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REVIEW & INTERPRETATION

Agronomic and Physiological Responses of Cool-Season Turfgrass to Fall-Applied Nitrogen

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ABSTRACT

Turfgrass is an integral component of the urban and suburban landscape and plays a key role in water quality and nutrient cycling. Nitrogen (N) is the mineral nutrient most limiting for turfgrass growth and development and is often applied as fertilizer to maintain adequate soil levels. Rising energy and subsequent N costs and environmental concerns have pressured turfgrass managers to schedule N applications to maximize N use efficiency. Late-fall N fertilization for cool-season turfgrass is a widely accepted practice among turf managers, with application rates ranging from 49 to 98 kg N ha^{-1} and accounting for 25 to 50% of annual N applied. Reported benefits from late-fall N fertilization include improved color in fall and spring without stimulation of shoot growth, improved rooting in late fall and early spring, carbohydrate accumulation in late fall, and the ability to delay or avoid fertilizing in the spring. However, research supporting these benefits in cool-season turfgrass is limited and has yielded mixed results. Much of this work was conducted in relatively warm or temperate coastal climates and may not be applicable to cooler temperature regimes of more northern climates. More recent research has indicated a greater potential for nitrate leaching losses from late-fall N due to cooler temperatures reducing plant uptake and microbial immobilization of N. This literature review finds that the often cited physiological and agronomic benefits of applying late-fall N applications are poorly supported by peer-reviewed research, with the exception of fall and spring color responses. More climate-specific research on plant utilization and response to fall-applied N is necessary to determine appropriate N rates and optimal timings for this highly specific application.

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Turf accounts for the vast majority of the pervious surface area in the urban and suburban landscape. The total area of turf in the United States is estimated to be larger than that of irrigated corn (*Zea mays* L.) (Milesi et al., 2005) and it will continue to grow, with urban populations expected to increase 79% in the next 25 yr (Alig et al., 2004). Through its relationship with the urban landscape, turfgrass plays a prominent role in nutrient cycling and urban water quality.

Nitrogen (N) is the mineral nutrient required in greatest amounts in plants and is often the most limiting nutrient for turfgrass growth and development (Liu et al., 2008). Nitrogen is essential in the structure and function of amino acids, amides, nucleotides, nucleic acids, pigments, and some hormones (Hull and Liu, 2005). The nearly perpetual vegetative state of turfgrass and the physiological importance of N for new growth make turfgrass capable of assimilating much higher rates of N than are generally applied (Kussow, 1987; Bowman, 2003). Under ideal conditions, increased shoot growth responses are linearly correlated with N fertilization rates up to 11.1 kg N ha^{-1} d^{-1} (Bowman, 2003) and 1000 kg N ha^{-1} yr^{-1} (Kussow, 1987). The importance of N to turfgrass growth and development coupled with the seasonally inconsistent availability of mineral N in the soil make N the nutrient required and applied in the largest quantity. In practice, fertility programs that moderate the supply of N to maintain

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submaximal levels of turfgrass growth and some level of N deficiency are often the normal state for turfgrass management (Bowman, 2003).

Traditional fertility programs that base nutrient application on historical practices or time of year often result in significant nutrient losses (Horgan and Rosen, 2010). Improving our understanding of efficient N use has been the goal of turfgrass researchers for many years (Hull and Liu, 2005). With increasing N fertilizer costs, turfgrass managers can no longer afford to make N applications that move off-site and/or do not benefit their system. In the United States alone, N fertilizer prices have more than doubled since 1990 (ERS, 2010), reaching historic highs in mid-2008 due to high fertilizer demand and the inability of manufacturers to increase production levels (Huang et al., 2008). In the future, energy-intensive products used in turfgrass management (such as N) may be less available, yet demands for new turfgrass areas will likely increase (Busey and Parker, 1992). For this reason, it is imperative that turfgrass managers understand how to maximize the efficiency of their N applications.

The fate of N in the turfgrass environment can be narrowed down to six basic processes: clipping disposition, N sequestration, nitrate leaching, nitrate runoff, denitrification, and ammonia volatilization (Hull and Liu, 2005). The latter four processes are off-target N losses that have environmental implications; particularly ground and surface water contamination and alteration of atmospheric composition. Research conducted on the environmental fate of applied N in turfgrass systems has concluded that proper N management practices greatly reduce N loss (Starr and DeRoo, 1981; Miltner et al., 1996; Horgan et al., 2002; Frank et al., 2006; Paré et al., 2006). However, research specific to late-fall N applications has identified a potential for increased NO_3 leaching due to restricted plant uptake, decreased microbial immobilization, and the disparity between high precipitation and low evapotranspiration (Petrovic, 1990; Geron et al., 1993; Miltner et al., 1996, 2001; Guillard and Kopp, 2004; Frank et al., 2006; Mangiafico and Guillard, 2006).

This review focuses on research surrounding the agronomic and physiological benefits of fall-applied N in cool-season turfgrass management, which is a widely accepted practice among turfgrass managers and researchers in temperate climates, accounting for as much as 50% of the annual N applied. Knowing that price and environmental impacts are important components in the cost–benefit analysis of N fertilizer applications, it is critical that we gain an understanding of the agronomic and physiological benefits of this highly specific application.

CURRENT FALL FERTILIZER RECOMMENDATIONS

Annually, 50 to 250 kg N ha^{-1} is typically recommended for cool-season turfgrasses, depending on a variety of factors (Liu et al., 2008). Nitrogen fertilizers are generally applied between one and 20 times with various rates, timings, and sources throughout the growing season. The recommended scheduling of N applications is often based on turfgrass function and expectations. In addition, scheduling can be influenced by the perceived N availability in the soil, which is largely derived from temperature- and moisture-dependent mineralization of the organic N pool. Although soil organic N is often abundant in turfgrass systems and can mineralize at the rate of 40 to 160 kg ha^{-1} yr^{-1} (Hull and Bushoven, 2001), the lower soil temperatures associated with spring and fall result in low rates of available mineral N, often creating a need for N fertilizer additions to maintain acceptable color and quality. Early-spring N fertilization in cold climates is widely considered undesirable by turf managers concerned that the characteristically low soil temperatures will inhibit root development and hinder the plant's ability to survive the heat and drought stresses of summer (Koski, 1988; Kussow, 1992). Therefore, fall—specifically late fall—has become the preferred time for N fertilization of cool-season turfgrass.

In cooler regions, it is generally recommended that late-fall N be applied shortly after turfgrass shoot growth ceases (Duff, 1976; Snow, 1982; Kussow, 1988; Rieke, 1995; Reicher, 2005; Baird, 2007). The timing for late-season application is thought to be extremely important, as this is when the plant remains metabolically active but does not partition photosynthates to shoot growth. Kussow (1988) described this short window of time as a period with high recuperative potential for the turf; a time when net photosynthesis is high as a result of moderate temperatures, which decreases respiration and yields high photosynthate due to less demand for shoot growth. Instead of partitioning photosynthate and assimilated N for shoot growth as is observed in spring, it is suggested that photosynthates are partitioned for root, rhizome, and stolon development as well as the accumulation of reserve carbohydrates considered important for winter hardiness, root growth, and spring green-up (Snow, 1982; Kussow, 1988; Rieke, 1997, 1998; Reicher, 2005; Danneberger, 2006; Baird, 2007). Recommended application rates for the late fall range from 25 to 98 kg N ha^{-1} (Snow, 1982; Koski, 1988; Kussow, 1992; Rieke, 1998; Reicher, 2005; Danneberger, 2006; Baird, 2007), usually accounting for 25 to 50% of the total annual N fertilizer applied. Nitrogen sources used for the late-fall application should release independent of microbial activity due to low air and soil temperatures. The most efficient N sources, such as urea or ammonium sulfate, are soluble and thus available for root uptake (Koski and Street, 2010). It is important to note that fertilization of turfgrass after plant metabolic activity declines is termed *dormant fertilization* and is different from late-fall N applications discussed here. Dormant fertilization is intended to be available for the plant in the spring, while late-fall fertilization is meant to be utilized by the turf during the autumn and to a lesser extent, the following spring.

HISTORICAL PERSPECTIVES OF FALL NITROGEN RECOMMENDATIONS AND PRACTICES

Fall N fertilizer recommendations have changed substantially over the past century, influenced both by research and popular opinion. Table 1 summarizes late-fall N research performed on cool-season turfgrass species in northern climates, dating back to 1930. In 1921, Piper and Oakley (1921) wrote that heavy fall N applications could be detrimental to the turf and at best have no advantage. While heavy application rates in 1921 likely exceeded 500 kg N ha^{-1} yr^{-1} as an organic source, the opinion remained that turf need not be fertilized in the fall. Carroll and Welton (1939) performed a cold-tolerance study on Kentucky bluegrass (*Poa pratensis* L.) and found that N applied at 245 kg N ha^{-1} in September or October increased susceptibility to winter injury; however, these rates are not relevant to today's turf managers. During a superintendent panel discussion on N fertility (Shields et al., 1953), a golf course superintendent in Maryland reported applying more than half of his annual 368 kg N ha^{-1} budget after 1 October. In this same panel discussion, a superintendent from Ohio reportedly did not apply any N fertilizer after 1 September while another superintendent in California claimed to apply N year-round at 6-wk intervals totaling 800 kg N ha^{-1} yr^{-1} on putting greens.

Although regional and individual differences during the mid-1900s were apparent, many turf professionals considered N applications after September to be risky. Noer (1963) recommended that N applications in the northern United States should cease in September or early October to allow adequate time for the grass to harden off and become dormant to avoid winter injury. Beard (1969) also suggested that late-fall fertilization of turfgrass stimulates growth and tissue hydration, which may increase turf susceptibility to cold injury. Recommendations in trade journals and industry opinions regarding fall N began to change in the early 1970s. Schmidt and Shoulders (1971) from Virginia recommended that both warm- and cool-season turfgrasses should be fertilized in the fall to improve vigor coming out of winter and into the summer. Griffin (1977, p. 39) wrote in a popular trade journal that "the old theory that fertilizer applications just before cold weather are detrimental to both warm and cool-season turf is being replaced." Griffin (1977) also stated that numerous benefits can be derived from fertilization before and during cold weather, and that tissue N levels do not necessarily impact cold hardiness, which he thought was determined by a more complex internal balance of other plant nutrients, including potassium (K). More recently, Webster and Ebdon (2005) evaluated late-season N and K fertilization in Massachusetts and concluded that late-fall-applied N does not increase the potential for winter injury in perennial ryegrass (*Lolium perenne* L.), which is one of the cool-season species most prone to winter injury (Rajashekar et al., 1983).

Late-fall N recommendations for cool-season grasses in northern climates have remained relatively consistent since the 1980s, ranging from 25 to 49 kg N ha^{-1} for golf course putting greens and 49 to 98 kg N ha^{-1} for turfgrass maintained at a higher height of cut (Kussow, 1988). It is also agreed that the timing for this application should be shortly after the last mowing (Snow, 1982; Koski, 1988; Kussow,1988; Rieke, 1997, 1998; Reicher, 2005; Danneberger, 2006; Baird, 2007). Results from a 1989 survey of 25 Wisconsin golf course superintendents showed that the practice of fall N applications closely followed these recommendations (Erdahl, 1989). In 1989, an average of 56 kg N ha^{-1} was applied to Wisconsin putting greens in October and November, accounting for 47% of the mean annual N budget. A follow-up survey was administered in 2007: the 41 Wisconsin golf course superintendents returning the survey applied a mean of 40 kg N ha^{-1} in October and November, accounting for 26% of the mean annual N budget (Lloyd, 2008), indicating a trend toward decreasing fall N application rates and an increase in annual application rates.

PREVIOUS RESEARCH ON FALL AND LATE-FALL NITROGEN FERTILIZATION OF COOL-SEASON TURFGRASS

Color, Quality, and Growth Response

The research literature states the primary benefits associated with late-fall fertilization of turfgrass include improved color and quality later into the fall and earlier in the spring without a surge of shoot growth. These reports followed research performed in Virginia on creeping bentgrass (*Agrostis stolonifera* L.) and tall fescue (*Festuca arundinacea* Schreb.) (Powell et al., 1967a). These researchers concluded that late-fall and winter N fertilization of cool-season grass in Virginia improved year-round color and quality without stimulating foliar growth in the winter. At the same time fall N was considered detrimental to cold acclimation (Carroll and Welton, 1939; Noer, 1963; Beard, 1969), Powell also reported that fall and winter N applications did not decrease the cold hardiness of cool-season turfgrass. Powell's study examined cumulative fall and winter N rates of 49, 98, 147, 245, and 490 kg N ha^{-1} applied as ammonium nitrate, using one to five applications of 49 or 98 kg N ha^{-1} between October and February. Water-insoluble N was also applied at the rate of 490 kg N ha^{-1}. All high N rates examined on bentgrass (147–490 kg N ha^{-1}) regardless of timing generally improved turf color throughout the winter and into the spring compared to lower N rates (49 and 98 kg N ha^{-1}). Growth was relatively unaffected during the winter months; however, growth in the spring was significantly increased by the high N rates compared to the low rates. By May, high N treatments were producing roughly

Table 1. Late-fall nitrogen research in northern turfgrass environments.

Site information				Nitrogen application		Measurement								
Location	Date	Turf species†	Soil type‡	Source§	Application time	Root growth	Clipping yield	Uptake	Color	TQ¶	CT#	PN††	CHO‡‡	Reference
Mid-Atlantic														
Maryland	1959–1960	KBG	—	NH4NO3	Sept.–Mar.	xxx	xxx							Hanson and Juska, 1961
Pennsylvania	1971–1972	KBG	—	Urea, UF, MO, IBDU, Urex	May–Sept.		xxx						xxx	Watschke and Waddington, 1974
Pennsylvania	1982	PRYE	—	NH4NO3	Sept.						xxx		xxx	Welterlen and Watschke, 1985
Rhode Island	1965	KBG	ST loam	10–2.6–3.3	May–Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1965	CRF	ST loam	10–2.6–3.3	May–Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1965	COB	ST loam	10–2.6–3.3	May–Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1966	KBG	ST loam	UF, NH4NO3	Apr.–Nov.		xxx			xxx				Ledeboer and Skogley, 1973
Rhode Island	1970	KBG	—	NH4NO3	Oct.–Dec.		xxx		xxx		xxx			Wilkinson and Duff, 1972
Rhode Island	1990–1991	PRYE	ST loam	Urea, MU, NH4NO3	Apr., June, Nov.		xxx	xxx						Liu and Hull, 2006
Rhode Island	1990–1991	TF	ST loam	Urea, MU, NH4NO3	Apr., June, Nov.		xxx	xxx						Liu and Hull, 2006
Rhode Island	1990–1991	KBG	ST loam	Urea, MU, NH4NO3	Apr., June, Nov.		xxx	xxx						Liu and Hull, 2006
Virginia	1965	CBG	—	NH4NO3	Oct.–Feb.		xxx		xxx			xxx	xxx	Powell et al., 1967a
Virginia	1965	CBG	—	NH4NO3, UF	Oct.–Feb.		xxx		xxx				xxx	Powell et al., 1967a
Virginia	1965	TF	—	NH4NO3, UF	Oct.–Feb.		xxx		xxx				xxx	Powell et al., 1967a
Virginia	1966	CBG	TS/sand	NH4NO3	Oct.–June	xxx								Powell et al., 1967b
New England														
Connecticut	2000–2003	KBG/CRF	Loam SD	NH4/urea	Sept.–Dec.	xxx	xxx		xxx					Mangiafico and Guillard, 2006
Connecticut	2006	KBG	—	Urea	Sept.			xxx	xxx					Guillard and Morris, 2008
Massachusetts	2000–2003	PRYE	ST loam	Urea	Apr.–Nov.		xxx				xxx			Webster and Ebdon, 2005
Pacific Northwest														
Washington	1998–1999	PRYE	SD loam	Urea	Apr.–Nov.			xxx						Miltner et al., 2004
Washington	1998–2000	PRYE	SD loam	(NH4)2SO4, PCU, PSCU, IBDU	Nov.–Feb.		xxx			xxx				Miltner et al., 2004
Washington	1998–2000	KBG	ST loam	(NH4)2SO4, PCU, PSCU, IBDU	Nov.–Feb.		xxx			xxx				Miltner et al., 2004
Washington	2000–2002	PRYE	SD loam	10–0.9–5, 24–1.3–8.3	Apr.–Nov.				xxx	xxx				Miltner et al., 2005
Midwest														
Illinois	1982–1985	KBG	ST loam	Urea, IBDU, SCU	Apr.–Nov.		xxx		xxx					Wehner et al., 1988
Illinois	1988–1991	KBG	ST loam	Urea, MO, SCU	Oct.–Jan.		xxx		xxx					Wehner and Haley, 1993
Indiana	2003–2005	TF	ST loam	Urea, SCU	Sept.–July		xxx	xxx	xxx	xxx				Walker et al., 2007
Indiana	2003–2005	KBG	ST loam	Urea, SCU	Sept.–July		xxx	xxx	xxx	xxx				Walker et al., 2007

(cont'd)

Table 1. Continued.

Site information				Nitrogen application		Measurement								
Location	Date	Turf species†	Soil type‡	Source§	Application time	Root growth	Clipping yield	Uptake	Color	TQ¶	CT#	PN††	CHO‡‡	Reference
Indiana	2003–2005	PRYE	ST loam	Urea, SCU	Sept.–July		xxx	xxx	xxx	xxx				Walker et al., 2007
Indiana	2003–2006	KBG	ST loam	Urea, SCU, PCU	Sept., Oct., Nov.		xxx		xxx	xxx				Bigelow et al., 2007
Iowa	1986–1988	KBG	Loam	Urea, UF, MU, MLU	Apr.–Nov.	xxx	xxx			xxx				Moore et al., 1996
Michigan	1991–1993	KBG	SD loam	Urea	Apr.–Nov.		xxx	xxx						Miltner et al., 1996
Michigan	1994–1995	KBG	SD loam	(NH4)2SO4	June–Nov.		xxx	xxx						Engelsjord et al., 2004
Michigan	1994–1995	PRYE	SD loam	(NH4)2SO4	June–Nov.		xxx	xxx						Engelsjord et al., 2004
Michigan	1998–2002	KBG	SD loam	Urea	May–Oct.	xxx	xxx	xxx						Frank et al., 2006
Ohio	1930–1936	KBG	—	(NH4)2SO4	Apr.–Oct.			xxx			xxx		xxx	Carroll and Welton, 1939
Wisconsin	1988–1990	FF/KBG	—	Urea, IBDU	May–Nov.	xxx	xxx	xxx	xxx					Kussow, 1992
Wisconsin	1988–1990	CBG	—	Urea, IBDU	May–Nov.	xxx	xxx	xxx	xxx					Kussow, 1992
International														
Italy	2002–2003	TF	CL loam	(NH4)2SO4	Sept.–Dec.		xxx		xxx	xxx	xxx			Grossi et al., 2005
Turkey	1994–1996	PRYE/ KBG/CRF/ CF	SD loam	NH4NO3	Apr.–Sept.		xxx		xxx	xxx	xxx			Oral and Acikgoz, 2001

† KBG, Kentucky bluegrass; PRYE, perennial ryegrass; CRF, creeping red fescue; COB, colonial bentgrass (*Agrostis capillaris* L.); TF, tall fescue; CBG, creeping bentgrass; FF, fine fescue; CF, Chewing's fescue [*Festuca rubra* L. subsp. *commutata* (Gaudin) Markgr.-Dann.].

‡ ST loam, silt-loam; SD loam, sandy-loam; Loam SD, loamy-sand; CL loam, clay-loam; TS, topsoil.

§ UF, urea–formaldehyde; MO, milorganite; IBDU, isobutylidene diurea; Urex, extruded urea–paraffin matrix; MU, methylene urea; SCU, sulfur-coated urea; PCU, polymer-coated urea; MLU, methylol urea; PSCU, polymer- and sulfur-coated urea.

¶ Turfgrass quality.

Cold tolerance.

†† Photosynthesis.

‡‡ Carbohydrate.

twice the clipping yield compared to the lower treatments.

Although Powell's research is often the primary justification cited for the benefits of late-fall fertilization across the country, research on the color, quality, and growth responses to fall N has been performed in different regions as well. Researchers in Rhode Island (Wilkinson and Duff, 1972; Ledeboer and Skogely, 1973) evaluated fall-applied N with rates and timings more typical of fertility practices in northern climates. Wilkinson and Duff (1972) evaluated color, cold resistance, and growth of Kentucky bluegrass under various fall N treatment timings. Six applications spaced at 2-wk intervals were made between 1 October and 15 December, using NH_4NO_3 at 98 kg N ha^{-1}. The researchers observed increased fall color for applications made before 1 November, and concluded that any application after this date was too late to produce a fall color response. All fall fertilizer treatments provided good spring green-up by mid-March, and the treatments applied after 1 November had greener color and greater clipping yield by mid-April. Fertilizer treatments applied before 1 November produced growth responses in the fall, while later applications increased clipping yields in the spring. Wilkinson and Duff (1972) also associated greater fall N fertilization rates with decreased cold resistance through laboratory freezing tests, although they cautioned that data may not be relevant to field plots.

Ledeboer and Skogely (1973) evaluated spring and fall application timings at rates ranging from 49 to 147 kg N ha^{-1} applied to various fescues (*Festuca* spp.), bluegrasses (*Poa* spp.), and mixtures of these species. They concluded that early- and/or late-fall N applications (September and late November; before and after foliar growth ceased) maintained more uniform turf quality, sustained green color longer in the fall and earlier in the spring, and did not increase mowing requirements compared to spring N treatments. Winter injury was not observed through 3 yr of field research in Rhode Island.

No evidence of increased winter injury on field plots from fall N was found in the Mid-Atlantic region (Hanson and

Juska, 1961; Powell et al., 1967a) or in coastal New England (Wilkinson and Duff, 1972; Ledeboer and Skogely, 1973); however, limited field research is available from harsher northern climates (Carroll and Welton, 1939; Noer, 1963; Beard, 1973). Wehner et al. (1988) in central Illinois compared annual N fertility programs including either a spring N application (early May) or a late-fall N application (early November). Fertility programs including late-fall N resulted in higher turf color ratings in early spring, although spring treatments had greater color ratings in late spring. Nitrogen treatments including spring N had 48 weekly ratings of acceptable color compared to the fall treatments, which displayed 39 ratings of acceptable color. The authors concluded that a urea application in early November improves color in the early spring but may necessitate a subsequent spring N application to maintain color and quality into the summer. No winter injury was reported in this study. Wehner and Haley (1993) initiated a follow-up study to determine if the benefits from November applications of N could be achieved through October, December, or January N applications. Different N rates (49 and 98 kg N ha^{-1}) and different sources (urea, sulfur-coated urea, and a biosolids-based fertilizer) were evaluated, as well as the November plus light April combination treatment suggested in their previous study. The results indicated that higher rates applied later into the winter sustained color longer in the spring, as did the lower rate November/April combination treatment. In Wisconsin, Kussow (1992) also found improved spring color with late-fall and dormant N treatments using different sources, although a spring growth response was also attributed to these late-fall and winter treatments. None of the research performed in the midwestern United States reported winter injury as a result of late-fall N fertilization. More recent studies of late-fall N in Washington (Miltner et al., 2004) and New England (Mangiafico and Guillard, 2006; Guillard and Morris, 2008) have suggested N applications should be applied earlier in the season to maximize fertilizer uptake while still achieving a spring color response. Researchers in Pisa, Italy (Grossi et al., 2005), evaluated seven different late-fall application timings of 100 kg N ha^{-1} of ammonium sulfate applied between 1 September and 23 December to tall fescue. They found that the highest shoot and leaf density at the end of winter were obtained from N applied after 11 November; though a single late-fall quick-release N application was not sufficient to maintain acceptable turf color or quality for the entire fall–winter period.

Root Growth

Research evaluating the effects of fall-applied N on late-season root development has yielded mixed results. Powell et al. (1967b) evaluated winter root growth of bentgrass putting greens in Virginia as affected by fall-applied N. Data collected during February indicated that winter rooting increased approximately 30% in treatments that received no fertilizer or low rates (49 kg N ha^{-1} in October) compared to treatments receiving N totaling 98 and 294 kg ha^{-1}. By April, no treatment differences were apparent and by June, the treatments receiving 98 and 147 kg N ha^{-1} between October and February had 40 and 50% greater root mass, respectively, compared to the control and treatments receiving the highest N rates (196 and 392 kg ha^{-1}).

Hanson and Juska (1961) evaluated root and rhizome growth in Kentucky bluegrass in the mid-Atlantic and found no differences in rhizome development but found some interesting results for root mass. Late-winter root mass was significantly greater in the treatments that received 147 kg N ha^{-1} in September as well as those having the 147 kg N ha^{-1} application split between September and October compared to the unfertilized control. Differences in root production in May were not as apparent, with the highest amount of root mass observed in the treatment fertilized in March. Working in Iowa, Moore et al. (1996) compared the effects of late-fall, heavy spring, and balanced-N fertility programs on Kentucky bluegrass root growth. The late-fall program, which included a 49 kg N ha^{-1} application in November, produced 9 and 8% more root mass than the spring and balanced-N program, respectively.

It was first reported by Stuckey (1941) that active root tip cell division takes place at temperatures as low as 0°C in the soil. Soil temperatures cool more slowly than air temperatures and photosynthesis continues at low temperatures, suggesting that temperate climates are suitable for root production in the winter months. Consequently, the rooting studies performed by Powell et al. (1967b) and Hanson and Juska (1961) in the Mid-Atlantic yielded results that may not be applicable to cooler climates where air temperatures decrease to near or below freezing for extended periods (e.g., months). Fall N rooting studies performed north of the Mid-Atlantic region (Kussow, 1992; Mangiafico and Guillard, 2006) did not find root mass differences as a result of N applied in either September, October, November, or December. Possible explanations for the lack of rooting differences include low carbohydrate production in the late fall, a rapid consumption of stored carbohydrates in early spring, and/or a short duration of fall soil temperatures ideal for root growth. Research by Moon et al. (1990) found a single chilling event substantially inhibits photosynthesis for the following 5 to 7 d. However, Moon's results are specific to perennial ryegrass, which is more susceptible to winter injury than other cool-season grasses, including Kentucky bluegrass and creeping bentgrass (Rajashekar et al., 1983).

Reserve Carbohydrates

Reserve nonstructural carbohydrates are beneficial for turfgrass to withstand and recover from periods of stress. Historically, this was one of the primary reasons to withhold N fertilizer in the fall, as N application was thought to expend reserve carbohydrates, necessary for cold tolerance, through metabolism associated with N assimilation (Beard, 1969). Currently, the accumulation of reserve carbohydrates is often listed among the benefits of late-fall fertilization (Rieke, 1998; Reicher, 2005; Danneberger, 2006; Baird, 2007); however, there are no research reports available to fully support this claim. Powell et al. (1967a) reported that reserve carbohydrates were lower in high-N compared to low-N treatments and late-season N did not seriously deplete reserve carbohydrates. Rather, they suggested late-season N might be beneficial if it reduces the need for a spring N application that would rapidly deplete reserve carbohydrates through a surge of shoot growth. They further hypothesized that high-N fertilization will not always deplete reserve carbohydrates during winter because of a net gain in the carbon energy balance resulting from sustained photosynthetic activity and diminished growth. While possibly true for the Mid-Atlantic region, this scenario is not as likely for cooler regions. Zanoni et al. (1969) in Massachusetts found an inverse relationship between soil temperatures and total soluble carbohydrates in turfgrass as well as consistently lower carbohydrates throughout the season in turfgrass receiving N. A potential explanation for this could be related to energy required for N assimilation, which has been estimated to be 25% of the energy generated through photosynthesis (Solomonson and Barber, 1990). In Pennsylvania, Watschke and Waddington (1974) also observed lower carbohydrate levels in fall-fertilized treatments, which they attributed to a growth response in October. Welterlen and Watschke (1985) evaluated fall-applied N and found no significant differences in total nonstructural carbohydrate levels between fertilized and unfertilized plants going into winter. However, in the laboratory, they observed a significant increase in freeze injury of crown tissue as a result of fall-applied N.

Photosynthesis

The plant net carbon energy balance mentioned by Powell et al. (1967a) describes the underlying assumption for many of the frequently proclaimed fall N benefits: as the plant is actively photosynthesizing and low temperatures are limiting top growth, then the carbohydrate production must be used elsewhere in the plant, either for belowground root and rhizome development, tillering, or reserve carbohydrate storage. The accompanying notion is that if the plant is metabolically active, N uptake will continue as long as photosynthesis is still occurring. Net photosynthesis rates often increase at cooler temperatures due to reduced respiration (Liu and Huang, 2001). However, measurements of turfgrass photosynthesis in cool temperatures are rare. In Virginia, Powell et al. (1967a) measured photosynthesis of creeping bentgrass in January, February, March, and June on plots that had been treated with fall and winter nitrogen at rates ranging from 49 to 490 kg N ha^{-1}. They observed the highest annual net photosynthetic rates in January when night temperatures did not reach freezing and day temperatures reached 16°C. Two days later when the soil was frozen and air temperatures remained below freezing for much of the day, photosynthetic rates were extremely low. Measurements in February, March, and June showed that net photosynthetic rates were slightly lower than in January when the soil was not frozen. Dark respiration rates for these spring and summer measurements were greater than during the winter, explaining the lower net photosynthetic rates. Powell et al. (1967a) also reported that the greener plots associated with the high N rates had higher levels of net photosynthesis as well as higher dark respiration. We are unaware of other research on low-temperature photosynthesis and N fertilization, although Moon et al. (1990) studied the impact that chilling temperatures can have on photosynthesis and found that just one chilling event (8°C day and 5°C night) inhibited perennial ryegrass photosynthetic capacity 85 to 90%; inhibition persisted for 5 to 7 d after plants were returned to 22°C day and 17°C night temperatures. Considering the implications of the research of Moon et al. (1990), temperatures that inhibit growth without greatly inhibiting photosynthesis may occur during a very short period in northern climates.

Plant Uptake of Fall-Applied Nitrogen

Fertilizer application effectiveness can be assessed in many ways. However, we feel that the percentage of applied N recovered by the plant represents the best way of evaluating and comparing N applications rates and timings from agronomic, economic, and environmental perspectives. Liu et al. (2008) concluded that nitrogen use efficiency (recovery by plant/N input × 100) of grasses is between 30 and 60%, with an average of below 50%. Miltner et al. (1996) evaluated N fertilizer uptake and fate in low temperatures with a mass balance study evaluating fall-applied N on Kentucky bluegrass in Michigan. Labeled ^{15}N fertilizer was applied on 8 Nov. 1991 at the rate of 39.2 kg N ha^{-1} and N fate was determined 18 d later. Two-thirds of the fertilizer N applied remained in the thatch and soil and one-third was recovered in the verdure. The study was repeated on the same plots 9 yr later, which evaluated high- and low-N fertilizer regimes including a ^{15}N-labeled urea application on 17 Oct. 2000 applied at a low rate of 24.5 kg N ha^{-1} and a high rate of 49 kg N ha^{-1} (Frank et al., 2006). On 1 December, 45 d after treatment, 17 and 19% of labeled fertilizer N was recovered in the verdure and clippings from the low and high rates, respectively. Although tissue or root N concentrations were not collected during the fall, total fall N uptake appears to be substantially lower than recommended application rates.

Other research evaluating plant physiological responses in low temperatures suggest that turfgrass is less proficient at taking up N in the late fall in northern climates than is often assumed. Researchers evaluating a range of plant species have found that temperatures below those for optimum growth reduce N uptake and adversely affect the process of

N assimilation (Dubey and Pessarakli, 2002). In perennial ryegrass and annual ryegrass (*Lolium multiflorum* L.), even a short-term exposure to a low-temperature treatment from 25 to 15°C resulted in decreased N uptake (Clarkson, 1988). One reason N uptake may be downregulated during periods of low growth is because N is not needed in the production of new amino acids, nucleic acids, and enzymes for new shoot growth, for which Bowman (2003) accounted for 88 to 119% usage of N uptake. Evapotranspiration also decreases markedly in cold temperatures, diminishing the N transport through mass flow, which is the dominant process by which N moves from soil solution to root surfaces. Xylem transport is also inhibited in cool temperatures, creating a buildup of N in the roots, which inhibits further uptake through diffusion (Laine et al., 1994).

Environmental Considerations

Late fall is considered a susceptible time of year for nitrate leaching as precipitation rates greatly exceed evapotranspiration rates in many regions of the world. Petrovic (1990) compiled a comprehensive review of the leaching studies conducted for turfgrass systems and suggested that there is a greater potential for leaching losses from late-fall N fertilization due to cooler temperatures restricting plant uptake and decreased microbial immobilization of N in the soil. He speculated that while late-fall N fertilization has potential agronomic benefits, the environmental consequences may overshadow the positive impact in areas susceptible to groundwater contamination. Recent studies evaluating late-fall N applications to turfgrass have found elevated NO_3 levels in the leachate (Geron et al., 1993; Miltner et al., 1996; Liu et al., 1997; Guillard and Kopp, 2004; Frank et al., 2006; Mangiafico and Guillard, 2006).

In Ohio, Geron et al. (1993) reported higher NO_3 leaching losses in the winter from Kentucky bluegrass fertilized on a program emphasizing late-fall N (3.37 mg NO_3–N L^{-1}) as compared to programs emphasizing spring and summer N (2.39 mg NO_3–N L^{-1}). Both programs received 218.2 kg N ha^{-1} yr^{-1} as urea or resin-coated urea. High winter leaching losses were attributed to low temperatures reducing plant and microbial activity. Miltner et al. (1996) also found significantly more NO_3 present in leachate from late-fall-applied N, although the total amount of N recovered was negligible (0.28% of applied N over the 2 yr study where urea was applied at 196 kg N ha^{-1} yr^{-1} to Kentucky bluegrass in Michigan). On the same plots, Frank et al. (2006) studied N uptake and leaching from urea applied at 98 or 245 kg N ha^{-1} yr^{-1}. Applications in mid-October were made with ^{15}N-labeled urea at rates of either 24.5 or 49 kg N ha^{-1}. Nitrate leaching values were 10 times higher for the 49 kg N ha^{-1} application, with 11% recovered in the leachate 2 yr after sampling. These researchers suggest that late-fall applications of soluble N fertilizers to mature turfgrass of 49 kg N ha^{-1} or greater should be avoided to minimize leaching losses. Similarly, Miltner et al. (2001) recommended eliminating single-dose 49 kg N ha^{-1} applications in the late fall due to reduced plant uptake.

Liu et al. (1997) compared NO_3 leaching from three cool-season turfgrasses with N applications of 149 kg N ha^{-1} yr^{-1} over two growing seasons in Rhode Island. The highest soil water NO_3 concentrations occurred during winter months, with tall fescue deemed most efficient at absorbing NO_3 compared to Kentucky bluegrass or perennial ryegrass. Guillard and Kopp (2004) evaluated leaching losses from a mixed-species stand maintained as a home lawn and fertilized with three applications of 49 kg N ha^{-1} as either ammonium nitrate, polymer-coated sulfur-coated urea, or an organic source. Greatest annual leaching losses occurred in the late-fall and early-spring period with the ammonium nitrate source (16.8%) as compared to polymer-coated sulfur-coated urea (1.7%) or organic N (0.6%). Mangiafico and Guillard (2006) evaluated four different late-fall N application timings to a Kentucky bluegrass–creeping red fescue (*Festuca rubra* L.) stand maintained as a home lawn. Applications were made on 15 September, 15 October, 15 November, or 15 December, with a complete fertilizer (10–7–17, 60% NH_4–N and 40% urea-N) at a rate of 49 kg N ha^{-1}. They reported greater nitrate leaching loss and N fertilizer losses from applications made later into the fall, concluding that late-fall fertilization in New England could be replaced by lower N application rates.

CONCLUSIONS

The benefits and recommendations for late-fall N fertilization are widely accepted across the cool-season region. However, after a thorough literature review, we suggest that recommendations be further evaluated through research and specified according to particular climatic regions, turfgrass species, and land-use situations. The research regarding environmental losses of soluble N applied in the late fall indicate a potential for significant N losses through leaching, bringing into question the actual costs–benefits of fall-applied N. With increasing N fertilizer costs and concern of losses from turfgrass systems, it is critical that turfgrass managers understand the agronomic and physiological benefits of their N fertilizer applications. The main reason that N fertilization in the late fall is so highly regarded appears to be based on the assumption of increased photosynthesis and rooting. However, there is minimal research on turfgrass photosynthesis at low temperatures and what has been reported does not unambiguously support such benefits. Applying this notion of increased photosynthesis from late-fall N fertilization across all cool-season turfgrass zones and species without supporting research is unwarranted. Additionally, results of studies examining the influence of fall nitrogen rates and timings on root growth are variable and indicate that responses are dependent on climatic zone, seasonal variability, and turfgrass species. Studies performed in more northern climates demonstrate that root growth may not be affected by fall-applied N (Kussow, 1992; Mangiafico and Guillard, 2006). Similarly, the perception that late-fall fertilization hastens spring green-up without a surge of top growth also appears to be highly dependent on species and seasonal weather conditions. Furthermore, scant data are available defining the uptake potential of cool-season grasses in cool temperatures; what do exist indicate uptake potential is low, suggesting that recommended late-fall N fertilizer rates are too high. Additional work is required to determine the appropriate late-fall N fertilizer rates, sources, and timings for cool-season turfgrass in northern climates, while understanding that recommendations should be based on seasonal variability. These studies should evaluate agronomic responses such as color, quality, rooting, and fertilizer uptake efficiency; and physiological responses such as photosynthetic rates and carbohydrate accumulation.

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