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Advances in managing organic matter in turfgrass ecosystems

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1 Introduction

Beard (1973) defined thatch as a layer of dead and living stems and roots that accumulates between the green vegetation and soil surface (Fig. 1). Thatch has high lignin content and is composed of stems and nodes that do not readily decay (Ledebauer and Skogley, 1967). Thatch accumulation is a common problem in turfgrass ecosystems because such surface organic matter (OM) is resistant to decomposition. Many factors contribute to excessive thatch accumulation, including rapid and dense growth of the turfgrass species, excessive fertility and irrigation, and infrequent cultivation programs. Excessive thatch can be detrimental and cause desiccation and hydrophobicity during dry conditions, thus enhancing turfgrass drought stress. Water repellency was observed to be more severe with high OM soil in turf and more difficult to alleviate by using wetting agents (Barton and Colmer, 2011a,b). On the opposite extreme, thatch can also retain excess water, thereby restricting air exchange in the root zone during wet periods. Sampling of 24 golf course putting greens in New Zealand found surface infiltration rates declined as OM content increased (Glasgow et al., 2005). Early research demonstrated that thatch layer limits initial or early-time infiltration rate but not steady-state infiltration rate because thatch has a larger pore size than the underlying soil profile (Hurto et al., 1980; Taylor and Blake, 1982). Similarly, Liang

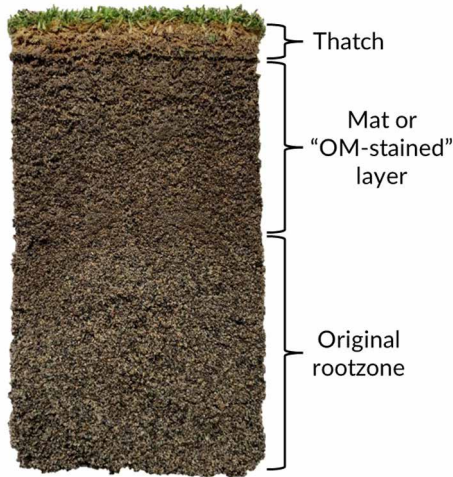


Figure 1 A putting green soil profile showing turfgrass, thatch, mat layer and the original rootzone.

et al. (2017) calculated early to intermediate infiltration rates (before approaching a constant infiltration rate) with a simulated rainfall method and reported that thatch held water, reduced runoff, and delayed infiltration. Furthermore, an examination of the physical properties of different sports turf root zone mixes indicated that saturated hydraulic conductivity (K_{sat}) was not affected by OM content but rather by pore size distribution (McCoy, 1992).

Although OM may not have a direct relationship with K_{sat} , OM can have an indirect effect by decreasing large pore spaces in the root zone. Large pores are an important factor influencing K_{sat} . As putting greens mature over the years OM will accumulate, which will decrease infiltration rates due to reductions in air-filled root zone porosity (Lewis et al., 2010; McClellan et al., 2009). Many researchers have shown evidence to support that decreases in air-filled porosity in sand root zones often result in decreased infiltration (Gibbs et al., 2000; Lewis et al., 2010; McCoy, 1992; Ok et al., 2003). Management practices such as sand topdressing and core cultivation introduce sand particles into the soil profile creating more pore spaces among OM. Measuring infiltration rates at five tensions from -5.5 to -0.5 cm, Wang et al. (2021) suggested that sand topdressing treatments increased K_{sat} by creating relatively larger pore spaces. Core cultivation physically removes thatch and plant tissue, and large amounts of sand are backfilled; therefore, a significant increase in infiltration was often observed, but the effects on OM reduction were inconsistent (McCarty et al., 2005, 2007; Schmid et al., 2014; Sidhu et al., 2014). This is likely because core cultivation is also very effective at promoting new growth/biomass.

2 Monitoring and measuring organic matter in turfgrass

Historically, researchers have quantified OM accumulation and/or reduction by measuring thatch thickness and OM content by combustion. However, with the increased frequency and quantity of topdressing applied to golf course putting greens and fairways, it has become very difficult to measure a thatch layer due to the mixing of sand or soil with thatch that produces a mat layer (Carrow et al., 1987). As a result, recent studies have focused on OM combustion, or loss on ignition (LOI), to quantify OM changes over time. Despite having numerous laboratory methods for determining OM in soils (Carrow et al., 1987; Nelson and Sommers, 1996), and putting green and sports turf root zone mixes (ASTM F1647-02, 2002), there is a lack of standardized sampling procedures for OM sampling in turf. Various sampling methods have been documented in the literature, including differing soil probe diameter size, soil sampling depth, whether the soil samples are stratified, and if the verdure is removed. Consequently, comparing results from OM studies is difficult due to nonuniformity in OM sampling/collection and measurement technique.

A summary of research papers related to OM management and their soil sampling methods is listed in Table 1. The diameter of soil cores used for OM analysis and the number of samples collected per plot vary greatly in the turfgrass literature. Most of these studies collected between two and five soil samples per plot (Barton et al., 2009; Carrow et al., 1987; Dunn et al., 1995; Espevig et al., 2012; Fu et al., 2009; McCarty et al., 2005; Murphy et al., 1993; Schmid et al., 2014; Stier and Hollman, 2003; Wang, 2015). Kauffman et al. (2013) conducted a field trial in which they investigated the effect of sample size (number per plot) on thatch/mat depth and OM content of four warm-season grasses. Results from this trial indicate that the number of samples required to detect a difference ($P=0.05$) of 3 mm in thatch depth ranged from 10 to 13, depending on species/cultivar. Moreover, the number of samples required to detect a 0.5% change in OM content ranged from 3 to 17 samples. The discrepancy between the number of soil samples collected per plot in previous OM studies and the estimated number of samples required to detect a 0.5% OM content change might explain why few studies have been able to consistently detect differences in OM content. It should also be noted that Kauffman et al. (2013) used a 100-mm diameter soil core, which is larger than most of the previous studies investigating OM content. Although extensive research has been carried out on OM in turfgrass, no previous study has investigated the impact of soil core diameter on OM content, particularly with respect to cultivation treatments. It is important that soil core diameter is sufficiently large enough to capture variations in OM, while not being too disruptive to the turfgrass surface. Future research is needed to investigate the impact of soil core diameter samples on OM content measurement.

Table 1 A summary of research papers related to organic matter management and their soil sampling methods in the turfgrass science literature

Reference	Year	Sample diameter (mm)	Sample depth (mm)	Number of samples per plot
Carrow et al.	1987	54	Variable - thatch or mat layer	2
Murphy et al.	1993	50	Variable - thatch/mat layer	5
Dunn et al.	1995	100	Variable - mat layer	5
Stier and Hollman	2003	25	50	3
Glasgow et al.	2005	25 or 50	80	NS ^a
McCarty et al.	2005	19	51	2
Barton et al.	2009	70	0-50	2
Fu et al.	2009	25	80	2
McClellan et al.	2009	25	152	NS
Fontanier et al.	2011	NS	13-89	NS
Espevig et al.	2012	24	Variable - mat layer	2
Kauffman et al.	2013	100	25	25
Schmid et al.	2014	19	76	2
Fidanza et al.	2017	19	Variable - thatch and OM-'stained' layer	8

^aNS, not stated.

Soil sampling depth for OM content in turfgrass research has varied greatly (Table 1). Several researchers have used a fixed soil core depth for OM samples and analyzed the entire soil sample minus the verdure (Barton et al., 2009; Fontanier et al., 2011; McCarty et al., 2005, 2007; Schmid et al., 2014; Stier and Hollman, 2003). While other researchers have also used a fixed soil core depth but stratified the soil core into specific depth increments prior to combusting the sample (Glasgow et al., 2005; McClellan et al., 2009; Windows and Bechelet, 2012). McClellan et al. (2009) divided the soil cores in their study into 0-76 mm and 76-152 mm increments, whereas Glasgow et al. (2005) and Windows and Bechelet (2012) both stratified their samples into 20-mm increments (0-20, 20-40, 40-60, and 60-80 mm). Other researchers have relied on variable depth sampling for OM based on the depth of the thatch/mat region (Carrow et al., 1987; Dunn et al., 1995; Espevig et al., 2012; Fidanza et al., 2017; Murphy et al., 1993; Wang, 2015). Early research by Carrow et al. (1987) looking at the effect of fertility and cultivation on Bermuda grass limited soil sampling to only the thatch region of the soil profile. The authors of this trial noted that it was difficult to make comparisons between treatments that received topdressing or core

aeration (with cores returned) and all other treatments since those treatments form a mat layer, thus significantly reducing thatch. With increased frequencies and quantities of sand topdressing applied to putting greens and fairways, some studies have focused sampling depth on the mat or thatch/mat layer (Dunn et al., 1995; Espevig et al., 2012; Murphy et al., 1993; Wang, 2015). A recent study by Fidanza et al. (2017) stratified soil samples into three layers, verdure/thatch, OM-'stained' layer, and original root zone. The authors found that as the Bermuda grass putting greens aged, the depth of the OM-'stained' layer increased, but the OM level remained consistent and relatively low. In contrast, the depth of the thatch layer was relatively consistent, and the OM level fluctuated greatly throughout the season, which was attributed to the cultivation program.

Combustion temperature for measuring OM content using the LOI method also varies considerably in the turfgrass literature. In studies referenced previously, combustion temperature ranged from 440°C (Glasgow et al., 2005; Schmid et al., 2014) to 550°C (Espevig et al., 2012; Fidanza et al., 2017; Fu et al., 2009) to 600°C (Barton et al., 2009; Carrow et al., 1987; Dunn et al., 1995; Kauffman et al., 2013; Murphy et al., 1993; Stier and Hollman, 2003), and even up to 700°C (McCarty et al., 2005). To date, no published research has evaluated the effect of combustion temperature on OM content measurements in turfgrass. In general, researchers have used higher combustion temperatures for soils or thatch samples that have high OM to ensure complete combustion of OM (ASTM, 2020) or to reduce the time required to completely combust a sample. However, heating a soil sample to temperatures $\geq 1000^\circ\text{C}$ could result in elevated OM measurements due to the combustion of carbonate C from CaCO_3 , especially in calcareous soil. Rabenhorst (1988) determined that the appropriate combustion temperature for determining organic carbon (OM) content for a calcareous soil was 575°C, whereas carbonate C from CaCO_3 was combusted when samples were heated to 1000°C. Because of this, the authors recommend heating soil samples to a maximum of 575°C for the measurement of OM content using LOI in turfgrass.

To date, all previous studies investigating OM content in turfgrass have removed the verdure, or living green plant tissue above the soil surface, prior to laboratory analysis (Barton et al., 2009; Carrow et al., 1987; Dunn et al., 1995; Espevig et al., 2012; Fidanza et al., 2017; Fontanier et al., 2011; Fu et al., 2009; Glasgow et al., 2005; Kauffman et al., 2013; McCarty et al., 2005; McClellan et al., 2009; Murphy et al., 1993; Schmid et al., 2014; Stier and Hollman, 2003; Wang, 2015). However recently, researchers have suggested leaving the verdure intact for OM sampling (Woods, 2019). Subjective removal of verdure and loss of soil material during the verdure removal process may reduce the accuracy and precision of the measurement; however, to date, no study has addressed the implication of verdure removal.

As stated previously, the generalizability of much of the published research on OM is problematic due to the varied sampling procedures described above. It is critical for developing standardized sampling procedures for OM content, so it is more effective and easier to make comparisons between studies and provide guidelines for turfgrass managers. Further work is needed to establish the impact of soil core diameter and core depth and leave the verdure intact on OM measurements.

3 Organic matter and turfgrass diseases

The relationships between OM content and turfgrass diseases are not well understood, and what is known is largely based on empirical evidence. Conflicting reports of the influence of OM content on dollar spot (*Clarireedia jacksonii*) have been noted in the literature (Carrow et al., 1987; Fermanian et al., 1985; Moeller et al., 2008; Stier and Hollman, 2003). Several studies have shown that cultural management practices aimed at reducing OM content (cultivation, topdressing, and dethatching) can increase dollar spot severity (Carrow et al., 1987; Fermanian et al., 1985). Carrow et al. (1987) found that dollar spot was greater in plots that received core cultivation twice annually plus dethatching, which the authors speculated was due to weakened turf, rather than reduced OM content. Fermanian et al. (1985) observed that all plots receiving topdressing (sand or sand plus soil) had greater dollar spot severity compared to the non-treated control. In contrast, Moeller (2008) found consistent reductions in dollar spot severity in plots that received hollow tine cultivation, in combination with seasonal topdressing with medium-coarse sand, compared to the non-treated control. Finally, Stier and Hollman (2003) observed that cultivation and topdressing treatments applied to four creeping bentgrass (*Agrostis stolonifera* L.) cultivars had no effect on OM accumulation. On annual bluegrass putting greens, topdressing treatments were reported to decrease OM concentration in the mat layer by increasing the mat layer depth, and anthracnose disease was linearly reduced as the amount of topdressing increased up to $6.0 \text{ L m}^{-2} \text{ yr}^{-1}$ (Wang, 2015; Wang et al., 2018). Kerns et al. (2009) investigated the impact of OM content at the establishment on the severity of pythium root dysfunction (*Pythium volutum*) and found the disease was more severe in treatments containing 100% sand compared to treatments that contain a 70:30 (% v/v) sand to sphagnum peat moss ratio. The authors noted that this result was likely due to heat stress prior to inoculation that significantly reduced root depth in the 100% sand treatments. Recently, researchers have begun to investigate the effects of OM concentration on fungicide bioavailability. Stephens (2021) conducted an *in vitro* bioavailability assay using three fungicides (*pyraclostrobin*, *azoxystrobin*, and *propiconazole*) and four OM concentrations (0%, 0.5%, 1.0%, and 1.5% OM in potato dextrose agar) and

found that more *pyraclostrobin* and *propiconazole* were required to inhibit take-all patch (*Gaeumannomyces graminis*) as OM concentration increased, whereas OM concentration did not influence *azoxystrobin* efficacy. This result suggests that some fungicides may have an affinity to bind to OM and this can reduce their efficacy. Further research is required to better understand the influence of OM on turfgrass diseases, as well as the impact of OM content on fungicide efficacy.

4 Organic matter and soil microbial populations

Putting green soils are often criticized for lacking microorganisms because they have high sand content and are intensively managed for OM reduction and control. Recent studies utilizing sequencing technology revealed that putting green turf in fact supports a diverse microbial community (Beirn et al., 2017; Allan-Perkins et al., 2019). In addition to OM management and control, putting green root zones are managed to increase porosity and avoid compaction, which also provides microorganisms with favorable habitats. Interestingly, golf course roughs, fairways, and putting greens vary in management intensity from low to high inputs but do not differ in microbial abundance and diversity (Allan-Perkins et al., 2019). One fairway study showed a high correlation between thatch microbial activities and thatch moisture (measured in the laboratory in g g^{-1}) but not thatch OM content (Mu and Carroll, 2013). Therefore, there is no evidence that management practices to limit OM accumulation of turfgrass could have a negative effect on the microbial community in the soil profile. Nevertheless, lacking soil OM is typically not a concern in managed turfgrass ecosystems. Ecological studies showed that turf used for golf courses accumulates soil OM at high rates, comparable to regenerating forests and fallowed cropland (López-Bellido et al., 2010; Qian and Follett, 2002; Qian et al., 2010).

5 Organic matter management practices

OM accumulation is often a problem when attempting to sustainably manage stoloniferous and rhizomatous turfgrass species such as creeping bentgrass, which is stoloniferous, Kentucky bluegrass, which is rhizomatous, zoysiagrass, kikuyugrass, and hybrid Bermud agrass which are both stoloniferous and rhizomatous. This problem, which is also often referred to as thatch accumulation, can be accelerated when maintaining newer, more aggressively spreading cultivars in sand-based systems like putting greens, tee boxes, and athletic fields or sports pitches (Fontainer et al., 2011; Stier and Hollman, 2003; White and Dickens, 1984). Excessive OM accumulation has been linked to a variety of problems, such as increased disease occurrence, reduced drainage, decline in turf appearance and playability, shallow rooting, localized dry spot

or dry patch, and mower scalping (Carrow et al., 1987; Dunn et al., 1995; Fontainer et al., 2011; Murphy et al., 1993; Schmid et al., 2014; Waddington, 1992). Cultivation has long been accepted as one of the primary methods of OM removal in turfgrass (Beard, 1973). Hollow tine core cultivation and vertical mowing can remove OM (Hempfling et al., 2020; McCarty et al., 2007). However, research has determined that traditional cultivation methods (hollow tine, as well as solid tine, and vertical mowing) have little effect on OM levels in managed turfgrass systems when these practices are not combined with sand topdressing, or if the soil removed during cultivation is not reincorporated back into the root zone after the OM has been separated (Barton et al., 2009; Carrow et al., 1987; Smith, 1979; White and Dickens, 1984). In recent years, several novel cultivation methods have been developed such as air, water, and sand injection, as well as grooming and venting equipment, but again these cultivation practices have little effect on soil OM content (Fontainer et al., 2011; McCarty et al., 2007; Schmid et al., 2014). Considering this, the available research would suggest that sand topdressing is one of the most important cultural practices required when sustainably managing OM, particularly in the upper root zone (Barton et al., 2007; Carrow et al., 1987; Dunn et al., 1995; Stier and Hollman, 2003; Wang, 2015; White and Dickens, 1984). In more recent years, research has explored non-destructive OM control methods using the application of decomposition enhancing products with varying success (Berndt et al., 2014; Chamberlain and Crawford, 2000; Ledebor and Skogley, 1967; McCarty et al., 2005; Sidhu et al., 2012, 2013, 2019; Weaver et al., 2021). This section will review the various cultural practices that have, and have not, been shown to effectively reduce OM accumulation.

The United States Golf Association recommendations for core cultivation or aerification are between 15% and 20% affected surface area per year (O'Brien and Hartwiger, 2001; O'Brien and Hartwiger, 2003). To achieve this affected surface area, researchers have explored the effects of core cultivation implemented from twice annually, to every other week, with varying tine diameters (6.4–15.8 mm) and spacings (50–76 mm), as well as varying tine depths (50–100 mm) (Barton et al., 2007; Carrow et al., 1987; Dunn et al., 1995; Fontainer et al., 2011; McCarty et al., 2007; Smith, 1979; White and Dickens, 1984).

However, hollow and solid tine cultivation (often referred to as aerification) have not been shown to effectively mitigate OM accumulation when soil cores are removed from hollow tine-cultivated turfgrass and sand topdressing is not applied to hollow tine- or solid tine-cultivated areas. Research conducted as early as 1979 by Smith found that hollow tine core cultivation every other week during the growing season did not adequately control thatch accumulation of a 'Tifdwarf' Bermuda grass green after 7 months, when frequent sand topdressing application or soil reincorporation was not implemented. Like

this work, White and Dickens (1984) determined that monthly versus twice-yearly core cultivation without soil reincorporation or sand topdressing did not change the thatch accumulation of three different dwarf Bermuda grass hybrid greens ('Tifgreen', 'Dothan', and Tifdwarf) over a 2-year period. After this, Carrow et al. (1987) determined that core cultivation with the cores removed, and no sand topdressing, increased OM content in a 'Tifway' Bermuda grass stand maintained at fairway/athletic field height-of-cut. Dunn et al. (1995) determined that core cultivation without sand topdressing over a 3-year period had no effect on percent OM on 'Meyer' zoysiagrass maintained at fairway height-of-cut. Barton et al. (2007) determined that core cultivation, without sand topdressing, on a mature kikuyugrass provided minimal OM reductions when compared to treatments that incorporated sand topdressing. Fontainer et al. (2011) also found that hollow tine aeration and solid tine aeration (both ranging from 14% to 16.8% affected surface area) did not reduce OM on three different Bermuda grass putting greens (Tifdwarf, 'Tifeagle', and 'Miniverde') when soil cores were not reincorporated, or sand topdressing was not applied. While solid or hollow tine core cultivation can improve root zone drainage and gas exchange, without the addition of sand topdressing or soil core reincorporation, these cultural practices will not reduce OM accumulation.

In addition to hollow and solid tine core cultivation, a variety of other cultivation practices such as vertical mowing, grooming, venting, and injection (air, water, and sand) have been introduced. Vertical mowing utilizes vertically mounted blades that are mechanically driven that bring soil and OM up to the surface. Vertical mowing can be done with varying blade widths (2.0–3.6 mm wide), that are set to different spacings (10–38 mm apart) and depths (3–20 mm into the soil) (Carrow et al., 1987; Barton et al., 2007; Hempfling et al., 2020; McCarty et al., 2007). Grooming on the other hand is often done with mower attachments that are ground driven and cut into the thatch layer (Hempfling et al., 2020; Fontainer et al., 2011; McCarty et al., 2007). Grooming equipment typically does not bring OM to the soil surface. Venting equipment is typically a thin, solid tine or knife-like tine, and like grooming, it does not bring OM to the soil or turfgrass surface (Schmid et al., 2014). Venting equipment includes 'quad' needle tines, bayonet tines, and the PlanetAir (PlanetAir Turf Products, Naples, FL). Injection equipment inserts a tool or probe into the soil surface and then injects sand [DryJect (DryJect, Inc., Hatboro, PA) and Landpride (LandPride, Salina, KS)], water [HydroJect (Toro, Bloomington, MN), or air [Air2G2 (Foley Company, Prescott, WI)] into the soil (Amgain and Fontainer, 2021; Carrow, 2003). Like grooming and venting, injection equipment does not remove OM.

Like core cultivation, vertical mowing, grooming, or injection with air, water, or sand have not been shown to effectively reduce OM accumulation when sand topdressing is not combined with these practices. For instance, White and Dickens (1984) determined that various vertical mowing intensities,

without soil reincorporation or topdressing, did not affect thatch accumulation in Bermuda grass hybrid greens. Carrow (2003) found that water injection (Hydroject) and sand injection (Landpride) did not decrease OM on a creeping bentgrass putting green. McCarty et al. (2007) found that walk mowing with a grooming attachment increased OM content on creeping bentgrass. Barton et al. (2007) determined that vertical mowing without sand topdressing, on a mature fairway-height kikuyugrass stand, provided minimal OM reductions. Fontainer et al. (2011) also found that venting aeration with the PlanetAir at various intensities (ranging from 7.4% to 37.8% affected surface area) did not decrease OM. Like these findings, Schmid et al. (2014) determined that the PlanetAir and Hydroject did not reduce OM content. Recent research by Amgain and Fontainer (2021) found that air and sand injection (Air2G2 and DryJect, respectively) into a 'Penncross' creeping bentgrass putting green had no effect on OM levels after 2 years of research. Though these cultural practices can provide advantages such as improved turfgrass appearance, drainage, and reduced disease occurrence, while producing minimal effects on playability (Amgain and Fontainer, 2021; Hempfling et al., 2020; Schmid et al., 2014), OM management practices, without the addition of sand topdressing, will not reduce OM content.

Although cultivation practices alone are not enough to mitigate OM accumulation, there seems to be some evidence to indicate that hollow or solid tine core cultivation practices, coupled with sand topdressing and/or soil core reincorporation, will provide the greatest amount of OM reductions. For example, Murray and Juska (1977) determined that 3 years of core cultivation with cores reincorporated back into common Kentucky bluegrass maintained at lawn height resulted in the greatest reduction in OM. Murphy et al. (1993) found that summer hollow tine core cultivation repeated over a 3-year period had the greatest reduction in the OM fraction within the thatch/mat layer of a 'Penneagle' creeping bentgrass green when soil cores were reincorporated back into the aerified plots. Later work completed by McCarty et al. (2007) observed the greatest reduction in OM content on an 'A-1' creeping bentgrass green over a 2-year period when cultivation cores were reincorporated back into the soil and combined with vertical mowing, grooming, and topdressing. Barton et al. (2007) determined that core cultivation combined with sand topdressing over a 2-year period provided the greatest OM reduction on a mature stand of fairway-height kikuyugrass. Research conducted by Schmid et al. (2014) found that quad needle tines, bayonet tines, hollow tines, and solid tines produced minor but significant OM reductions when repeated over a 2-year period on 'Providence' creeping bentgrass greens, when all treatments received relatively high annual sand topdressing treatments. Considering all of this evidence, it suggests that hollow tine core cultivation combined with soil core reincorporation or sand topdressing and solid tine cultivation combined

with sand topdressing have consistently shown to be effective methods for reducing large percentages of OM in the soil profile.

If cultivation practices require the additional input of sand topdressing to effectively reduce OM levels, the next logical conclusion would be that topdressing alone is adequate for mitigating OM accumulation. Like the core cultivation work, a wide variety of sand topdressing frequencies (every other week to once a year) and rates [(0.01 cm (0.15 kg m²) to 0.95 cm (14.65 kg m²)] have been explored (Barton et al., 2009; Carrow et al., 1987; Dunn et al., 1995; Green et al., 2019; Kowalewski et al., 2010; McCarty et al., 2007; Obasa et al., 2013; Proctor et al., 2014; Smith, 1979; Schmid et al., 2014; Stier and Hollman, 2003; Wang et al., 2015). Together, these studies indicate the possibility of managing OM with sand topdressing alone. For example, in as early as 1984, White and Dickens determined that sand topdressing applied four times per year, compared to annual topdressing, and various cultivation practices (core cultivation and vertical mowing), had the greatest reduction on thatch accumulation on three different hybrid Bermuda grasses. Similar to these findings, Carrow et al. (1987) found the largest OM reduction in 'Tifway' Bermuda grass when sand topdressing was applied twice annually. This research also determined that sand topdressing applied once annually was better than dethatching or core cultivation with cores reincorporated in the soil. Dunn et al. (1995) determined that sand topdressing applied twice annually over a 3-year period produced the greatest reduction of OM in fairway-height 'Meyer' zoysiagrass. Stier and Hollman (2003) suggested that sand topdressing applied monthly, or every other week, was adequate enough to prevent the development of a visible thatch layer on three different bentgrass greens ('A-4', 'G-2', and 'Penncross') and a 'DW-182' annual bluegrass green over a 2-year period. Barton et al. (2007) determined that sand topdressing alone over a 2-year period provided a significant reduction in OM content of a mature kikuyugrass stand. This research also determined that sand topdressing was more effective at reducing OM than coring alone. Wang (2015) found that sand topdressing applied every 2 weeks reduced OM content on an annual bluegrass putting green. In addition to reduced OM, research has shown that sand topdressing can provide several benefits such as a decrease in disease occurrence, improved strength, increased shoot density, and faster water infiltration (Green et al., 2019; Kowalewski et al., 2010; Wang et al., 2018). However, there is a risk of developing a sand/thatch stratification layer when cultivation practices are not combined with sand topdressing. Considering this, the soil profile should be monitored regularly for the development of stratified layers if cultural practices are not combined with sand topdressing.

Ongoing research has been exploring non-destructive OM management methods with various degrees of success. Treatments of a liquid vermicompost extract (Worm Power; Aqua Aid Solutions, Rocky Mount, NC), a liquid humate

derivative (EarthMAX; Harrell's LLC, Lakeland, FL), and blackstrap molasses (Plant Food Company, Inc., East Windsor, NJ) on zoysia golf greens did not affect thatch measured by weight (Weaver et al., 2021). Other commercial products Thatch-less (Novozymes Biologicals, Le Pecq, France) (Espevig et al., 2012) and Thatch-X (Ocean Organics/Emerald Isle Ltd., Ann Arbor, MI) (McCarty et al., 2005), as well as biological agents lignocellulolytic *Streptomyces* spp. (Chamberlain and Crawford, 2000) were not effective at reducing OM in putting green turf. However, another study showed some promising results with Thatch-X. Even though the thatch-mat depth was greater in the Thatch-X-treated plots compared with untreated control, the plots that received Thatch-X, as well as other cultural management practices, were able to maintain the OM at pre-study level, whereas the untreated control increased in OM concentration overtime (McCarty et al., 2007). Plant cell wall-degrading enzymes are hypothesized to accelerate the decomposition of thatch. Early research showed cellulase had no effect on OM (Ledebøer and Skogley, 1967), while a further investigation demonstrated that cellulase only accelerated short-term thatch-mat decomposition, but this effect was not sustained after 15 days (Berndt et al., 2014). Recent research has explored the potential of utilizing lignin-degrading enzymes such as fungal laccases because turfgrass thatch contains high lignin content and thereby resists microbial decomposition. Laccase applications showed promising effects on reducing OM accumulation in several turfgrass species and increasing K_{sat} (Sidhu et al., 2012, 2013). In contrast to cellulose, applying laccase for 6 months had a residual effect of OM reduction for another 6 months (Sidhu et al., 2019). The hypothesis is that laccase degrades lignin and loosens the cell wall structure allowing microorganisms to access and decompose the cell wall substances cellulose and hemicellulose.

6 Conclusion

OM accumulation will often become problematic when trying to sustainably manage turfgrass. While moderate OM can be beneficial and support a diverse microbial population, several detrimental effects and turfgrass diseases are linked to excess levels of OM and thatch in the turfgrass root zone. A variety of monitoring and measuring methods are available for evaluating changes in OM over time. There are also several cultural management practices for reducing accumulation, with the most consistently successful being a combination of cultivation and sand topdressing.

7 Where to look for further information

For basics on OM, management with cultivation and sand topdressing see textbooks and research by James Beard (Beard, 1973) and Bert McCarty

(McCarty, 2001; McCarty et al., 2005; McCarty et al., 2007). Future research needs on OM management in turfgrass ecosystems include the development of standardized sampling and analysis procedures. For potential OM sampling standardization protocol see American Standards for Testing and Materials (ASTM) F1647-02 (2002) and ASTM D2974-20 recommendations (2020). Another need is the exploration of more OM reduction methods that do not disrupt turfgrass playing surfaces. This includes further exploration into sand topdressing methods and thatch decomposition accelerators, such as cellulose and lignin-degrading enzymes. For research on these topics see recent works by Charles Fontanier at Oklahoma State University, Robert Carrow at the University of Georgia and Charles Schmid at Oregon State University. Other places to look for recent research on OM management include the Agronomy Monograph 'Turfgrass: Biology, Use, and Management' (Stier et al., 2013), and the annual Turfgrass (C-5) proceedings and abstracts of the American Society of Agronomy, Crop Science Society of America and Soil Science Society of America (ASA-CSSA-SSSA) International Annual Meeting. Funding organizations that have expressed a need for this research and often produce popular press articles on OM management include the United States Golf Association (USGA) and the Golf Course Superintendents Association of America (GCSAA).

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