ABSTRACT

MCCAULEY, RAYMOND KEVIN. Fraise Mowing Effects, Uses, and Recovery in North Carolina. (Under the direction of Dr. Grady Miller).

Fraise (fraze) mowing is a turfgrass cultural practice that has the potential to remove all organic matter and soil to 5-cm depths in a single pass. Despite nearly 25 years of use, limited research on fraise mowing exists. Field studies were conducted to evaluate fraise mowing's impact on soil physical properties, its ability to remove shallow compaction, and practices to expedite the recovery of hybrid bermudagrass (*C. dactylon x C. transvaalensis* Burtt. Davy) after fraise mowing.

Fraise mowing is primarily performed on bermudagrass to remove thatch, a layer of living and dead plant material that accumulates between turfgrass' verdure and soil surface. Field research was conducted from mid-June through mid-August each year for four years to evaluate the impact of three fraise mowing depths on the soil physical properties of two soils. Thatch content decreased after fraise mowing in both soils. Soil surface hardness increased with 1.2 and 2.5-cm fraise mowing depths in both soils. Shear strength in the sand decreased with fraise mowing depth but increased in the loam at the 2.5-cm fraise mowing depth. Saturated hydraulic conductivity (Ksat) in the sand decreased with fraise mowing depths. Results from this research inform turfgrass managers of the positive and negative effects of fraise mowing on soil physical properties of two soils.

Fraise mowing is an excellent thatch management practice, and hollow-tine aerification is often performed concurrently with other cultural practices to relieve soil compaction. Field research evaluated the effects of three fraise mowing depths with or without hollow-tine aerification on bermudagrass recovery and soil physical properties of two soils. Combining fraise mowing with aerification did not delay bermudagrass recovery. Thatch content decreased with fraise mowing depth but was unaffected by hollow-tine aerification. Immediately after treatment, Ksat decreased with fraise mowing depth. Aerification increased Ksat by 36 cm hr^{-1}, decreased surface hardness by ≤12 gravities, and lowered shear strength by ≤16 N·m. Results from this research demonstrated that fraise mowing and hollow-tine aerification can be practiced concurrently to positively affect soil physical properties and without delaying bermudagrass recovery.

Fraise mowing's functional depths (≤5-cm) overlap with compaction depths from routine turfgrass traffic (≤8-cm). Field research evaluated the potential of fraise mowing at 2.0, 2.5, or 5.0-cm depths to relieve shallow soil compaction following simulated traffic in varying soils. Soil surface hardness and soil resistance in a 15-cm sand-capped and sand-based field decreased after fraise mowing at 2.0-cm depth. In a sand-capped field, infiltration rate increased by 2.5 cm hr^{-1} after fraise mowing. In a Candor sand, infiltration rate of trafficked treatments increased by ≥115% after fraise mowing to 5.0-cm depth. Results from this research demonstrated fraise mowing's ability to remove surface compaction in heavily trafficked sports fields and may expand fraise mowing's usage beyond thatch control.

Bermudagrass requires ≥3 weeks to recover from fraise mowing, which can result in facility downtime and lost revenues. Field research evaluated the potential of sand topdressing volume and timing or nitrogen fertility to hasten hybrid bermudagrass recovery following fraise mowing to 0.6-cm depth. Water soluble nitrogen treatments ≥36.6 kg ha^{-1} per week had acceptable turf quality and cover in 21 days after fraise mowing. Sand topdressing at any depth did not accelerate bermudagrass recovery following fraise mowing. Results from this research demonstrated that nitrogen fertilization at 36.6 kg ha^{-1} per week was the most effective practice at hastening bermudagrass recovery following fraise mowing.

Fraise mowing is a very disruptive cultural practice, and bermudagrass requires ≥3 weeks to recover from it. Results from our research provide turfgrass managers with definitive steps to shorten this downtime with nitrogen fertilization while informing them of fraise mowing's effects on soil physical properties. The successful pairing of aerification with fraise mowing was also demonstrated, as well as fraise mowing's potential to remove shallow soil compaction. These results will remove some of the apprehension of fraise mowing and may lead to its expanded use.

Fraise Mowing Effects, Uses, and Recovery in North Carolina

by
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DEDICATION

To Abigail, Ma, Dad, Mike, Jack, and everyone else that’s helped me along the way.

BIOGRAPHY

Raymond Kevin McCauley hails from Stateburg, SC where he, his older (Mike) and younger brother (Jack), as well as a steady run of German shepherds were raised by his mother and father (Debbie and Kevin). He survived Dr. Bert McCarty and Tommy Bowden for his BS and MS degrees in Turfgrass Management at Clemson University. After a seven-year hiatus in sportsturf industry, he showed-up on Dr. Miller and Drew Pinnix's doorstep in January 2016. His dissertation concentration has been on fraise mowing and its effects on soil physical properties. He married his Williams Hall sweetheart Abigail in 2019, and they (happily) reside in South Raleigh.

His plans after graduation include Lake Wheeler Turf Field Lab, Williams Hall, and continuing turfgrass research.

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LITERATURE REVIEW

Turfgrasses provide therapeutic benefits through their aesthetics and recreational uses. In athletic settings, turfgrasses provide safe playing surfaces for athletes to perform controlled maneuvers and forgiving surfaces when they fall (Daniel and Freeborg, 1979). The majority (72%) of professional American football players prefer playing on natural grass (Anonymous, 2009). Extensive studies that monitored professional and amateur athletes have documented the decreased risk of lower extremity injuries associated with playing on natural grass compared to alternative surfaces (Loughran et al., 2019; Mack et al., 2019). However, the cost to construct a natural grass field is a considerable expense: \$16.14 to \$86.11 m^{-2} (\$1.50 to \$8.00 ft-^{2}), and these surfaces are not devoid of issues after construction (Anonymous, 2019). Compaction, wear, and thatch can compromise playing conditions, player safety, and turfgrass aesthetics (Beard, 1973; Adams and Gibbs, 1994; Mascitti et al., 2017; McCarty et al., 2005). Therefore, management practices to keep these investments and participants safe must be routinely performed (Beard, 1973; McCarty and Miller, 2002).

Soil Compaction

Traffic on turfgrass can cause soil compaction, displacement, and rutting, as well as turfgrass divoting and wear (Carrow and Petrovic, 1992). Compaction causes soil aggregates to collapse, compresses soil particles into a smaller volume, increases soil inter-particle attraction, and increases the soil's bulk density- the mass per volume of soil. Compaction increases the soil's penetration resistance, decreases soil macroporosity, diminishes hydraulic conductivity, and compromises soil aeration and drainage (Adams and Gibbs, 1994; Dest et al., 2009). Soil compaction occurs when an applied force is greater than a soil's capacity to support it, and compaction's extent is determined by the load and footprint of an applying object. Greater applied pressures place more force on the soil's surface, and these pressures dissipate with soil depth. Therefore, higher pressures cause deeper soil compaction (Jorajuria et al., 1997).

The United States Golf Association (USGA) recommends bulk density values between 1.2 and 1.6 g cm^{-3} and soil air-filled porosity ranges of 15 to 40% to sustain healthy turfgrass growth (Chong et al., 2003; Guertal and Han, 2012). Macropores, their continuity, as well as acceptable bulk densities must be maintained to ensure rapid drainage, aerobic soil conditions, and channels for root growth (Adams and Gibbs, 1994). However, compaction from routine traffic converts macropores in in the top 7-cm of the soil to micropores, which are inadequate at conducting air and water through the profile (Depew, 2000).

Brown and McCarty (2005) noted that athletic training fields and recreational fields are most prone to compaction because of their repetitive play and unrestricted use. A typical soccer match produces 42 footprints m^{-2}. When expanded to a 35 week, 100 games soccer season, a total of 42,000 footprints m^{-2} can be anticipated on a soccer field (Adams and Gibbs, 1994). American football games are even more aggressive and generate 603 cleat marks per m^2 per game in the highest trafficked areas of the field (Cockerham and Brinkman, 1989). Given the number of footprints soccer and American football fields receive over the course of a season, it is not surprising that high traffic areas suffered poor water infiltration, poor air-filled capacity (<5%), and soil compaction to the 7.0 cm depth (Adams and Gibbs, 1994; Gibbs et al., 1993b).

Despite their high use intensity, compaction from routine sports turf traffic typically does not exceed the surface 8 cm of the soil, and the majority is restricted to the top 3 cm (Beard, 1973; O'Neil and Carrow, 1982; Sills and Carrow, 1982). Shallower compaction depths are within the functional range of most cultivation equipment and are amendable. However, heavy machinery used during construction often causes deeper compaction and often occurs in the subsoil. Subsoil compaction is more harmful and more difficult to amend after turfgrass establishment (Hamilton and Waddington, 1999; Jim, 1998; Kelling and Peterson, 1975 Vavrek, 2002).

Traffic on sports fields often causes turfgrass wear in addition to soil compaction. Wear is the divoting, scuffing, and tearing of turfgrass leaf tissue and causes the immediate, acute thinning of turfgrass canopy (Samaranayake et al., 2008). Wear is the dominant stress impacting sandy rootzones and soils with moisture contents below field capacity (Agnew, 1990; McNitt and Landschoot, 1999). Wear can also cause soil surface crusting and smearing, which can disrupt water infiltration rates (Adams and Gibbs, 1994). Turfgrass wear and compaction are often interdependent. Because most of the forces exerted from foot traffic are absorbed by the turfgrass' verdure and thatch, compaction may only progress after sufficient buffering verdure is lost through wear (Gibbs et al., 1993; Minner and Valverde,2005).

Compaction indirectly affects plant growth by increasing the soil's water holding capacity, which can potentially create waterlogged conditions. Oxygen diffuses 10,000× slower through water than the atmosphere (McCarty, 2010). Therefore, compaction can disrupt soil gas exchange, decrease soil aeration, reduce the availability of nutrients, and increase the concentrations of toxic gases (CO_2, hydrogen sulfide, sulfur dioxide, and methane) in the soil (Agnew, 1990; Bunnell and McCarty, 1999; Thien, 1994). These gases may kill turfgrass roots, impact their ability to absorb nutrients, and/or uptake water (Unger and Kaspar, 1994).

Compaction can decrease the availability of soil nutrients by impeding their downward movement through the soil profile and by limiting the volume of soil that roots can exploit (Agnew, 1990; Goss 1988). Compaction blocks channels for root growth by increasing the soil's penetration resistance beyond the roots' growing pressure (Dest and Ebdon, 2007; Murphy and

Rieke, 1991). As a reference, soil resistances >2.3 MPa decreased root growth of perennial ryegrass (*Lolium perenne* L.*)* (Passioura, 2002). Roots respond to compaction by exploiting shallower volumes of soil, increasing their density at shallower depths, increasing in diameter, forming aerenchyma tissue (air conducting tissue), and decreasing water and nutrient uptake (Dest et al., 2009; Murphy et al. 1993; Thien, 1994; Wherley et al., 2011).

Compaction's negative effects are not restricted to the turfgrass root system and can disrupt shoot physiological processes, as well (Dest et al., 2009; Thien, 1994). Agnew and Carrow (1985) noted that heavy compaction lowered the soil oxygen diffusion rate. Less soil oxygen resulted in less water uptake and permeability, which decreased leaf cell expansion and decreased shoot and root growth (Carrow and Petrovic,1992). Compaction also induces thinning of the turfgrass canopy and decreases the production and allocation of total nonstructural carbohydrates (Agnew and Carrow, 1985; Carrow and Petrovic, 1992). Soil compaction and resulting soil waterlogging can decrease evapo-transpiration rates, delay turfgrass establishment, and diminish turf quality (Agnew, 1990; Dest and Ebdon, 2007; Materechera et al., 1992; Wherley et al., 2011).

Because plants in compacted soil lack readily available carbohydrates, they respond poorly to added stresses (Thien, 1994). For this reason, Vavrek (2002) labelled compaction as the 'hidden threat' because its negative effects on turfgrass may not be evident until secondary stresses occur -- especially water stress (Materechera et al., 1992; Thien, 1994; Vavrek, 2002). Compaction can lead to increased pest pressures. Weed encroachment, disease, and/or insect pressure increase with compaction (Landry, 1994). Rossi (2003) suggested that compaction reduces carbohydrate reserves, raises turf canopy temperatures, increases disease incidence.

Thien (1994) postulated that compaction may encourage disease pressure by tipping the scales towards “pathogenic virulence” of soil fungi.

Thatch

Bermudagrass is often planted on golf courses and sports fields in the southeastern United States because of its excellent turf quality, tolerance to abiotic and biotic stresses, and rapid recovery rate. Recovery occurs from growth of aerial shoots from nodes on adventitious lateral stems (rhizomes and stolons) (McCarty, 2010). However, these lateral stems and other sclerenchyma containing tissues, (roots, leaf sheaths) do not readily decompose and contribute to the thatch layer, which is a layer of living and dead plant material that forms between the green turfgrass shoots and the soil surface. The thatch layer amasses when its accumulation outpaces control measures and decomposition rate (Beard, 1973).

A moderate thatch layer < 1.2 cm depth is preferred because it protects turfgrass crowns from traffic, moderates soil temperatures, accepts approaching golf shots, and provides cushioning for falling athletes (Beard, 1973; Smith, 1979). Turfgrass health, playability, and soil physical properties are compromised when thatch levels exceed 1.2-cm depth (Beard 1973; McCarty et al., 2005). Excessive thatch causes shallower turfgrass rooting and decreases turfgrass’ drought tolerance. Excessive thatch decreases water infiltration rates into the soil and increases the incidence of localized dry spots (Beard, 1973; Carrow, 2004). The efficacy of chemical inputs (fertilizers and pesticides) is compromised with an excessive thatch layer (Hutchens 2019; McCarty, 2010; Musser, 1960). Thatch elevates bermudagrass crowns above the insulating soil and increases their susceptibility to winterkill (Carrow, 2004). Thatch can result in increased disease and insect pressures (Gregg and McCarty, 2004; Hutchens et al., 2019; White and Dickens, 1984).

Excessive thatch can negatively affect turfgrass aesthetics by creating puffy, soft surfaces. Mowers can settle into thatchy surfaces and cause inconsistent heights of cut and turfgrass scalping (White and Dickens, 1984). Soft, thatchy surfaces can negatively affect surface playability and athlete performance by increasing player fatigue, reducing traction, and decreasing ball bounce (McCarty et al., 2007; Mascitti et al., 2017; Minner and Hudson, 2005). Thatch reduces infiltration rates, which prologs the duration of standing water (Lewis et al., 2010; McCarty et al., 2007). Wetter surfaces provide less traction, thus increasing the likelihood of participant injury (Dickson et al., 2018).

Soil microbes- bacteria and fungi- are responsible for thatch decomposition; therefore, edaphic conditions that encourage soil microbes should be maintained. Soil pH should be maintained between 6 to 7.0, and soil moisture should not be excessively moist to encourage thatch decomposition (Beard, 1982; Potter, et al., 1985).

Nitrogen fertility encourages turfgrass shoot growth (Gaudreau, 1997; Kim, 1985; Meinhold et al., 1973), and at higher rates, thatch accumulation outpaces microbial degradation. Liberal pesticide usage is also thought to indiscriminately decrease micro-organism populations (Smiley et al., 1985). Therefore, Beard (1982) recommended applying judicious nitrogen and pesticide applications to limit thatch accumulation.

Macro-soil organisms work in concert with soil microbes to decompose thatch. Earthworms have been shown to decrease thatch content in Kentucky bluegrass (*Poa pratensis* L.) (Potter et al., 1990). Lee (1985) and Potter (1990) proposed that earthworms decrease thatch through natural topdressing and by improving soil aeration through burrowing (Lee, 1985; Potter, 1990). However, earthworms are often viewed as a nuisance in intensively managed turfgrass settings because their casts disrupt turfgrass aesthetics, playability, and mowing equipment. Therefore, earthworms' presence is often discouraged in intensively managed turfgrass settings (McCarty, 2010)

Thatch levels decrease with increasing traffic levels (Gibbs et al., 1993; Thien, 1994). However, traffic occurs in regular, concentrated areas on sports fields, and these areas are more prone to soil compaction. Therefore, traffic is not an effective method to uniformly decrease thatch content across a surface (Cockerham et al., 1990; Gibbs et al.,1993).

Mowing frequency and height impact thatch accumulation. Madison (1971) predicted that higher mowing heights encouraged thatch accumulation by encouraging the maturation and lignification of leaf tissue. On putting greens, frequent close mowing is recommended to limit thatch accumulation (Beard, 1982). In residential settings, thatch rarely increases if < 33% of the leaf blade is removed during each mowing (McCarty, 2003).

Ideally, thatch removal by cultural practices is achieved with minimal surface and turfgrass quality disruption (Turgeon and Fidanza, 2017). However, removing thatch is often laborious, expensive, and disruptive of turfgrass quality, and it often requires multiple years of biological and/ aggressive mechanical treatments (Beard, 1973; Gregg and McCarty, 2004; Smith, 1979).

Compaction and Thatch Management

Sands resist changes to their structure and retain their desirable porosity with traffic (Bingaman and Kohnke, 1976). Therefore, compaction is more of a problem in heavier soils compared to sand mediums (Beard, 1982), However, sand rootzones are not devoid of problems. Sand rootzones can be expensive to install, they often require more intensive fertilizer and water inputs (Brown, 2018) and they can lack stability until turfgrass roots, stolons, and/ rhizomes develop (Murphy and Ebdon, 2013). Once established, sand rootzones can accumulate excessive organic matter (> 3 to 4% by weight), which can compromise vertical drainage, turfgrass growth, and playability (Carrow, 2004).

Controlling traffic across a surface can aid in the prevention of soil compaction. Management practices that minimize repeated traffic passes and disperse traffic over a wider area help to limit wear and compaction. In sports turf settings, practices include altering the orientation of fields, the location of boundaries, and goal locations (Wienecke, 2004). The movement of tee markers and hole locations, as well as restricting golf car access can aid in dispersing traffic, wear, and compaction on golf courses (Beard, 1973). Limiting or stopping traffic on wet surfaces is an effective means to limit soil compaction in both golf and sports turf settings (Brown and McCarty, 2005).

To alleviate soil compaction, the soil must be physically altered by adjusting soil structure or removing part of the soil. Because soil compaction on intensively used sports fields is usually confined to the top 5 to 7.6-cm of the soil profile, amending cultivation practices should be concentrated to these depths (Gibbs et al., 1993; Minner and Valverde, 2005; Varvek, 2002).

Tillage is often practiced in production agriculture before sowing a new annual crop. Tillage’s benefits in agriculture are numerous: incorporating nutrients, burying weed seeds and previous crop residues, and increasing soil macroporosity. Tillage is often practiced before turfgrass establishment, as well. However, tillage is discouraged in perennial turfgrass settings after establishment because of the desire to maintain acceptable turfgrass quality (Turgeon and Fidanza, 2017).

Correcting soil compaction after establishment is difficult; however, various forms and combinations of cultivation exist (McCarty, 2011). Regardless of the method(s), the objective of cultivation is to alter the soil while maintaining sod with (ideally) minimal loss of turf quality (Turgeon and Fidanza, 2017). However, cultivation is a destructive process, and favorable growing conditions should follow cultivation to ensure rapid turfgrass recovery (McCarty, 2010).

Turf practitioners have an array of aerification equipment to employ that vary in form, function, and aggressiveness. Aerification practices can be practiced independently or in tandem with each other (McCarty, 2011). Generally, more yearly aerification events and more area impacted yield better soil physical properties at the expense of temporary loss of turf quality (Atkinson et al., 2012). Minimally disruptive aerification practices include water-, sand- and air-injection, spiking, and slitting. More disruptive aerification practices include solid- and hollow-tine aerification, drill and fill, rotary decompactors, and sand-/gravel-injection cultivators. Generally, these aerification practices impact more of the turfgrass surface, are more disruptive of turfgrass quality, and require longer turfgrass recovery times (Turgeon and Fidanza, 2017).

Aerification decreases soil compaction by decreasing the mass of the soil and/ increasing the volume of soil (Murphy et al., 1993). Hollow-tine aerification lowers bulk density by removing a plug or ‘core’ composed of verdure, thatch-mat, and soil, thus decreasing the mass (and density) of the soil. Conversely, air injection can decrease the soil’s bulk density by increasing the volume of the soil while maintaining the same mass (Dickson et al., 2015).

Infiltration rates are decreased by soil compaction, as well as soil layering, accumulated organic matter, and hydrophobic thatch layers. Aerification can fracture the soil, create macropores, and pierce restrictive layers, which improves infiltration rates and saturated hydraulic conductivity (Bunnell et al., 2001; McCarty et al., 2007; Murphy et al., 1993). Improved soil aeration from aerification can improve root-growth, -viability, and rooting depth, as well as stimulate shoot growth above aerification holes (Engel and Alderfer, 1967).

Aerification's ability to reduce thatch content has seen contrasting results. Atkinson et al. (2012) observed a slight reduction in thatch following hollow-tine aerification. McCarty et al. (2005) did not observe a reduction in thatch of creeping bentgrass putting greens following hollow-tine aerification. Because aerification impacts a finite surface area, it is inconsistent at physically removing thatch. Instead, Beard (1973) suggested that hollow-tine aerification encourages thatch decomposition by incorporating soil into the thatch layer (like topdressing) and by increasing soil aeration.

Aerification's benefits are numerous; however, they are often transient and dissipate after approximately four weeks (Bigelow and Soldat, 2013). Aerification's capacity to reduce soil compaction is not always realized (Sorokovsky et al., 2007). Repeated aerifications to the same depth can create hardpans, which can diminish hydraulic conductivity (Murphy et al., 1993; Raney et al., 1955). Aerification of non-compacted or wet soils can lower the soil's Ksat (Murphy et al., 1991; Murphy et al., 1993). Aerification can increase the potential for plant desiccation and potentially provide a foothold for insect and weed infestations (Bevard, 2011; Madison, 1971).

Topdressing is the broadcasting of sand, soil, expanded clays, compost, and crumb rubber across the turfgrass' surfaces (Miller, 2008; Rogers et al., 1998). Topdressing with sand is an excellent biological control option for thatch management and is thought to maintain water infiltration (Carrow, 2004; Murphy, 1983). Topdressing is thought to improve thatch decomposition by re-inoculating the thatch layer with micro-organisms and/ by increasing microbial activity through increased moisture retention (Hurto et al., 1980).

Topdressing with crumb rubber improved wear tolerance reduced surface hardness, shear strength, and bulk density in Kentucky bluegrass and bermudagrass (Goddard et al., 2006;

Rogers et al., 1998). Sand topdressing and nitrogen fertilization improved the resilience of perennial ryegrass compared to aerification treatments. Specifically, sand and nitrogen treatments were less compacted, had better turf cover, and playing quality than fields that received slitting or solid-tine aerification (Spring et al., 2007). Aggressive sand topdressing or sand capping- topdressing with sand to depths ≥ 2.5-cm- is an effective way to bypass the restrictive texture of native soil fields. Sand capping is a cheaper alternative to constructing sand-based fields with gravel and tile drainage (Brown, 2018)

Vertical mowers have a series of vertical blades mounted onto a rotating horizontal shaft that cut grooves into the turf surface and physically dislodge thatch. The aggressiveness of vertical mowing can be manipulated by adjusting the blade-thickness, -spacing, and -cutting depth. However, vertical mowing does not impact the entire surface in a single pass (<30%; Turgeon and Fidanza, 2017). Because of its limited impact, Gregg and McCarty (2004) cautioned that multiple years of aggressive mechanical treatments would be necessary to remove the thatch-mat layer in ultradwarf bermudagrass.

Vertical mowing has had mixed effects on infiltration rates. McCarty et al. (2007) observed increased infiltration rates after vertical mowing. However, Gibbs et al. (2001) observed decreased infiltration rates because of soil smearing from vertical mowing. Although Turgeon and Fidanza (2017) speculated that deep vertical mowing could alleviate soil compaction, no research to date has substantiated this claim.

Beard (1982) cautioned that putting greens with excessively thick thatch layers (≥ 3.8 cm) require renovation and re-establishment. Madison (1971) recounted a drastic bermudagrass thatch removal practice of stripping all bermudagrass verdure and thatch with sod cutters to 0.6 cm above the soil surface and allowing regrowth from remnant stolons and rhizomes.

Approximately 25 years later (1996), Ko Rotenburg devised fraise (fraze) mowing for thatch and annual bluegrass management in soccer fields (Carson, 2015). Although highly disruptive, fraise mowing provides turf managers with an option to completely remove all thatch without the added steps and expense of total renovation or gradual thatch reduction.

Fraise Mowing

Fraise mowers function similarly to vertical mowers. Both fraise mowers and vertical mowers have a series of vertical blades mounted on a horizontal rotating shaft/rotor. Fraise mowers differ from vertical mowing in the surface area they impact in a single pass. Fraise mowing's impact is absolute and encompasses the entire surface to (potentially) 5-cm depths (McCauley et al., 2019). Fraise mowing has the potential to remove everything (verdure, organic matter, soil) to a consistent cutting depth. An attached, adjustable elevator on tractor mounted units enables the controlled, tidy, disposal of debris (Lewis, 2015). Depending on the cutting depth, uncut stolons, rhizomes, and/ bare soil are all that remain after fraise mowing. A visually jarring appearance often persists for weeks until sufficient turfgrass shoots emerge from remnant nodes and/ sown seed (Hansen and Christians, 2015; Stewart et al., 2016). Turfgrass recovery time and the disposal of generated debris are two negatives of fraise mowing. Although fraise mowing was originally devised for thatch and annual bluegrass management, it is widely used as a renovation tool- especially before resodding (Miller, 2019).

Despite being in service for >20 years, limited fraise mowing research has been conducted. Fraise mowing to depths ≤1.8 cm were effective at decreasing annual bluegrass populations in perennial ryegrass (Baker et al., 2005). Fraise mowing to 2.5-cm depth did not reduce the annual bluegrass seedbank in zoysiagrass (*Zoysia* spp.) (Brosnan et al., 2020). Fraise mowing's efficacy on bermudagrass control has produced mixed results (McCalla et al., 2018).

Fraise mowing to 0.8 cm depth decreased spring dead spot pressure but was less effective than preventative fungicide applications (Miller et al., 2017). Fraise mowing made a suitable seedbed for overseeded perennial ryegrass but caused unacceptable turfgrass quality until sufficient ryegrass established (Munshaw et al., 2017). Overseeded ryegrass effectively removed in the spring when fraise mowing was performed in mid-May or mid-June to ≥1.2-cm depths (McCauley et al., 2019).

As previously mentioned, prolonged turfgrass recovery times ≥ 3 weeks ensue after fraise mowing. Bermudagrass recovery is dependent on fraise mowing depth and growing degree days after treatment (Shelton et al., 2016; Stewart et al., 2016). Hansen and Christians (2015) observed expediated Kentucky bluegrass recovery from fraise mowing when overseeding and/ growth covers were used.

Anecdotally, fraise mowing is thought to improve infiltration rates and reduce the soil's bulk density (Baker et al., 2005; Miller, personal communication). To date, Baker et al. (2005) observed increased soil surface hardness and inconsistent results with traction following fraise mowing. Holes still remain in fraise mowing's research- especially its effects on soil physical properties, as well as practices to improve bermudagrass' recovery following fraise mowing.

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CHAPTER 1: FRAISE MOWING IMPACTS SOIL PHYSICAL PROPERTIES OF BERMUDAGRASS SURFACES

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Abbreviations: θg, gravimetric soil water content; Ksat, saturated hydraulic conductivity; NC, North Carolina; OM, organic matter; RCBD, randomized complete block design; WAF, weeks after fraise mowing

ABSTRACT

Fraise mowing is an aggressive cultural practice used for bermudagrass thatch management in golf and sports turf settings. Despite expanded use, its effect on edaphic characteristics has yet to be thoroughly explored. The objective of this research was to evaluate soil physical properties of two soils beneath established 'Tifway' hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt. Davy) following fraise mowing. A study was conducted during the summers of 2016-2019 on a Cecil sandy loam (SL) and a sand capped soccer field (S) in Wake County, NC. Four fraise mowing depths: 0.6 cm, 1.2 cm, 2.5 cm and an untreated control were administered in mid-June of each year. Thatch content decreased after fraise mowing in both soils. Soil surface hardness increased with 1.2 and 2.5-cm fraise mowing depths, and differences were more pronounced in the SL (≤49 gravities) compared to the S (≤ 15 gravities). Shear strength in the S decreased with fraise mowing depths and the removal of more reinforcing roots rhizomes, and stolons. In the SL, the 2.5-cm fraise mowing depth had the highest shear strength because it engaged the cohesive, underlying soil. Saturated hydraulic conductivity in the S decreased with increasing fraise mowing depths. At saturation (0-cm tension) and field capacity (100-cm tension) water retention decreased with increasing fraise mowing depths in the S. These results indicate that fraise mowing did alter the soil physical properties in both soils and that deeper fraise mowing depths had a more pronounced effect.

Bermudagrass is often selected for golf course and sports turf settings in the southeastern United States because of its excellent turf quality and tolerances to abiotic and biotic stresses. It can establish and recover from canopy damage quickly through the production of rhizomes and stolons. However, these horizontal stems and other sclerenchyma containing tissues contribute to the thatch layer, which forms between the turfgrass canopy and soil surface. Thatch's high lignin content delays its decomposition, and it amasses when accumulation outpaces control measures and decomposition rate (Beard, 1973).

A moderate thatch layer < 1.2 cm depth is preferred because it protects turfgrass crowns from traffic, moderates soil temperatures, and provides cushioning for athletes (Beard, 1973; Smith, 1979). However, turfgrass health, playability, and soil physical properties, are compromised when thatch levels exceed 1.2 cm (Beard, 1973; McCarty et al., 2005). Excessive thatch decreases turfgrass' drought and cold tolerance, water infiltration rates, and the efficacy of chemical (fertilizer and pesticide) inputs (Beard, 1973; McCarty and Miller, 2002; Musser, 1960). Scalping and pest incidences can increase with rising thatch contents (Hutchens et al., 2019; White and Dickens, 1984). Thatch can affect playability by creating softer surfaces, which can negatively affect athlete performance by hastening their muscle fatigue (Baker et al., 2007; Minner and Hudson, 2005).

Removing thatch is laborious, expensive, and disruptive of turfgrass quality (Smith, 1979). Alone and in tandem, aerification, vertical mowing, grooming, and sand/soil topdressing have traditionally been used to manage thatch (McCarty et al., 2007). These cultural practices induce varying soil physical responses (Mascitti, 2015). Aerification lowers bulk density and surface hardness, and it increases infiltration rates (Bunnell et al., 2001; Murphy et al.,1993). Vertical mowing increases soil hardness, soil shear strength, traction, and infiltration rate

(Sheratt et al., 2005; McCarty et al., 2007). Topdressing increases soil surface hardness, traction, and soil shear strength (Kowalewski et al., 2011; Miller, 2008; Spring et al., 2007).

Fraise mowing is an aggressive cultural practice that impacts 100% of the playing surface and has the potential to remove all plant and soil material to 5-cm depths. The practice is gaining acceptance for bermudagrass thatch management especially in the southeastern United States. Hansen and Christians (2015) speculated that fraise mowers could potentially remove all thatch and organic matter while leaving viable nodes for bermudagrass to recover. Other fraise mowing benefits include annual bluegrass (*Poa annua* L.) control, potential weed seedbank reduction, overseeding establishment and removal, turfgrass renovation, and reduced spring dead spot pressure (Baker et al., 2005; Dickson et al., 2016; McCauley et al., 2019; Shelton et al., 2016).

Despite its growing popularity, fraise mowing's effect on soil physical properties is largely unknown. Baker et al. (2005) observed higher soil surface hardness values and mixed traction responses after fraise mowing. Baker et al. (2005) suggested implementing deep fraise mowing treatments (≥1.8 cm depths) to minimize organic matter's negative effects on drainage and playing quality. To date, fraise mowing's effect on soil physical properties has yet to be thoroughly explored. The objective of this research was to evaluate the effects of fraise mowing on the soil physical properties of two soils beneath established hybrid bermudagrass (*Cyodon dactylon* x *C. transvaalensis* Burtt. Davy).

MATERIALS AND METHODS

A study was repeated for four consecutive years (2016-2019) on a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) (loam) at NCSU's Lake Wheeler Turf Field Laboratory in Raleigh, NC (35.737740,-78.677240) and a sand capped soccer field (sand) at WakeMed Soccer Park in Cary, NC (35.788720, -78.753760). An untreated control (control) and three fraise mowing depths 0.6 cm (shallowest); 1.2 cm (intermediate); 2.5 cm (deepest) were applied in mid-June each year with a fraise mower (Koro Field TopMaker 1200 Campey Imants Cheshire, UK) to hybrid bermudagrass. The placement of experimental units at each location was changed each year. Fraise mowing plots measured 1.2 x 2.4 m and were arranged in randomized complete block design (RCBD) with four replications. Starting one week after fraise mowing, plots were fertilized with N at 12.21 kg ha^{-1} $week^{-1}$ for four weeks with granular ammonium sulfate (21 N – 0 P_2O_5 – 0 K_20). Six weeks after fraise mowing, plots were fertilized with N at 49 kg ha^{-1} with granular ammonium sulfate. Plots were clipped three times per week at 1.3 cm height with clippings returned and were irrigated as needed to prevent moisture stress.

Measurements

Surface soil hardness, shallow soil shear strength, gravimetric moisture contents (θg), and bulk density were measured in both soils. Saturated hydraulic conductivity (Ksat) and soil water retention were measured in the sand. Measurements were taken every 14 d from mid-June to mid-August each year.

Thatch Height and Organic Carbon Content

Thatch height and organic matter content were measured in both soils. One intact 5.0-cm diameter soil core was randomly collected from each plot to a depth of 7.6 cm. Thatch was separated from the verdure and soil, compressed with a 0.45 kg weight, and thatch height was measured at three points (Mascitti, 2015). Separated thatch samples were oven dried at 105°C for 48 h and weighed. Samples were then combusted in a muffle furnace at 700°C for 5 h, weighed, and their organic matter contents were determined (Carrow et al., 1987).

Divot Resistance/Shallow Soil Shear Strength

Divot resistance/shallow soil shear strength was measured once randomly in each plot with a Clegg turf shear tester (TST) (Balden Clegg PTY Ltd., Wembley DC, WA, Australia) as described by Sherratt et al. (2005). The TST is equipped with a 50.0-mm-wide x 40.0-mm insertion-depth paddle that is attached to a 1 m handle. The paddle causes surface displacement in the horizontal direction when the handle is rotated. The unit measures the amount of torque (N·m) required to horizontally displace the turf and generate a divot. Measurements were taken in both soils immediately after fraise mowing and continued at 14 d intervals.

Saturated Hydraulic Conductivity (Ksat)

Saturated hydraulic conductivity (Ksat) was measured from one intact 5.0-cm diameter soil core that was randomly collected from each plot to 7.6-cm depth every 14 days. Parent material present in the loam led to inconsistent soil cores that produced erratic Ksat values during the first year. Therefore, Ksat was only measured in the sand. A double layer of cheese cloth was affixed to the bottom of each core with rubber bands, and cores were saturated in standing tap water for 1 d. Saturated hydraulic conductivity was measured using the constant-head method (Klute and Dirksen, 1986; Reynolds and Elrick, 2002).

Soil Surface Hardness

Soil surface hardness was measured in both soils at 14 d intervals with a Clegg impact soil tester (CIST) (Lafayette Instrument Company, Lafayette, IN) using a 2.25 kg missile. The missile was dropped once from a height of 47.5 cm at three random locations per plot with peak deceleration measured (gravities or Gmax). The three values from each plot were averaged before statistical analysis (ASTM 2010).

Gravimetric Moisture Content

Gravimetric moisture content (θg) was measured every 14 d in both soils from one intact one intact 5.0-cm diameter soil core that was randomly collected from each plot to 7.6-cm depth as described in Klute (1986). Initial core weights were recorded after collection. Verdure and thatch were separated from the soil and weighed in separate aluminum containers. Thatch and soil samples were oven dried at 105°C for 48 hours, weighed, and their θg were calculated (g g^{-1}).

Soil Water Retention

Soil water retention was measured from each plot in the sand with an intact 137.5 cm^3 core. Cores were collected at 0 and 4 weeks after fraise mowing (WAF). Cores were saturated for 24 h before being placed on a porous plate and equilibrated at water tensions: 0, 3.5, 10, 20, 30, 50, 100, 200, and 333 cm H_20. Drained water at each tension was recorded. After equilibrating at the final tension, core weights were recorded. Cores were then oven dried at 105°C for 48 h, weighed, and gravimetric water contents (θg) at each tension were calculated. Only results for saturation and field capacity (0 and 100 cm H_20) were presented (Klute, 1986).

Statistical Analysis

The study was analyzed as a RCBD with multiple rating dates analyzed using repeated measures. Soil water retention was analyzed with two repeated measures for multiple rating dates (0 and 4 WAF) and nine applied tensions. All data were subjected to analysis of variance using the GLIMMIX procedure in the Statistical Analysis System software (version 9.4; SAS Inst. Inc., Cary, NC) to determine treatment effects and interactions. Significant effects were further evaluated with Fisher’s protected LSD test with a 0.05 level of probability.

RESULTS AND DISCUSSION

Thatch Content

A significant soil × year × fraise mowing depth interaction with thatch organic ash weight was determined using ANOVA (*P* = 0.0033); therefore, thatch was analyzed by year and soil. Thatch content decreased with deeper fraise mowing depths in both soils. In the loam, all fraise mowing depths had less thatch compared to the untreated control in 2016, 2017, and 2019. The intermediate (1.2 cm) and deepest (2.5 cm) depths had less thatch compared to the shallowest (0.6 cm) depth and the control every year (Table 1).

Table 1. Thatch organic ash weight per 148 cm^3 samples of fraise mowing treatments in sandy loam and sand pooled over rating dates within each year.

	Sandy Loam				**Sand**			
Depth[a]	**2016**	**2017**	**2018**	**2019**	**2016**	**2017**	**2018**	**2019**
	grams							
Control	5.8 a[b]	5.4 a	3.6 a	3.8 a	3.2 a	2.9 a	3.5 a	2.8 a
Shallow	4.6 b	4.0 b	3.3 a	2.8 b	2.5 b	2.7 a	2.9 b	2.2 b
Intermediate	4.0 bc	2.8 c	2.6 ab	2.5 c	2.5 b	2.3 b	2.1 c	1.6 c
Deep	3.0 c	2.2 c	1.7 b	1.4 d	2.1 b	2.1 b	1.5 d	1.0 d

[a] Fraise mowing depth.

[b] Means within year followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

In the sand, thatch content decreased with deeper fraise mowing depths, and all fraise mowing depths had less thatch compared to the control in 2016, 2018, and 2019. The intermediate and deepest depths had less thatch compared to the control every year (Table 1). Thatch content in the sand was lower compared to the loam. This was attributed to the more aggressive aerification and topdressing program practiced on the sand. Loam plots received no aerification or topdressing since their establishment (>8 years).

These results demonstrate the efficacy of fraise mowing to remove thatch. Fraise mowing at the shallowest depth reduced thatch by 8 and 7% in the loam and sand, respectively. However, one annual fraise mowing at the deepest depth reduced thatch by ≥27% and ≥52% in the loam and sand, respectively. Although aerification and vertical mowing physically remove thatch, neither practice affects the entire surface and both leave most of the thatch layer intact (O'Brien and Hartwiger, 2003). Carrow et al. (1987) observed 0 to 8% reduction in ‘Tifway’ bermudagrass organic matter after vertical mowing once or twice per year, respectively. McWhirter and Ward (1976) only observed a decrease in thatch accumulation by 4 to 12% following vertical mowing of a ‘Tifgreen’ bermudagrass putting green at 2 to 4 wk intervals, respectively. McCarty et al. (2005) and White and Dickens (1984) did not observe a decrease in organic matter following hollow-tine aerification. McCarty et al. (2007) noted multiple aerification, grooming, and vertical mowing treatments were required to reduce the thatch-mat layer over two years. Although, fraise mowing in this study failed to remove the entire thatch layer, it did impact 100% of the surface and reduced thatch height and content. Pre-sampling thatch depths at both locations and implementing deeper fraise mowing depths into this study would have likely produced greater differences in percent thatch reduction.

Shallow Soil Shear Strength/ Divot Resistance

Analysis of variance determined a significant fraise mowing depth × soil interaction with shallow soil shear strength (N·m) ($P < 0.0001$); therefore, shear strength was analyzed by soil. In the loam, the deepest depth had the highest shear values (Fig. 1). Because the deepest depth removed the most thatch, the turf shear tester (TST) engaged more of the underlying cohesive loam. This increased the shallow soil shear strength of the deepest depth. Sherratt et al. (2005) observed increased soil shear strength with more organic matter removal following vertical mowing.

In the sand, shear strength decreased at the intermediate and deepest depths. These deeper fraise mowing depths removed more reinforcing roots, rhizomes, and stolons from the sand rootzone. With less reinforcement, the shear strength of the non-cohesive sand decreased. Adams et al. (1985) and Rogers (1988) found that root biomass is a key contributor of sand rootzone stability and traction in perennial ryegrass (*Lolium perenne*) and Kentucky bluegrass (*Poa pratensis*) surfaces. Van Wijk (1980) noted that turfgrass roots can improve soil shear resistance by 300%. Turfgrass ground cover retention has a similar positive effect on maintaining stability and traction (Adams et al., 1993; Rogers, 1988). Without added biomass stability, sand rootzones can shift/deform, which negatively affects player performance and safety (Adams et al., 1985; Rogers, 1988). Despite these changes, shear strength values throughout this study were within previously defined acceptable range (20 to 120 N·m) of surface shear strength for Australian football, regardless of soil type (Chivers and Aldous, 2003).

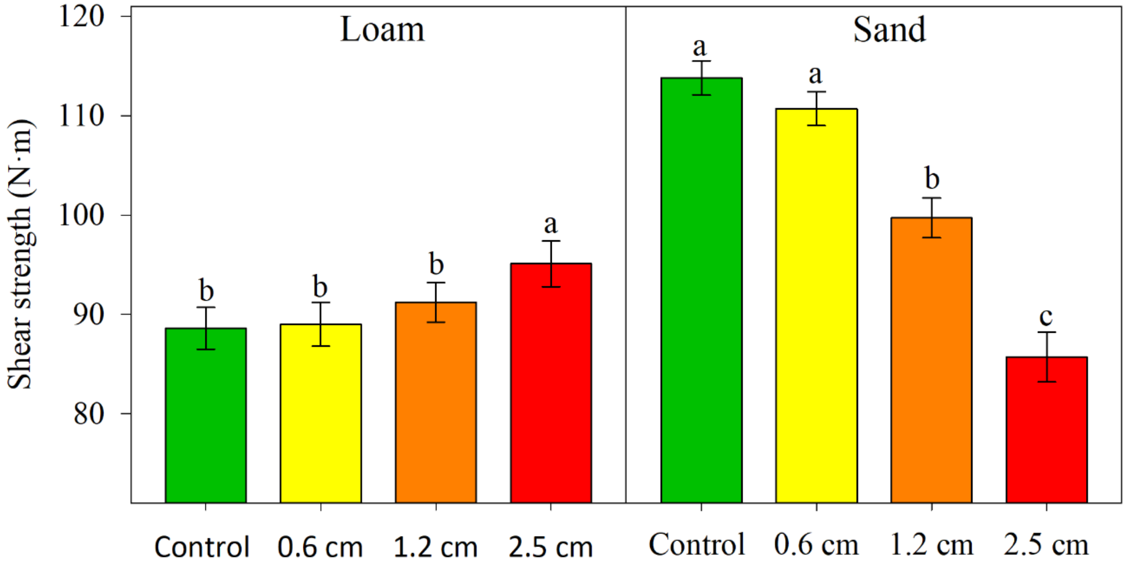

Figure 1. Soil shear strength (N·m) measured with a turf shear tester in a sandy loam and sand following mid-June fraise mowing. Bars are pooled over five rating dates per year and all four years. Bars with same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Saturated Hydraulic Conductivity (Ksat)

Analysis of variance determined a significant fraise mowing depth effect with saturated hydraulic conductivity (Ksat) ($P < 0.0001$) in the sand. Saturated hydraulic conductivity was highest in the untreated control and decreased with deeper fraise mowing depths. The intermediate and deepest depths were 34 and 48% slower than the untreated control, respectively (Fig. 2). The deepest depth was 41% slower than the shallowest depth. Baker and Richards (1993) recommended Ksat $\geq$15 cm hr^{-1} as the preferred range for soccer fields. The Ksat rates of all treatments in this study met or exceeded Baker and Richards (1993) threshold. However, the marginal Ksat rate of the deepest fraise mowing depth may require added cultivation inputs for improvement.

These Ksat results were contrary to previous research where macroporosity and Ksat decreased with increasing surface organic matter content (Glasgow et al., 2005) and less aggressive cultivation (Carrow, 2000). However, aerification and vertical mowing have elicited similar negative Ksat responses when performed at higher soil moisture contents (Gibbs et al., 2001; Murphy et al., 1993). In this study, soil moisture contents during fraise mowing were not normalized between years. Soil moisture contents above field capacity during fraise mowing may have exacerbated soil smearing in this study. Murphy et al. (1993) attributed aerification induced hardpan formation for their observed reduction in Ksat. Gibbs et al. (2001) credited surface smearing from vertical mowing for decreasing Ksat. Although vertical mowing does not impact the entire surface, it and fraise mowing are similar in action. Therefore, fraise mowing likely smeared and sealed the soil surface and decreased Ksat.

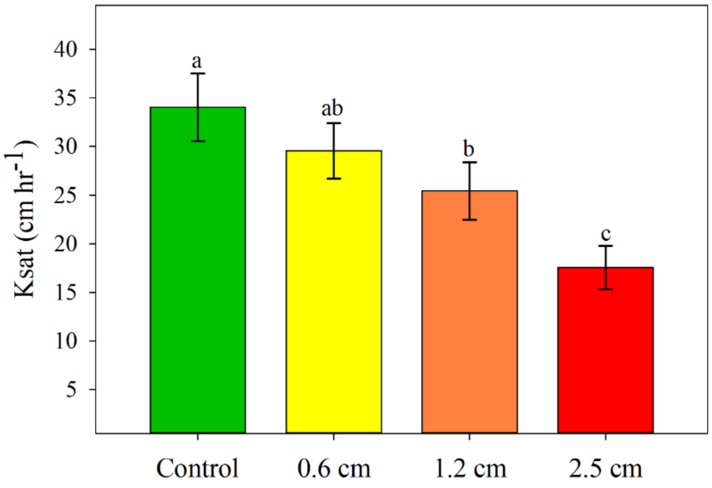

Figure 2. Saturated hydraulic conductivity (Ksat) (cm hr^{-1}) in a sand following mid-June fraise mowing treatment. Bars are pooled over five rating dates per year and all four years. Bars with same letter are not significantly different according to Fisher's Protected LSD (P=0.05).

Soil Surface Hardness

Analysis of variance determined a significant soil × year × depth × weeks after fraise mowing interaction with soil surface hardness (hardness) (P = 0.0003); therefore, hardness was analyzed by location, year, and weeks after fraise mowing (WAF). Fraise mowing- especially at the intermediate and deepest depths removed the cushioning thatch layer and increased hardness (Table 2). In the loam, the 2.5-cm depth was consistently the hardest. The 2.5 and 1.2 cm depths were consistently harder than the control. The 0.6-cm depth and control had similar hardness throughout the study, and their higher thatch contents and greater turfgrass coverage likely lowered their hardness. Baker et al. (2005) and Dickson et al. (2016) also observed higher soil hardness following fraise mowing.

Hardness differences in the sand were less evident (≤14 gravities) between all treatments (Table 3). The deepest depth was harder than the control throughout the study, but the intermediate depth was harder than the control only intermittently. Increases in hardness of the intermediate and deepest treatments were attributed to less thatch and organic matter with deeper fraise mowing depths. However, poor irrigation uniformity, concerns of localized dry spot development, and the high visibility of the sand-capped soccer field lead to overwatering to ensure acceptable aesthetics of the field. Therefore, high soil water contents in the sand likely depressed differences in surface hardness. Segars et al. (2018) observed similar subdued soil surface hardness effects on sand-based sports fields when irrigated to field capacity daily. Miller (2008) observed depressed surface hardness values with elevated soil moisture contents, as well.

Table 2. Soil surface hardness of fraise mowing treatments in a sandy loam soil presented by weeks after fraise mowing (WAF) within each year.

	2016					2017					2018					2019				
Depth[a]	0[b]	2	4	6	8	0	2	4	6	8	0	2	4	6	8	0	2	4	6	8
	Gravities [c]																			
Control	-	53.8 b[d]	44.8 c	52.8 b	50.8 c	40.4 c	44.4 b	48.1 b	53.5 b	54.3 C	77.3 b	59.3 b	61.7 b	50.8 b	54.9 b	44.2 a	53.0 c	51.4 c	49.5 b	52.4 b
0.6 cm	-	59.9 b	56.3 c	59.8 b	61.4 bc	46.2 bc	51.4 b	58.8 b	65.3 a	67.4 bc	89.9 b	59.8 ab	68.2 b	61.0 ab	55.3 b	42.7 a	56.8 bc	53.2 bc	53.2 b	53.1 b
1.2 cm	-	82.8 a	70.8 b	70.3 b	70.5 b	51.2 b	65.6 a	75.1 a	73.0 a	85.6 ab	90.3 b	61.7 ab	67.8 b	63.0 ab	60.9 ab	46.7 a	62.7 ab	56.4 b	62.3 a	62.4 a
2.5 cm	-	102.4 a	84.3 a	94.3 a	87.9 a	63.1 a	73.6 a	80.7 a	75.6 a	101.2 a	126.4 a	90.6 a	89.7 a	76.3 a	73.1 a	43.4 a	66.6 a	64.0 a	67.2 a	61.2 ab

[a] Fraise mowing depth.

[b] Weeks after mid-June fraise mowing (WAF) in each year.

[c] Soil surface hardness was measured in gravities with a Clegg impact soil tester and a 2.25 kg hammer.

[d] Means within year and WAF followed by the same letter are not significantly different according to Fisher’s Protected LSD (*P*=0.05).

Table 3. Soil surface hardness in gravities of fraise mowing treatments in a sand presented by weeks after fraise mowing (WAF) within each year.

	2016					2017					2018					2019				
Depth[a]	0[b]	2	4	6	8	0	2	4	6	8	0	2	4	6	8	0	2	4	6	8
	Gravities[c]																			
Control	-	42.5 b[d]	47.2 a	41.8 c	62.0 b	38.1 a	48.5 ab	79.0 b	61.9 a	58.9 a	66.3 a	63.7 b	55.3 b	52.3 c	52.8 b	39.3 a	42.6 a	50.5 a	44.6 a	41.7 c
0.6 cm	-	46.8 ab	46.7 a	47.6 ab	67.2 b	38.9 a	47.5 ab	70.9 a	59.3 a	57.8 a	64.7 a	70.8 ab	62.9 a	58.2 bc	55.5 b	38.7 a	44.6 a	52.3 a	47.0 a	45.4 b
1.2 cm	-	46.0 ab	46.3 a	44.3 bc	63.4 b	38.1 a	47.3 b	79.6 a	65.7 a	57.3 a	68.3 a	70.2 ab	63.2 a	59.0 b	57.2 ab	41.0 a	45.5 a	55.0 a	46.0 a	45.8 b
2.5 cm	-	50.5 a	50.3 a	51.5 a	76.2 a	41.8 a	52.0 a	84.8 a	68.3 a	60.5 a	70.7 a	77.8 a	67.3 a	66.7 a	61.7 a	40.9 a	42.9 a	52.4 a	48.1 a	48.9 a

[a] Fraise mowing depth.

[b] Weeks after mid-June fraise mowing (WAF) in each year.

[c] Soil surface hardness was measured in gravities with a Clegg impact soil tester and a 2.25 kg hammer.

[d] Means within year and WAF followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Gravimetric Moisture Content (θg)

Analysis of variance determined a significant soil × year × fraise mowing depth interaction with gravimetric moisture content (θg) (*P* = 0.0032); therefore, θg was analyzed by year and soil. In the loam, θg decreased with deeper fraise mowing depths (Table 4). The intermediate and deepest depths had lower θg than the control every year. The deepest depth had less θg compared to the shallowest depth in 2016, 2017 and 2019.

In the sand, θg decreased with fraise mowing depth in 2016, 2018, and 2019 (Table 4). The deepest depth had the lowest θg every year. The intermediate depth had lower θg than the control in 2016 and 2019. The presence of localized dry spots in the control during July 2017 likely depressed θg differences in that year. All fraise mowing depths had less θg compared to control in 2019 (Table 4).

In both soils, reductions in θg were attributed to fraise mowing removing thatch and shallow organic matter. Liang et al. (2017) observed higher water retention in thatch than mineral soil. Carrow (1998) noted that microporosity and water retention increased with more shallow organic matter. As deeper fraise depths removed more organic matter, the microporosity and total porosity of the soil decreased.

Table 4. Gravimetric moisture content of a sandy loam and sand following fraise mowing that is presented by year and pooled over weeks after fraise mowing.

	Loam				**Sand**			
Depth[a]	**2016**	**2017**	**2018**	**2019**	**2016**	**2017**	**2018**	**2019**
	g g^{-1}[b]							
Control	28.5 a[c]	48.0 a	37.9 a	41.7 a	22.0 a	26.9 a	30.4 a	44.9 a
0.6 cm	26.8 ab	38.0 B	35.8 ab	35.0 b	20.7 ab	30.5 a	23.1 ab	41.0 b
1.2 cm	26.0 b	32.3 c	32.5 ab	30.9 b	20.2 ab	29.4 a	22.7 ab	35.3 c
2.5 cm	20.7 c	32.0 C	27.1 b	24.4 c	18.2 b	26.6 a	19.4 b	27.7 d

[a] Fraise mowing depth.

[b] Gravimetric moisture content measured in grams of water per gram of soil (g g^{-1}).

[c] Means within year followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Soil Water Retention

Analysis of variance determined a significant fraise mowing depth × tension response with soil water retention of intact sand cores ($P < 0.0001$). Therefore, water retention was pooled over both rating dates and analyzed at saturation (0 cm tension) and field capacity (100 cm tension). At both tensions, θg decreased with deeper fraise mowing depths (Fig. 3). The untreated control had the highest θg at both tensions. At saturation, the control had 9 and 14% higher θg compared to the intermediate and deepest fraise mowing depths, respectively. Although differences at field capacity were less pronounced, the control retained 4, 5, and 9% more θg than the shallowest, intermediate, and deepest depths, respectively. Less organic matter in the deeper fraise mowing depths decreased their microporosity and θg. Carrow (1998) observed similar increases in soil water retention with rising organic matter contents. Liang et al.

(2017) observed less evaporative water loss and higher water retention when a thatch layer was present. Dickson et al. (2018) noted that higher soil moisture contents exacerbate turfgrass wear and decrease traction. The likelihood of sports injuries increases with decreasing surface stability (Powell and Schootman 1993; Waddington and McNitt, 1955). Ramirez et al. (2006) found that wet or muddy soil playing surfaces increased the risk of participant injury 1.2× compared to 'normal' surfaces. With less organic matter and lower θg, fraise mowing may improve the wear tolerance and increase the traffic load of bermudagrass playing surfaces.

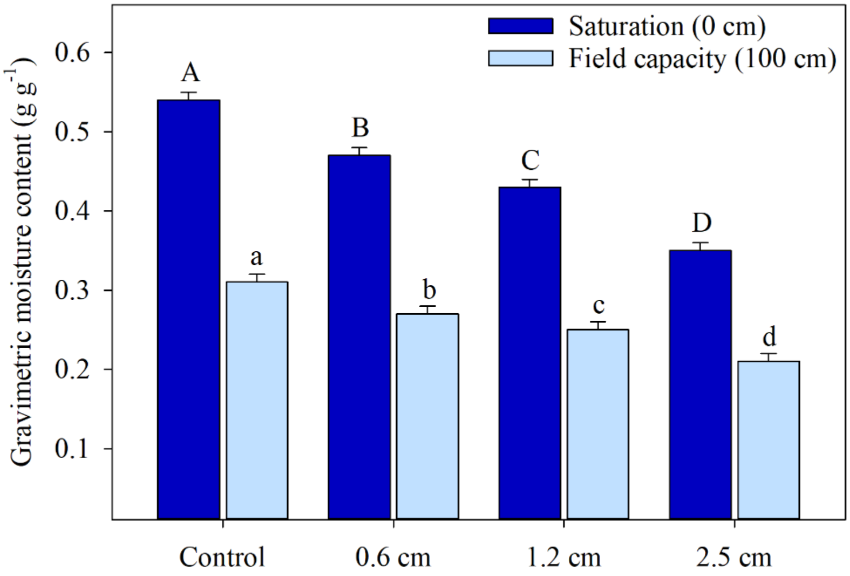

Figure 3. Soil water retention of fraise mowing treatments in a sand at saturation (dark blue bars) and field capacity (light blue bars). Cores were equilibrated at 0 and 100 cm water tensions. Bars are pooled over four years and at 0 and 4 weeks after mid-June fraise mowing. Bars with same letter and case are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Conclusion

In this study, fraise mowing altered soil physical properties in both soils. Deeper fraise mowing depths- the 1.2 cm (intermediate) and 2.5 cm (deepest) depths- had the most impact on soil physical properties. The removal of more thatch at deeper fraise mowing depths dictated these differences. Previous research marginally studied fraise mowing's effect on soil physical properties. Baker et al. (2005) observed increased soil hardness and mixed traction effects following fraise mowing of perennial ryegrass. This current study provided a more comprehensive evaluation of fraise mowing's effects on the soil physical properties within a sand and loam. Soil hardness (higher), gravimetric moisture content (θg) (lower), and thatch (lower) responses were consistent in both soils following fraise mowing. However, fraise mowing elicited diverging divot resistance responses in both soils. Saturated hydraulic conductivity, as well as, soil water retention decreased with deeper fraise mowing depths. Despite these changes in soil physical properties, results were within acceptable/previously defined ranges (Chivers and Aldous, 2003). Fraise mowing effectively removed shallow organic matter and produced acceptable playing surfaces after bermudagrass recovery. Fraise mowing may provide turf managers with more control of soil water contents and may improve turfgrass' wear tolerance. Future research to mitigate fraise mowing's effect on increasing surface hardness in the loam and lower Ksat rates in the sand may be warranted. Pairing fraise mowing with aerification, slicing, and/spiking, as well as fraise mowing when soil moisture contents are at field capacity may offset the effects of soil smearing and improve Ksat rates. This warrants further investigation. In Raleigh, North Carolina, fraise mowing- especially at 1.2 and 2.5 cm- positively and negatively altered the soil physical properties of a sandy loam and sand.

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CHAPTER 2: FRAISE MOWING AND HOLLOW-TINE AERIFICATION IMPACT SOIL PHYSICAL PROPERTIES OF BERMUDAGRASS SURFACES

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Abstract

Fraise mowing and hollow-tine aerification are disruptive cultural practices that remove thatch and alter soil physical properties. The objective of this study was to evaluate the effects of fraise mowing followed by hollow-tine aerification on soil physical properties in a Cecil sandy loam (loam) and a sand capped soccer field (sand) beneath established ‘Tifway’ hybrid bermudagrass (*C. dactylon x C. transvaalensis* Burtt. Davy). Three fraise mowing depths (0.25, 0.5, 1.0 inches) and hollow-tine aerification were applied in mid-June in two consecutive years. Turfgrass and soil quality parameters were evaluated in both soils. Saturated hydraulic conductivity (Ksat) was measured in the sand through mid-August each year. All fraise mowing and aerification treatments resulted in unacceptable TQ during the study. However, combining aerification with fraise mowing did not delay bermudagrass recovery. Thatch content decreased with deeper fraise mowing depths but was unaffected by hollow-tine aerification. Immediately after treatment, Ksat was highest in the untreated control (36.5 inches hr^{-1}) and decreased with deeper fraise mowing depths. Aerification increased Ksat from 37 to 79% during the study. Soil shear strength decreased from 18 to 32% with deeper fraise mowing depths in the sand but was unaffected in the loam. Aerification decreased surface hardness (5 to 21%) and shear strength (2 to 17%) in both soils. When practiced concurrently, fraise mowing and hollow-tine aerification were complimentary and positively affected the soil physical properties in both soils.

Soil compaction and thatch accumulation compromise soil physical properties as well as turfgrass health, playability, and participant safety (Beard, 1973; Brown and McCarty, 2005). Compaction from human and vehicle traffic collapses macropores, increases soil bulk density, and increases soil resistance (Murphy and Rieke, 1990). Loss of macropores can limit the movement of water and gases into and through the soil profile and can potentially create anoxic soils (Carrow and Petrovic, 1992). These changes in soil physical properties can restrict root and plant growth (Carrow and Petrovic, 1992).

Thatch-mat layering >1 inch is detrimental to turfgrass management (McCarty et al., 2005). Thatch is a layer of living and dead plant material that forms above the soil surface. Mat is thatch intermingled with soil (Williams and McCarty, 2005). Thatch builds-up when its accumulation outpaces decomposition. Excessive thatch limits hydraulic conductivity, decreases soil aeration, and diminishes the efficacy of chemical and irrigation inputs (Beard, 1973; Carrow, 2004b). Excessive thatch creates softer surfaces and inconsistent heights of cut. Turfgrass scalping and diminished aesthetics usually ensue (Rowland et al., 2009; White and Dickens, 1984).

Soil compaction and thatch-mat accumulation negatively affect field playability. Reduced infiltration rates lead to increased water ponding, which reduces player traction and increases their likelihood of injury (Dickson et al., 2018). Compaction increases surface hardness, which can increase joint strain, the frequency of contusions, and the concussion risk (Brosnan et al., 2014; Finch et al., 2003). Conversely, excessive thatch can cause softer surfaces that hastens player fatigue (Baker et al., 2007; Minner and Hudson, 2005).

Various cultivation practices are employed to alleviate soil compaction and thatch accumulation (McCarty and Miller, 2002). Aerification- especially hollow-tine aerification-temporarily alleviates soil compaction by creating macropores (McCarty and Miller, 2002). Aerification increases water and gas exchange into the soil while decreasing soil-resistance and surface hardness (Atkinson et al., 2012; Carrow, 2004b; Guertal et al., 2003). Bunnell et al. (2001) observed ≥37% improvement in Ksat following aerifation. However, hollow-tine aerification has had little (Atkinson et al., 2012) to no effect (McCarty et al., 2007) at decreasing thatch content. Therefore, McCarty et al. (2007) suggested augmenting hollow-tine aerification with other cultural practices- vertical mowing, grooming, and/ topdressing – to reduce thatch content.

Fraise mowing is an aggressive cultural practice that has the potential to remove all plant and soil material to 2-inch depths. However, fraise mowing alters soil physical properties as it removes thatch. Baker et al. (2005) observed increased soil hardness following fraise mowing.

Independently, aerification and fraise mowing temporarily disrupt turfgrass quality and alter soil physical properties (Atkinson et al., 2012; Baker et al., 2005; Hansen and Christians, 2015). In tandem, their impact on bermudagrass recovery and soil physical properties are unknown. The objective of this research was to evaluate the effects of combining fraise mowing with hollow-tine aerification on bermudagrass recovery and soil physical properties in two soils.

Fraise Testing Methods

A study was conducted from mid-June to mid-August in 2018 and 2019 on a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) (loam) at NC State University’s Lake Wheeler Turf Field Laboratory in Raleigh, NC and a 6-inches deep sand capped soccer field (sand) at WakeMed Soccer Park in Cary, NC. A non-fraise mowed untreated control (control) and three fraise mowing depths 0.25 (shallow); 0.5 (intermediate); 1.0-inches (deepest) were applied in mid-June both years with a Koro Field TopMaker (FTM) 1200 (Campey Imants

Cheshire, UK). Hollow-tine aerification treatments (aerified/none) were applied immediately after fraise mowing with a ProCore 648 (The Toro Co. Bloomington, MN). The aerifier was fitted with 0.63 inches (outside diameter) tines that were set to 3.0 inches depth and 3.0 × 3.0 inches spacing. Soil from the cores was reincorporated into the plots and the organic debris was removed. Starting one week after treatment, plots were fertilized once a week with nitrogen at 0.25 lb 1,000 ft^{-2} for four weeks with granular ammonium sulfate. Six weeks after treatment, plots were fertilized with nitrogen at 1.0 lb 1,000 ft^{-2} with granular ammonium sulfate. Plots were clipped three times per week at 0.5 inches with clippings returned and were irrigated as needed to prevent moisture stress.

Rated Parameters

Turf quality (TQ) ratings were recorded weekly starting immediately after treatment (0 WAT) and continued through early August (8 WAT) during both years. Turf quality was evaluated on a 1 to 9 scale with 1 = poor quality, 9 = excellent, and ≥6 deemed acceptable (Morris and Shearman, 1998). Soil surface hardness, soil shear strength, and gravimetric moisture contents (θg) were measured in both soils immediately after treatment and every subsequent 14 days (noted as *every other week*). Saturated hydraulic conductivity (Ksat) was measured at 14 day intervals in the sand. Soil surface hardness was measured in gravities with a Clegg impact soil tester (Lafayette Instrument Company, Lafayette, IN) with a 5.0-pound missile. Three independent drops were taken per plot, and values were averaged before statistical analysis (ASTM 2010). Shallow soil shear strength (N·m) was measured once randomly per subplot with a turf shear tester (Baden Clegg PTY Ltd., Wembley DC, WA, Australia). One undisturbed soil core (2.0 inches diameter x 3.0 inches deep) was randomly collected per subplot and was used to measure Ksat (Klute and Dirksen, 1986), gravimetric moisture content (Klute, 1986), and thatch organic ash weights (Carrow et al., 1987).

Statistical Analysis

Fraise mowing whole plots measured 4 x 8 ft and were arranged in randomized complete block design with four replications. Aerification was stripped across whole plots, and subplots measured 4.0 x 4.0 ft. The study was analyzed as strip-plot design with repeated measures as a result of multiple rating dates. All data were subjected to analysis of variance to determine treatment effects and interactions. Identified significant main effects and interactions were sorted and analyzed using Fisher's protected LSD test with a probability level of 0.05. The PROC GLIMMIX procedure and subsequent means separations were performed with Statistical Analysis System (version 9.4; SAS Inst. Inc., Cary, NC).

Turfgrass Quality

Analysis of variance determined a significant fraise mowing depth × aerification × weeks after fraise mowing (WAT) with turfgrass quality (TQ) ($P < 0.0001$); therefore, TQ was analyzed by aerification and WAT and pooled over years and soil type. All fraise mowing depths had unacceptable TQ after treatment from the removal of all turfgrass verdure (Table 1). The shallowest (0.25 inches) and intermediate (0.5 inches) fraise mowing depths recovered to acceptable TQ by 3 WAT. The deepest fraise mowing depth (1.0 inches) was the slowest to recover but was evaluated to be acceptable TQ by 6 WAT. Shelton et al. (2016) observed longer recovery times following deeper fraise mowing depths (0.16 vs. 0.31 inches). In our study, turf 'scalping' and the presence of localized dry spots diminished the TQ of the untreated control from 5 to 6 WAT. Turf quality of the intermediate and shallowest depths exceeded the untreated control during this interval.

Aerification decreased TQ of non-fraise mowing treatments for two weeks after treatment (Table 1). However, aerification did not delay bermudagrass recovery when combined with fraise mowing at any depth. Therefore, aerification did not have an antagonistic effect on bermudagrass recovery following fraise mowing.

Thatch Content

Analysis of variance determined a significant fraise mowing depth × WAT interaction with thatch content ($P = 0.0043$); therefore, thatch content was analyzed by WAT and pooled over both soil types. Thatch content decreased with deeper fraise mowing depths, and the control consistently had the most thatch (data not shown). Although fraise mowing depths at both locations failed to remove the entire thatch layer, fraise mowing effectively reduced thatch content.

Analysis of variance determined an insignificant aerification effect with thatch content ($P = 0.3337$); therefore, aerification did not reduce the thatch content in either soil. This lack of effect was likely due to the limited surface area that aerification impacted. McCarty et al. (2007) noted that hollow-tine aerification alone was insufficient at decreasing thatch content. Similarly, White and Dickens (1984) did not observe a difference in thatch content between twice yearly or monthly aerifcation treatments.

Saturated hydraulic conductivity (Ksat)

Analysis of variance determined an insignificant fraise mowing depth × aerification interaction with saturated hydraulic conductivity (Ksat) ($P>0.05$). However, analysis of variance determined a significant fraise mowing depth × WAT interaction ($P = 0.0063$), as well as an aerification × WAT interaction with (Ksat) ($P = 0.0082$). Therefore, data were pooled over both years, and Ksat was analyzed by WAT. Immediately after treatment, the untreated control had the highest Ksat (36.5 inches hr^{-1}), and Ksat decreased 25 to 50% with deeper fraise mowing depths (Table 2). The deepest fraise mowing depth had the slowest Ksat throughout the study and was 20 to 50% slower than the control. The untreated control and shallowest depth had the highest Ksat from 2 to 6 WAT. By 4 WAT, the shallowest depth, intermediate depth, and untreated control had similar Ksat (15.0 inches hr^{-1}). Gibbs et al. (2001) and Engel and Alderfer (1967) observed lower Ksat following vertical mowing. Gibbs et al. (2001) attributed this decrease to surface smearing from vertical mowing during wet soil conditions. Fraise mowing likely had a similar, smearing effect that disrupted macropore continuity, limited water permeability, and lowered Ksat.

Analysis of variance determined a significant aerification × WAT interaction with (Ksat) ($P = 0.0082$). Therefore, data were pooled over years and fraise mowing depths and were analyzed by rating date. Aerification increased Ksat by 79 and 58% at 0 and 2 WAT, respectively (Table 3). Carrow (2004a) concluded that surface conditions dictate Ksat, and cultivation treatments that create ≥0.25 inch holes increased Ksat. However, aerification's effect waned with time, and its Ksat was similar to those untreated from 4 to 6 WAT. These results agreed with previous research that demonstrated the transient benefits of hollow-tine aerification (Canaway et al., 1986; Carrow, 2004a; McAuliffe et al., 1993).

Soil Surface Hardness

Analysis of variance determined a significant soil type × year × fraise mowing depth × WAT interaction with soil surface hardness (gravities) ($P < 0.0001$); therefore, surface hardness was analyzed by soil type, year, and WAT. In 2018, fraise mowing- especially at the deepest depth- removed the cushioning thatch layer and increased surface hardness in the loam by 30 to 50% compared to the control (Table 4). The deepest depth had the highest surface hardness throughout 2018. The untreated control, shallowest, and intermediate depths had similar surface hardness at 0, 2, 4, and 8 WAT.

During 2019, the deepest treatment had the highest surface hardness from 2 to 8 WAT (Table 4). The shallowest depth and the control had similar surface hardness (±4 gravities) during 2019. The deepest treatment was 20 to 33% harder compared to the control from 2 to 8 WAT. The presence of more turfgrass coverage and thatch in the shallowest depth and control likely decreased their hardness compared to the intermediate and deepest treatments. Over two years, Baker et al. (2005) observed similar increases (8 to 27%) in surface hardness following fraise mowing at ≤0.7 inches depths.

Throughout 2018 in the sand, differences in surface hardness between fraise mowing depths were less pronounced and ranged from 50 to 69 gravities (Table 5). Although differences were less evident, the deepest depth averaged 4 to 21% higher surface hardness compared to the control during 2018. The intermediate depth averaged 9, 6, and 9% harder compared to control at 4, 6, and 8 WAT, respectively. The shallowest depth averaged 10, 9, and 6% harder compared to the control at 2, 4, and 8 WAT, respectively.

In 2019, the range of surface hardness between fraise mowing depths in the sand differed by ≤ 8 gravities at each WAT. All depths had similar surface hardness at 0 and 2 WAT (35 and 41 gravities, respectively). The deepest depth averaged 7 to 20% harder compared to the control from 4 through 8 WAT. The intermediate depth averaged 7 to 10% harder compared to the control at 4 and 8 WAT. The shallowest depth averaged 5 to 7% harder compared to the control at 6 and 8 WAT. High soil moisture contents (θg) of the sand likely depressed differences in surface hardness. Dickson et al. (2018) observed lower surface hardness values at high soil moisture contents and cautioned against overwatering.

Analysis of variance determined a significant aerification × WAT interaction ($P <$ 0.0001); therefore, surface hardness was analyzed by WAT and averaged over both soil types and years. Hollow-tine aerification decreased surface hardness from 5 to 26% at all dates (Table 6). McCarty et al. (2005; 2007) observed 19 and 9% reduction in surface hardness following hollow -tine aerification of a creeping bentgrass [*Agrostis stoloniferous* L. var. *palustris* (Huds.)] putting green. Differences in surface hardness between aerified and non-aerified treatments were most pronounced from 0 to 2 WAT (~10 gravities). These differences dissipated with time and were ≤ 5 gravities at 6 and 8 WAT (Table 4). Guertal et al. (2003) observed waning compaction relief benefits that dissipated in one to seven weeks after deep-tine aerification. Murphy et al. (1993) observed diminishing benefits in compaction relief three weeks after aerification and recommended routine hollow-tine aerification to sustain these benefits.

Shallow Soil Shear Strength

Analysis of variance determined a significant soil type × fraise mowing depth with shallow soil shear strength (N·m) (P =0.0243); therefore, shear strength was analyzed by soil type and averaged over aerification, years, and WATs. In the sand, shear strength decreased an average 17 and 32% at the intermediate and deepest fraise mowing depths, respectively (Table 5). Reductions were attributed to the poor cohesiveness of sand and the removal of reinforcing stolons and roots, which are essential for stability in sand-based playing surfaces (Minner and Hudson, 2005; Rogers, 1988). All fraise mowing depths in the loam had similar shear strength values, with values ranging from 86 to 96 N·m.

Analysis of variance determined a significant soil type × WAT × aerification interaction with shallow soil shear strength (P =0.0217); therefore, shallow shear strength was analyzed by soil type and WAT and averaged over years and fraise mowing depths (Table 8). Aerification lowered the shallow shear strength in both soils by 2 to 15%. Aerification decreased shear strength in the sand by 8 to 14 N·m (8 to 15%) at all rating dates. Like fraise mowing, hollow-tine aerification removed reinforcing roots and stems and decreased the sand's shear strength. Despite these reductions, all values in the sand exceeded 81 N·m. Chivers and Aldous (2004) defined the acceptable range of surface shear strength for Australian football to be between 20 to 120 N·m with the preferred range between 55 to 84 N·m.

In the loam, aerification decreased the shear strength by 13 to 16 N·m (14 to 17%) at 0 and 4 WAT, respectively. However, aerification treatments had similar values (85 N·m) at 6 WAT. Sherratt et al. (2005) observed averaged reductions in soil shear strength of 18 to 20% of Kentucky bluegrass (*Poa pratensis* L.) reinforced with a carpet natural grass stabilizer following solid-tine aerification. Therefore, shear strength in both soils was not compromised in any fraise mowing and/ aerification treatment.

Hollow-tine Aerification Complimented Fraise Mowing

Previous research has demonstrated that fraise mowing and hollow-tine aerification independently influence soil physical properties and turfgrass quality (Atkinson et al., 2012; Baker et al., 2005). This current study demonstrated that fraise mowing and hollow-tine aerification have a beneficial effect when performed in tandem. Fraise mowing decreased thatch content; however, it decreased saturated hydraulic conductivity (Ksat). Hollow-tine aerification with 0.63 inches tines at a 3.0 × 3.0-inches spacing did not affect thatch content but improved Ksat. Similarly, Gibbs et al. (2001) recommended combining vertical mowing with other cultivation treatments because it decreased Ksat. McCarty et al. (2007) found that HTA alone did not decrease the organic matter content in a creeping bentgrass putting green and suggested combining it with more aggressive cultural practices. Saturated hydraulic conductivities of all treatments met or exceeded the preferred Ksat of >6 inches hr^{-1} for soccer fields (Baker and Richards, 1993). Both cultural treatments decreased turfgrass quality. All fraise mowing depths resulted in unacceptable TQ for a period of time; however, combining HTA with fraise mowing did not delay bermudagrass recovery. Fraise mowing increased soil surface hardness in both soils but decreased the shallow shear strength in the sand. Aerification decreased surface hardness and shear strength in both soils by reducing compaction and removing vegetative material. In both soils, all treatments had acceptable surface hardness and shallow soil shear strength values as defined by Chivers and Aldous (2004). This study demonstrated that fraise mowing to ≤1.0-inches depth and hollow-tine aerification with 0.63-inches tines at 3.0 × 3.0 inches spacing can be performed in tandem without compromising hybrid bermudagrass recovery and soil physical properties in both sand and loam soils.

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Table 1. Turf quality (TQ) as a function of fraise mowing depth, and hollow-tine aerification for six weeks after treatment (WAT). Data were pooled over soil types and years.

Depth	Aerified	0†	1	2	3	4	5	6
		Turf Quality (1-9)‡						
Control	Yes	5.2 b§	5.9 b	7.2 a	7.4 a	7.6 a	6.6 b	7.0 bc
	No	7.8 a	7.9 a	7.6 a	7.2 a	7.4 a	6.2 bc	6.8 cd
0.25 in	Yes	2.1 c	2.8 c	4.6 bc	6.9 ab	7.6 a	7.7 a	7.9 a
	No	2.3 c	3.0 c	4.9 b	6.7 ab	7.4 a	7.9 a	7.9 a
0.5 in	Yes	1.2 d	1.5 d	4.0 d	6.2 b	7.4 a	7.4 a	7.4 ab
	No	1.1 d	1.5 d	4.1 cd	6.3 b	7.3 a	7.5 a	7.4 ab
1.0 in	Yes	1.0 d	1.0 e	3.1 e	3.9 c	5.4 b	5.6 c	6.4 de
	No	1.0 d	1.0 e	3.1 e	3.9 c	5.1 b	5.6 c	6.1 e

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Turf quality (TQ) was rated on a 1 to 9 scale. Ratings ≥6 were acceptable.

§ Means within WAT followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05).

Table 2. Saturated hydraulic conductivity (Ksat) as a function of fraise mowing depth every other week for 8 weeks after (WAT). Data were pooled over years and hollow tine aerification.

Depth	0†	2	4	6	8
	Ksat (in hr^{-1})‡				
Control	36.5 a§	18.3 a	16.0 a	6.8 ab	8.5 b
0.25 inch	27.4 b	20.6 a	15.2 a	10.7 a	12.3 a
0.5 inch	18.4 b	12.2 b	14.3 a	10.4 ab	8.0 b
1.0 inch	18.7 b	11.2 b	8.0 b	5.5 b	5.3 b

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Saturated hydraulic conductivity (Ksat) measured in inches $hour^{-1}$.

§ Means within WAT followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05).

Table 3. Saturated hydraulic conductivity (Ksat) following hollow-tine aerification treatments after fraise mowing taken every other week for 8 weeks. Data were pooled over fraise mowing depths and years.

Depth	0	2	4	6	8
	Ksat (in hr^{-1})‡				
Non-aerified	18.2 b	12.2 b	11.4 a	7.1 a	7.0 b
Aerified	32.5 a	19.0 a	15.4 a	9.7 a	10.1 a

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Saturated hydraulic conductivity (Ksat) measured in inches hour^{-1}.

§ Means within WAT followed by the same letter are not significantly different according to Fisher’s Protected LSD (P=0.05).

Table 4. Soil surface hardness (gravities) of a sandy loam in 2018 and 2019 measured every other week for 8 weeks and pooled over hollow tine aerification treatments.

	2018					2019				
Depth	0†	2	4	6	8	0	2	4	6	8
	Soil hardness (gravities) ‡									
Control	76.0 b§	54.0 b	56.2 b	48.7 c	53.0 b	38.0 a	49.3 c	48.2 c	47.4 c	50.3 b
0.25 in	83.8 b	56.7 b	63.2 b	58.3 b	56.2 b	37.5 a	51.7 bc	49.6 c	51.1 c	52.5 b
0.5 in	87.5 b	58.0 b	63.4 b	60.0 b	58.5 b	38.7 a	56.2 ab	53.3 b	56.7 b	58.5 a
1.0 in	116.3 a	77.4 a	83.6 a	73.1 a	69.3 a	36.7 a	60.3 a	57.9 a	63.2 a	62.8 a

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Soil surface hardness measured in gravities.

§ Means within WAT followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Table 5. Soil surface hardness (gravities) of a sand in 2018 and 2019 taken every other week and pooled over hollow tine aerification treatments.

	2018					2019				
Depth	0†	2	4	6	8	0	2	4	6	8
	Soil hardness (gravities) ‡									
Control	58.2 ab§	58.8 c	52.8 c	52.7 c	50.1 c	35.8 a	41.7 a	48.7 b	43.9 b	41.3 c
0.25 in	56.0 b	64.7 ab	57.3 b	56.1 bc	53.5 b	35.4 a	42.4 a	51.2 ab	46.1 a	44.6 b
0.5 in	57.2 ab	62.4 bc	57.6 b	56.2 b	54.6 b	36.6 a	41.7 a	52.2 a	45.3 ab	45.6 b
1.0 in	60.4 a	69.1 a	62.8 a	64.1 a	59.0 a	36.0 a	40.2 a	52.3 a	47.1 a	49.5 a

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Soil surface hardness measured in gravities.

§ Means within WAT followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Table 6. Soil surface hardness (gravities) of aerification treatments taken every other week. Data were pooled over years, soils, and fraise mowing depths.

Depth	0†	2	4	6	8
	——— Surface hardness (gravities)‡ ———				
Non-aerified	61.9 a§	60.5 a	60.7 a	56.8 a	55.1 a
Aerified	49.0 b	50.0 b	53.1 b	52.0 b	52.3 b

† Weeks after mid-June fraise mowing and/ hollow-tine aerification treatment (WAT).

‡ Soil surface hardness measured in gravities.

§ Means within WAT followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Table 7. Shallow soil shear strength (N·m) of sand and loam. Data pooled over year and hollow tine core aerification treatments.

	Sand†	Loam
Depth	— Divot Resistance (N·m)‡ —	
Control	108.4 a§	96.4 a
0.25 in	104.3 a	86.5 a
0.5 in	89.0 b	86.2 a
1.0 in	73.8 c	87.7 a

†Soil type.

‡ Soil shear strength/divot resistance measured in N·m.

§ Means within the same soil followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05).

Table 8. Shallow soil shear strength (N·m) of sand and sandy loam soils following aerification. Data pooled over years and fraise mowing depths.

	Sand†				Sandy Loam			
Treatment	0	2	4	6	0	2`	4	6
	Shear Strength (N·m)‡							
Non-aerified	94.9 a§	99.6 a	99.3 a	103.1 a	93.3 a	86.4 a	96.6 a	86.0 a
Aerified	80.8 b	88.9 b	91.7 b	92.8 b	80.3 b	78.1 b	80.4 b	84.4 a

†Soil type.

‡ Soil shear strength/divot resistance measured in N·m.

§ Means within the same soil followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05).

CHAPTER 3: COMPACTION RELIEF IN NATURAL GRASS SPORTS FIELDS THROUGH FRAISE MOWING

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Abbreviations: Ksat, saturated hydraulic conductivity; NC, North Carolina; θ_g, gravimetric water content.

ABSTRACT

Fraise mowing is an aggressive cultural practice that can remove all plant and soil material to 5.0 cm depths in turfgrass settings. Fraise mower's functional depths overlap with compaction from daily foot and maintenance traffic in natural grass sports fields (<8.0 cm depth). The objective of two studies was to evaluate fraise mowing's potential for relieving shallow soil compaction. Study I was conducted on four athletic fields in Chapel Hill, NC. Simulated traffic was applied to heavily trafficked sports fields before fraise mowing at 2.0 cm depth. Soil surface hardness and soil resistance decreased by ≥15 and ≥25%, respectively, after fraise mowing sand-capped and sand-based fields. In situ saturated hydraulic conductivity (Ksat) of a sand-capped field increased by 17% after fraise mowing. Laboratory Ksat of the sand-based field increased by ≥359% after fraise mowing. These improvements in soil physical properties demonstrated fraise mowing's potential to relieve shallow soil compaction. Study II was conducted in a sandy soil in Jackson Springs, NC to evaluate fraise mowing depth. Simulated traffic was applied before fraise mowing to 2.5 or 5.0 cm depths. In situ Ksat of trafficked treatments increased by ≥115% after fraise mowing to 5.0 cm depth. Soil resistances at the 0- and 2.5-cm depths were similar after traffic simulation and fraise mowing at the 5.0-cm depth. During both studies, the improvement of soil physical properties after fraise mowing demonstrated its ability to remove surface compaction in heavily trafficked sports fields.

INTRODUCTION

Soil compaction compromises turfgrass health and playability. The degree of compaction is dependent upon soil texture, soil water content, plant density, and the intensity of an applied pressure (Agnew, 1990). Compaction from daily foot and light vehicle traffic on golf courses and sports fields is usually confined to the surface 8 cm of the soil, and the majority occurs within the surface 3 cm (Beard, 1973; O’Neil & Carrow ,1982; Sills & Carrow, 1982). Excessive compaction compromises soil physical properties, turfgrass health, surface playability, and participant safety (Adams & Gibbs, 1994; Thien, 1994; Wiecko, Carrow, &

Karnok,1993). Compaction increases soil strength, bulk density, and microporosity, which can physically impede root growth, restrict water passage through the soil, and increase soil hypoxia (Thien, 1994; Wiecko et al., 1993; Adams and Gibbs, 1994; Murphy & Rieke, 1990).

Compaction can limit root proliferation at deeper depths thus restricting their access to resources and potentially predisposing turfgrass to biotic and abiotic stresses (Atkinson et al., 2012). Compaction affects field playability by increasing surface hardness and diminishing infiltration rates (Gregory et al., 2006; Serensits & McNitt, 2004). Harder surfaces can increase the likelihood participants suffering injuries- especially concussions, strains, sprains, fractures, abrasions, and hematomas (Cockerham & Brinkman, 1989; Dickson, Strunk, & Sorochan, 2018; Guise, 1996; Hodgson, Standen, Batt, 2006). As a reference, the National Football League limits soil surface hardness to 100 gravities for players’ safety. Fields that exceed this threshold necessitate amelioration (Serensits & McNitt, 2004). With the surface 8.0 cm of the soil compacted, infiltration rates, and soil permeability decrease. The soil surface then retains excessive moisture for longer durations, traction decreases with increasing soil moisture content, and soil structure deteriorates with more traffic (Goss, 1998; Tengbeh, 1993). Compacted, wetter surfaces are more prone to turf cover loss, which can further negatively reduce participant traction (Dickson et al., 2018).

Because of the shallow nature of golf and sports field compaction, Minner and Valverde (2005) recommended concentrating amendment practices to the top 5 to 7.6 cm of the soil profile. Although, complete renovation and tillage improve soil physical properties, neither is an acceptable nor popular option because of turfgrass' perennial nature (Turgeon & Fidanza, 2017). Instead, various forms of aerification are utilized to help alleviate soil compaction. Aerifcation decreases bulk density, improves macroporosity, increases infiltration rates, enhances soil gas exchange, and improves turfgrass rooting (Beard, 1973). With less standing water, traction and playability can improve following aerification (McCarty, Gregg, & Toler, 2007). However, aerification does not affect the entire surface, and its benefits are transient. Aggressive aerification configurations (1.6 cm outside diameter tines at 2.5 × 2.5 cm spacing) impact <31% of the soil surface (O'Brien & Hartwiger, 2003). Aerification's benefits dissipate in ≤ 7 weeks after treatment (Canaway, Issac, & Bennet., 1986; Carrow, 2004a; Fry & Huang, 2004; Guertal, Derrick, & Shaw, 2003; Murphy, Rieke, & Erickson, 1993). Therefore, repeat aerifications are necessary to sustain its benefits (Atkinson et al., 2012; Murphy et al.,1993).

Fraise mowing is an aggressive cultural practice that impacts 100% of the soil surface. Through a series of rotating teeth, fraise mowers have the potential to remove all plant and soil material to 5.0 cm depths (Hansen & Christians, 2015). Baker, Owen, and Woollacott (2005) observed increased soil hardness following fraise mowing and suggested implementing deeper fraise mowing treatments ('koroing') to depths >2.0 cm at three to four-year intervals to improve soil physical properties. Notably, Baker et al. (2005) speculated that infiltration rates would improve after deeper fraise mowing. Although fraise mowing is primarily used for thatch management, its functional depths overlap with most golf and athletic field compaction. Therefore, fraise mowing may be a viable cultural practice to alleviate soil compaction. The objective of two studies was to determine if fraise mowing could alleviate shallow soil compaction in sports turf settings.

MATERIALS AND METHODS

Field Fraise Mowing Study- Study I

Study I assessed fraise mowing's potential to alleviate surface compaction on heavily trafficked 'Tifway' bermudagrass [Cynodon dactylon (L.) Pers. × Cynodon transvaalensis Burtt-Davy] athletic fields. The study was conducted in Chapel Hill, NC during the spring and summers of 2016 and 2017 on four fields. Two sand capped American football and lacrosse practice fields (Capped I and Capped II) with 15-cm of medium sand above an Appling sandy loam, one United States Golf Association (USGA) specification sand-based American football game field (Sand), and one native-soil (Appling sandy loam) soccer and lacrosse game field (Native). Capped I and Capped II hosted varsity, collegiate football and men and women's lacrosse practices. Sand hosted varsity, collegiate and high school American football games. Additional simulated traffic was administered with a modified Baldree traffic simulator (Kowalewski et al., 2013). The traffic simulator produced 1,129 cleat marks m^{-2} per pass, which is approximately equivalent to the number of cleat marks that occur in the highest trafficked areas of a National Football League field during two games (Cockerham & Brinkman, 1989; Kowalewski et al., 2013). Traffic was administered to the equivalent of 0, 20, or 40 American football games to the first two fields (Capped I and Sand). Simulated traffic before fraise mowing was intensified to 0, 40, or 60 American football games on the latter two fields (Capped II and Native) to promote soil compaction. All treatments were fraise mowed to 2.0 cm depth with a Blec Combinator and digging rotor (Blec Redexim North America, MO). Plots at all locations measured 0.6 × 1.5 m and were arranged as a randomized complete block design with four replications.

Study II

Study II was conducted in 2018 and 2019 to 'Tifway' hybrid bermudagrass grown on a Candor sand (Sandy, siliceous, thermic, Arenic Paleudult) at NC State University's Sandhills Research Station in Jackson Springs, NC to evaluate two fraise mowing depths. Simulated traffic was administered with a modified Baldree traffic simulator to give the equivalent of 0, 40, or 60 American football games. Plots were fraise mowed (Koro Topmaker with Universe rotor, Campey Imants Cheshire, UK) perpendicular to traffic treatments at 2.5 or 5.0 cm depths 24 to 48 hr. after traffic treatments. Traffic treatments were arranged in a randomized complete block design, and fraise mowing treatments were arranged in strip-plots across all three replications. The same treatments design was applied to separate research areas in 2018 and 2019.

Evaluation Parameters

Similar parameters were measured during both studies after traffic simulation and after fraise mowing. Two intact 5.0 cm diameter soil cores were collected from each plot for 0 to 7.6- and 0 to 15.2-cm depths. Cores were used to measure saturated hydraulic conductivity (Ksat) and gravimetric soil water content (θ_g) (Richards, 1965; Van Wijk, Verhaegh, & Beuving, 1977). Laboratory Ksat was measured with a Ksat table as described by Topp and Zebchuk (1979). The technique used a double layer of 60 mesh cheese cloth affixed to the bottom of each 7.6 and 15.2 cm core with two elastic bands. A 7.6-cm tall cap (5.0 cm diameter tube with nipple) was secured to the top of each core with a 3.0 cm rubber gasket. Prepared cores were placed in a partially filled five-gallon bucket of tap water and were saturated from the bottom for 24 hr.

Saturated cores were placed on a Ksat table that supplied a constant head with a Mariotte bottle supplied reservoir. Vertically drained water was collected at one-minute intervals and weighed. Measurements ceased when three consecutive, consistent outputs were collected. Infiltration rate was measured using a constant head double ring infiltrometer (Gregory, Dukes, Miller, & Jones, 2005). The diameters of the inner and outer rings were 25 and 50 cm, respectively. Rings were 22.9 cm tall and were inserted into the ground to 11.4 cm depth.

Soil hardness was measured with a Clegg impact soil tester (Lafayette Instrument Company, Lafayette, IN) equipped with a 2.25-kg missile (ASTM, 2010). Three independent drops from a height of 47.5 cm were taken per plot, and gravities (g) were averaged before statistical analysis. Soil resistance was measured with a Fieldscout SC 900 Soil Compaction Meter (Spectrum Technologies, Inc., Plainfield, Illinois). Soil resistance was measured from three random locations within each plot at 2.5 cm increments from the 0 cm (surface) to 7.5 cm depths. Soil resistance (kPa) values were averaged at each depth before statistical analysis.

Statistical Analysis

Study I was analyzed as a randomized complete block design with repeated measures because of sampling date. Each location in study I had four replications, and traffic treatments were randomly arranged within replications. Study II was analyzed as strip-plot design with three replications and repeated measures. Penetrometer data were analyzed with two repeated measures: sampling depth and sampling date. All data were subjected to analysis of variance (ANOVA) to determine treatment effects and interactions, which were sorted and analyzed using Fisher’s protected LSD test with a probability level of 0.05. The PROC GLIMIXX procedure and subsequent means separation were performed with Statistical Analysis System (version 9.4; SAS Inst. Inc., Cary, NC).

RESULTS AND DISCUSSION

Study I

Field was significant in study I; therefore, results were presented by field. Analysis of variance determined a significant field × timing interaction with in situ Ksat (*P* = 0.0406) (Table 1). Saturated hydraulic conductivity in Capped I increased by 17% following fraise mowing. This increase in Ksat was not drastic; however, it demonstrated compaction relief in a sand capped field. Results for in situ Ksat were not significant at the other three fields. Differences in rootzones were responsible for differences in Ksat between fields. After fraise mowing, the Ksat of the USGA specification sand rootzone was 11 to 329% faster compared to the sand capped fields and 4,186% faster compared to the native soil field.

Table 1. Infiltration rates of four athletic fields after traffic simulation (Before) and after fraise mowing (After). Measurements were recorded with double ring infiltrometers with constant hydraulic heads. Infiltration rates were not different among traffic treatments ($P<0.05$); therefore, results were averaged over traffic levels.

	Infiltration rates (*in situ*)	
Field[a]	Before	After
	cm hr^{-1}	
Sand	7.4 a[b]	6.0 a
Capped I	4.6 b	5.4 a
Capped II	1.7 a	1.4 a
Native	0.2 a	0.1 a

[a] Fraise mowing's effect was evaluated on four athletic fields: a USGA specification sand rootzone (Sand); two sand capped fields (Capped I and II); and a native soil field (Native).

[b] Means in the same field row followed by the same letter are not significantly different at an alpha = 0.05.

Analysis of variance determined a significant field × timing × traffic interaction with laboratory Ksat using soil cores taken to 15.2 cm depth ($P = 0.0041$). In Sand, Ksat increased from 359% to 2,278% after fraise mowing. No differences in Ksat between traffic levels were observed before fraise mowing, but Ksat mean of all traffic levels was ≥359% higher following fraise mowing. No differences in laboratory Ksat were observed in the other fields during either date. Sand's USGA sand-based rootzone and lower field usage probably contributed to its observed increased Ksat differences. The lack of in situ and laboratory Ksat responses to fraise mowing in Capped II was not expected. However, Capped II's Ksat rates exceeded the preferred rate of >15 cm hr^{-1} for soccer fields (Baker & Richards, 1993) during both evaluation timings. This suggesats that fraise mowing did not decrease Ksat rates of heavily compacted fields. The lack of response at the native soil field was understandable because of its higher silt and clay content, disturbed soil structure, and intrinsically lower Ksat rate (Brown, 2018).

Analysis of variance determined a significant field × timing × sampling depth interaction with soil resistance (P= 0.011). For Capped I, soil resistance decreased by ≥30% at all depths after fraise mowing. At Sand, the 0 cm (surface) through 5.0-cm depths had 25 to 44% lower soil resistance after fraise mowing (Table 2). Lower soil resistance after fraise mowing indicates compaction removal (Aust et al., 1998). During both timings for Capped II, soil resistances increased with deeper sampling depths. However, resistance values at each depth were similar both before and after fraise mowing. For Native, soil resistances of the surface and 2.5-cm depths were similar on both dates. Native's soil resistances at the 5.0- and 7.5-cm depths increased by 15 and 25%, respectively, following fraise mowing. Compaction occurs to deeper depths in soils with higher soil moisture contents, as well as in soils with higher initial porosities. Native's heavier soil texture and high initial moisture content (41%) during traffic simulation likely contributed to deeper compaction (Jamison, Weaver, & Reed, 1950; Lull, 1959; Parker & Jenny, 1945).

Table 2. Soil resistance of four athletic fields after traffic simulation (Before) and after fraise mowing (After). Measurements were evaluated with a cone penetrometer at four sampling depths. Soil resistance values were not different among traffic treatments ($P<0.05$); therefore, results were averaged over traffic levels.

Depth[a]	Native[b]		Capped II		Sand		Capped I	
	Before	After	Before	After	Before	After	Before	After
	Soil resistance (kPa)							
0 cm	504.0 f[c]	430.2 f	877.7 c	444.7 E	826.7 c	536.4 d	529.5 d	623.3 d
2.5 cm	716.4 e	667.5 e	1145.2 b	533.7 de	1527.2 ab	847.4 c	1065.2 c	1287.9 c
5.0 cm	847.4 d	974.8 c	1128.7 b	695.0 D	1312.8 b	972.8 c	2044.3 b	1986.4 b
7.5 cm	1148.0 b	1439.6 a	1443.8 a	1001.8 bc	1581.0 a	1393.4 ab	2428.3 a	2418.0 a

[a] Cone penetrometer sampling depths.

[b] Fraise mowing's effect on relieving soil compaction was evaluated in four athletic fields: USGA specification sand rootzone (Sand); two sand-capped fields (Capped I and II); and a native soil field (Native).

[c] Means in the same athletic field followed by the same letter are not significantly different at an alpha = 0.05.

Analysis of variance determined a significant field × timing interaction with soil hardness ($P < 0.0001$). The interaction with traffic was not different ($P<0.05$), and means were averaged over traffic level. Soil hardness decreased following fraise mowing at Sand and Capped I by 15% and 36%, respectively, after fraise mowing. Surface hardness in Sand was 10 gravities lower after fraise mowing. However, soil hardness in Capped I decreased by 58% after fraise mowing (Table 3). Rogers (1988) noted that soil moisture has an inverse relationship with soil hardness. Surface hardness decreased at Sand despite the field having lower soil moisture (θg) after fraise mowing. Capped I served as a dual football and lacrosse practice field, and its more intensive use likely led to its higher initial hardness values. Rogers (1988) observed a direct relationship with surface hardness and soil bulk densities. Thus, fraise mowing decreased soil compaction for Capped I and Sand. In Native and Capped II, soil hardness increased by 14% and 13% after fraise mowing. Increased soil hardness for Native and Capped II was attributed to fraise mowing removing the cushioning thatch layer, and decreasing θg by 41 and 63%, respectively (Liang, Su, Wang, & Qiao, 2017; Rogers, 1988).

Table 3. Soil surface hardness in gravities of four fields after simulated traffic and after fraise mowing at 2.0 cm depth. Soil surface hardness values were not different among traffic treatments (*P*<0.05); therefore, soil surface hardness was averaged over traffic levels.

Field[a]	Soil surface hardness	
	Before[b]	After
	gravities	
Native	44.9 b[c]	51.3 a
Sand	65.0 a	55.5 b
Capped I	82.5 a	52.4 b
Capped II	68.1 b	77.5 a

[a] Four fields were sampled

[b] Sampling timings: before and after fraise mowing.

[c] Means in the same athletic field row followed by the same letter are not significantly different at an alpha = 0.05.

Fraise mowing is primarily used for shallow organic matter management (Hansen and Christians, 2015). Results from Study I demonstrated that fraise mowing at 2.0 cm depth provided relief of shallow compaction. Compaction relief was most evident in Sand, a sand-based game field. Soil surface hardness and soil resistance decreased, and laboratory Ksat increased after fraise mowing Sand. These positive results along with the increase of infiltration rate (<2.5 cm hr^{-1}) at Capped I were favorable for compaction relief following fraise mowing at 2.0 cm depth.

Study II

Analysis of variance determined a significant fraise mowing depth × traffic level × timing interaction with infiltration rate ($P = 0.024$). Therefore, results were presented by timing. The non-trafficked control before fraise mowing had the highest infiltration rate (8 cm hr^{-1}; Table 4). No other treatment's infiltration rate exceeded the non-trafficked control before fraise mowing. Both fraise mowing depths removed the entire thatch layer, but neither depth improved the infiltration rate of the non-trafficked control. Fraise mowing at 2.5-cm depth did not affect the infiltration rate of any traffic level (0, 40, or 60 games) and likely did not pierce the compacted layer. However, fraise mowing at 5.0-cm depth increased the infiltration rates of 40 and 60 simulated games by 115% and 134%, respectively. This increase in infiltration rates was likely from compaction removal and reinforces observations by O'Neil and Carrow (1982) and Sills and Carrow (1982) that the majority of soil compaction from routine turf traffic is shallow (≤3 cm depth).

Table 4. Infiltration rates using double ring infiltrometers. Results are presented by fraise mowing depth, traffic level, and evaluation timing. Infiltration rates were not different ($P<0.05$) due to year; therefore, results were averaged over both years.

	Fraise mowing timing			
	2.5-cm fraise mowing depth[b]		5.0-cm fraise mowing depth	
Games[a]	Before[c]	After	Before	After
	Infiltration rates cm hr^{-1}			
Zero	8.0 a[d]	6.8 a	8.0 a	7.0 a
Forty	4.7 a	3.9 a	3.9 b	8.4 a
Sixty	4.2 a	3.9 a	2.9 b	6.8 a

[a] Number of simulated American football games applied with a modified Baldree traffic simulator.
[b] Fraise mowing depth (machine setting).
[c] Timing of measurements. 'Before' measurements were taken before fraise mowing. 'After' measurements were taken after fraise mowing.
[d] Means within fraise mowing depth with the same letter are not significantly different at alpha=0.05.

Analysis of variance determined a significant traffic level × timing interaction (P = 0.037) with laboratory Ksat of intact soil cores collected to 15 cm depth. Results were averaged over both years and both fraise mowing depths. The non-trafficked control before fraise mowing had the highest Ksat of all treatments (22.0 cm hr^{-1}) and dates. Saturated hydraulic conductivity of the 0 and 40 simulated games was unaffected by fraise mowing. However, Ksat of the 60 simulated games improved by 12% after fraise mowing (Table 5). This improvement in Ksat demonstrated fraise mowing's potential to remove shallow soil compaction and reinforced in situ Ksat results.

Table 5. Saturated hydraulic conductivity (Ksat) of 5.0-cm diameter × 15.0-cm deep soil cores collected before and after fraise mowing. Saturated hydraulic conductivity values were not different among fraise mowing depths and years ($P<0.05$); therefore, Ksat results were averaged over fraise mowing depths and years.

	Fraise mowing timing	
Games[a]	Before[b]	After
	Saturated hydraulic conductivity (cm hr^{-1})	
Control	22.0 a[c]	16.1 a
Forty	15.4 a	17.9 a
Sixty	13.7 b	15.4 a

[a] Number of simulated American football games with a modified Baldree traffic simulator.

[b] Timing of measurements. ‘Before’ measurements were taken before fraise mowing. ‘After’ measurements were taken after fraise mowing.

[c] Means within same rows with the same letter are not different at alpha=0.05.

Analysis of variance determined a significant fraise mowing depth × penetrometer sampling depth × timing interaction with soil resistance (P = 0.047); therefore, results were averaged over both years and separated by fraise mowing depth. From the surface (0 cm) to 2.5 cm sampling depths, soil resistance decreased after fraise mowing at the shallower 2.5-cm depth. This decrease in resistance was attributed to the removal of surface compaction. However, soil resistance increased from 5.0- to 7.5- cm sampling depths after fraise mowing. Soil organic matter content decreases with soil depth in putting greens (Glasgow, Gibbs, McAuliffe, & Liu, 2005). Less organic matter at the deeper sampling depths likely increased resistance values. After fraise mowing at the 5.0-cm depth, soil resistances from the surface to 2.5-cm depths were similar at both dates. However, soil resistances at 5.0- through 7.5-cm sampling depths increased after fraise mowing (Table 6). Ekwu, Birch, and Chadee (2014) noted that soil organic matter decreases soil resistance. The removal of more organic matter with the 5.0 cm fraise mowing depth reset sampling depths and caused deeper sections of the soil profile with less organic matter to be sampled (Glasgow et al., 2005). Less organic matter at deeper sampling depths increased soil resistance after fraise mowing.

Table 6. Soil resistance of a sandy soil after traffic simulation (Before) and after fraise mowing (After) to 2.5 or 5.0 cm depths. Soil resistance was measured at 2.5-cm intervals from 0 to 7.5 cm depths with a cone penetrometer. Soil resistance values were not different among traffic treatments and years (*P*<0.05); therefore, results were averaged over traffic levels and year.

Depth[a]	Fraise mowing timing			
	2.5-cm fraise mowing depth		5.0-cm fraise mowing depth	
	Before	After	Before	After
	Soil resistance (kPa)			
0.0-cm	715.0 d[c]	478.5 e	715.0 d	721.2 d
2.5-cm	931.5 c	770.8 d	931.5 c	1048.0 c
5.0-cm	1032.1 c	1287.9 b	1032.1 c	1434.1 b
7.5-cm	1430.0 b	1721.6 a	1430.0 b	1705.7 a

Penetrometer sampling depths.
[b]Fraise mowing depths.
[c]Means within fraise mowing depth followed with the same letter are not significantly different at alpha=0.05.

Analysis of variance determined a significant traffic level × timing interaction with soil hardness (*P* < 0.0001). Both years and fraise mowing depths were not significant; therefore, soil hardness was analyzed by traffic level and averaged over both years and fraise mowing depths. Surface hardness increased from 10 to 50% following fraise mowing (data not shown). Soil hardness is a function of thatch, shallow organic matter content, soil moisture content, and bulk density (Linde, Stowell, Gelernter, & McAuliffe, 2011), and Rogers (1988) observed an inverse relationship with thatch content and surface hardness. Both fraise mowing depths removed the entire thatch layer. Without the cushioning thatch layer, soil surface hardness of all trafficked treatments increased following fraise mowing.

Conclusion

Previous research has demonstrated fraise mowing’s potential to remove thatch and impact soil physical properties at ≤1.8-cm depths (Baker et al., 2005). These current studies demonstrated that fraise mowing ≥ 2.0 cm provided compaction relief in sandy soils. During Study I, soil hardness and resistance decreased in a USGA specification sand-based American football game field. Saturated hydraulic conductivity increased in sand-based and sand-capped fields after fraise mowing to 2.0-cm depth. These improvements in soil physical properties demonstrated that fraise mowing provided some (although inconsistent) compaction relief in highly trafficked fields. Study II utilized two deeper fraise mowing depths (2.5 and 5.0- cm) with the objective of producing more consistent compaction relief. However, only fraise mowing at 5.0-cm depth improved Ksat of trafficked treatments. Lull (1959) noted that infiltration rates are the soil physical property influenced the most by compaction. Thus, fraise mowing at 5.0-cm depth was effective at decreasing soil compaction. Conversely, soil hardness and soil resistance increased after fraise mowing at 2.5 and 5.0-cm depths. Increased soil hardness and resistance were likely not the result of shallow compaction. Instead, increased soil resistance and shallow soil hardness were the result of fraise mowing removing the entire thatch layer, which decreases both when present. Fraise mowing is an aggressive cultural practice- especially at 5.0-cm depth. Hybrid bermudagrass would require >4 weeks to recover at this depth (McCauley, Pinnix, & Miller, 2019). Because of the limited bermudagrass growing season and extended down-time following fraise mowing, >1 application a year at 5.0 cm depths would be difficult. Although compaction relief was observed immediately following fraise mowing, its duration following fraise mowing merits further investigation. In sandy soils, fraise mowing at depths ≥ 2.0 cm provided compaction relief.

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CHAPTER 4: APPLICATIONS OF NITROGEN OR SAND TO IMPROVE BERMUDAGRASS RECOVERY FOLLOWING FRAISE MOWING

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Abstract

Fraise mowing is a disruptive cultural practice, and any inputs to hasten bermudagrass recovery following it should be explored. The objective of two concurrent studies was to evaluate the effects of nitrogen fertility (study I) or sand topdressing (study II) on hastening bermudagrass recovery following fraise mowing. Both studies were conducted on established ‘Tifway’ hybrid-bermudagrass (*C. dactylon* (L)Pers. x *C. transvaalensis* Burtt-Davy) in Raleigh, NC that was fraise mowed in mid-June to 0.25 inches depth. Starting 7 days after fraise mowing (DAF), study I plots received granular nitrogen at rate of 0.25, 0.5, 0.75,or 1.0 lb. 1,000 ft^{-2} per week for four consecutive weeks from ammonium sulfate or one application of controlled release nitrogen at 2.0 lb 1,000 ft^{-2} from polymer-coated urea. Water soluble nitrogen treatments had acceptable visual turf quality (TQ) (≥6) and cover in 21 DAF. All fertilized treatments had acceptable TQ by 28 DAF. Withholding nitrogen (control) delayed bermudagrass recovery beyond 28 DAF. In study II, all plots received one independent sand topdressing application at 0, 7, or 14 DAF to volume of 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy). Control, shallow, and medium treatments had acceptable TQ and cover in 28 DAF, regardless of sand application date. All topdressing depths applied immediately after fraise mowing had acceptable TQ by 28 DAF. Sand topdressing did not accelerate bermudagrass recovery following fraise mowing. Therefore, nitrogen fertilization at ≥0.75 lbs 1,000 ft^{-2} was the most effective practice at hastening bermudagrass recovery following fraise mowing.

Fraise mowing is an aggressive cultural practice that impacts 100% of the soil surface. Fraise mowing has the potential to remove all plant and soil material to 2-inch depths in a single pass. This capacity makes fraise mowing an attractive practice for bermudagrass thatch management (Hansen and Christians, 2015). However, bermudagrass recovery can exceed 6 weeks depending on depth and timing of fraise mowing (McCauley et al., 2019; Stewart et al., 2016).

Research on turfgrass recovery after fraise mowing is limited. Kentucky bluegrass (*Poa pratensis L.*) recovery was hastened with the use of woven polyethylene covers and high seeding rates (10 pounds 1,000ft^{-2}; Hansen and Christians, 2015). Stewart et al. (2016) observed faster hybrid bermudagrass recovery with more growing degree days following fraise mowing at 0.4 inches.

Vertical mowing is a disruptive cultural practice akin to fraise mowing. Although vertical mowing is less aggressive than fraise mowing (impacting <30% of the surface), both practices have similar prolonged recovery times (approximately 30 days; Beard, 1973; McCauley et al., 2019). Recovery recommendations after vertical mowing include increased water and nitrogen inputs during the recovery period (Beard, 1973). McCarty and Miller (2002) recommended an application of water-soluble nitrogen at 1.0 lb 1,000 ft^{-2} five to seven days after vertical mowing to expedite turfgrass recovery. Topdressing with sand is recommended to improve bermudagrass recovery by increasing soil to vegetation contact and reducing tissue desiccation (McCarty and Miller, 2002)

Nitrogen fertilization improves bermudagrass shoot growth and is commonly used to improve bermudagrass' quality, playability, establishment, and recovery (Beard 1973; McCarty, 2001). Nitrogen fertilization at 1.0 lb 1,000 ft^{-2} at 7-day intervals is recommended to improve the establishment of ultradwarf bermudagrass putting greens from sprigs (Rodriguez et al., 2001). Rowland et al. (2010) observed similar establishment of 'TifDwarf' dwarf and 'TifEagle' ultradwarf bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt Davy] putting greens with nitrogen rates of 0.5, 0.75, and 1.0 lb 1,000 ft^{-2} per week. Therefore, nitrogen fertilization may accelerate bermudagrass recovery following fraise mowing.

Sand/soil topdressing is commonly applied to improve turfgrass quality, cover, playability, recovery, and establishment (Kowalewski et al., 2010; Miller, 2008). Improved spring green-up, recovery, and clipping yields have been observed following sand topdressing of creeping bentgrass (Bigelow et al., 2005; Christians et al., 1985). Beard (1973) recommended higher topdressing rates and/ frequencies during establishment to level irregularities and to cover stolons. Richardson and Boyd (2001) observed better zoysiagrass (*Zoysia japonica*) sprig establishment from soil topdressing compared to nitrogen fertility. Sand topdressing may have a similar effect on bermudagrass recovery following fraise mowing.

Cultural practices used to improve bermudagrass recovery after vertical mowing may be applicable following fraise mowing. The objectives of two concurrent studies were to evaluate the effects of nitrogen fertilization (Study I) or sand topdressing depth and timing (Study II) on bermudagrass regrowth after fraise mowing.

Fraise mowing and nitrogen fertility or sand topdressing field studies

Studies I and II were conducted concurrently in 2017 and 2018 on 'Tifway' hybrid bermudagrass (*Cynodon dactylon* (L)Pers. x *C. transvaalensis* Burtt-Davy) at NC State University's Lake Wheeler Turfgrass Laboratory in Raleigh, NC. Plots were fraise mowed (Koro Topmaker with Universe rotor, Campey Imants Cheshire, UK) in mid-June to 0.25 inches depth. Starting seven days after fraise mowing (DAF) plots in study I received nitrogen fertilization

(0.25, 0.5, 0.75, or 1.0 pounds 1,000 ft^{-2} per week for four weeks) from water soluble nitrogen (WSN) with ammonium sulfate, one application of controlled release nitrogen (2.0 pounds 1,000 ft^{-2}) with polymer-coated urea (Polyon Harrell's, Lakeland, Florida), or no nitrogen fertilization (control). Pre-measured amounts of fertilizer were broadcast by shaker jar to each 5 × 5 ft. plot and irrigated with 0.25 inches of water. Plots were arranged in a randomized complete block design with three replications.

Topdressing plots in study II measured 5.0 × 5.0 ft and were arranged in a split-plot design with three replications. Each topdressing plot received one independent sand topdressing treatment after fraise mowing. Whole plot treatments were sand topdressing volume: 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy). Sub-plots were timing of sand application after fraise mowing: 0, 7, or 14 DAF. Pre-measured volumes of sand were broadcast by hand to each plot, raked to level, and irrigated with 0.25 inch of water. Starting 7 DAF, plots received soluble nitrogen (21% N) at 0.25-pound 1,000 ft^{-2} per week for four consecutive weeks. Plots in both studies were mowed three times a week at 0.5 inch with clippings returned and were irrigated to prevent moisture stress.

Bermudagrass Recovery

In both studies, turf quality and cover were recorded once a week starting seven DAF. Turf quality was visually rated on a 1 to 9 scale with 1 = poor quality, 9 = excellent, ≥6 acceptable. Turf cover was recorded on a 0 to 100% scale where 0 = bare ground and 100 = complete bermudagrass coverage (Morris and Shearman, 1988).

In both years of study I at 28 DAF, two intact 2-inch diameter soil cores were randomly collected from each plot to a depth of 3 inches to measure thatch content through loss on ignition (Carrow et al., 1987). Thatch was separated from the verdure and soil, oven dried at 221°F for

48 h, and weighed. Thatch samples were then combusted in a muffle furnace at 1,292°F for 5 h, weighed, and their organic ash weights were determined.

Statistical Analysis

Study I was analyzed as randomized complete block design with three replications and repeated measures. Study II was analyzed as a split-plot design with three replications and repeated measures. Turf cover and quality data in both studies were subjected to analysis of variation (ANOVA) to determine treatment effects and interactions. Identified significant main effects and interactions were sorted and analyzed using Fisher's protected LSD test with a probability level of 0.05. Analysis of variance and mean separation were performed with the PROC GLIMMIX procedure in Statistical Analysis System (version 9.4; SAS Inst. Inc., Cary, NC).

Nitrogen Fertility Effect after Fraise Mowing

Analysis of variance determined a fertility × rating date interaction with turf quality (TQ) data ($P < 0.003$). An interaction with year was not significant; therefore, TQ was presented as a mean of both years. Fraise mowing removed all turf verdure, and all treatments had unacceptable TQ (<6) through 14 DAF (Table 1). The untreated control had unacceptable TQ through 28 DAF. Water soluble nitrogen at 0.75 and 1.0 lb 1,000 ft^{-2} had acceptable turf quality 21 DAF. Beard (1973) recommended higher nitrogen rates to encourage shoot growth during establishment and recovery. All fertilized treatments had acceptable TQ at 28 DAF. Nitrogen fertilization at 0.25 lb 1,000 ft^{-2} per week required 7 d longer than higher rates to regain acceptable turf quality. However, this rate would be less prone to leaching and would be a better environmental option if facilities have time (Rowland et al., 2010). McCarty (2001) noted that water soluble nitrogen increases shoot growth in approximately two days after application and peaks in 7 to 10 days after application. This timing coincides with our observed bermudagrass recovery timing when using water soluble nitrogen ≥0.75 lb 1,000 ft^{-2}.

Analysis of variance determined a significant fertility × rating date interaction with turf cover data ($P = 0.0424$). Year was not significant; therefore, turf cover was averaged over both years. All plots had similar, poor turfgrass cover 1 WAF (≤28%). Water soluble nitrogen at 1.0 lb 1,000 ft^{-2} per week had 14% and 7% more turf cover compared to the untreated control and the lowest water-soluble nitrogen rate (0.25 lb. 1,000 ft^{-2}) at 21 DAF, respectively. Higher nitrogen rates promote more shoot growth (McCarty, 2001), and turf cover improved with higher nitrogen rates. All nitrogen rates ≥0.5 lb. 1,000 ft^{-2} had similar cover 21 DAF (≥88%). All fertilized treatments had similar cover (≥96%) at 28 DAF. The untreated control had ≥8% less cover than all fertilized treatments at 28 DAF.

Analysis of variance determined no significant nitrogen rate effect with bermudagrass thatch content when measured through loss on ignition ($P = 0.6075$). Therefore, thatch content was not affected by nitrogen rate and formulation during this relatively short study. Differences in thatch content may have arisen with a longer study duration and continued nitrogen applications. This lack of thatch differences justifies higher nitrogen rates to promote faster bermudagrass recovery.

Topdressing Depth and Timing Effect after Fraise Mowing

Analysis of variance determined a significant topdressing depth × application date × rating date interaction with turf quality (TQ) data ($P < 0.0001$). Year was not significant; therefore, TQ was averaged over both years and presented by application date. Fraise mowing removed all turf verdure, and all treatments had unacceptable TQ until 21 DAF. When applied immediately after fraise mowing, shallow, medium, and heavy (0.13, 0.25, and 0.5 inches, respectively) topdressing depths had similar TQ as the control throughout the study (Table 3).

When applied 7 DAF, the shallow topdressing treatment had similar TQ as the control throughout the study. The control had acceptable TQ at 21 DAF. Applying topdressing at ≥0.25 inches seven days after fraise mowing delayed bermudagrass recovery. The medium and heavy rates likely smothered any emerged bermudagrass foliage and delayed bermudagrass recovery. The medium and heavy treatments had acceptable turf quality at 28 and 35 DAF, respectively (Table 3).

All treatments that received topdressing sand 14 DAF had similar TQ until application. Turf quality decreased with deeper topdressing depths (data not shown). Medium and heavy topdressing depths slowed bermudagrass recovery, and this negative trend continued through 28 DAF. Shallow and medium treatments had acceptable TQ by 28 DAF and had similar TQ to the control at 35 DAF. The heavy treatment did not have acceptable TQ by the end of the study (Table 3). Geisel et al. (2001) observed a similar smothering of bermudagrass following compost applications at 0.5 inches depth, which caused unacceptable TQ for >4 weeks. Beard (1973) cautioned against excessively thick topdressing layers because they may exclude sunlight and injure or kill turfgrass shoots with extended covering.

Topdressing Affected Turfgrass Cover Following Fraise Mowing

Analysis of variance determined a significant topdressing depth × application date × rating date interaction with turf cover data ($P = 0.0029$). The interaction with year was not significant; therefore, turf cover was averaged over both years. Fraise mowing removed all turf cover, and all treatments had ≤90% cover for a minimum of 21 DAF. Turf cover of shallow and medium treatments applied 0 DAF were similar to the control throughout the study. Heavy treatments applied immediately after fraise mowing had 8% less cover than the control at 21 DAF. This reduction was attributed to sand lingering in the turf canopy. Mittlesteadt et al. (2008) observed similar negative visual effects with white topdressing sand and attributed this reduction to its sharp visual contrast with turfgrass verdure. All treatments applied 0 DAF and the control had similar cover (>97%) at 28 and 35 DAF.

When treatments were applied 7 DAF, turf cover decreased with deeper topdressing depths. The untreated control and shallow treatment had similar cover (<3.3% difference) from 21 through 35 DAF. Medium treatments had 10% less turf cover than the control at 21 DAF but had similar cover (>99%) as the control from 28 to 35 DAF. The heavy treatment had ≥90% turf cover by 28 DAF. However, it had 8 and 23% less cover than the control at 21 and 28 DAF, respectively.

All treatments applied 14 DAF had similar turf cover until receiving topdressing. Turf cover diminished with deeper topdressing depths after application (data not shown). Turf cover of shallow and medium treatments was 7 and 14% less than the control at 21 DAF, respectively, but was similar from 28 to 35 DAF (≥94%). The heavy treatment had <83% cover for the duration of the study. Heavy topdressing applications likely buried emerging bermudagrass foliage thus reducing light interception and delaying bermudagrass recovery (Turgeon, 2008). All topdressing treatments at all application dates had similar or less turf cover than the controls throughout the study.

Nitrogen Fertilization Improved Bermudagrass Regrowth Following Fraise Mowing

Nitrogen fertilization is necessary to improve bermudagrass quality after vertical mowing (Hanna, 2005). Topdressing with soil is recommended after vertical mowing and during bermudagrass establishment to decrease desiccation (McCarty and Miller, 2002). These cultural practices have not been studied on fraise mowing's recovery. In our studies, nitrogen fertilization ≥0.75 1,000ft^{-2} per week had the fastest bermudagrass recovery following fraise mowing at 0.25 inches depth in Raleigh, NC. All treatments that received nitrogen had faster bermudagrass recovery and regained acceptable turfgrass quality sooner than the non-fertilized control. The shallow topdressing depth (0.125 inches) at all application dates had similar TQ as the untreated control throughout the study. Surprisingly, topdressing at any depth immediately after fraise mowing did not delay bermudagrass recovery. However, delaying medium (0.25-inches) and heavy (0.5-inches) topdressing applications by 7 to 14 days slowed bermudagrass regrowth. These applications likely excluded sunlight and smothered emerged bermudagrass verdure (McCarty and Miller, 2002; Turgeon, 2008). Regardless of the sand depth or application date, turf cover and quality of all topdressing treatments did not surpass the control during the study. Although sand topdressing may further level surfaces after fraise mowing, it did not accelerate bermudagrass recovery. This study demonstrated that in Raleigh, NC, hybrid bermudagrass had the fastest recovery following fraise mowing at 0.25 inches depth when fertilized with water soluble nitrogen at ≥0.75 lbs 1,000ft^{-2} per week.

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Table 1. Turfgrass quality following fraise mowing and granular nitrogen applications. Starting one week after fraise mowing, plots received water soluble nitrogen once a week for four consecutive weeks at 0.25, 0.5, 0.75, or 1.0 lbs. 1,000 ft^{-2}; controlled release nitrogen at 2.0 lbs. 1,000 ft^{-2}; or no nitrogen (control). Turf quality was evaluated at seven-day intervals through 28 days after fraise mowing. Means were averaged over two years.

Nitrogen†	7‡	14	21	28
	——— Visual Turf Quality§ ———			
Control	1.9 a¶	3.3 c	4.3 c	4.9 b
0.25	2.1 a	3.6 bc	5.2 bc	6.4 a
0.50	1.9 a	3.9 ab	5.6 ab	6.8 a
0.75	2.1 a	4.3 ab	6.1 ab	6.6 a
1.00	1.9 a	4.3 a	6.4 a	6.8 a
2.00	1.9 a	3.8 ab	5.6 ab	6.8 a

† Granular nitrogen treatments: 0.25-1.0 lbs. of water-soluble nitrogen applied on a weekly basis; 2.0 lbs. of controlled release nitrogen applied once seven days after fraise mowing; and a non-fertilized control.

‡ Days after fraise mowing (DAF) when turf quality was recorded.

§Turf quality was visually rated from 1-9 where ≥6 was acceptable.

¶ Means in DAF followed by the same letter are not different according to Fisher's Protected LSD (*P*=0.05).

Table 2. Turfgrass cover following fraise mowing and granular nitrogen applications. Starting one week after fraise mowing, plots received water soluble nitrogen once a week for four consecutive weeks at 0.25, 0.5, 0.75, or 1.0 lbs. 1,000 ft^{-2}; controlled release nitrogen at 2.0 lbs. 1,000 ft^{-2}; or no nitrogen (control). Turf cover was evaluated at seven-day intervals through 28 days after fraise mowing. Means were averaged over two years.

Nitrogen†	7‡	14	21	28
	Turf Cover (%)§			
Control	27.5 a¶	71.3 b	80.0 c	88.8 b
0.25	26.9 a	74.1 ab	86.9 bc	95.6 a
0.50	28.1 a	74.6 ab	91.3 ab	96.6 a
0.75	26.3 a	74.6 ab	93.1 ab	95.6 a
1.00	26.6 a	82.5 a	94.3 a	96.4 a
2.00	27.8 a	77.5 ab	88.4 ab	96.4 a

† Granular nitrogen treatments: 0.25-1.0 lbs. of water-soluble nitrogen applied on a weekly basis; 2.0 lbs. of controlled release nitrogen applied once seven days after fraise mowing; and a non-fertilized control.

‡ Days after fraise mowing (DAF) when turf quality was recorded.

§ Turf cover was recorded on a 0 to 100% scale where 0 = bare ground and 100 = complete coverage.

¶ Means in DAF followed by the same letter are not different according to Fisher’s Protected LSD (*P*=0.05).

Table 3. Turfgrass quality following fraise mowing and one independent sand topdressing application. Volumes of sand were broadcast on 0, 7, or 14 days after fraise mowing at 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy) and visual turf quality was evaluated at 7-day intervals through 35 days after fraise mowing. Results are averaged over two years and are presented at 21, 28, and 35 days after fraise mowing.

Depth†	0 DAF‡			7 DAF			14 DAF		
	21§	28	35	21	28	35	21	28	35
	Visual Turf Quality¶								
Control	6.0 a	7.7 a	7.8 a	6.2 a	8.0 a	8.0 a	5.8 a	7.7 a	7.5 a
Shallow	5.7 a	7.0 a	7.7 a	5.5 ab	7.2 ab	7.7 a	4.8 b	6.7 ab	7.7 a
Medium	6.0 a	7.0 a	7.8 a	4.7 bc	7.0 b	8.0 a	4.3 c	6.0 b	7.7 a
Heavy	5.0 a	7.5 a	8.2 a	3.8 c	5.5 c	6.5 b	2.5 d	3.8 c	4.7 b

† Topdressing volumes: 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy)

‡ Days after fraise mowing (DAF) that sand topdressing was applied: 0 (same day), 7, and 14 DAF.

§ Turf quality was evaluated at 7-day intervals. Results from 21, 28, and 35 DAF are presented.

¶ Turf quality (TQ) was rated on a 1 to 9 scale. Ratings ≥6 were acceptable.

Means within DAF and rating date followed by the same letter are not different according to Fisher's Protected LSD (*P* =0.05).

Table 4. Turf cover following fraise mowing and one independent sand topdressing application. Volumes of Sand were broadcast on 0, 7, or 14 days after fraise mowing at volume: 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy), and turf cover was evaluated at seven-day intervals through 35 days after fraise mowing. Means of two years are presented at 21, 28, and 35 days after fraise mowing.

Depth†	0 DAF‡			7 DAF			14 DAF		
	21§	28	35	21	28	35	21	28	35
	Turf Cover (%)¶								
Control	94.2 a#	100.0 a	99.5 a	95.0 a	98.3 a	99.8 a	94.8 a	99.0 a	98.0 a
Shallow	90.0 ab	97.5 a	98.2 a	91.7 ab	99.2 a	99.5 a	87.5 b	97.3 a	99.7 a
Medium	91.7 ab	97.5 a	98.8 a	85.0 b	97.5 a	98.6 a	80.0 c	94.0 a	98.8 a
Heavy	85.8 b	98.3 a	99.7 a	72.5 c	90.0 b	95.8 b	50.0 d	72.5 b	82.8 b

† Topdressing volumes: 0 (control), 0.39 (shallow), 0.77 (medium), or 1.54 yd^3 1,000 ft^{-2} (heavy).

‡ Days after fraise mowing (DAF) that sand topdressing was applied: 0 (same day), 7, and 14 DAF.

§ Turf cover was evaluated at 7-day intervals. Results from 21, 28, and 35 DAF are presented.

¶ Turf cover was recorded on a 0 to 100% scale where 0 = bare ground and 100 = complete coverage.

Means within DAF and rating date followed by the same letter are not different according to Fisher's Protected LSD (*P* =0.05).