen et al. 2004). Similarly, golf course putting greens often have a zero weed tolerance to prevent declined playability or disruption to trueness of ball roll (McElroy and Martins 2013).

Assessing aesthetic quality of amenity grassland using stakeholders and consumers result in highly variable thresholds (Templeton et al. 1998). Distractions created by contrasting plant color or height uniformity can be determining factors in the aesthetic threshold for weed species like yellow nutsedge (*Cyperus esculentus* L.*)*. Overtime, the yellow nutsedge competes with turfgrasses for nutrients, space, light, and water and can serve as hosts for pests such as plant pathogens, nematodes and insects (McCarty et al. 1994).

The changing climate continues to challenge the overall sustainability of amenity grasslands and current weed control practices. Increasing herbicide resistance, slowing chemistry discovery and public pressure to reduce synthetic chemical use, require the development and implementation of alternative, non-chemical weed control strategies. Furthermore, these strategies can no longer focus solely on annual management of the aboveground weed flora (Schwartz et al. 2015) but must consider biological weaknesses of targeted weed species (Walsh et al. 2013), seek to prevent weed seed production, deplete the soil weed seedbank, and utilize crop competitiveness to suppress weeds (Norsworthy et al. 2012).

Amenity Grassland Establishment

Effective weed management begins at pre-planting (Bertin and Weston 2004). Proper site selection, preparation and establishment methods will favor an effective long-term weed management program (Bertin and Weston 2004). Specifically, amending soil physical properties at establishment is the most effective means of improving internal drainage or nutrient holding capacity (Caron et al. 2017).

Well-adapted grassland species and cultivars improve stress tolerance and possess characteristics such as rapid establishment and ability to maintain cover that reduces weed recruitment (Busey 2003). Time required for establishment of full cover can be reduced by higher planting density (Busey 2003). Beard et al. (1980) found a 20 percent reduction in weed cover resulted from increasing Kentucky bluegrass (*Poa pratensis* L.) seed rate from 45 kg ha^{-1} to 90 kg ha^{-1}. Similarly, Bertin et al. (2009) found that higher seedling vigor in *Festuca* spp., 90 days after seeding, results in greater weed suppression and aggressively creeping varieties maintained a high level of weed suppression.

Minimizing weed introduction in the seedbed begins with proper sanitation practices. Grassland establishment with weed-free seed or sod reduces weed recruitment and spread. The Federal Seed Act of 1939 (2020) requires information such as other crop seed, inert matter, and weed seed to be listed on seed labels. Similarly, Turfgrass Producers International, previously the American Sod Producers Association, sets thresholds for maximum weed infestation levels for sod to be considered weed-free (McCarty et al. 1994). However, no regulation and minimal research exists on potential weed seed transport in the soil and organic layers of harvested sod.

<u>Species and Variety Selection</u>

Climate, use of the site and management exert selection pressure on amenity grasslands and in traditional turfgrass stands include adaptation to mowing height, nutrient and, pest management (Nelson et al. 2004). Aamlid et al. (2012) recently evaluated several turfgrass species and varieties for Scandinavian golf course putting greens managed without pesticides in light of increasing pesticide restrictions. Mixtures of Kentucky bluegrass, a cool-season species, and bermudagrass (*Cynodon dactylon* (L.) Pers.), a warm-season species, are being explored for optimizing performance across seasons in the "transition" zone of the United States where monocultures struggle (Munshaw 2018).

Cultural Management of Weeds

The recruitment level of weeds in amenity grasslands is proportional to the competitive ability of the existing sward under the prevalent growing conditions (Larsen and Fisher 2005; McCarty and Tucker 2005). Consequently, weed control using cultural maintenance such as water management, enhances amenity grassland species competitive ability by reducing weed establishment and/or maintaining populations below established threshold. Still, weeds that are common to amenity grasslands compete for resources across a wide range of conditions and do not allow maintenance of an ecological niche that favors the amenity species over the weed without chemicals. (McElroy and Martins 2013).

<u>Mowing</u>

Mowing is a fundamental selection pressure unique to amenity grasslands, especially more intensively managed areas such as golf courses and sports fields. Additionally, heights of cut, mowing frequency, and clipping management all contribute to shifts in plant growth and development that further influences light interception, water loss, soil surface disruption. There are clear impacts of mowing heights that can increase or decrease weed infestation based on maintenance of adequate turf density that reduces light penetration to the soil surface (McCarty and Tucker 2005). Additionally, mowing frequency rates that remove approximately one-third of the total leaf height maintain adequate turf quality and reduce challenges like severe defoliation and growing point injury related to mowing too often or infrequently that can lead to reductions in plant carbohydrate production and root development (Crider 1955; Howieson and Christians 2008).

Vertically oriented mowers are designed to clip along a vertical axis to the soil surface to remove lateral growing plant material and surface organic matter depending on depth of penetration (Soller 2013). Vertical mowing often leads to increased weed pressure from intentionally reducing surface plant density and increasing light penetration to the soil surface. Johnson (1979) reported a 50-60 percent increase in large crabgrass groundcover in non-chemically managed Bermudagrass vertically mowed but became these same plots became weed-free after cessation of vertical mowing treatments.

Water Management

Water management exerts very strong selection pressure on amenity grasslands and is made more complex by the range of grassland soil types and growing conditions. Grassland soils can be engineered to be well-drained, resist compaction or be maintained on a native loamy soil, often less well drained (Baker 2006). Managing soil physical properties enhances soil moisture management and ultimately influences grassland species competitiveness. For example, a well-drained, compaction resistant soil improves resiliency of common amenity grassland species under high traffic conditions.

Supplementing soil moisture with irrigation maintains grassland species completeness during periods of limited precipitation (Jiang et al. 1998). When soil moisture is limiting, existing grassland plants with effective escape, avoidance, or tolerance mechanisms are favored (Karcher et al. 2008). However, often these responses lead to thinning of sward density and recruitment of weeds more tolerant of limiting moisture (Turner et al. 2012).

Traditional water management of high traffic amenity grasslands includes intentional imposition of wetting and drying cycles that enhance safety and performance but also could break weed seed dormancy and encourage germination (Busey 2003, Landschoot 2014). Gibeault et al. (1985) found sub-surface irrigation system designed to reduce wetting and drying cycles in a Kentucky bluegrass and tall fescue (*Festuca arundinacea* Schreb.) stand lead to a reduction in spotted spurge (*Euphorbia maculata* L.), creeping woodsorrel (*Oxalis corniculata* L.), and smooth crabgrass (*Digitaria ischaemum* (Schreb.) Muhl.).

Soil Management

Physical Property Management

Soil physical property management in amenity grasslands that favor grassland species traditionally involves practices such as cultivation and topdressing that often reduce plant surface density and significantly disrupt the soil surface. Additionally, amenity grassland surfaces often receive regular, highly focused traffic that increases bulk density, (Harivandi 2002) limits root growth (Murphy et al. 1993), limits gas exchange (Atkinson et al. 2012), and alters water holding (Yang and Zhang 2011). Consequently, competitive turfgrass growth is compromised and can result in weed infestation. Cultivation programs have been shown to mitigate the impact of foot and mechanical traffic by reducing the bulk density (Atkinson et al. 2012; Emmons 2000).

Reducing soil compaction using cultivation has improved desirable species competitiveness over certain weeds that thrive in low oxygen soils such as goosegrass (*Eleusine indica* (L.) Gaertn.) and prostrate knotweed (*Polygonum aviculare* L.) (Bertin and Weston 2004). However, cultivation can also result in localized soil compaction at the bottom of the cultivation zone (Murphy et al. 1993), reduce turf quality (Atkinson et al. 2012), and increase weed encroachment if timed during advantageous emergence periods for species like annual bluegrass (*Poa annua* L.) (Kaminski and Dernoeden 2007; Youngner 1968).

Therefore, managing soil physical properties in amenity grasslands requires proper mitigation practice, timing of intervention and follow up return to adequate growth of desirable grassland species. The longer soil remains bare the greater risk of weed recruitment.

Soil Chemical Property Management

Proper chemical property management of amenity grasslands is designed to maximize and sustain a conducive chemical environment capable of meeting plant nutrient needs specific to expectations and use. Nitrogen has the greatest effect on plant growth and when limited can alter competition. Additionally, N availability fluctuates with temperature and water movement in soil, that modulates uptake, leaching, volatilization, and conversion (Liu et al. 2014). Traditional nutrient management programs recommend supplemental nitrogen applications to encourage vigorous growth and increase competitive ability of amenity grasses to maintain full surface cover and reduce weed species recruitment (Larsen et al. 2004).

There is some evidence that other macronutrients and pH levels can exert a significant selection pressure in amenity grasslands. Competition for potassium has been shown to influence common dandelion (*Taraxacum officinale* F.H. Wigg.) populations associated with soil potassium levels (Densmore 2008; Tilman et al. 1999). Maintaining acid soil conditions (pH < 5.5) and eliminating supplemental phosphorous and potassium additions can reduce annual bluegrass and encourage creeping bentgrass (*Agrostis stolonifera* L.) in mixed stands (Ervin et al. 2003).

Biological Management of Weeds

Biological weed management utilizes herbivores, parasites, predators, pathogens or interspecific competition for resources as control agents (Tilman et al. 1999). Unlike most non-chemical methods, biological methods are usually species specific (Hatcher and Melander 2003). For example, biological weed management of rangeland and pastures utilize prescription grazing of livestock to manipulate plant community competition (Frost and

Launchbaugh 2003). Successful prescription grazing is dependent on proper animal selection, time of year, intensity, frequency, and compatibility with production goals (Frost and Launchbaugh 2003). However, grazing is not well suited for highly managed amenity grassland systems. Instead, less disruptive approaches, like the use of microbial inoculants, could better align with performance goals.

Several strategies have been found to be successful, however, few have been scaled to meet widespread industry demand. The efficacy of biological control can be enhanced when integrated into a diversified weed management plan since biocontrol includes methods specific to a wide spectrum including weak and young weeds (Abu-Dieyeh and Watson 2007) and physiologically mature plants (Hatcher and Melander 2003).

Chemical Management of Weeds

Selective chemical weed control dates to the early 20th century (McCarty et al. 1994). Early chemical options had low efficacy, application difficulties, and high costs that led to limited acceptance (Hansen 1921). The discovery of 2,4-D (2,4-dichlorophenoxyacetic acid) during World War II catalyzed an unprecedented movement in plant biochemistry and implementation of synthetic chemical-based weed control (Busey 2003; Peterson 1967). Currently, herbicides are the primary tool for weed management. In fact, McElroy and Martins (2013) suggest complete control of weeds in traditional turfgrass systems is not possible without herbicides.

The chronic reliance on chemical weed control has led to the rapid evolution of herbicide-resistant weeds. Currently, the International Survey of Herbicide Resistant Weeds recognizes 512 unique cases (species x site of action) of herbicide resistance (Heap 2020). Additionally, precautionary regulations are restricting pesticide use, challenging the sustainability of synthetic chemical-based weed control. Yet, chemical control continues to be both the most widely studied and used weed management strategy (Harker and O'Donovan 2013).

Physical Management of Weeds

Tillage is a common mechanical tool for managing weeds in agronomic systems. Effective control of weed seedlings requires burial to 1 cm depth and cutting at the soil surface (Bond and Grundy 2001). Unfortunately, repeated tillage is not practical in amenity grassland systems, therefore, control methods less disruptive to the soil surface are required. Additionally, many studies continue to question the value of tillage when considering the long-term impacts on soil physical properties and release of GHG. (REF). Finally, cultivation practices used in amenity grassland often lead to increased weed pressure if done improperly. (REF)

<u>Thermal Weed Control</u>

Thermal weed control uses heat to kill weed seeds or emerged plants by denaturing proteins (Hoyle et al. 2012). Several application methods currently exist including: soil solarization, flame weeding, steaming, electrocution, lasers, ultraviolet light, and radiation (Hoyle et al. 2012). Applications of flaming and steaming are non-selective and cause objectionable injury to grassland species. This will limit implementation of this technology to established stands not in regular use (Bertin and Weston 2004; Bertin et al. 2009). Additionally, weed management through flame-burning or steaming is non-selective and contact control requiring frequent applications (Bertin and Weston 2004) that become cost prohibitive at scale (Bertin et al. 2009).

Use of thermal technology during the grassland establishment process has been shown to reduce weed populations comparable to soil fumigants in commercial snapdragon fields (Mcsorley et al. 2009). Similarly, Hoyle et al. (2012) recorded equal or greater weed control in tall fescue establishment from soil solarization and flaming treatments compared to soil fumigation. However, fall-timing thermal applications showed increased weed control compared with summer timing, suggesting the need to further refine thermal application timing and expand evaluated weed species (Hoyle et al. 2012).

Weed Seed Bank Management

Historically, soil seed bank analysis in grasslands focused on relatively low maintenance systems including pastures, haylands, and native grasslands. Studies examine the seed bank response to grazing (Sternberg et al. 2003), fertilization (Kirkham et al. 1997), or the role in succession and site restoration (Bekker et al. 1997, Smith et al. 2002). However, translating these findings to amenity grasslands is difficult due to differing species composition and management regimes. Therefore, further study of the amenity grassland soil seedbank is needed to help reduce reliance on traditional chemicals and address the growing public concern with pesticide use in society.

The study of the soil seedbank in amenity grasslands is dominated by annual bluegrass in intensively managed, high value systems like golf course fairways and putting greens. Lush (1988) estimated the seedbank of an annual bluegrass infested putting green to contain 168,000 seeds/m^2 and suggests the majority of seeds is in the transient seedbank. Similarly, Branham et al. (2004) found 80% of the viable annual bluegrass seed in the 0 to 1 cm soil layer in a mixed stand of annual bluegrass and creeping bentgrass. However, when the mixed stand was renovated with dazomet (etrahydro-3,5-dimethyl-2H-1,3,5-thiodiazin-2-thione), a soil sterilant, annual bluegrass re-infestation occurred at all dazomet rates. Therefore, if annual bluegrass soil seedbank destruction during renovation is not effective, management must include practices that reduce or remove the soil seedbank. One example, Gaussoin and Branham (1989) measured a 60% reduction in the viable annual bluegrass seedbank of a fairway where clippings were collected during mowing and removed.

Weed Seed Harvest

Harvest weed seed control (HWSC) systems in commercial grain operations reduce annual seed inputs into the soil seedbank (Walsh et al. 2013). HWSC focuses on aboveground weed seed collection and destruction during grain harvest and include direct bale, chaff carts, narrow windrow burning, and the Harrington seed destructor (Walsh et al. 2013). However, the efficacy of HWSC relies on the amount of weed seed retained on the plant at the time of crop harvest, which can vary among weed species and climatic conditions (Walsh et al. 2014). In general, except for Gaussoin and Branham (1989) annual bluegrass clipping collection, there are few studies that have demonstrated HWSC in amenity grassland systems.

An alternative method to HWSC is to physically remove grassland soil surface to harvest seedbank and reestablish competitive advantage of desirable grassland species. Fraise mowing grassland surfaces to 25mm depth could offer more effective means for weed seed harvest and long-term reductions in the soil seed bank (Miller et al. 2017). Fraise mowing is an aggressive cultivation technique involving a rotary tiller type machine practice designed to harvest verdure, organic matter, and soil to a depth of 5 cm while allowing turfgrass to reestablish from unharvested rhizomes or provide an advantageous seedbed for establishing via seed or sod (Hansen and Christians 2015; Miller et al. 2017). Harvesting the weed seedbank during timely grassland renovation could provide a tactic to rapidly reduce weed seed pressure and establish well-adapted species.

INTRODUCTION

Chemical control is both the most widely implemented and commonly studied weed management method in agriculture (Harker and O'Donovan 2013). Weed management in amenity grasslands is dominated by chemical control and McElroy and Martins (2013) suggest complete control of weeds in amenity grassland systems is not possible without herbicides. A paucity of options for non-chemical weed management in amenity grasslands remains an obstacle and will require innovation similar to the development of 2,4-D, but with additional limitations.

Non-chemical weed management strategies are common in organic agriculture that enhance the ecological processes and biodiversity adapted to local conditions (International Federation of Organic Agriculture Movements 2005). Still, organic farmers when surveyed consistently rank non-chemical weed management as a high research priority (Baker and Mohler 2015; Jerkins and Ory 2016).

The application of organic or non-chemical management of weeds in grassland systems will be challenging due to the perennial nature of grassland cover and site use. Consequently, traditional tillage, cultivation, crop rotation, cover cropping, sanitation, nutrient management, flaming and mulching are not easily transferable to amenity grasslands (Baker and Mohler 2015). Therefore, the study of non-chemical weed control might best be conducted where alternative practices, such as non-chemical weed control, might not be viewed as disruptive and provide efficacious solutions that can be adapted for other areas.

Naturalized grasslands found on golf courses are a unique type of amenity grassland that offer opportunities to promote various types of grassland cover where regular mowing might not be required, feasible or desirable. They comprise as much as 25 percent of all managed land and offer the promise of reducing inputs and providing potential ecosystem services beyond golf (Oatis and Vavrek 2017). However, current practices rely heavily on chemical herbicide use to maintain the desirable characteristic of these naturalized grassland on golf courses (Brosnan 2015).

Skorulski (2017) concludes that sites with abundant rainfall and more fertile soils will require more maintenance if expectations call for playable, open grassland. The level of management required for these areas depends on the relationship among golfer, course official expectations and site conditions. Furthermore, Skorulski (2017) suggests that weed management programs designed for these systems integrate a variety of strategies, however areas closer to play are more reliant on herbicides than areas farther removed from play.

Existing non-chemical strategies in amenity grasslands often encourage increased plant surface density through nutrient and mowing management. However, these strategies make naturalized grasslands on golf courses less desirable. In fact, management is designed to maintain open soil cover to enhance ability to locate golf ball and swing golf club through higher mown vegetation (Figure 1) (Figure 2).

Decreased plant surface density and reductions in mowing frequency in naturalized golf course grasslands influence weed recruitment in these systems. Specifically, increased light penetration to the soil surface and extended time for plant reproduction between mowings can enhance undesirable species' establishment and persistence. However, analysis of surface vegetation provides only a snapshot in time of weed management challenges. Understanding the soil weed seedbank could enhance knowledge of both existing and future weed infestation. Outside of annual bluegrass in highly managed systems like golf course putting greens and fairways (Branham et al. 2004; Lush 1988), limited research on seedbank composition and vertical distribution has been conducted in amenity grasslands. However, several studies of agricultural systems suggest low-soil-disturbance, like no-till management, accumulates weed seeds near the soil surface (Figure 3) (Chauhan et al. 2012).

Figure 1. Naturalized fine fescue rough with high playability. Ease of locating golf ball enhances pace of play and low density allows attempt to play ball forward. However, the low density is conducive to weed encroachment if adequate weed seedbank and environmental conditions persist.

Figure 2. Naturalized fine fescue rough displaying preferred non-lodged and low shoot density aesthetic qualities. However, the low density is conducive to weed encroachment if adequate weed seedbank and environmental conditions persist.

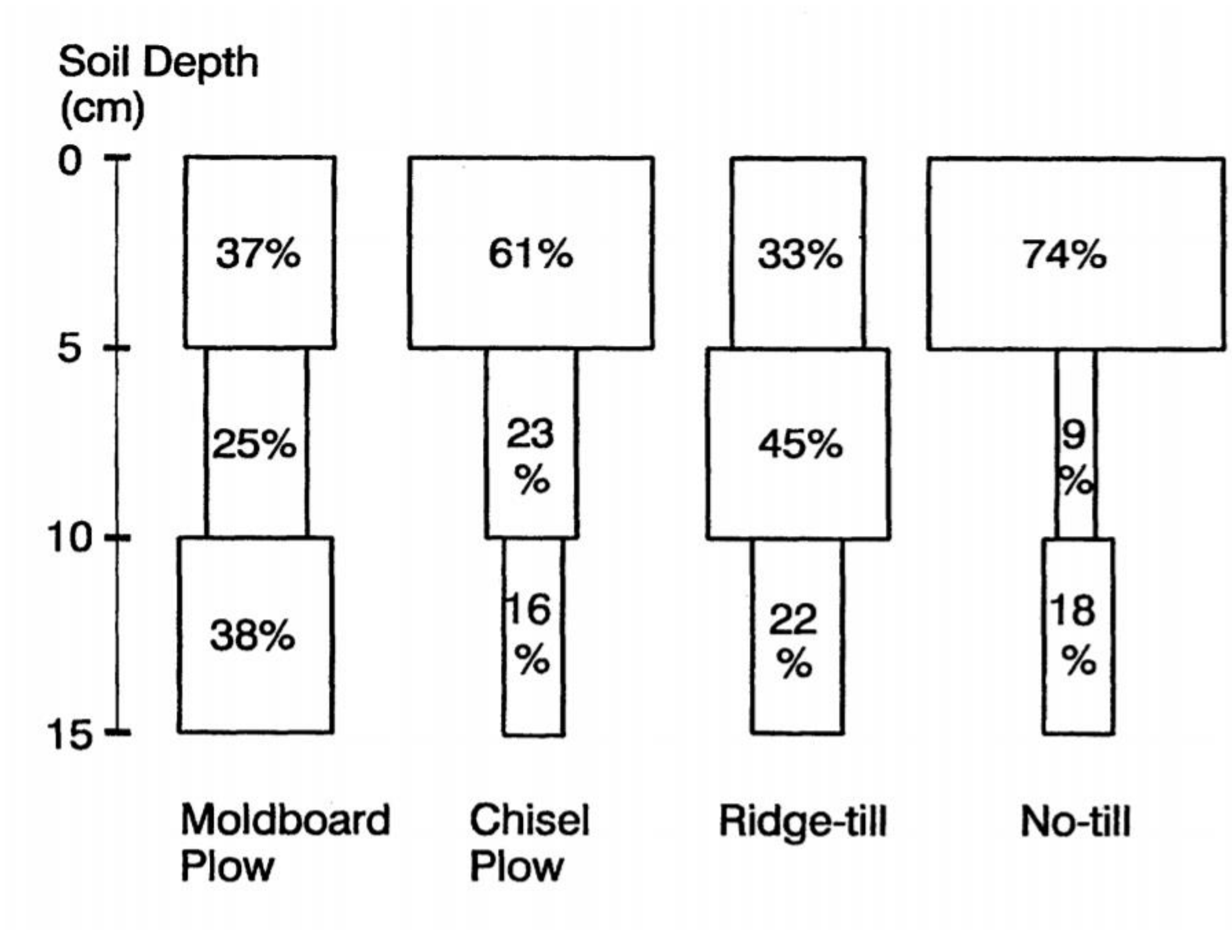

Figure 3. Vertical distribution of weed seeds in a silty-loam soil differentiated by tillage practices. Weed seeds likely accumulate near the soil surface in amenity grasslands due to low soil disturbance similar to no-till agricultural systems. Source: Clements et al. (1996).

Weed seedbank management in agronomic systems relies on minimizing new additions from annual seed rain and maximizing reductions or removals (Figure 4), using tillage, crop rotation, harvest weed seed control, and cover cropping. To be effective, these practices must be implemented repeatedly over time to deplete the soil weed seedbank. These practices are highly disruptive and do not translate into most amenity grassland systems. However, if performed occasionally and efficiently, harvest weed seed control followed by rapid re-establishment of adequate canopy cover and bare soil could be maintained weed-free more effectively.

The physical removal of the weed seedbank that accumulates near the soil surface in amenity grasslands could be harvested if it the process could be conducted when site is not in use and a favorable landscape conditions exists. Fraise mowing is an aggressive cultivation technique involving a rotary tiller type machine practice designed to harvest verdure, organic matter, and soil to a depth of 5 cm while allowing turfgrass to reestablish from unharvested rhizomes or provide an advantageous seedbed for establishing via seed or sod (Hansen and Christians 2015; Miller et al. 2017).

Rapid grassland renovation via fraise mowing could effectively remove existing weeds, reduce weed seed pressure, enhance long-term, non-chemical weed control, and establish well-adapted grassland species. The objectives of this study were to (1) characterize the weed seed bank in low-maintenance fine fescue naturalized rough with a history of crabgrass infestation and (2) evaluate the efficacy of fraise mow timing, removal depth, and seed establishment rate on weed re-infestation.

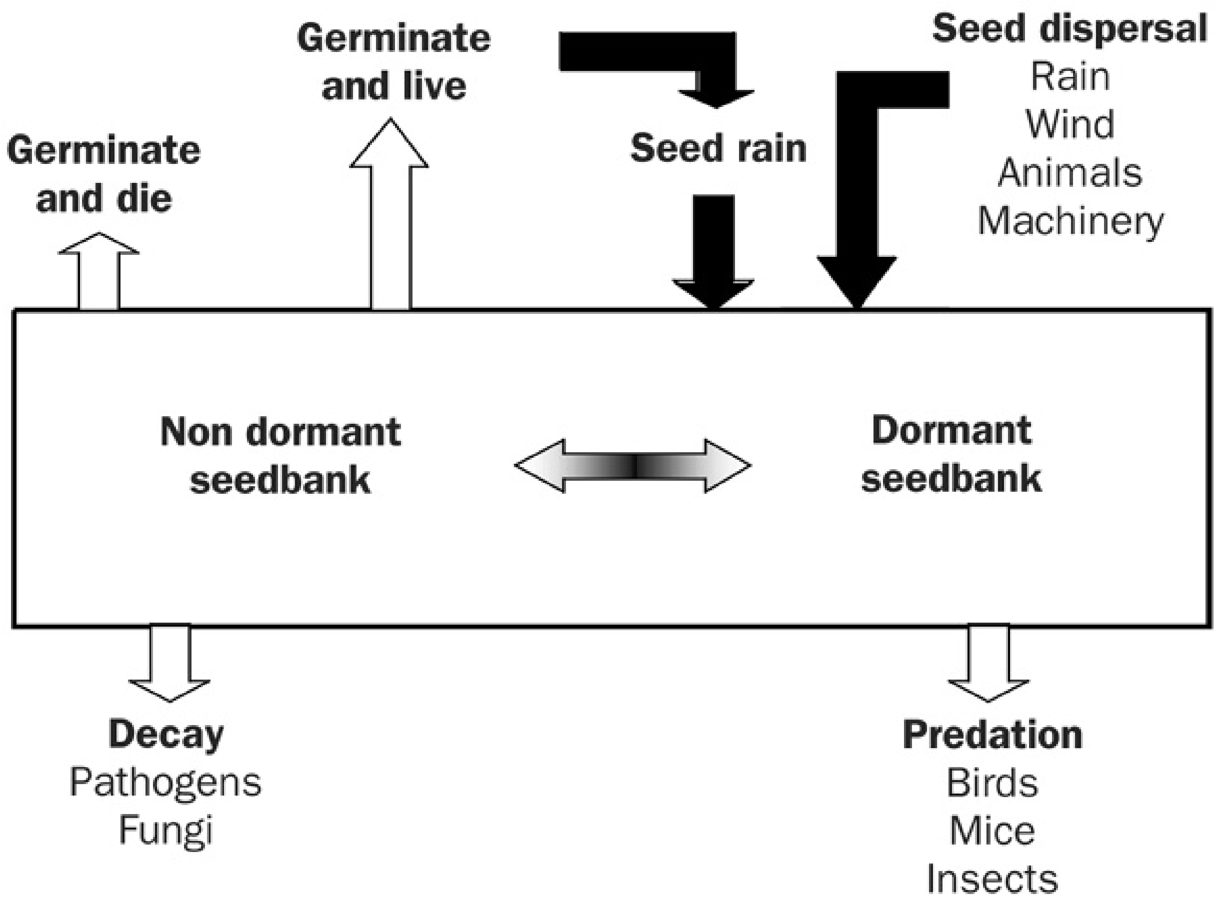

Figure 4. Weed seedbank dynamics. Inputs to the seedbank are shown with black arrows and losses with white arrows. Weed seedbank management focuses on maximizing losses and minimizing additions. Fraise mowing could potentially remove weed seeds from both the non-dormant and dormant seedbanks. Source: Menalled (2008).

MATERIALS AND METHODS

Field Site

Field experiments were conducted in the naturalized grasslands at The Vineyard Golf Club (VGC), Edgartown, MA (41°23’28.11” N, 70°33’19.50” W) from 2017 – 2019. The naturalized grassland was planted to a fine fescue mix including Creeping red, Chewings, Sheep, and Hard fescues in 2013 on a Carver loamy coarse sand with less than 3% slope and pH 5. The predominant weedy vegetation of the site is smooth crabgrass (*Digitaria ischaemum* (Schreb.) Muhl.) and distracts from the quality of the golfing experience at VGC. The site is mown one to two times per year and have never received a synthetic herbicide application.

Figure 5. Existing weed pressure of VGC naturalized fine fescue rough in August 2017 prior to experiment initiation. Botanical assessment of surface population determined smooth crabgrass as the most invasive and troublesome species to the golf experience at VGC.

Experimental Design and Application Method

Treatments were arranged within harvest timings as a strip plot design with weed seed harvest depth as the main plot factor and seed establishment rate as the subplot factor. Six treatments with nine replications were applied at five monthly intervals beginning in fall 2017 (Oct 3, Oct 30, Nov 21) and again in spring 2018 (Apr 20, May 18). Harvest timings were selected based on the VGC golfing schedule that restricted grassland renovations to outside the primary summer golf season.

Fraise mowing for weed seed bank harvest was conducted using a tractor-mounted GKB Combinator model CB120™ (Figure 6) fitted with L-shaped blades designed for complete surface removal. Harvest depths (3 mm, 6 mm, 25 mm) were measured from the soil surface below the grassland verdure (Figure 8).

Following fraise mowing, a fine fescue mixture (Appendix A) consistent with existing naturalized rough at VGC was drilled-seeded using a Turfco Triwave TM 45 overseeder equipped with fairway cutting blades at approximately 1-cm depth. The Triwave overseeder was calibrated to apply seed rates of 293 and 586 kg ha^{-1}. Multiple passes with the overseeder were required to obtain both seeding rates. After planting, the entire plot area was rolled.

Post-harvest care

Nutrient and water management after planting was designed to promote grassland establishment within the restrictions of VGC's organic management protocol that did not allow for synthetic N use. Soil test information indicated nutrient deficiencies (Appendix B), especially in phosphorous, therefore a 10-2-8 fertilizer (Appendix C) was applied at time of seeding to supply 25 kg ha^{-1} N, 5 kg ha^{-1} P, and 20 kg ha^{-1} K. Supplemental irrigation was supplied to maintain adequate soil surface moisture and promote germination only in first 60 days of planting. No other maintenance, nor irrigation, was conducted until mowing 12 mos. after planting.

Climate

Naturalized grasslands are traditionally non-irrigated areas and therefore dependent on prevailing climate for successful establishment. The three growing seasons of the study were highly variable. Below average temperatures and above average precipitation in 2017 at planting was followed by above average temperatures and below average precipitation in 2018 and above average temperature and precipitation in 2019 (Table1) (Table 2).

Soil Seedbank and Harvested Debris Sampling

Fifty-four soil cores of 5 cm diameter and 10 cm depth were collected in fall of 2017 prior to weed seedbank harvest using a systematic unaligned grid method (Harrell 2014). Soil cores were sectioned by 1.3-cm depths to 5.2 cm and then pooled and stored at 3°C for approximately seven weeks. Pooled samples were randomly sub-sampled for germination assays. Subsamples were spread in a 1.5-cm layer in plastic nursery trays (25by 25 cm) over sterilized soilless media composed of sphagnum peat moss, vermiculite, perlite, ground dolomitic limestone, fertilizer, and a wetting agent.

The seedling emergence method described by Zobel et al. (2007) with modifications was used to estimate the germinable seedbank. Vegetative material was retained in the 0 – 1.3 cm soil core layer to ensure the current year's seed rain (Smith et al. 2002). Additionally, the surface harvest debris was sampled to assess weed seed bank composition and determine weed seed bank harvest efficacy. Following persistent germination, typically 10 to 12 weeks, the flats were placed in a freezer (-4°C) for 3 weeks. Flats were returned to the greenhouse, material stirred, and the process was repeated for a total of three germination cycles.

Germination assays took place over a 10 to 11-month period. Two control trays filled with sterilized potting soil monitored potential seed contaminants in the potting soil or airborne in the greenhouse (Zobel et al. 2007). Photoperiods (16 h) were used to stimulate maximum germination with high-pressure sodium (HPS). Temperature was 21°C day and 15.5°C night.

Vegetation Sampling

Desirable grassland species and weed population data were collected and expressed as a percent ground cover estimate (Morris and Shearman 1998). Initial surface weed cover estimates were uniformly greater than 60 percent at in fall 2017. Smooth crabgrass (*Digitaria ischaemum* (Schreb.) Muhl.), common catsear (*Hypochaeris radicata* L.), white clover (*Trifolium repens* L.), and horseweed (*Conyza canadensis* (L.) Cronquist) were the most common species visually evident in existing grassland stand.

Grassland establishment data were collected using digital imagery as described by Debels et al. (2012) prior to smooth crabgrass emergence and occurred on May 16, 2018 and May 8, 2019. Weed infestation data were collected monthly using line-intersect analysis. Collection dates in each year with the highest weed populations, August 8, 2018 and July 28, 2019, were used for statistical analysis to reflect peak weed cover.

Data Analysis

R software was used for all statistical analysis (Version 1.1.463 © 2009-2018 RStudio, Inc). A mixed effects model was used to analyze differences in harvest timing, harvest depth, and grassland establishment rate at the $p = 0.05$ probability level. Harvest timing, harvest depth, and grassland establishment were treated as fixed effects and plot as a random effect. Tukeys HSD tests were used to determine significant differences between treatments.

Figure 6. Fraise mowing using a GKB Combinator model CB120. Fraise mowing is an aggressive cultivation technique designed to harvest verdure, organic matter, and soil to a depth of 5 cm while allowing turfgrass to reestablish from unharvested rhizomes or provide an advantageous seedbed for establishing via seed or sod.

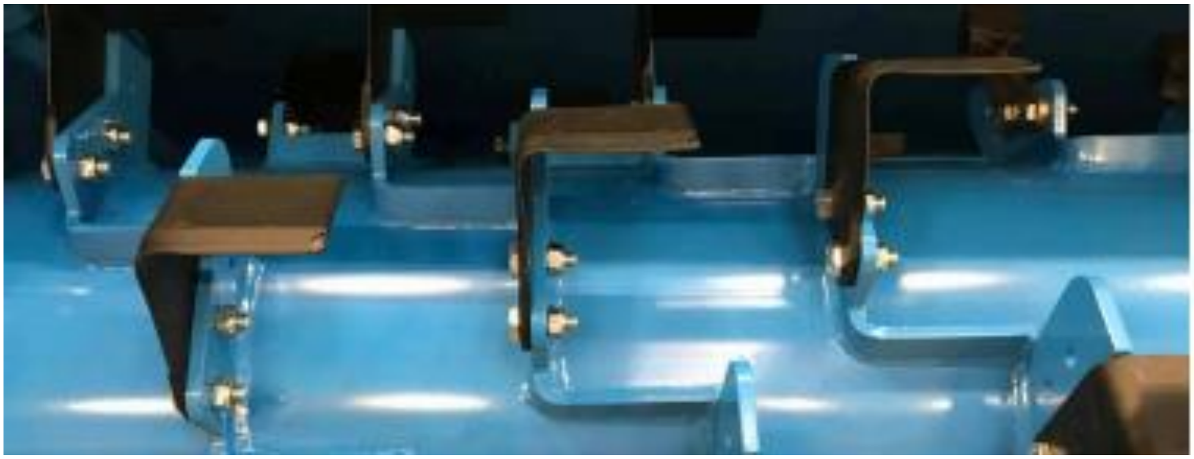

Figure 7. Digging blades on GKB Combinator model CB120 used for seedbank harvest (GKB Combinator, 2018). Digging blades are used for complete surface removal during fraise mowing.

Figure 8. Surface harvest depths are measured from the soil surface below the grassland verdure.

Table 1. Monthly temperature for year prior to (2017) and study years (2018, 2019) compared to 30-year average at Vineyard Golf Club, Edgartown, MA. Information provided by the Northeast Regional Climate Center.

Month	Actual Temperature			Average Temperature	Departure from Normal		
	2017	2018	2019		2017	2018	2019
				°C			
April	9.6	7.1	9.3	8.6	1	-1.5	0.7
May	13.1	14.6	12.7	13.7	-0.6	0.9	1
June	18.3	18.1	18.2	18.8	-0.5	-0.7	-0.6
July	21.9	22.4	23.3	22.1	-0.2	0.3	1.2
August	21.2	24.1	22.4	21.8	-0.6	2.3	0.6

Table 2. Monthly precipitation for year prior to (2017) and study years (2018, 2019) compared to 30-year average at Vineyard Golf Club, Edgartown, MA. Information provided by the Northeast Regional Climate Center.

Month	Actual Precipitation			Average Precipitation	Departure from Normal		
	2017	2018	2019		2017	2018	2019
				mm			
April	175	87.4	137.2	108.5	66.5	-21.1	28.7
May	164.3	47.5	116.3	89.9	74.4	-42.4	26.4
June	62.5	95.8	152.9	95	-32.5	0.8	57.9
July	65.8	37.1	71.1	77.2	-11.4	-40.1	-6.1
August	144.8	28.2	87.4	101.1	43.7	-72.9	-13.7

RESULTS AND DISCUSSION

Seedbank Analysis

Smooth crabgrass dominated the germinable seedbank after three cycles of both initial soil cores and collected surface debris (Table 3). The harvested debris had 33 percent greater germinable smooth crabgrass than soil cores in the 2.5 cm soil layer (Table 4) with minor increases in large crabgrass and white clover.

The increased amount of germinable seeds in the surface debris could be related to mechanical scarification from fraise mowing or mixing of seed with organic matter enhanced germination by increasing water holding of mixture (Baskin and Baskin 2004; Turner et al. 2012). It is likely the disruptive harvest process with fraise mowing physically scarified and disrupted dormancy and enhanced germination (Turner et al. 2012). The same fraise mowing scarification that enhances germination, might disrupt it by physically destroying the seed.

The difference in germinability between debris and soil cores could be an artifact of random sampling of debris and aligned grid sampling of soil cores. Also, full seedbank recovery through filtration and viability testing should be included in future.

Mowing of the naturalized grassland at VGC during the season likely enhances seed rain by chopping and depositing the debris on to the surface, permitting smooth crabgrass seed rain to contribute to soil reserves. The desired thin surface coverage for naturalized grasslands on golf courses likely intensifies susceptibility to weed recruitment from the soil seedbank. Interestingly, Turner (2012) found that seedbank estimates alone are not reliable for predicting subsequent crabgrass infestations and requires regular monitoring of weed seed recruitment during the growing season.

Table 3. Estimated number of germinating seeds of naturalized fine fescue rough experimental site at VGC from soil cores. All species are included to show entire data set. Average number of emerged weed seedlings / 1000cm^3 soil at three soil layers.

			Emerged seedlings / 1000cm^3 at three soil layers		
Weed Species	Common Name	Life cycle[a]	0 - 1.2 cm[b]	1.3 - 2.5 cm	2.6 - 5.0 cm
Digitaria ischaemum	Smooth crabgrass	SA	491	18	6.3
Euphorbia maculata	Prostrate spurge	SA	10	< 1	---
Lamium amplexicaule	Henbit	WA	4.7	---	---
Conyza canadensis	Horseweed	SA	4.3	---	< 1
Digitaria sanguinalis	Large crabgrass	SA	3.7	< 1	
Trifolium repens	White clover	P	3.7	< 1	< 1
Juncus tenuis	Slender rush	P	2.7	1.7	1.3
Hypochoeris radicata	Common catsear	P	2	---	< 1
Glechoma hederacea	Ground ivy	P	1.3	---	---
Taraxacum officinale	Common dandelion	P	1.3	---	---
Oxalis stricta	Yellow woodsorrel	P	1	---	---
Trifolium arvense	Rabbit foot clover	SA	< 1	---	< 1
Capsella bursa-pastoris	Shepherd's purse	WA	< 1	< 1	---
Mollugo verticillata	Carpetweed	A	< 1	< 1	---
Veronica arvensis	Corn speedwell	WA	< 1	---	---
Spergularia marina	Saltmarsh sand spurry	A	---	< 1	---
Arenaria serphyllifolia L.	Thyme-leaf sandwort	WA	---	< 1	< 1
Veronica peregrina	Purslane speedwell	WA	---	< 1	---
Solidago rugosa	Wrinkleleaf goldenrod	P	---	---	< 1
Cyperus esculentus	Yellow nutsedge	P	---	---	< 1
Unidentified		N/A	---	---	< 1

[a] Life cycles of species. A, Annual; SA, Summer Annual; WA, Winter Annual; P, Perennial.
[b] --- indicates no emerged seedling was recorded for the species.

Table 4. Estimated number of germinating seeds of naturalized fine fescue rough experimental site at VGC from soil cores and harvested fraise debris. All species are included to show full extent of the data. Average number of emerged weed seedlings / 1000cm^3.

			Emerged seedlings / 1000cm3 in harvested fraise debris compared to soil core analysis	
Weed Species	Common Name	Life cycle[a]	2.5 cm fraise debris[b]	0 - 2.5 cm soil layer
Digitaria ischaemum	Smooth crabgrass	SA	355	255
Digitaria sanguinalis	Large crabgrass	SA	15	2.3
Trifolium repens	White clover	P	5.7	2.5
Euphorbia maculata	Prostrate spurge	SA	3	5.5
Hypochoeris radicata	Common catsear	P	1.7	1
Conyza canadensis	Horseweed	SA	1.7	2.2
Trifolium arvense	Rabbit foot clover	SA	< 1	< 1
Veronica arvensis	Corn speedwell	WA	< 1	< 1
Poa annua	Annual Bluegrass	WA	< 1	---
Lamium amplexicaule	Henbit	WA	---	2.4
Juncus tenuis	Slender rush	P	---	2.2
Glechoma hederacea	Ground Ivy	P	---	< 1
Taraxacum officinale	Common dandelion	P	---	< 1
Oxalis stricta	Yellow woodsorrel	P	---	< 1
Capsella bursa-pastoris	Shepherd's purse	WA	---	< 1
Mollugo verticillata	Carpetweed	A	---	< 1
Spergularia marina	Saltmarsh sand spurry	A	---	< 1
Arenaria serphyllifolia L.	Thyme-leaf sandwort	WA	---	< 1
Veronica peregrina	Purslane speedwell	WA	---	< 1
Solidago rugosa	Wrinkleleaf goldenrod	P	---	< 1
Cyperus esculentus	Yellow nutsedge	P	---	< 1

[a] Life cycles of species. A, Annual; SA, Summer Annual; WA, Winter Annual; P, Perennial.
[b] --- indicates no emerged seedling were recorded for the species.

Fraise Mow Effect on Weed Infestation

There were significant main effects of harvest depth and timing on weed cover, but not for planting rate 12 mos after planting. Weed cover changes, mostly from smooth crabgrass, seemed to the summer annual nature with a long emergence period. Crabgrass recruitment was greatest in spring renovated treatments that disturbed soil at crabgrass emergence and did not allow for rapid development of grassland species cover.

Smooth crabgrass emergence in the experimental area was first recorded at 126 growing degree-days (GDD) (base 10°C) in 2018, nearly consistent with the emergence model developed by Fidanza et al. (1996). The emergence model suggests first emergence occurs between 42 and 78 GDD (base 12°C) and major emergence occurs between 140 and 230 GDD.

Seedbank analysis of harvested fraise debris suggests the 25mm fraise depth removed the entire smooth crabgrass seedbank based on total number of germinable seeds. However, smooth crabgrass recruitment occurred in the first growing season following harvest. The process of fraise mowing can be considered less than sanitary as it often left small swaths of debris that would subsequently germinate into strips of weeds (show image). Additionally, soil core seedbank analysis measured a small amount of smooth crabgrass below the 25mm harvest depth and the soil removal could enhance germination from seeds in this layer after fraise mowing. Although the maximum seed bank depth analyzed for soil cores was only 5cm, it is unlikely natural seed burial moves the smooth crabgrass bank below this depth (Benvenuti 2007).

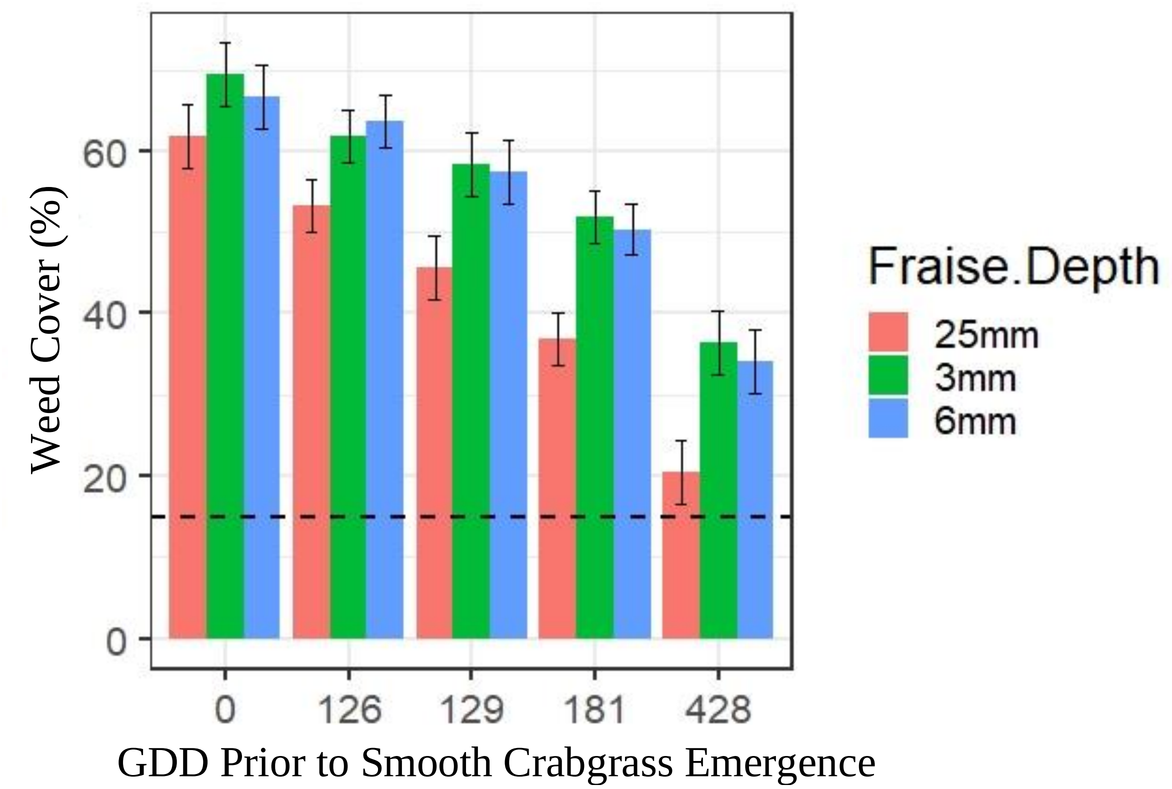

Figure 9. Influence of surface harvest depth and timing on weed re-infestation measured on August 8, 2018. Surface harvest timings are presented as growing degree-days (base 10°C) prior to smooth crabgrass emergence in the study location. The black dotted line represents the weed threshold (15%) for this naturalized grassland rough.

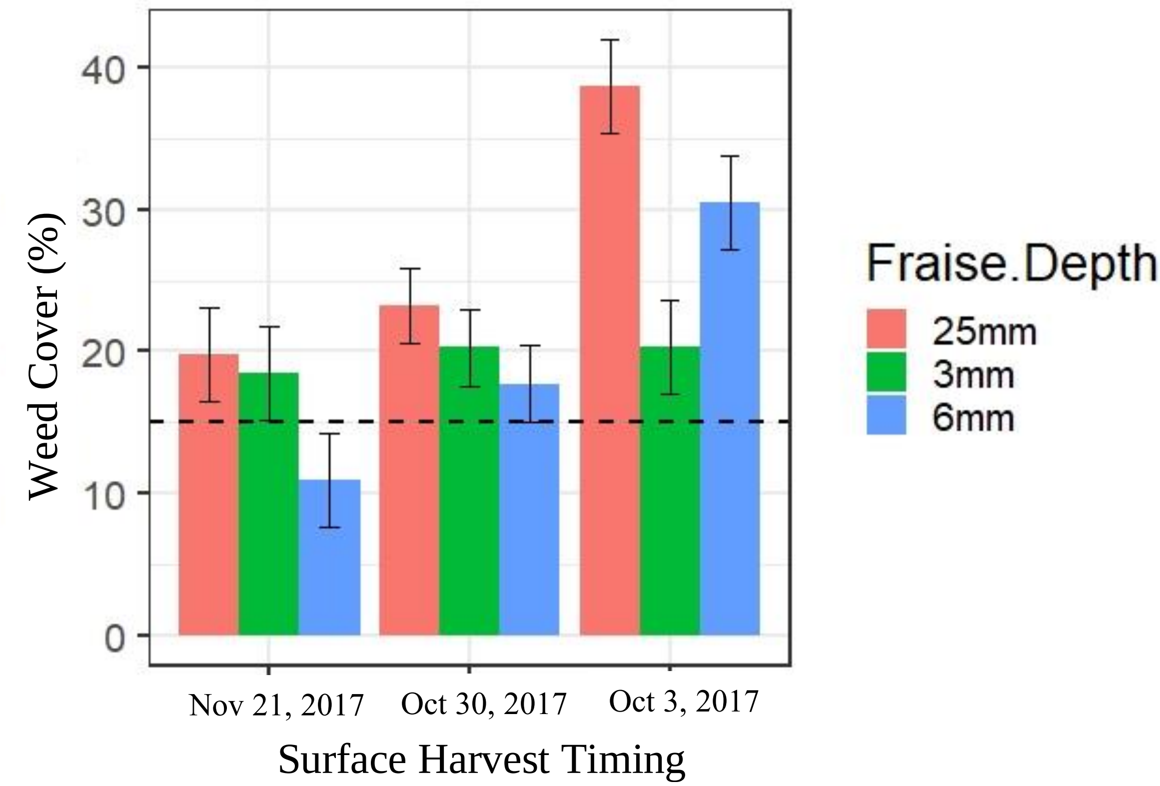

Figure 10. Influence of surface harvest depth and timing on weed re-infestation measured on July 28, 2019. Surface harvest timings in spring 2018 were terminated and data were not collected in 2019. The black dotted line represents the weed threshold (15%) for this naturalized grassland rough.

Weed infestation levels were lower in year two following planting based on harvest depth and timing on weed infestation. Weed infestation decreased with later fall timings that is in contrast to year 1 data . The greatest weed cover was now found on the 25mm harvest depth (Figure 10). Grassland species cover in year 2 was not significantly different and does not explain changes in weed cover.

It's possible the 25 mm harvest depth allowed for movement of weed seed from adjacent plots as there was no barrier between plots and 25mm plots were below grade. Additionally, fine fescue production of allelochemicals (Bertin et al. 2009) could be enhanced by binding to soil organic matter and preventing leaching or decay (Purvis and Jones 1990). However, soil organic matter levels were not measured, and direct comparisons are not possible.

Fraise Mow Effect on Grassland Establishment

Grassland species cover was related to harvest and planting dates (Figure 11), suggesting duration of cover enhances competitive ability

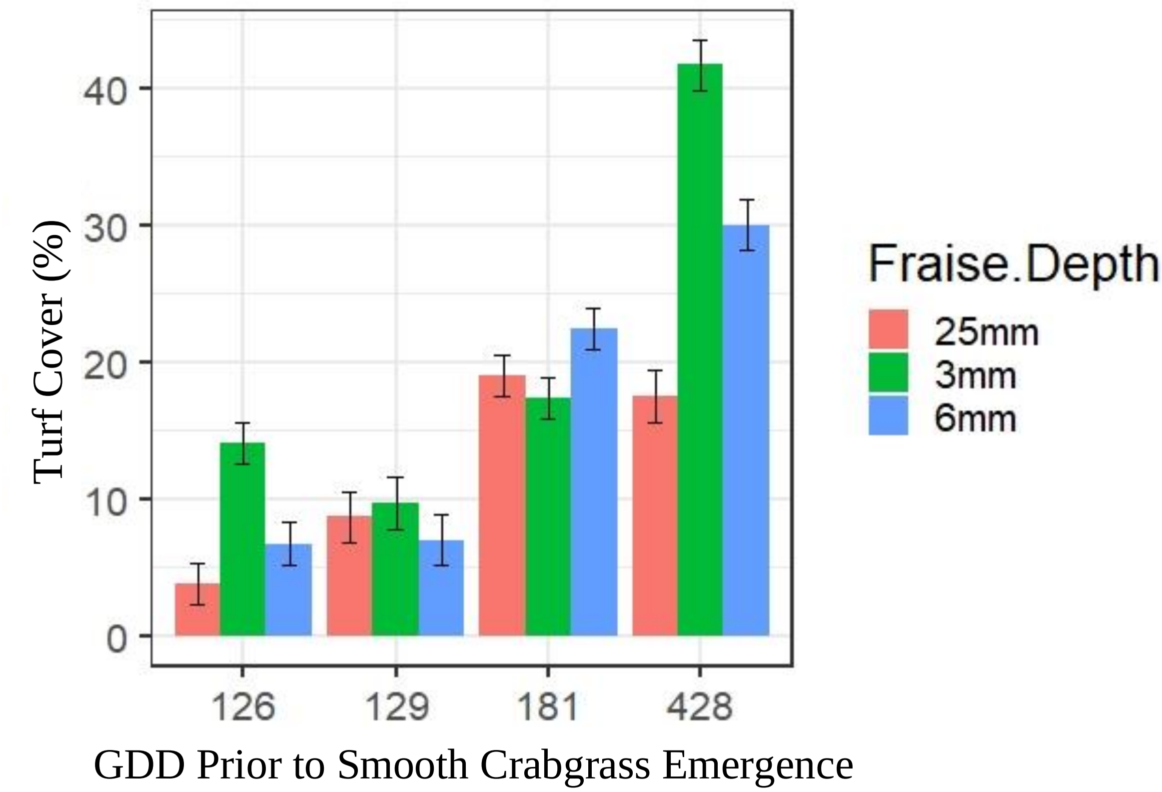

Figure 11. Influence of surface harvest depth and timing on turf cover (%) measured on May 16, 2018. Surface harvest timings are presented as growing degree-days (base 10°C) prior to smooth crabgrass emergence in the study location. The surface harvest timing May 18 was installed after the sampling date and is not included in this figure.

against weed encroachment. The 25 mm fraise depth had significantly lower weed cover across all harvest timings, suggesting weed seed harvest was substantial enough to reduce re-infestation independent of grassland establishment. The highest grassland species cover for the 25mm fraise depth treatments averaged only 17 percent 8mos after planting. In fact, the

126 GDD timing and 3 mm depth had 42 percent grassland cover in 8mos after planting and averaged 15 percent higher weed coverage at 12 months after planting.

Doubling planting rate from 293 to 586 kg ha^{-1} lead to a 3% increase in turf coverage in year 1 and did not significantly influence turf coverage in year 2. Prolonged period of establishing full cover is likely related to low nutrient and water holding capacity of soils at VGC that could not be overcome by increasing planting density.

There were interactive effects of harvest depth and timing on establishment of grassland cover. The shallowest depth, 3 mm, resulted in the highest turf density at the 428 GDD, 129 GDD, and 126 GDD timings. Its possible removal of more fertile soil near the surface at greater harvest depths may have influenced grassland establishment. Given the low fertility system and relatively low supplemental fertilizer applied at seeding, the organic matter unharvested in the 3 mm deep fraise could have enhanced grassland establishment. Skorulski (2017) introduced the concept of contra-agronomy as a descriptive term for managing naturalized grasslands on golf courses by intentionally reducing biomass production such as eliminating fugitive water, periodic mowing with clipping removal, and practices that decrease plant-available nutrients.

This study demonstrates the importance of amenity grassland renovation timing on weed recruitment in systems that do not rely on synthetic herbicides. Timing and harvest depth had the greatest influence on weed re-infestation following grassland renovation via fraise mowing. Preliminary experiments suggest soil moisture levels significantly influence surface removal and seedbed preparation quality, justifying further evaluation across different amenity grassland systems and soil types. Despite a substantial reduction in the smooth crabgrass weed seed bank, smooth crabgrass surpassed thresholds (<15%) by the end of the first full growing season, indicating the need for additional follow-up treatments for commercially acceptable control. Large differences in soil seed bank estimates between soil core and harvested fraise debris warrants additional study and should analyze deeper soil layers (>5cm) and include seed recovery. Lastly, further research is necessary to measure seed bank composition immediately following fraise mowing and to consider post-fraise mowing management strategies that may improve weed seed harvest cleanliness, enhance turf establishment, and further reduce weed re-infestation.

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APPENDIX

Appendix A. Fine fescue mixture seeded during naturalized grassland establishment at Vineyard Golf Club. Data obtained from product label.

Cultivar	Species	Pure Seed	Germination	Origin
		%		
Reliant IV	Hard Fescue	34.9	85	Washington
Ambrose	Chewings Fescue	34.3	85	Oregon
Epic	Creeping Red Fescue	19.8	85	Oregon
Azure	Sheep Fescue	9.7	85	Canada

Appendix B. Soil chemical analysis of experimental naturalized grassland rough at Vineyard Golf Club. Testing was conducted by Cornell Nutrient Analysis Laboratory.

pH	Organic Matter	Calcium	Pottasium	Magnesium	Phosphorous	Sulfur
	%	mg / Kg				
0.25	9	0.75	2	8	1.8	3

Appendix C. Nutrient analysis of NatureSafe™ 10-2-8 fertilizer used in naturalized grassland establishment at Vineyard Golf Club. Data obtained from product label.

Ammoniacal Nitrogen	Water Insoluble Nitrogen	Other Water Soluble Nitrogen*	Phosphate (P_2O_5)	Potash (K_2O)	Calcium	Sulfur
%						
0.25	9	0.75	2	8	1.8	3

*Derived from feather meal and meat and bone meal.