

Characterization, Development, and Management of Organic Matter in Turfgrass Systems

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Organic matter (OM) abounds in the environment and has long fascinated scientists with its formation and nature (Beyer, 1996; Hayes and Clapp, 2001). The development of OM in turfgrass systems is a significant management consideration, especially in putting greens. Many factors influence OM accumulation, including the grass type, rate of plant growth and decay, soil chemical and physical properties, biological activity, cultural practices, and environmental conditions. Considerable effort has been focused on gaining a better understanding of what OM is and how it is influenced by management practices. Much of this effort has built on the long history of research on OM in the soil of natural and agro-ecosystems (Manlay et al., 2007; Kögel-Knabner et al., 2008a, 2008b).

Components of Organic Matter

Organic matter associated with turfgrasses is a pool of biological substances that exhibits a continuum of complexity. It consists of recognizable and unrecognizable grass-plant materials in various stages of decay, microbial biomass, small fauna, the by-products of plant growth and decay, and other components. The relative amounts of these substances differ depending on the nature of the turfgrass

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system. Plant organic materials primarily comprise the constituents of the cell walls and cytoplasm. These include structural carbohydrates, such as cellulose, hemicellulose, and lignin; nonstructural carbohydrates, such as sucrose, fructose, and starch; proteins and other nitrogenous compounds, such as enzymes and nucleic acids; lipids, including waxes, pectins, and pigments; and secondary metabolites, such as terpenoids, alkaloids, and phenylpropanoids (Shearman and Beard, 1975; Hull, 1992; Paul and Clark, 1996; Horwath, 2002, 2007; Narra et al., 2004, 2005; Brosnan et al., 2005; Watkins et al., 2006; He and Huang, 2007; Turgeon, 2008). These vary in proportion depending on the plant type and part, the age of the material, and the extent of decay (Shearman and Beard, 1975; Martens, 2000; Trenholm et al., 2000; Johnson et al., 2007). The Soil Science Society of America (2008, p. 39) defines microbial biomass as "the total mass of living microorganisms in a given volume or mass of soil, or as the total weight of all microorganisms in a particular environment." Organic matter supports large amounts of microbial biomass (Mancino et al. 1993; Kerek et al., 2002; Shi et al., 2006, 2007; Hixson et al., 2009), which is an important determinant of the quantity and quality of soil organic matter (SOM; Guggenberger et al., 1999). Kerek et al. (2002) reported that the microbial biomass associated with particulate organic matter (POM) in putting greens ranged from 27.7 to 124.5 nmol lipid-phosphorus g^{-1} soil, depending on the age of the green. The leaf surfaces and roots of grasses support large amounts of microbial biomass, containing up to 10×10^6 bacteria g^{-1} leaves to 120×10^9 bacteria cm^{-3} soil at a distance of 0 to 1 mm from the roots (Paul and Clark, 1996). The return of clippings and rooting would contribute microbial biomass, as well as plant material, to the OM pool. Fauna also contribute to the pool. These include organisms such as protozoa, nematodes, mites, earthworms, and insects, which are present in most turfgrass systems (Coleman and Wall, 2007; Turgeon, 2008). The decay of microbial biomass contributes materials such as chitin, cellulose, peptidoglycans, nucleic acids, lipids, and enzymes and their respective breakdown products and is an important precursor in the formation of stable SOM (Paul and Clark, 1996; Horwath, 2002, 2007; Salton and Kim, 2009). By-products of plant growth include exudates and secretions. Leaf exudates from wounding, guttation, and leaf structures such as trichomes, contain organic compounds, including sugars, amino acids, amides, proteins, and other compounds of metabolic significance (Williams et al., 1998; Pilot et al., 2004; Wagner et al., 2004; Singh et al., 2008; Turgeon, 2008).

Roots exude simple sugars, amino compounds, secondary metabolites, and biostatic compounds, such as phytoalexins and allelochemicals (Lynch, 1990; Vasilakoglou et al., 2005; Horwath, 2007; Broeckling et al., 2008). Mucigels, which are highly hydrated polysaccharides, are the main excretory products of roots and account for up to 80% of the total carbon lost from wheat (*Triticum aestivum* L.) roots (Paul and Clark, 1996). Information on root exudates for turfgrasses is lacking, although Carrow and Petrovic (1992) suggested that high amounts of root exudates could constitute a carbon drain on plants. Root-secretion profiles of *Arabidopsis thaliana* L. contain 289 different secondary metabolites and thus deposit a unique array of exudates into the rhizosphere (Biedrzycki and Bais, 2009; Micallef et al., 2009).

The by-products of decay contribute important components to the OM pool in the form of microbially produced carbohydrates, aromatics, lipids, and nitrogen-containing compounds. Repeated oxidation and hydrolysis of decay by-products

and subsequent condensation reactions lead to the formation of humic substances, which have higher carbon, nitrogen, and hydrogen and lower oxygen contents than the original residues (Paul and Clark, 1996; Horwath, 2002, 2007). Thus, humic substances are defined as refractory, dark-colored, heterogeneous collections of molecules formed by the action of microorganisms on plant and other biological materials (Sutton and Sposito, 2005). Organic pesticides and other organic chemicals may sorb to OM and constitute a part of the OM pool (Balogh and Anderson, 1992). Binding to OM is an important process that regulates the fate of pesticides in turfgrass soils (Hixson et al., 2009). Inorganic metals such as calcium and potassium, ions like ammonium, and inorganic pesticides or chemicals may also sorb to OM and contribute to the OM pool. Sorption may occur via bonding with functional groups (i.e., $-\text{COOH}$, $-\text{OH}$) associated with quinonic or phenolic rings and enolic hydroxyls on OM or plant roots (Carrow et al., 2001; McCarty et al., 2003; Kaiser et al., 2008). Grass roots are reported to have a cation exchange capacity (CEC) of 10 to 30 $\text{cmol}_c \text{kg}^{-1}$ and OM has 120 to 250 $\text{cmol}_c \text{kg}^{-1}$ or more, with the vast majority (90–100%) being pH dependent (Carrow et al., 2001). Chelation is another binding mechanism (Shenker et al., 1996, 1999, 2001; Carrow et al., 2001). Organic chelates, such as citric and oxalic acid, and siderophores are highly effective at complexing iron (Fe^{2+}), zinc (Zn^{2+}), copper (Cu^{2+}), and manganese (Mn^{2+}) (Carrow et al., 2001). Siderophores are produced by fungi (e.g., rhizoferrin by *Rhizopus arrhizus* Fisher) (Shenker et al., 1996, 1999) and bacteria, whereas phyto siderophores (e.g., mugineic acid) are plant-based root exudates (Carrow et al., 2001) secreted by grasses such as wheat and barley (*Hordeum vulgare* L.) (Shenker et al., 2001). The extent of siderophore production in turfgrasses is unknown.

Organic Matter Fractions

Organic matter may accumulate as a layer on soil supporting turfgrass, and there may be a distinct boundary between the layer and the soil surface. The OM layer, if it exists, may be intermixed with soil that originates from topdressing or other deposition, from the activities of fauna, or from other sources. Organic matter may also occur below the soil surface in the rhizosphere and elsewhere deeper in the profile. Where OM exists, as well as the extent of its accrual, depends on many factors, including the nature of the system and cultural practices.

Thatch-Mat

References to OM in turfgrass soils appeared in the literature in the late 1920s (Ingalls, 1928). Early references viewed it as being a mat of excess stolons and noted that the problem of mat formation on creeping bentgrass (*Agrostis stolonifera* L.) and bermudagrass [*Cynodon dactylon* (L.) Pers. var. *dactylon*] greens was becoming serious (Anonymous, 1943, 1944). In the 1950s the term *thatch* began to appear. Thatch was used interchangeably with *mat* and was considered an accumulation of stems and leaves built up on the surface of greens (Anonymous, 1956). However, at some point, the terms *mat* and *thatch* were said to relate to different conditions (Ferguson, 1964). *Mat* was defined as an undecomposed mass of living roots and stems hidden below green vegetation, whereas *thatch* was defined as an accumulation of dead but undecomposed stems and leaves at the soil surface (Ferguson, 1964). The perception that mat was live and thatch was dead persisted into the early 1970s (Madison, 1971), resulting in the publication of other definitions

(Ledeboer and Skogley, 1967; Holt, 1969; Juska et al., 1969; Beard, 1973; Turgeon, 2008). The distinction between the terms in the literature has continued to evolve and often is left to the definition and interpretation of the authors.

The most widely recognized definition for *thatch* is “a tightly intermingled layer of dead and living stems and roots that develops between the zone of green vegetation and the soil surface” (Beard, 1973, p. 495). Beard’s definition was revised in 1980 to “a loose intermingled layer” (Waddington, 1992, p. 336). Turgeon (2008, p. 414) defined thatch as a “layer of undecomposed or partially decomposed organic residues situated above the soil surface and constituting the upper stratum of the medium that supports turfgrass growth.” If thatch is intermixed with soil from topdressing or other sources it is called mat (Turgeon, 2008). Barton et al. (2009) described mat as a “tightly intermingled layer of decomposing OM and soil, usually brown in color and easily distinguishable at the upper surface of the root zone.” Because of inherent ambiguity in terminology and sampling techniques, the term *thatch-mat* has appeared frequently since the late 2000s (McCarty et al., 2007; Barton et al., 2009; Fu et al., 2009). Close observation reveals that the thatch-mat layer, if it exists, is the uppermost portion of the growing medium for turf. It is a layer of OM of variable thickness having other variable physical, chemical, and biological properties. It resides under the turf canopy, and its lower surface is in intimate contact with supporting soil. It may be separate and distinct from the soil or a part of the soil profile with a diffuse boundary. It consists of recognizable and unrecognizable turfgrass plant materials in various stages of life and decay together with microbial biomass and other organisms in various stages of life and decay, plus associated by-products of growth and decay and miscellaneous organic and inorganic substances, including pesticides, nutrients, and mineral soil from topdressing or other sources. Contributions from these components toward the nature of OM vary considerably. On intensively cultivated sand-based putting greens and sports fields, the thatch-mat may be dominated by topdressing material, whereas in home lawns, mineral soil may be minimally present and the layer dominated by OM and highly dependent on the degree of core cultivation.

Soil Organic Matter

The Soil Science Society of America (2008, p. 59) defines SOM as “the organic fraction of the soil exclusive of undecayed plant and animal residues.” In turfgrass systems, SOM is further defined as OM occurring below the thatch-mat layer and deeper into the soil profile, along with microbial biomass, soluble organic substances, humic substances, and by-products of decomposition (Haider et al., 1975; Schnitzer, 1982; Stevenson, 1994; Paul and Clark, 1996; Horwath, 2002, 2007). Soil organic matter is in intimate contact with the surrounding soil. Depending on the age and nature of the system, humic substances may comprise 60 to 80% or more of SOM (Schnitzer, 1982; Carrow et al., 2001).

Humic Substances

Classical approaches to studying SOM have involved extraction of humic substances in a base followed by acidification to produce two fractions: humic acid, which is soluble in a dilute base but precipitates on acidification of the alkali extract to pH 2, and fulvic acid, which remains in solution after acidification.

Humins, a third fraction, is not soluble in either acids or bases (Paul and Clark, 1996; Horwath, 2007). The three fractions differ in molecular weight, functional group content, and elemental analysis (Schnitzer, 1982; Stevenson, 1994; Paul and Clark, 1996; Horwath, 2007). Commercial products containing humic substances have been promoted for use in turfgrass systems (Cooper et al., 1998).

A new definition of humic substances as collections of diverse molecules forming dynamic associations stabilized by hydrophobic interactions and hydrogen bonds has begun to emerge (Kandeler, 2007). In spite of the ubiquity of humic substances and their importance to ecosystem processes, the vast majority of humic substances remain "molecularly uncharacterized." The lack of structural information on humic substances is primarily due to the complex nature and uniqueness of humic substances, but also to the lack of analytical tools capable of unraveling their complexity. More recently however, information gathered using spectroscopy (Simpson et al., 2003, 2007), pyrolysis (Grandy et al., 2008), and soft ionization (Sleighter and Hatcher, 2007) supports a model of humic substances as "supramolecular associations" (Sutton and Sposito, 2005) in which more labile compounds, such as proteins, can be encapsulated into micelles for greater protection from decomposition (Piccolo et al., 2004; Rillig et al., 2007).

Particulate Organic Matter

Particulate OM (POM) (aka macro OM) is OM isolated by size fractionation (Gregorich et al., 2006). It is the microbially active fraction of SOM and consists of fine particles of partially decomposed plant tissues; microbial biomass, including fungal hyphae; faunal residues; and other biologically oriented materials, such as seed and spores (SSSA, 2008). It is an estimate of the labile SOM (Mirsky et al., 2008), because it is considered a labile intermediate in the SOM continuum from fresh to humified SOM (Pikul et al., 2007). Dispersion of soil with sodium hexametaphosphate or sonic disassociation followed by wet sieving through a 53- μm sieve yields POM, which is retained on the sieve, and a mineral-associated organic fraction plus solubles, which passes through the sieve (Cambardella and Elliott, 1992; Paul and Clark, 1996). Subsequent density separation of POM with sodium metatungstate yields light POM and heavy POM fractions (Cambardella and Elliott, 1992). In golf-course putting greens, the light POM contains undecomposed root and plant fragments in addition to unrecognizable plant residues, and the heavy POM fraction contains organic residues that appear more altered, as well as small aggregates and free sand particles (Kerek et al., 2002).

Absorption

Characterization and quantification of functional groups, elemental composition, and other characteristics of OM has been accomplished with a variety of spectrographic methods (Mao et al., 2000; Dai et al., 2001; Stone et al., 2001; Narra et al., 2004, 2005; Kinyangi et al., 2006; Muscolo et al., 2007; Baduel et al., 2009; Leinweber et al., 2009; Muscolo and Sidari, 2009). Specific absorbance with UV spectroscopy has been used extensively for the characterization of OM, especially of humic substances (Chen et al., 1977; Jaffrain et al., 2007). Berndt (unpublished data, 2009) cited E_4/E_6 values (at 465 and 665 nm) for humic acid extracts of thatch-mat from 'TifEagle' and 'Tifdwarf' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. var. *dactylon* \times *Cynodon transvaalensis* Burt-Davy] of 8.4 and 9.2. The corresponding

values for humic acid extracts from thatch-mat fractionated as acid-detergent fiber were 8.3 and 8.6, and those for acid-detergent lignin were 7.7 and 7.4. The E_4/E_6 for unfractionated humus and its associated carboxylic and phenolic fractions were 3.04, 3.37, and 1.23 (Muscolo and Sidari, 2009), while those for humic acid after sequential adsorption to montmorillonite or kaolinite clays ranged from 7.79 to 5.24 (Wang and Xing, 2005). A high E_4/E_6 indicates a smaller molecule that has less carbon but more oxygen and $-\text{CO}_2\text{H}$ groups and greater total acidity; there appears to be an inverse relationship between molecular weight and the E_4/E_6 (Chen et al., 1977). This ratio has also been used to indicate aromaticity (Wang and Xing, 2005), as has the specific absorbance at wavelengths of 250, 254, 272, and 365 nm (Jaffrain et al., 2007). The ratio of absorbance at 250 and 365 nm (E_2/E_3) decreases with increasing aromaticity and molecular size (Baduel et al., 2009). The E_2/E_3 for pure humic acid and Suwannee River fulvic acid were approximately 2.5 and 4 (Baduel et al., 2009).

Adsorption

Organic matter binds metals (Jeong et al., 2007), inorganic nutrients (Danneberger et al., 1984; Kaiser et al., 2008; Kang et al., 2009), pesticides (Hurto and Turgeon, 1979; Balogh and Anderson, 1992; Dell et al., 1994; Lickfeldt and Branham, 1995; Cisar and Snyder, 1996; Raturi et al., 1997, 2003; Wu et al., 2002; Cummings et al., 2009; Hixson et al., 2009; Magri and Haith, 2009), organic compounds (Shih, 2007), and compounds such as tetracycline (Gu and Karthikeyan, 2008). In turn, OM can also be bound to soil minerals such as clays (Zhang et al., 2008; Kothawala et al., 2009). Both low- and high-energy bonds are involved in OM adsorption processes (Balogh and Anderson, 1992; McCarty et al., 2003). Sorption of *s*-triazine herbicides to OM is governed by hydrogen bonding and hydrogen ion transfer between the *s*-triazines and the acid groups of humic substances (Cummings et al., 2009), while sorption of humic acid to clay minerals involves a combination of ionic bonds, van der Waal's interactions, and hydrogen bonds (Paul and Clark, 1996; Wang and Xing, 2005; Horwath, 2007). Addition of ^{14}C -simazine (6-chloro-*N,N'*-diethyl-1,3,5-triazine-2,4-diamine) to sterile turfgrass soils, where microbial activity was suppressed, resulted in high levels of ^{14}C bound to OM, with binding directly related to the amount of OM (Hixson et al., 2009). The percentage of bound ^{14}C increased with the age of the turf, which had soil carbon contents of 16.6 mg kg^{-1} soil for 4-yr-old turf (52% bound), 24.5 mg kg^{-1} for 21-yr-old turf (70% bound), and 39.0 mg kg^{-1} for 99-yr-old turf (71% bound). In other work with ^{14}C -simazine, Cummings et al. (2009) indicated that applied herbicide may have adsorbed to the rhizoplane of dormant bermudagrass roots. Grass roots are reported to have a CEC of 10 to 30 $\text{cmol}_c \text{kg}^{-1}$ and OM has 120 to 250 or more, with most (90–100%) being pH dependent (Carrow et al., 2001).

Physicochemical and Biological Properties of Organic Matter in Thatch

Organic matter has distinctive properties that influence turf quality and help shape the direction of management strategies. Much of the effort spent characterizing the properties of OM in turfgrass systems has focused on the thatch or thatch-mat layer. Accurately characterizing the properties of OM is essential to gaining a better understanding of its behavior and management.

Thickness of Thatch

Numerous authors have reported thatch-mat thickness data (White and Dickens, 1984; Berndt et al., 1990; Callahan et al., 1997, 1998; McCarty et al., 2005, 2007; Barton et al., 2009; Fu et al., 2009). Measurements have been made on uncompressed thatch (Callahan et al., 1997; McCarty et al., 2007; Berndt, 2008; Fu et al., 2009) and compressed thatch (White and Dickens, 1984; Mancino et al., 1993; Callahan et al., 1997, 1998). Berndt (2008) reported that the uncompressed thickness of hybrid bermudagrass thatch-mat from Tifdwarf and TifEagle putting greens averaged 32 mm. Callahan et al. (1998) reported compressed thickness of thatch-mat from a 'Penncross' creeping bentgrass green ranged from 4.70 to 8.29 mm. Variation in the thickness of the thatch-mat layer has been observed among turfgrass types, management regimes, regions, and methods of measurement. In consumer lawn care, recommendations for thatch thickness are often used to indicate which, if any, corrective actions may be necessary.

Mass

Soluble organic substances that have a low molecular weight include aliphatic acids, aromatic acids, amino acids, monosaccharides, and oligosaccharides (Homann and Grigal, 1992). The molecular weight of glucose is 180.15, and that of glycine is 75.07 g mol⁻¹. The weight-average molecular weight of a population of cellulose chains in crystalline cellulose from TM-1 cotton (*Gossypium* spp.) fibers was 1.83 × 10⁵ Da (Benedict et al., 1994). The molecular weight for citrus pectin was 3.5 × 10⁴ g mol⁻¹ (Diaz et al., 2007). The molecular size distribution of total hemicelluloses in *Sandersonia aurantiaca* Hook. floral tissues ranged from approximately 9.3 to 5 × 10³ kDa (O'Donoghue et al., 2002). Wheat-straw lignin varied in molecular weight from less than 1 × 10³ g mol⁻¹ to more than 100 × 10³ g mol⁻¹ (Guerra et al., 2007). The weight-average molecular of large-size Pahokee peat humic acid ranged from 38.5 to 50.5 kDa, and for small-size humic acid, the range was 4.3 to 5.9 kDa (Li et al., 2003). The weight-average molecular weights of Suwannee River humic acid and fulvic acid were reported to be 3.67 and 2.18 kDa (Hur and Schlautman, 2004). Molecular weight or other mass determinations for OM components in turfgrass systems has not been reported, due in part to the difficulty of methods for separation and the complex matrix of OM components in most turfgrass systems. It is also questionable that such data will increase the understanding of OM components above that of other information related to OM in the turfgrass environment.

Concentration¹

The concentration of OM in thatch and the SOM have been frequently reported (Carrow et al., 1987; McCoy, 1992; Murphy et al., 1993; Callahan et al., 1997; Li et al., 2000, 2009; McCarty et al., 2007; Pikul et al., 2007; Berndt, 2008; Barton et al., 2009; Fu et al., 2009; McClellan et al., 2009). The OM concentration by weight for thatch-mat from a 3-yr-old 'Penn A-1' creeping bentgrass green ranged from 16 to 25 g kg⁻¹ (McCarty et al., 2007), and a hybrid bermudagrass thatch-mat from Tifdwarf and TifEagle greens averaged 68 g kg⁻¹ (Berndt, 2008). The OM content for

¹ In turfgrass trade publications and, on occasion, scientific literature, the SOM is expressed as a percentage. For clarity in comparing results from cited publications, all references to OM concentration will be reported as g kg⁻¹ throughout this chapter.

organic materials used in sports-turf root-zone mixtures ranged from 960 g kg⁻¹ (Canadian sphagnum peat) to 400 g kg⁻¹ (Ohio muck peat soil) (McCoy, 1992). The percentage by weight for OM in aging creeping bentgrass putting greens varied from 21.9 g kg⁻¹ (0–7.6 cm root-zone depth) to 18.5 g kg⁻¹ (7.6–15.2 cm root-zone depth) (McClellan et al., 2009). The OM content for sand-based golf green root-zone soils ranged from 4 to 6 g kg⁻¹ (Li et al., 2000). The wide range of reported OM concentrations is due to markedly different sampling techniques and environmental and species differences.

Bulk Density and Porosity of Thatch

Intact thatch-mat from Tifdwarf and TifEagle hybrid bermudagrass putting greens had an average bulk density (ρ_b) of 0.62 g cm⁻³ (Berndt, 2008). Murphy et al. (1993) reported that the thatch-mat ρ_b of 3-yr-old 'Penneagle' creeping bentgrass maintained under greens conditions increased following reincorporation of hollow-tine cores and ranged from 0.24 to 0.70 g cm⁻³. The bulk density of reed sedge peat and sphagnum peat moss used for organic root-zone amendments has been reported as 0.253 and 0.141 g cm⁻³, respectively (Moody et al., 2009). The particle density (ρ_s) of materials in three organic horizons in undrained and naturally vegetated Carolina Bays averaged 1.6 g cm⁻³ (Caldwell et al., 2007), which is similar to the density of glucose, cellulose, and lignin (Kellogg and Wangaard, 1969; Dinar et al., 2006). Dinar et al. (2006) reported that the ρ_b values for Suwannee River fulvic acid and Pahokee Peat humic acid were 1.39 and 1.52 g cm⁻³. The variability of OM sources will affect estimates of the OM concentration in a sand-based, constructed root zone. The effect will be diluted as the green matures if the green is topdressed with sand. The duration of the effect will also be influenced by the sampling depth and analytical technique.

Information on the percentage of pore space in OM is limited. The term *pore space* is not usually applied to the individual components of OM, although cellulose does appear to have a porous internal matrix (Kuga and Brown, 1991; Hubbe et al., 2009). Tan (1985) referred to fulvic acid and humic acid as "fabrics" and presented scanning electron microscopy photomicrographs showing fulvic acid with a porous matrix. References have been made to pores in OM aggregates (Raturi et al., 2003). The total porosity (f) for hybrid bermudagrass thatch-mat from Tifdwarf and TifEagle putting greens averaged 77% (Berndt, 2008) when $f = 1 - (\rho_b / \rho_s)$ (Hillel, 1982). The total porosity of thatch from four cultivars of Kentucky bluegrass (*Poa pratensis* L.) averaged 66% when measured with an air pycnometer (Hurto et al., 1980).

Moisture Retention

Organic matter can retain or repel water. The hydrophilic or hydrophobic character of OM depends on the nature of the microstructures, the functional groups, and other surface properties (Ellerbrock et al., 2005; Koch et al., 2008). Peat and thatch may be hydrophilic and sorb water (Beard, 1973). Reed-sedge peat has a water-absorbing capacity (v/v) of 400 to 1200%, whereas other peat types vary from 150 to 3000% (Beard, 1973). Berndt (1986) reported volumetric water contents ranging from 113% at saturation to 64% at 10 cm tension to 24% at 60 cm tension for 'Touchdown' Kentucky bluegrass thatch. Volumetric water contents in excess of 100% are indicative of the extreme capacity for some OM sources to

sorb water. Humic substances also sorb water (Brooks et al., 2004). The hygroscopic growth factor (G), which is the ratio of the particle diameter at a given relative humidity (RH) compared with the particle diameter at 5% RH, indicated that for Fluka (a readily available humic source harvested in Switzerland) humic acid particles ranging in size from 50 to 200 nm in aerosols, G increased from near 1.1 at 60% RH to 1.9 at 90% RH. Pesticides used in turfgrass systems, such as dicamba (3,6-dichloro-2-methoxybenzoic acid), have a hydrophilic character and very small sorption coefficients (K_d), of less than 1 (Ochsner et al., 2006), whereas others may have a strongly hydrophobic nature and a K_d of more than 10,000 (Balogh and Anderson, 1992; Muwamba et al., 2009).

Hydrophobic soil associated with localized dry spot on creeping bentgrass putting greens has been shown to be caused by humic acid and fulvic acid coating the sand particles (Karnok et al., 1993). That humic substances cause localized dry spot may be a result of the conformation and spatial orientation of the polar (i.e., aliphatic) and nonpolar (i.e., carboxyl) surface groups in relation to the surfaces of the sand particles, and the ratio of OM phase to the mineral phase (Karnok et al., 1993; Ellerbrock et al., 2005). Particulate organic matter and organic coatings on mineral-fraction constituents are the recognized causes of hydrophobicity in soils (Moody et al., 2009). Fungi may contribute to soil water repellency by producing hydrophobic mycelia and exuding compounds such as waxes and fatty acids that form hydrophobic films (Fidanza et al., 2007; Moody et al., 2009). The hydrophobicity associated with OM is a management consideration, because it may lead to environmental problems such as leaching of surface-applied pesticides (Larsbo et al., 2008).

Solubility

The solubility of OM ranges from highly soluble to insoluble. The degree of solubility varies with physicochemical aspects such as polarity, pH, solvent, temperature, and atmospheric pressure. Glucose was reported to have a solubility of 91 g 100 mL⁻¹ H₂O at 25°C, whereas at 90°C, it was 556 (Bishop, 2009). The solubility of phenol was reported to be 8.7 g 100 mL⁻¹ H₂O (Reusch, 2008). Humic-substance fractions are separated based on their solubility in acid and base (Schnitzer, 1982). Both fulvic acid and humic acid are soluble in 0.1 M NaOH but humin remains insoluble. Acidification of the alkaline extract to pH 2 with 2 M HCl precipitates humic acid, while fulvic acid remains in solution. Berndt (2008) classified the carbon pools of hybrid bermudagrass thatch-mat as being fast-pool (FP) carbon or slow-pool (SP) carbon. The FP, or labile constituents (i.e., sugars, amino acids), are soluble carbon components with turnover times of 3 to 4 d, whereas the SP components consist of polymeric carbon compounds and are resistant to decay, having turnover times of 300 d or more because of the limited solubility of the constituents (Paul and Clark, 1996; McMahan et al., 2005; Coyne and Thompson, 2006; Berndt, 2008). Berndt (unpublished data, 2009) showed that the fraction of hybrid bermudagrass thatch-mat soluble in acid-detergent solution was 47 g kg⁻¹ for TifEagle and 42 g kg⁻¹ for Tifdwarf. These data were descriptive in nature and supported no structured research hypothesis. These results are similar to the results of proposed degradation models, which indicated that the size of the FP ranged from 2.5 to 6% of thatch carbon for Tifdwarf and from 1.7 to 4.4% of thatch carbon for TifEagle (Berndt, 2008).

Mineralization

Microbes are intimately associated with OM and use it as an energy substrate, mineralizing organic carbon to carbon dioxide and organic nitrogen to ammonium ion at rates controlled by factors such as solubility, substrate specificity, enzyme production, carbon-to-nitrogen ratio, size and age of the residue, and rate of nitrogen assimilation.

Mineralization rates may be described by first-order kinetics (Paul and Clark, 1996; Plante and Parton, 2007). First-order decay constants (k) for organic substances have been reported as 0.2 d^{-1} for sugars and amino acids, 0.08 d^{-1} for cellulose-hemicellulose, 0.02 d^{-1} for fungal cell wall, 0.003 d^{-1} for lignin, and $8 \times 10^{-7} \text{ d}^{-1}$ for old OM, with turnover times ($TT = 1/k$) ranging up to 3300 yr for stabilized SOM (Paul and Clark, 1996). Berndt (2008) used first-order kinetics to describe the rate of carbon mineralization for hybrid bermudagrass thatch-mat from Tifdwarf and TifEagle greens. The rate constant varied between 0.2 d^{-1} and 0.3 d^{-1} for FP, and 0.001 d^{-1} and 0.01 d^{-1} for SP. The corresponding carbon-pool half-life ($t_{1/2} = 0.693/k$) ranged from 2 d to more than 500 d. Similar data has been reported for the carbon mineralization of leaves, roots, and stems of production crops (Johnson et al., 2007). Kopp and Guillard (2004) reported nitrogen mineralization rates for cool-season turfgrass clippings that varied between 3.7 and 2.2 d^{-1} for k_1 and 0.16 and 0.11 d^{-1} for k_2 , while carbon mineralization rates varied between 6.6 and 2.3 d^{-1} for k_1 and 0.18 and 0.12 d^{-1} for k_2 . Qualls (2004) reported k values for the humic acid and fulvic acid of decomposing leaf litter of 7.8 yr^{-1} and 28 yr^{-1} for the labile phase (FP), and 0.066 yr^{-1} and 0.16 yr^{-1} for the refractory phase (SP). The corresponding $t_{1/2}$ ranged from 0.089 yr to 0.024 yr for the labile phase and 1.0 yr to 4.3 yr for the refractory phase. For various organic pesticides in soil supporting zoysiagrass (*Zoysia japonica* Steud.), Suzuki et al. (2001) reported k values from 0.08 d^{-1} to 0.00056 d^{-1} , with a $t_{1/2}$ from 8 to 1246 d. Decay constants may be derived from carbon dioxide evolution data corrected for efficiency using the equation $C = C_i[1 + Y/(100 - Y)]$, where C is the substrate decomposed, C_i is carbon dioxide carbon evolved, and Y is the efficiency (yield) of the use of carbon for biosynthesis, which is expressed as a percentage of the total carbon used for microbial material (Paul and Clark, 1996). Values of k corrected for efficiency may differ from uncorrected values. For example, the k for lignin of 0.003 d^{-1} (uncorrected) was reported as 0.006 d^{-1} when it was corrected for a microbial growth efficiency of 20% (Paul and Clark, 1996).

Biological Activities and Effects

Components of the OM pool have biological effects on plants and other life forms (Muscolo et al., 2007). Depending on their molecular weight and chemical structure, humic substances may display auxin-like activity, similar to that of indole-3-acetic acid (IAA) and 2,4-D [(2,4-dichlorophenoxy)acetic acid], and influence ion uptake by plant roots by affecting membrane permeability (Muscolo et al., 1998, 2007; Nardi et al., 2000, 2002a, 2002b). Lower molecular weight humic acids increased nitrate uptake and inhibited potassium-stimulated ATPase in maize (*Zea mays* L. 'Polaris') in a manner similar to gibberellic acid (Nardi et al., 2000). In addition, changes in mRNA occurred after treatment with humic acid. Analysis of polypeptides demonstrated that there was a posttranslational effect on protein synthesis, and thus on overall plant nutrition. Observed effects on

mRNA appeared to be related to the number of phenolic and carboxyl groups in the humic acid. Muscolo and Sidari (2009) found that the carboxylic and phenolic fractions of humic substances affected callus growth and enzyme activity in *Pinus nigra* Arnold. The carboxylic fraction improved the growth of the calluses and stimulated enzymatic activity, whereas the phenolic fraction had an inhibitory effect. These authors also reported that humic substances may modify metabolic processes such as respiration, induce morpho-functional changes in root architecture, and influence microalgae growth and seed germination. Zhang et al. (2009) reported that biosolids from anaerobically digested wastewater treatment plants contained $2.1 \mu\text{g auxin g}^{-1}$ and that the previously measured IAA content of the humic fraction of various biosolids ranged from 0.5 to $2.4 \mu\text{g g}^{-1}$.

Other constituents of OM may also have biological activity. Low-molecular weight organic fractions extracted from root exudates from maize and applied to *Picea abies* L. and *Pinus sylvestris* L. seedlings stimulated the uptake of nitrate and ammonium ions and also the activities of nitrate reductase, glutamine synthetase, and glutamate dehydrogenase in *P. sylvestris* seedlings (Nardi et al., 2005). These results indicated that low-molecular-size fractions in the soil affect a plant's capacity to adapt to low soil-nitrogen levels (Nardi et al., 2002a, 2002b, 2005), which may be a competitive advantage. Yoshitomi and Shann (2001) reported that root exudates enhanced the mineralization of pyrene (benzo[def]phenanthrene), parathion [*O,O*-diethyl *O*-(4-nitrophenyl) phosphorothioate], 3-chlorobenzoate, atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine), and petroleum hydrocarbons. Castaldini et al. (2005) and LeBlanc et al. (2007) reported that the insecticidal toxin produced by transgenic plants transformation with genes from *Bacillus thuringiensis* Berliner (Bt) is released via root exudates, the decay of plant residues, and pollen. The Bt toxin is an approximately 66 kDa protein with a residual activity of 180 to 234 d when adsorbed to humic acid or clays. Residues from Bt plants also had significant effects on rhizospheric eubacterial communities and levels of mycorrhizal colonization compared with non-Bt plants (Castaldini et al., 2005).

Siderophores, phenols, plant growth regulators such as ethylene, antibiotics, phytoalexins and allelochemicals, and volatile organic compounds all have biological activity (Paul and Clark, 1996). Certain strains of *Pseudomonas fluorescens* Flügge, which may be present in both bentgrass and bermudagrass greens (Elliott et al., 2008), produce siderophores that are detrimental to rhizosphere pathogens (Paul and Clark, 1996). The fluorescent pigment pyoverdinin is the siderophore, and under certain conditions, the pigment can act as a diffusible bacteriostatic or fungistatic antibiotic (Haas and Defago, 2005). Tricin is a phenolic compound that occurs in high concentrations in the leaves of *Festuca* spp. and is being studied for its ability to prevent colon and breast tumor formation in humans (Hudson et al., 2000). Of the compounds investigated, tricetin had the most potent anticarcinogenic effect, with an IC_{50} (concentration of an inhibitor where the response, or binding, is reduced by half) of $16 \mu\text{mol L}^{-1}$ in colon cells and $0.6 \mu\text{mol L}^{-1}$ in breast cells. Wegner et al. (2010a) identified supina bluegrass (*Poa supina* Schrad. 'Supra-nova') and bermudagrass ('Sovereign') as having elevated phenolic compounds, with resulting antioxidant activities twice that of blueberries, a commonly referenced nutraceutical. Wegner et al. (2010b) also reported in vitro antiproliferation of liver carcinoma cells with phenolic extracts of the same species. Allelopathy between turfgrasses and other plants has been reported (Brede, 1991; Smith and

Martin, 1994; Springer, 1996; Mattner and Parbery, 2001). Mattner and Parbery (2001) reported that soil under perennial ryegrass (*Lolium perenne* L.) infected with crown rust (caused by *Puccinia coronata* Corda f. sp. *lolii* Brown) suppressed white clover (*Trifolium repens* L.) biomass from 27 to 56% compared with soil under uninfected ryegrass. Botanical extracts from *Brassica juncea* (L.) Czern., poinsettia (*Euphorbia pulcherrima* Willd.), and spotted spurge (*Chamaesyce maculatae* L. Small) were effective in suppressing populations of sting nematode (*Belonolaimus longicaudatus* Rau) as shown by direct mortality counts (Cox et al., 2006).

Results in the literature on the biological activity of various OM fractions and compounds could influence future research conducted on turfgrass and other agricultural systems. The research reported here on components of the OM pool in turfgrass systems that might be studied for use as plant growth regulators, pesticides, antibiotics, or therapeutic cancer agents alludes to that potential but will require additional and creative research.

Microbial Biomass

While not a property of OM per se, there is a characteristic diversity among microorganisms within the continuum of OM. Such diversity may be spatially or temporally distinct, or both, due in part to the wide range of available substrates in the OM pool (Killham and Prosser, 2007). Many microorganisms grow on simple constituents found in the OM pool, such as glucose (Degens, 1998; Kelso et al., 1999; Haas and Defago, 2005; Basu et al., 2006; Killham and Prosser, 2007), whereas others can utilize more complex substrates. Shary et al. (2008) grew *Phanerochaete chrysosporium* P. Karst on cellulose as the carbon source and monitored the mineralization of ¹⁴C-labeled lignin. Pinchuk et al. (2008) reported that the metal-reducing bacterium *Shewanella* spp. used DNA as the sole source of both phosphorus and carbon, and de la Peña Mattozzi et al. (2006) reported that a transgenically constructed strain of *Pseudomonas putidia* Trevisan was able to utilize the organophosphate pesticide paraoxon (diethyl 4-nitrophenyl phosphate) as the sole source of phosphorus and carbon.

The concentration of OM may play a role in the diversity of microorganisms (Haas and Defago, 2005). Sites of intense root exudation are more strongly colonized by fluorescent pseudomonads than are root tips (Haas and Defago, 2005). Estimates of stationary-phase bacterial biomass in batch cultures with water from a humic lake ranged from 0.07 to 6.2 $\mu\text{mol L}^{-1}$ carbon and increased linearly with the concentration of dissolved organic carbon ($R^2 = 0.96$) (Eiler et al., 2003). The dissolved organic carbon concentration also influenced the composition of bacterial communities that developed in the cultures. Allison et al. (2005) reported that an increasing amount of soil organic carbon in row-crop soil was positively correlated with higher ratios of fungi to bacteria, ($R^2 = 0.82$), assessed as relative abundances of phospholipid fatty acids, but in prairie chronosequence soils, the association was weak and negatively correlated ($R^2 = 0.28$). Mancino et al. (1993) reported differences in fungal populations between thatch (4.8 $\log_{10} \text{g}^{-1}$) and 80:20 sand/peat soil (1.1 $\log_{10} \text{g}^{-1}$) in a USGA-style creeping bentgrass green. Fungal counts in thatch were 500 to 1600 times higher than in sand-peat soil. These results imply that plant communities may be a determinant of microbial community structure (Frey, 2007).

The physicochemical properties of OM may also play a role in microbial diversity. Grigera et al. (2006) reported that bacterial and actinomycete biomarkers were more highly correlated with fine POM ($r = 0.85, 0.71$) than with coarse POM ($r = 0.69, 0.48$), whereas fungal and mycorrhizal biomarker concentrations correlated only with coarse POM ($r = 0.77, 0.78$). Kerek et al. (2002) found that microbial biomass increased with the age of greens ($R^2 = 0.87$), due mainly to the accumulation of POM. Spatial distribution of microbial biomass was determined by the location of the humic substances and vice versa.

Other Properties

In addition to those discussed above, other properties of OM include the following: The pH_{dist} of hybrid bermudagrass thatch-mat was reported to average 6.75, and the carbon/nitrogen ratio was 13.9 for Tifdwarf to 19.9 for TifEagle (Berndt, 2008). The electrical conductivity for both cultivars averaged 1.43 dS m^{-1} . Moody et al. (2009) reported that organic root-zone amendments had carbon/nitrogen ratios ranging from 18.6 to 68.1 and electrical conductivities from 0.51 to 13.52 dS m^{-1} . Wu et al. (2003) presented data in which the carbon/nitrogen ratio of agricultural runoff material varied from 4.9 to 10.6 and was highly correlated with the size fraction (light or heavy). The carbon/nitrogen ratio of the light POM from agricultural, forest, and grassland ecosystems ranged from 15.5 to 33.7 (Gregorich et al., 2006). Glutamine has a carbon/nitrogen ratio of 2.5 (Paul and Clark, 1996). Thompson et al. (1983) reported redox potential values between 0 and +500 mV for Kentucky bluegrass thatch. Berndt and Vargas (1992) reported that lactate decreased the redox potential ($\text{pe} + \text{pH}$) in putting-green sand. Equilibrium reactions for various organic compounds at 25°C were presented by Lindsay (1979). The $\log K^\circ$ value for the oxidation of glucose to carbon dioxide was reported to be 5.03, whereas for acetate it was -9.64 . For the reduction of carbon dioxide to methane, $\log K^\circ$ was 22.91. Danneberger et al. (1984) reported that CEC values for Merion Kentucky bluegrass thatch ranged from $46.5 \text{ cmol}_c(\text{Na}) \text{ kg}^{-1}$ to $116.2 \text{ cmol}_c(1/2\text{-Ba}) \text{ kg}^{-1}$. Many other characteristics have been reported for humic substances and OM, including variables such as atomic ratios (hydrogen/carbon, oxygen/carbon), distribution coefficients (K_d), various sorption parameters (K_{oc}), and nutrient contents (nitrogen, phosphorus, potassium) (Mao et al., 2000; Balcke et al., 2002; Hur and Schlautman, 2004; Wang and Xing, 2005; He et al., 2006).

Advantages and Disadvantages of Organic Matter

The presence of OM in turfgrass soils has benefits and liabilities depending on its nature, the extent of accumulation, and the intended use of the site. Thatch-mat may provide resiliency, cushion, wear tolerance, insulation from environmental extremes, raise the CEC and water holding capacity, and reduce the pH in calcareous soils when moderate in quantity, but if OM becomes excessive, then disadvantages prevail (Beard, 1973; White and Dickens, 1984; Callahan et al., 1997; McCarty et al., 2005, 2007; McClellan et al., 2007; Barton et al., 2009; Fu et al., 2009). McCarty et al. (2005, 2007) summarized the disadvantages associated with excessive thatch-mat, including reduced hydraulic conductivity, lower rates of water infiltration, the appearance of localized dry spot, reduced tolerance to environmental extremes, more disease and insect problems, and reduced pesticide effectiveness. Other associated problems include the elevation of crowns

and reduced rooting into the subsoil, winter desiccation, chlorosis, footprinting, scalping, and puffiness (Beard, 1973); reduced gas exchange and low redox potential (Thompson et al., 1983); reduced aesthetic value (Meinhold et al., 1973); and development of uneven playing surfaces (Murray and Juska, 1977). McClellan et al. (2007) and Lewis et al. (2010) indicated development of the mat layer is responsible for temporal changes in chemical and physical properties of putting-green root zones. Carrow (2004a, 2004b) reported that lower oxygen levels resulting from increasing amounts of OM in a sand-based root zone is the primary cause of many secondary problems, including reduced saturated hydraulic conductivity and decreased rooting. Lewis et al. (2010) reported that differences in the particle size distribution between root-zone and post-construction topdressing sand were, in addition to OM accumulation, responsible for the decrease in water infiltration over time in aging golf greens. The authors, however, did not discuss which factor (i.e., OM accumulation or particle size distribution) was more significant.

The presence of SOM or humic substances are advantageous because they release and store nutrients (Paul and Clark, 1996, Kerek et al., 2003), increase CEC (McCarty et al., 2003; McClellan et al., 2007; Kaiser et al., 2008), conserve microbial biomass (Kerek et al., 2002), suppress diseases (Stone et al., 2001), enhance water retention (Brooks et al., 2004), and improve soil structure and aggregation (Abbas and Fares, 2009). They may also have desirable biological activity, such as enhancing enzymatic activity and nutrient uptake (Nardi et al., 2005). Supplemental additions of OM may also be beneficial. Biosolids may enhance plant stress tolerance and growth as a result of their biological activity (Zhang et al., 2009). These authors reported data suggesting that the application of biosolids alters the IAA and cytokinin contents in tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh.] and improves plant resistance to drought. When perennial ryegrass was exposed to a prolonged stress of high air temperatures, treatments with an amino acid-based biostimulant resulted in 95% better photochemical efficiency and 65% better membrane thermostability over that of the controls (Kauffman et al., 2007). Treating Kentucky bluegrass with salicylic acid improved its heat tolerance (He et al., 2005). Melero et al. (2008) reported that organically fertilized soils showed greater total organic carbon, Kjeldahl nitrogen, available phosphorus and potassium, microbial biomass, and enzymatic activity compared with inorganically fertilized soils. Tejada and Gonzalez (2007) reported that application of an organic residue (cotton-gin-crushed compost) improved the physical, chemical, and biological properties of the soil and increased the yield parameters of wheat. The application of sewage sludge, however, adversely affected the biological properties and reduced the wheat yield because of the presence of heavy metals, and the application of beet vinasse had an adverse effect on properties and wheat yield because of the high amounts of sodium and fulvic acid, which destabilized the soil structure.

Mineralization of OM may be problematic. Abbas and Fares (2009) reported that increasing amounts of SOC in tropical soil raised the amount of carbon dioxide released ($R^2 = 0.91$), contributing to the greenhouse gas emissions thought responsible for global climate change. Warmer soil temperatures may also induce the mineralization of SOM, thus stimulating the release of carbon dioxide release (Plante et al., 2009). Subsidence of drained organic soils due to mineralization by aerobic microbial biomass has been reported (Shih et al., 1981; Rojstaczer and Deverel, 1995; Morris et al., 2004a, 2004b). Rates of subsidence in organic soils

in the Everglades in Florida ranged from 1.84 to 2.34 cm yr⁻¹ (Shih et al., 1981), although more recent reports cite average rates of 1.4 cm yr⁻¹ (Morris et al., 2004b). Historical rates of subsidence in drained histosols and highly organic mineral soils in California have ranged from 2.8 to 11.7 cm yr⁻¹ (Rojstaczer and Deverel, 1995). Minimum tillage can be used on histosols to reduce carbon loss and thereby reduce subsidence (Morris et al., 2004a), which means that turfgrass systems may represent an advanced carbon-conservation strategy. The reader is encouraged to view the chapter on sustainability (Johnson et al., 2013) in this monograph for more information.

Analytical and Sampling Methods to Determine Organic Matter Concentration

Methods exist for in-depth characterization of biological, chemical, and physical properties of OM. Many of these methods have been mentioned earlier in this chapter, but it is not the purpose of this discussion to compare and contrast these methods. (Readers interested in doing so are encouraged to use the extensive literature cited at the end of this chapter.) Within the scope of this chapter, however, is a review of the methods used to quantify OM concentration. Historically, two methods have been used: loss on ignition (LOI) (Storer, 1984) and the Walkley–Black procedure (Walkley and Black, 1934). The LOI method is used more extensively because of the ease of sample preparation, the capacity to process large number of samples, and the lesser chance of method error than with the wet chemistry required for the Walkley–Black procedure (Sollins et al., 1999). The Walkley–Black method also produces hazardous waste that is known to be carcinogenic (Combs and Nathan, 1998).

The LOI method combusts the OM fraction of a sample at high temperature and determines the content of OM via the subtraction of the final weight from the initial weight. While elegant in its simplicity, the correct ignition temperature is critical for the accurate determination of the OM concentration. Ball (1964) tested samples at both 850 and 375°C and reported a high correlation between temperatures but suggested that using the lower temperature is the preferred procedure because heating soils in excess of 500°C can volatilize substances other than the OM of interest. Those substances are primarily calcareous in nature and are common in many soils throughout the world. Ashing below 500°C will not affect the results for the OM (Jackson 1958; Ben-Dor and Banin, 1989). Schulte et al. (1991) have also reported sample-size and preheating effects when using the LOI technique. Walkley and Black (1934) reported a 60 to 86% recovery of organic carbon in agricultural soils, resulting in a recovery factor of 77%, which is commonly used to convert “easily oxidizable” organic carbon to total organic carbon (Combs and Nathan, 1998). Nelson and Sommers (1982) suggested that the use of the Walkley–Black method is problematic because of the potential for underestimating soil carbon by 20 to 30%. The Walkley–Black method is used in few contemporary papers but is often in the older literature on OM.

VanLoo (2008) provided a side-by-side comparison of the LOI and Walkley–Black methods in sand-based turfgrass root zones. Additionally, Sollins et al. (1999) compared a carbon–nitrogen (CN) analyzer with the LOI and Walkley–Black procedures. The CN analyzer measures total carbon in the soil through high-temperature, multiple-sample, dry-combustion analyzers. While relatively

expensive, the method provides precise and reproducible results. However, LOI consistently showed higher OM contents than either the Walkley–Black method or CN analyzer, both of which produced comparable results. The three analytical procedures used in this study (Sollins et al., 1999) resulted in different values for the same sample, indicating the importance of using the same procedure when measuring OM concentrations and caution when comparing data from other locations or studies in which a different technique is used.

While turfgrass research has primarily restricted sample analysis to the LOI or Walkley–Black procedures, more refined methods have been used in other soil systems. These systems use the biologically active OM to better characterize the dynamics of SOM. Changes in SOM occurring over short periods are differentiated by turnover rates (Paul and van Veen, 1978; Parton et al., 1987). In these models, biologically active SOM has been represented by active and slow fractions (Parton et al., 1987) and the microbial biomass and decomposable pools (Paul and van Veen, 1978). Measures of biologically active SOM can be used as early indicators of change in the status of the SOM (Powlson et al., 1987; Gregorich et al., 1994).

The American Society for Testing and Materials (ASTM) has published procedures to determine OM concentration (i.e., LOI), but they do not provide specifications for sampling procedures, specifically the depth of the sample (ASTM, 2002). Sampling procedures for OM in turfgrass systems presents a unique set of challenges, not the least of which is inconsistency from study to study in the depth and size of the samples and the inclusion or exclusion of the thatch and verdure layers. A random review of 20 of the refereed papers cited in this chapter indicated a range of sampling depths from 5.0 to 30 cm and sample diameters of 2.0 to 10.9 cm. The most frequent sampling diameter and depth were 2.5 and 15 cm. Differences in sampling procedures are a result of a lack of recognized standardized sampling procedures for OM concentration in turfgrass research and of a reliance on a traditional sample depth of 15 or 30 cm, which are commonly used in agricultural crop production research and practice. The comparison of treatments within a study is usually not an issue; however, comparison of results from studies using different sampling procedures will be confounded. Until a standardized testing procedure is developed, sampling will continue to be somewhat arbitrary. When determining a sampling procedure for a scientific investigation the objective should be clearly understood and plans made accordingly. When determining an appropriate sampling depth, the spatial distribution of the organic layer should be considered, and the sample should represent the zone of interest. McClellan et al. (2009) indicated that separating soil samples into mat and original root zone instead of predetermined soil sampling depths eliminated most of the confounding interactions in a multifactor, multiyear study on sand-based root zones. From a practical standpoint, when turfgrass professionals are advised on how to obtain a sample, consistency is critical because in most instances they will be evaluating effectiveness on proposed or ongoing management practices.

Organic Matter Management

Routine management practices, such as mowing, fertility, irrigation, etc., will influence OM accumulation to varying extents, and textbooks by Beard (1973),

Madison (1971), Turgeon (2008), and others discuss those influences. The intent here is to summarize current research related specifically to OM management in sand-based root zones. The well-documented physical, chemical, and biological complexity of OM presents a significant challenge in simplifying the understanding of the dynamics of accumulation and degradation; however, management strategies can be simplified into three processes: enhanced degradation, mechanical removal (i.e., cultivation), and dilution (i.e., topdressing). These processes often augment each other, and practitioners will use multiple strategies to achieve a desired result. These processes will be described below, with the primary emphasis on OM management in highly managed sand-based root zones. In the literature, recommendations for optimal OM levels vary greatly, ranging from 15 to 80 g kg⁻¹ (Adams, 1986; McCoy, 1992; Murphy et al., 1993; Carrow, 2004a, 2004b; Vermeulen and Hartwiger, 2005). This variability is indicative of the previously mentioned concerns with sampling and analytical differences in addition to possible environmental differences from the reporting research locations and different or modified analytical techniques.

Enhanced degradation occurs when management practices improve biological activity by creating or amplifying conditions favorable for the degradation of OM components. Many cultivation techniques increase the surface area and the airflow, and thus potential oxidation of OM, properties that are well documented to accelerate degradation. Numerous products are marketed to practitioners purported to elevate biological activity, resulting in accelerated degradation of OM, primarily thatch (Berndt, 1986; Berndt et al., 1990; Callahan et al., 1998; Kaminski et al., 2004).

Physical removal involves some form of cultivation. Turfgrass cultivation includes many mechanical processes used to modify the characteristics of the turf and the root zone. Those practices are intended to alleviate the problems of compaction, poor aeration, and thatch build-up, whereas other practices, such as grooming, are more often used to improve surface uniformity by reducing the grain. The principal cultivation practices used are coring, spiking, slicing, drilling, vertical mowing, and, to a limited extent, air or water injection. Cultivation improves growing conditions in the upper portion of the root zone by increasing air movement to the roots and air exchange to the atmosphere, improving wetting and drying, enhancing water infiltration, stimulating root growth, and improving the response of turfgrass to applied fertilizers (Turgeon, 2008). Tine (core or solid) cultivation is one of the most practiced procedures used in the management of turfgrass; however, there are distinct differences in the cultivation methods used worldwide. Tremendous variability exists in the timing, frequency, intensity, equipment used, and follow-up operations, including topdressing. Core cultivation is the most frequently recommended cultivation technique for removing OM. Core cultivation is achieved by inserting hollow tines into the root zone, removing small cores of soil and OM (if present) that are between 0.64 and 2.54 cm in diameter. The amount of the putting green impacted by core cultivation is related to the coring frequency, tine spacing, and tine size (Table 12-1). Based on surface area impacted, for core cultivation to effectively remove SOM and have an effect on SOM concentration, the tine diameter needs to be large, the spacing between cores small, and cultivation frequent (Hartwiger and O'Brien, 2001; Oatis, 2002; Ervin and Nichols, 2011). The recovery time after core cultivation is primarily affected by the tine diameter and not by the depth and spacing. When smaller tines (0.65 cm diam.) are used, the recovery time will be minimized and

Table 12-1. Surface area impacted by cultivation tines as affected by tine spacing and diameter.†

Tine diameter		Tine spacing		Surface area
in	mm	in	mm	%
0.25	6.4	1 × 1	25.4 × 25.4	4.91
0.25	6.4	1 × 2	25.4 × 50.8	2.45
0.25	6.4	2 × 2	50.8 × 50.8	1.23
0.38	9.5	1 × 1	25.4 × 25.4	11.04
0.38	9.5	1 × 2	25.4 × 50.8	5.52
0.38	9.5	2 × 2	50.8 × 50.8	2.76
0.50	12.7	1 × 1	25.4 × 25.4	19.63
0.50	12.7	1 × 2	25.4 × 50.8	9.82
0.50	12.7	2 × 2	50.8 × 50.8	4.91
0.63	15.9	1 × 1	25.4 × 25.4	30.68
0.63	15.9	1 × 2	25.4 × 50.8	15.34
0.63	15.8	2 × 2	50.8 × 50.8	7.67

† Adapted from Hartiwiger and O'Brien, 2001 (with permission).

will be approximately half the time it takes turf to recover from coring with bigger tines (0.13 cm diam.) given an equal surface area (Landreth, 2005; Landreth et al., 2008; Ervin and Nichols, 2011).

Scarification is a broad term used to describe the cultivation of the putting-green surface by raking, vertical cutting, or both. Various mechanical devices are used to cut vertically into the root zone, the main differences between them being the depth, spacing, and thickness of the knives or blades. Surface grooming involves cutting at a minimal depth into the turf to sever stolons and decumbent leaves. This process is used more to reduce the grain and will have only a minor effect, when not combined with topdressing, on thatch development. Deep scarification is a very disruptive process and is often performed as part of major renovation. It involves setting the vertical blades to penetrate into the root zone and will result in a large quantity of thatch and soil being deposited on the surface (Shildrick 1985; Dernoeden, 2002; Landreth et al., 2008). Vertical cutting has been shown to be more effective than core cultivation for removing SOM (Landreth et al., 2008). The effectiveness of vertical cutting is related to the thickness of the blades and the depth of cutting. The greatest amounts of OM are removed when the thickest blades (3 mm) and the closest blade spacing are used to depths of 2.5 to 3 cm (Lockyer, 2009). A cultivation of this intensity will result in severe surface disruption, and reports suggest a long recovery process (Landreth et al., 2008). The timing of this process is critical, and research indicates that intensive verticutting should be performed only during a greens renovation program, before a period of active growth, or when recovery time is not a major consideration (Landreth et al., 2008). In a 2-yr study, Schmid (2008) reported no differences in OM concentration between solid- or hollow-tine cultivation and no-tine treatment when topdressing application quantities were equal Sorokovsky et al. (2006)

reported no differences in the reduction of OM over time whether plots were core cultivated or not cultivated. The authors attributed their results to the low surface area impacted by the cultivation used in their investigation.

Topdressing

The practice of topdressing putting greens is not a new or unique practice. It is often credited to a historical icon in turfgrass management, Old Tom Morris (1821–1908). He is thought to have discovered the benefits of topdressing accidentally when he spilled a wheelbarrow of sand on a putting green and noted how the turf thrived shortly afterward (Hurdzan, 2004).

The practice of topdressing golf greens is used for a multitude of reasons. Sand topdressing will help to maintain a fast, level surface that will produce uniform ball roll. Topdressing requirements for golf greens will be proportional to the rate of build-up or OM relative to the grass species, environmental and climatic conditions, the degree of management, and the required playing conditions (Turgeon, 2008). The main considerations in developing a topdressing program for putting greens are the nature of the material used, the intensity of application (including quantity and timing), and the methods of application and incorporation. Sand is the most common material used on putting greens, including those with native-soil and sand-based root zones.

If the main purpose for topdressing is thatch management, it is reasonable to assume that the quantity of topdressing should match the rate of thatch accumulation. Adams and Saxon (1979) developed a predictive equation in which annual topdressing is related to the input of humified plant residues (% OM content of the topdressing), and the desired SOM content as follows:

$$T = \frac{I(D-100)}{P-D} \quad [1]$$

where T is the amount of annual topdressing (kg m^{-2}), I is the input of humified plant residues (kg m^{-2}) (% OM content of topdressing $\times 0.25$), D is the required SOM content (%), and P is the OM content of the topdressing (%). A literature review indicates that, although this equation has been referenced in several publications, it does not appear to have been widely adopted. Given the apparent lack of rigorous testing of the equation across locations and conditions, its evaluation and refinement is a logical avenue of research.

Combining Topdressing and Cultivation

Sand is often applied following cultivation, and in this case, the quantity applied will be related to the cultivation method used. Researchers have reported that topdressing improved water infiltration for up to 8 wk and minimized OM accumulation when combined with core cultivation (Oatis, 2002; Carrow 2004a, 2004b; Ervin and Nichols, 2011). McCarty et al. (2007) reported that sand topdressing alone did not adequately control thatch accumulation or increase water infiltration rates in bermudagrass, whereas combination treatments with core cultivation, verticutting, and topdressing controlled thatch accumulation without causing detrimental effects to the turfgrass surface.

Table 12-2. Application frequency needed and cultivation combinations to apply 0.67 m³ m⁻² topdressing sand on creeping bentgrass putting greens in Mead, NE, 2006–2007.†

Treatment	Interval‡
	d
No tine treatment/no summer cultivation	5–10
Solid and hollow tine/no summer cultivation	7–14
Solid and hollow tine/summer cultivation	14–18

† Adapted from Schmid, 2008.

‡ Recorded and calculated based on desired topdressing quantity, tine displacement, and exposed surface area receptive to sand incorporation.

Schmid (2008) surveyed 105 golf courses in 15 states for cultural practices and OM content to determine if a cause-and-effect relationship could be determined. Data collection included location demographics and environmental data, and a superintendent supplied a summary of routine management practices and OM concentrations as determined by LOI from samples 2.54 cm in diameter by 7.6 cm deep. Variables that caused significant differences in OM concentrations were entered into multivariate linear regression models using backward, forward, and stepwise selection procedures to construct the final model. Variables in the final model included the frequency and quantity of sand topdressing, the cultivation frequency, and the age of the putting green. Older greens had more OM, which was an artifact of the consistent sampling depth regardless of the green's age and the depth of the mat layer. Sites that applied topdressing every 7 to 14 d had significantly lower OM contents than greens topdressed less frequently. Sites using summer cultivation techniques (i.e., venting) had less OM than those cultivating once or twice per year. When used as a prediction equation, however, the fit of the regression model was statistically weak, a result that supports the complexity of the parameters involved in OM concentration. Cultural practices, such as frequent topdressing and cultivation timing, were identified as consistent factors that reduced OM concentrations.

In a more controlled, 2-yr field study, Schmid (2008) investigated tine type (hollow, solid, or none) combined with spring and fall cultivation; summer cultivation (needle and bayonet tine, PlanetAir, Hydroject and no summer cultivation) resulting in a 3 (tine type) × 5 (summer cultivation) factorial design. A unique approach to this study was equalizing the topdressing quantity across all treatments and adjusting the frequency of application to ensure that the main effects would not be confounded by variable topdressing amounts. After 2 yr of treatment, results indicated that no cultivation treatment combination resulted in significant reduction in OM compared with no cultivation. Misinterpretation of this data would imply that cultivation is not critical for OM management, which is fraught with potential adverse impacts. The equalization of the topdressing quantity across all treatment combinations and the estimates of the needed increase in frequency (Table 12-2) reveal the impracticality of not using cultivation in combination with topdressing and overlook the positive impact that many cultivation techniques have on properties other than OM management.

Research Priorities

There is a significant body of literature characterizing the physical, chemical, and biological properties of OM in a variety of plant systems. While it may be relatively simple to duplicate that research in turfgrass systems, it is clearly overshadowed by the practitioners' need for investigations of more general protocols that will facilitate a better understanding and more successful management of OM in highly managed turfgrass installations. Before such research can even begin, however, it is critical to have fundamental information about the OM concentrations that have adverse effects on turfgrass function and growth across environments (i.e., the "magic number" requiring reduction) and about standardized sampling and analysis techniques. While numerous concentrations have been identified either by structured research or speculation, the wide range of reported values indicates that there is no all-inclusive understanding of what constitutes an adverse OM concentration. While this may be a lofty research objective, it would appear feasible given the foundation of past research and the advent of inclusive computer modeling and statistical techniques.

Summary

Understanding the management of OM accumulation in turfgrass systems is complex and often contradictory. Many factors influence OM accumulation, including the type of grass, the rate of plant growth and decay, chemical and physical properties of the soil, biological activity, cultural practices, and environmental conditions. In turfgrass installations, OM may range from simply a predominantly organic thatch layer in a Kentucky bluegrass home lawn to a mixture of OM, sand, and biological by-products in a well-managed golf putting green. As is typical of most biologically based systems it is difficult to simplify the dynamic, diverse, and multifaceted condition of OM accumulation in turfgrass. The reader is encouraged to use this chapter as a guide to a better understanding of the current body of literature on the topic and if so inclined, pursue research to fill the voids in understanding OM accumulation in turfgrass or, if a turfgrass practitioner, use the information as an aid in developing management strategies.

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