Foliar Fertilization for Turfgrasses

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ABSTRACT

Nutrient use efficiency by turfgrasses is still one of the major challenges for turf managers world wide. Limited research exists on sports turf foliar nutrient absorption and comparisons with granular fertilizer. However, to date, findings on foliar fertilization include: 1) younger leaves have better foliar nutrient absorption; 2) lower (underneath) leaf surfaces (with more stomata) absorb more nutrients than upper side of the leaf; 3) neutral ion absorption seems more efficient than cation (positively charged ions) and anion (negatively charged ions) absorption; 4) all 16 plant nutrients including some beneficial elements have been reported to be absorbed by leaves; 5) cuticle penetration is possible and is genetically regulated; 6) the total fertilizer input may be reduced by using foliar fertilization; 7) there may be synergetic effects by using foliar fertilizers and plant growth regulators; and 8) it is environmentally safer to use more foliar fertilizers. Thus, this review is trying to provide the most updated research results on turfgrass foliar fertilization including sports turfgrasses.

Introduction

Foliar fertilization has been practiced for many years for different turfgrasses and the trend in recent years has shown a rapid increase of foliar fertilizer applications for all levels of turfgrass maintenance and management including golf courses, sports turf, and home lawns. There may be multi-reasons or motivations for such changes using more foliar fertilizers than granular fertilizers for turfgrass management and these may include: 1) the new findings and approval of foliar absorption of nutrients; 2) rapid responses of turf; 3) reduced total fertilizer input; 4) superior advantages using lower rate foliar fertilizers than granular fertilizers when a turf is under stress; and 5) environmental concerns with further minimized potential losses by runoff and leaching. This review article attempts to address current research findings related to foliar fertilization for plants and turfgrasses and offers perspectives and discussion on the subject based on possible needs of the current and future turfgrass management.

Foliar Application and Foliar Absorption

The subject of foliar fertilization automatically raises the question: How much liquid fertilizer do leaves actually absorb? It is a very reasonable question and points to uncertainty about the process of foliar absorption. In fact, when radio-labeled isotopes first became available in the 1950s for research, the search for answers to this question was immediately started by tracking the chemical movement in plant parts based on the labeled element's radioactivity (Boynton, 1954; Table 1). This method is still being used as an accurate research tool to track element distribution in turfgrasses and even in soils (Horgan et al., 2002a, 2002b). The most commonly labeled plant nutrient has been ^{15}N, which has a much longer half life and minimum hazardous impact in comparison with ^{13}N, with a half life of only seven minutes (Below, et al., 1985; Table 1). In addition to nitrogen, Fe, Mg, B, and Ca have been applied as liquid fertilizers to turfgrasses (McCaslin and Watson, 1977; Fu and Huang, 2003; Stiegler et al., 2003; Guertal, 2004). The following provides general characteristics of foliar fertilization (Boynton, 1954; Wittwer and Teubner, 1959; Stewart, 1963; Sargent, 1965; Franke, 1967; Riederer and Müller, 2006):

- Younger leaves have better foliar absorption.
- Plants have both cuticular and stomatal absorption of liquid materials through above ground tissues, mainly leaves.
- Lower (underneath) leaf surfaces (with more stomata) absorb more nutrients than upper side of the leaf.
- The first research on foliar absorption was documented in 1844.
- Neutral ion absorption seems more efficient than cation (positively charged ions) and anion (negatively charged ions) absorption.
- All 16 plant nutrients including some beneficial elements have been reported to be absorbed by leaves (Table 1).
- Cuticular penetration follows physical laws.
- Cuticular layer biosynthesis, development, and functions are dependent on species and cultivars and genetically controlled.

Several studies on both cool-season and warm-season turfgrasses indicate a foliar absorption rate normally between 30 and 60 percent of the nitrogen applied (Eliot, 1960; Eliot, 1972; McCaslin and Watson, 1977; Rieke et al., 1982; Wesly et al., 1985; Spangenberg et al., 1986; Wesly et al., 1987; Bowman and Paul 1989; Bowman and Paul 1990; Bowman and Paul 1992; McCarty, et al., 1994; Liu et al., 2005; Totten, 2006). For P and K, absorption efficiencies vary between 43 and 74.8 percent (Table 1). So another question arises for turfgrass management: Where does the rest of the liquid fertilizer go? The rest may be left in the soil and the turf-soil system, lost by removal of clippings, or held in the thatch layer similarly to a granular fertilizer. However, the unabsorbed liquid fertilizer in the turf-soil system is still available to turfgrasses with a better chance being reabsorbed than granular fertilizers simply because it does not require a process to be dissolved in the soil solution before being absorbed by roots in comparison with solid granular fertilizers.

Cuticular and Stomatal Nutrient Uptake

The primary function of cuticle is to prevent uncontrolled water losses (Riederer and Müller, 2006). The plant cuticle is not only exposed to abiotic factors like sunlight, temperature, wind, and rain but it also interacts with biotic factors including microbes, fungi, and insects. Furthermore, the plant cuticle is the initial contact point and the main barrier of penetration between an agrochemical and the plant. Cuticles include various structural types occur in higher plants and typical cuticles proper epicuticular and intracuticular waxes with a lamellate layer between in a thickness range of 50–150 nm. Efficiency of cuticular penetration of solute of agrochemicals depends on plant species, cultivars in the thickness of cuticles and cuticular pore size and distribution (pore sizes range between 1 to 10nm with a density of 10^6 -10^9/mm^2) (Riederer and Müller, 2006).

The debate on folair stomatal uptake had been continued for decades with an initial denial and till recent evidences for stomatal uptake of solutes by leaves have been provided (Eichert et al., 1998; Eichert and Burkhardt. 2001). In these studies, Eichert et al., (1998, 2001) found that the stomatal uptake of nutrients was influenced by humidity, light, and stomatal density. Uptake increased with humidity and stomatal density. The number of stomata that had been penetrated was highly variable, increasing extremely significantly with the number of repeated drying/wetting cycles. These results indicate that stomatal uptake can be a major pathway for the foliar uptake of ionic solutes.

Although there is a shortage of literature at both the species level and cultivar level of turfgrasses for cuticular and stomatal uptake, turfgrasses and cultivars vary in their cuticular layer thickness and stomatal density (Shearman and Beard, 1972; Casnoff et al., 1989; Green et al., 1990 and 1993) due to the genetic diversity of grass species used as turfgrasses (Anderson and Briske, 1990; Casler and Duncan, 2003; Fu and Huang, 2004). It would not be difficult to imagine that cuticular and stomatal uptake can also be influenced from management practices such as mowing, irrigation, and topdressing and turf use from both foot and vehicular traffics. However, there is a lack of documents in stomatal uptake among turfgrasses facing a challenge of dominant distribution of stomata on the lower side leaves in the most species (Shearman and Beard, 1972; Casnoff et al., 1989; Green et al., 1990 and 1993).

Advantages and Disadvantages of Foliar Fertilization

The major advantages of foliar fertilization include a lower total fertilizer input than a 100 percent granular fertilizer program particularly for turf with a lower mowing height (Liu et al., 2005; McCullough et al., 2006; Totten, 2006). Foliar fertilization also provides a quicker response than a granular fertilizer. Foliar fertilization by proper applications and practices will further minimize losses through leaching and runoff. Foliar fertilizer applications also have been reported to reduce foliar diseases (Garling et al., 1999). Foliar fertilization can correct plant nutrient deficiencies rapidly including both macro- and micro-nutrients (Marschner, 1995). For turfgrass management, foliar fertilization at lower rates has been practiced for years when the turf is under stresses. When soil conditions are nor favorable for root absorption, foliar nutrient application is the only choices for turf managers.

Significant concerns with foliar fertilization include frequent application costs with more labors and equipment use, and potential burn of the turf applied at high rates, a wrong application time (Johnson and Christians, 1984; Wehner and Haley 1988), a potential of high volatilization rate (Wesly et al., 1987), and a potential of enhancement of unwanted species (Stiegler et al., 2003).

Importance of Urea and Urease for Foliar N Nutrition

Nitrogen is the most demanded plant nutrient and it has been the most frequently used nutrient through foliar application for turfgrasses. Nitrogen can be absorbed both by roots and above ground parts including leaves and shoots (Marschner, 1995; Carrow et al., 2001; Hull and Liu, 2005). The primary absorbed N forms are nitrate (NO_3^-) and ammonium (NH_4^+) for roots. For foliar absorption, urea is absorbed more than NO_3^- and NH_4^+ with improved understanding of cuticular penetrations (Bowman and Paul, 1989; Bowman and Paul, 1990; Bowman and Paul, 1992). Urea is one of the most frequently used N fertilizers for warm-season turfgrasses (Beard, 1973; Carrow et al., 2001; McCarty, 2005; Turgeon, 2005). The reaction catalyzed by urease is essential to make urea N accessible to plants (Marschner, 1995). Urease, the first enzyme ever being crystallized, catalyzes the hydrolysis of urea to carbamate and NH_3 where carbamate is unstable and yields a second molecule of NH_3 and carbonic acid. Then, the released NH_3 during the urease reaction leads to a pH rise because at neutral pH most NH_3 will become protonated as $NH_3 + H^+$ to NH_4^+, which is the ready form for nitrogen assimilation in plants (Marschner, 1995; Sirko and Brodzik, 2000). Urease activity has been detected in many plants (Frankenberger and Tabatabai, 1982 ; Hogan et al., 1983 ; Witte and Medina-Escobar, 2001; Witte et al., 2002) and is reported to be inducible by urea in rice (*Oryza sativa*) (Matsumoto et al., 1966), jack bean (*Canavalia ensiformis*) (Matsumoto et al., 1968), and barley (*Hordeum vulgare*) (Chen and

Ching, 1988). Urea can also be supplied to plants through the foliage to facilitate optimal N management, which minimizes N losses to the environment without affecting turf quality.

Foliar Application and Root Growth

Although leaves and shoots are not ideal plant organs for nutrient uptake in comparison with roots, foliar fertilization itself has minimum impacts to root growth. Based on two year field research results, differences were not found in root mass treated with 100% foliar fertilizers and 100% granular fertilizers for both creeping bentgrass and hydrid bermudagrass (Liu et al., 2005; Totten et al., 2005a and 2005b; Totten, 2006). However, excessive nitrogen application can cause more carbohydrates produced through photosynthesis for shoot growth, leaving fewer carbohydrates for roots (Carrow et al., 2001; Hull and Liu, 2005). Under stressful conditions, the situation is worsened and the turfgrass becomes weaker. Foliar nutrient absorption has much less impact on root growth because foliar absorption itself is more of a physical and chemical process than a biological process (Riederer and Müller, 2006) to penetrate through cuticles. Foliar nutrients are absorbed mainly through very small channels of the cuticle layer in addition to stomata absorption. For nitrogen, urea (NH_2=CO=NH_2) is much more easily foliar-absorbed than nitrate (NO_3^-) and ammonium (NH_4^+) even though the molecule sizes (Bowman and Paul, 1989; Bowman and Paul, 1990; Bowman and Paul, 1992; Riederer and Müller, 2006) of the latter two are smaller than urea. Somehow, these small channels do not let charged molecules, like nitrate and ammonium, pass through easily but let neutrally charged molecules such as urea pass more freely. The bio-energy relationships in comparison of root and foliar cell membrane nutrient uptake require more fundamental research. However, if the differences do exist, the negative impacts to root growth from foliar nutrient uptake may be not significant as other factors influencing root growth.

Nutrients in soils are taken up by roots through soil solutions. Whether enough nutrients exist in the soil solution or not, the water potential differences will keep the soil solution, including available nutrients, moving from the soil to the roots and into the upper parts of plants. (Marschner, 1995; Taiz and Zeiger. 2005). Under slight to moderate water stress, root growth will be stimulated to search for more water due to a drought resistant mechanism, or drought avoidance (Taiz and Zeiger. 2005; Baldwin et al, 2006). In addition to water, many other factors may have a greater impact on root growth than foliar fertilization such as stressful soil conditions, mowing, traffic, and pests (Beard, 1973; Carrow et al., 2001; McCarty, 2005; Turgeon, 2005).

Are There Better Times of the Day to Apply Foliar Fertilizers?

Based on two studies carried out for two years for both creeping bentgrass (L93) and ultradwarf bermudagrass (TifEagle) greens at Clemson University, no differences in turf quality were found between applications at 10am versus applications at 5pm. However, evening applications are recommended (Liu et al, 2005).

Foliar nutrient absorption is more of a physical and chemical process (penetrating through the cuticle layer) than a biological process and it requires time (Riederer and Müller, 2006). A minimum of three hours or more is recommended to maximize foliar absorption for turfgrasses. So, after a foliar application, an irrigation or rainfall should be avoided for three hours. For a cool-season turfgrass used on golf courses or sports fields during summer months, the first syringing of the day may be applied as early as late morning. After morning mowing, this may leave insufficient time for a foliar fertilization. If a foliar application is conducted in the late morning, rising day temperatures will reduce foliar absorption efficiency and may increase burn potential to the turf since more salts are in contact with the leaf surface. Most forms of N foliar fertilizer are urea and the heat will promote volatilization losses (Wesly et al., 1987). Still, turfgrass managers have practiced late morning foliar fertilizer application for years with little problems during the summer months. This is probably due to syringing practice that washes the foliar fertilizer into the soil with roots eventually absorbing it. This may be another advantage to foliar fertilization because foliar applications provide a “second chance” for plants to access the material. However, minimizing volatilization losses, varying the time length between foliar application and the first irrigation afterwards, and hourly changes of turfgrass turgor pressure on foliar absorption deserve more attention and research.

When heavy dews exist, foliar fertilization along with a foliar absorbed plant growth regulator such as trinexapac-ethyl (Primo) is not recommended. Without a mowing first, heavy dews exist as water droplets on the leaf surface causing immediate runoff of applied liquids from leaves and a high potential of leaf burn. Finally, during the evening, more stomata are typically open which increases the chances for foliar absorption (Eichert and Burkhardt. 2001).

Foliar Fertilization Practices for Warm-season and Cool-season Turfgrasses

Warm-season turfgrasses grow best in the temperature range between 25 to 35 ^{o}C and they require relatively more fertilizers than cool-season turfgrasses during the summer months. Unlike soils, there are no physical sites such as cation and anion exchange interfaces between roots and soil particles soil solutions for foliar applied fertilizers to stay before absorption except the plant above ground surfaces. High concentrations of salts sitting on turfgrass leaves and shoots will burn the turf particularly under high air temperatures. The management practices to avoid foliar fertilizer burning include more frequent applications with a lower rate. Each single foliar application rate of fertilizers for warm-season turfgrass can be varied depending on mowing height, species and cultivar, and maintenance level. Rates greater than 12 kg N ha^{-1} for each single foliar application can increase fertilizer burning potential for warm-season turfgrasses even during the summer months (Totten et al., 2005b). The frequency of foliar application can be controlled between 7 to 10 days.

Cool-season turfgrasses grow best in the temperature range between 20 to 25 ^{o}C and they require relatively more fertilizers than warm-season turfgrasses during the early spring and fall months. Avoiding midday foliar applications during summer months and a combination of several foliar fertilizers are also recommended (Fu and Huang, 2003). A rate greater than 10 kg N ha^{-1} for each single foliar application can increase fertilizer burning potential for cool-season turfgrasses even during the spring and fall season months (Liu et al., 2005; Totten et al, 2005a). The frequency of foliar application can be controlled between 7 to 10 days.

There is a need of future research on formulas of foliar fertilizers specified for each types of turf use particularly for sports turf and home lawns. The challenges of long-term or slow-release effects of foliar fertilizers for turfgrass management exist due to facts that there are no ionic pools surrounding leaves and shoots unlike in soil conditions, in where fertilizers can stay in soils for much longer times.

Balanced Foliar and Granular Fertilization Programs

Foliar fertilization provides more uniform coverage than the granular fertilization or the next mowing might have removed some granular fertilizers (Mancino et al., 2001; Totten, 2006). Granular fertilizers require less labor (less frequently applied) and the relatively slow releasing effects mean longer availability in the soil, which liquid foliar fertilizers do not have. Combination of both methods rather than relying on one method exclusively has been adapted by many turf mangers with consideration of season of the year, labor, fuel, and budget conditions. During the summer months, foliar liquid fertilization at lower rate with high frequency of 7 to 10 days is highly recommended for both warm-season and cool season turfgrasses. During the fall and early spring growing seasons, a slower release granular fertilizer provides an economic alternative. For soils with unbalanced nutrients or poor conditions such as a lower P concentration or under an acidic condition, granular P fertilizer is recommended to efficiently correct the problem of P deficiency at a longer term.

Foliar Applications of Products Other than Mineral Nutrients

Foliar applied pesticides, plant growth regulators (PGR), and bio-stimulants are commonly used for turfgrass performance enhancement including stress relief or amelioration (Zhang and Schmidt. 2000a and 200b). Among these foliar-applied bio-stimulant products, cytokinin-containing seaweed and humic acid extracts are most commonly used to enhance overall turfgrass performance or to ameliorate stresses such as heat and drought stresses for cool-season turfgrasses (Liu et al., 1998; Zhang and Ervin, 2004; Kauffman et al., 2007). A foliar applied PGR, trinexapac-ethyl, has been applied to both cool-season and warm-season turfgrasses to enhance turf quality and ameliorate shaded and other conditions (Quian and Engelke, 1999; Stier and Rogers, 2001). The foliar absorption of these products is essential for turfgrass management and the future trend of research may include practices with improved foliar absorption such as nozzle sizes, surfactants, and tank mixes, and concerns on turfgrass species and variety differences.

Conclusions

In summary, foliar fertilization requires more attention and research for future turfgrass management. Very limited information exists on differences between turfgrass species and cultivars in cuticular and stomatal uptake of different nutrients. There is a lack of evidences of foliar uptake of other foliar nutrients other than N for turfgrasses. The synergetic effects between foliar fertilization and plant protection chemicals have not been fully understood. The influencing factors of efficient foliar nutrition absorption have not been fully studied. However, these new research and findings will heavily depend on the new research of dynamics of cuticular and stomatal penetration and absorption as well as the functions of related enzymes such as urease for foliar applied urea. The uniqueness of turfgrass management provides challenges of mowing cuts of turfgrass leaves and shoots. The roles of these cuts and wounds affecting foliar absorption have not been investigated yet. The foliar fertilizer formulas including surfactants and other plant protect chemicals require further development for efficient nutrition absorption and plant needs.

References

Adedipe, N.O. and D.P. Ormrod. 1975. Absorption of foliar-Applied ^{32}P by successive leaves, and distribution patterns in relation to early fruiting and abscission in the cowpea (*Vigna unguiculata* L.). *Annals of Botany* 39: 639-646.

Altman, D.W., W.L. McCuistion, and W.F. Kronstad. 1983. Grain protein percentage, kernel hardness, and grain yield of winter wheat with foliar applied urea. *Agron. J.* 75: 87-91.

Anderson, V.J. and D.D. Briske. Stomatal distribution, density and conductance of three perennial grasses native to southern true prairie of Texas. *Am. Midle. Nat.* 123:152-159.

Baldwin, C.M., H. Liu, L.B. McCarty, W.L. Bauerle, and J.E. Toler. 2006. Responses of six bermudagrass cultivars to different irrigation intervals. *HortTechnology*. 16(3): 466-470.

Beard. J.B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Inc. Englewood, Cliffs. N.J.

Below, F.E., S.J. Crafts-Brandner, J.E. Harper, and R.H. Hageman. 1985. Uptake, distribution, and remobilization of ^{15}N-labeled urea applied to maize canopies. *Agron. J.* 77:412-415.

Bondada, B.R., D.M. Oosterhuis, and R.J. Norman. 1997. Cotton leaf age, epicuticular wax, and nitrogen[15] absorption. *Crop Sci.* 37: 807-811.

Bowman, D.C. and J.L. Paul. 1989. The foliar absorption of urea-N by Kentucky bluegrass turf. *J. of Plant Nutrition*. 13(5): 659-673.

Bowman, D.C. and J.L. Paul. 1990. The foliar absorption of urea-N by tall fescue and creeping bentgrass turf. *J. of Plant Nutrition*. 13(9): 1095-1113.

Bowman, D.C. and J.L. Paul. 1992. Foliar absorption of urea, ammonium, and nitrate by perennial ryegrass turf. *J. Amer. Soc. Hort. Sci*. 117(1):75-79.

Boynton, D. 1954. Nutrition by foliar application. *Annual Review of Plant Physiology*. 5: 31-54.

Bukovac, M.J. and S.H. Wittwer. 1957. Absorption and mobility of foliar applied nutrients. *Plant Physiol.* 32: 428-435.

Carrow, R.N., D.V. Waddington, and P. E. Rieke. 2001. Turfgrass Soil Fertility and Chemical Problems – Assessment and Management. Ann Arbor Press, Chelsea, MI.

Casler, M. D. and R.R. Duncan. 2003. Turfgrass Biology, Genetics, and Cytotaxonomy. Sleeping Bear Press. Chelsea, MI.

Casnoff, D.M., R.L. Green, and J.B. Beard. 1989. Leaf blade stomatal densities of ten warm-season perennial grasses and their evapotranspiration rates. *Proceedings of the Sixth International Turfgrass Research Conference:* 129-131.

Chamel, A.R., A.M. Andréani, and J.F. Eloy. 1981. Distribution of foliar-applied boron measured by spark-source mass spectrometry and laser-probe mass spectrography. *Plant Physiol.* 67: 457-459.

Chen, Y.G. and T. M. Ching. 1988. Induction of barley leaf urease. Plant Physiol. 86: 941-945.

Eberhardt, P.J. and W.L. Pritchett. 1971. Foliar applications of nitrogen to slash pine seedlings. *Plant and Soil* 34(1):731-739.

Eliot, R.C. 1960. Relationship between foliar and root development of turfgrass species and strains. *Illinois Turfgrass Conference Proceedings*. 32-35.

Eliot, R.C. 1972. The use of soluble fertilizers for lawn care. *Proceedings of the 42nd Annual Michigan Turfgrass.* 1: 61-71.

Eliot, R.C. 1972. The use of soluble fertilizers for lawn care. *Proceedings of the 42nd Annual Michigan Turfgrass*. 1: 61-71.

Eichert, T., H.E. Goldbach, and J. Burkhardt. 1998. Evidence for the uptake of large anions through stomatal pores. *Botanica Acta* 111: 461–466.

Eichert, T. and J. Burkhardt. 2001. Quantification of stomatal uptake of ionic solutes using a new model system. *J. Exp. Bot.* 52: 771-781

Franke, W. 1967. Mechanisms of foliar penetration of solutions. *Annual Review of Plant Physiology*. 18: 281-300.

Frankenberger, W.T. and M. A. Tabatabai. 1982. Amidase and urease activities in plants. *Plant Soil* 64: 153-166.

Fu, J. and J. Huang. 2003. Effects of foliar application of nutrients on heat tolerance of creeping bentgrass. *J. of Plant Nutrition*. 26(1): 81-96.

Fu, J. and J. Huang. 2004. Leaf characteristics associated with drought resistance in tall fescue cultivars. *I International Conference on Turfgrass Management and Science for Sports Fields. ISHS Acta Horticulturae* 661: 233-239.

Garling, D.D., J.W. Rimelspach, J.R. Street, and M.J. Boehm. 1999. The impact of foliar nitrogen concentration on dollar spot severity and turfgrass quality. *Annual Meeting Abstracts* 91: 135.

Green, R.L., D.M. Casnoff, and J.B. Beard. 1993. Stomatal-row patterns among warm-season turfgrasses with a discussion of water conservation via stomatal anatomy. *International Turfgrass Society Research Journal* 7: 614-620.

Green, R.L., J.B. Beard, and D.M. 1990. Leaf blade stomatal characterizations and evapotranspiration rates of 12 cool-season perennial grasses. *HortScience.* 25(7): p. 760-761.

Guertal, E.A. 2004. Boron fertilization of bentgrass. *Crop Sci.* 44: 204-208.

Hogan, M.E., I. E. Swift, and J. Done. 1983. Urease assay and ammonia release from leaf tissues. *Phytochemistry* 22: 663-667.

Horgan, B. P., B. E . Branham, and R. L. Mulvaney. 2002a. Direct measurement of denitrification using ^{15}N-labeled fertilizer applied to turfgrass. *Crop Sci.* 42:1602-1610.

Horgan, B. P., B. E. Branham, and R. L. Mulvaney. 2002b. Mass balance of ^{15}N applied to Kentucky bluegrass including direct measurement of denitrification. *Crop Sci.* 42:1595–1601.

Hull, R.J. and H. Liu. 2005. Turfgrass nitrogen: physiology and environmental impacts. *Inter. Turfgrass Soc. Res. J.* 10:962-975.

Johnson, S.J. and N.E. Christians. 1984. Fertilizer burn comparison of concentrated liquid fertilizers applied to Kentucky bluegrass turf. *J. Amer. Soc. Hort. Sci.* 109(6): 890-893.

Kauffman, G.L., D. P. Kneivel, and T.L. Watschke. 2007. Effects of a biostimulant on the heat tolerance associated with photosynthetic capacity, membrane thermostability, and polyphenol production of perennial ryegrass. *Crop Sci.* 47: 261-267.

Liu, C., R.J. Cooper, and D.C. Bowman. 1998. Humic acid application affects photosynthesis, root development, and nutrient content of creeping bentgrass. HortScience 33(6):1023–1025.

Liu, H., L.B. McCarty, C.M. Baldwin, F.W. Totten, S.H. Long, and J.A. Thackston. 2005. Enhanced bermudagrass putting green turf quality by using a combination of foliar fertilization and plant growth regulator. *Agronomy Abstract.*

Ma, B.L., K.D. Subedi, and L.M. Dwyer. 2006. Timing and method of ^{15}Nitrogen-labeled fertilizer application on grain protein and nitrogen use efficiency of spring wheat. *J. of Plant Nutrition*. 29(3): 469-483.

Mancino, C.F., D.M. Petrunak, and D. Wilkinson. 2001. Loss of putting greens-grade fertilizer granules due to mowing. *HortScience* 36(6):1123-1126.

Marschner, H. 1995. Mineral Nutrition of Higher Plants. Second Edition. Academic Press. New York.

Matsumoto, H., T. Yasuda, M. Koayashi, and E. Takahashi. 1966. The inducible formation of urease in rice plants. *Soil Sci. Plant Nutr*. 12: 239-244.

Matsumoto, H., Y. Hasegawa, M. Kobayashi, and E. Takahashi. 1968. Inducible formation of urease in *Canavalia ensiformis*. *Physiol. Plant* 21: 872-881.

McCarty, L.B, G.H. Snyder, and J.B. Sartain. 1994. Foliar feeding: How effective and safe is it? *Florida Turf Digest.* 11(3): 16-19.

McCarty, L.B. 2005. Best Golf Course Management Practices, 2nd Ed. Prentice Hall, Upper Saddle River, NJ.

McCaslin, B.D and C.E. Watson. 1977. Fertilization of common bermudagrass *Cynodon dactylon* L. with foliar application of iron. *New Mexico Agricultural Experiment Station, State College.* No. 334. p. 4.

McCullough, P.E., H. Liu, L.B. McCarty, T. Whitwell, and J.E. Toler. 2006. Bermudagrass putting green growth, quality, and nutrient partitioning influenced by nitrogen and trinexapac-ethyl. *Crop Sci.* 46: 1515-1525

Nicoulaud, B.A. and A.J. Bloom. 1996. Absorption and assimilation of foliarly applied urea in tomato. *J. Amer. Soc. Hort. Sci.* 121(16): 1117-1121.

Qian, Y.L., and M.C. Engelke. 1999. Influence of trinexapac-ethyl on Diamond zoysiagrass in a shade environment. *Crop Sci.* 39:202–208.

Riederer, M. and C. Müller. 2006. Biology of the Plant Cuticle. Blackwell Pub., Oxford, Ames, Iowa.

Rieke, P.E., S.L. McBurney, and R.A. Bay. 1982. Turfgrass soils report - effect of foliar applications of urea nitrogen and ferrous sulfate on quality of Adelphi Kentucky bluegrass. *Proceedings of the 53rd Annual Michigan Turfgrass*. Vol. 12: 24-25.

Sargent, J.A. 1965. The penetration of growth regulators into leaves. *Annual Review of Plant Physiology*. Vol. 16: 1-12.

Schlegel, T.K. and J. Schonherr. 2002. Selective permeability of cuticles over stomata and trichome to calcium chloride. *In Proceedings of the International Symposium on Foliar Nutrition of Perennial Fruit Plants (eds. M. Tagliavini and W. dranhorad). Maran, Italy, Acta Hort. 594, ISHS* 2002: 91-96.

Shearman, R.C. and J.B. Beard. 1972. Stomatal density and distribution in *Agrostis* as influenced by species, cultivar, and leaf blade surface and position. *Crop Sci.* 12: 822-823.

Sirko, A. and R. Brodzik. 2000. Plant ureases: roles and regulations. *Acta Biochimica Polonica*. 47: 1189-1195.

Spangenberg, B.G., T.W. Fermanian, and D.J. Wehner. 1986. Evaluation of liquid-applied nitrogen fertilizers on Kentucky bluegrass turf. *Agron. J.* 78:1002-1006.

Stewart, I. 1963. Chelation in the Absorption and Translocation of Mineral Elements. *Annual Review of Plant Physiology.* Vol. 14: 295-310.

Stiegler, J.C., G.E. Bell, and D.L. Martin. 2003. Foliar applications off magnesium and iron encourage annual bluegrass in shaded creeping bentgrass putting greens. *On-Line Applied Turfgrass Science, published 21 August, 2003*.

Stier, J. C., and J. N. Rogers, III. 2001. Trinexapac-ethyl and iron effects on supina and Kentucky bluegrasses under low irradiance. *Crop Sci.* 41:457-465.

Tan, X.W., H. Ikeda, and M. Oda. 1999. Absorption, translocation, and assimilation of foliar-applied urea compared with nitrate and ammonium in tomato plants. *Soil Sci. Plant Nutr.* 45(3): 609-616.

Taiz, L., and E. Zeiger. 2005. Plant physiology. 4th ed. The Benjamin/Cummings Publishing Company, Inc., Redwood City, CA.

Totten, F.W. 2006. Long-term evaluation of liquid vs. granular nitrogen fertilization in creeping bentgrass. Ph.D. diss. Clemson University, Clemson, SC.

Totten, F.W., H. Liu, L.B. McCarty, and C.M. Baldwin. 2005a. Comparison of granular and liquid fertility on creeping bentgrass. *Agronomy Abstracts*.

Totten, F.W., H. Liu, L.B. McCarty, and C.M. Baldwin. 2005b. Comparison of granular and liquid fertility on “TifEagle’ bermudagrass. *Agronomy Abstracts*.

Turgeon, A.J. 2005. Turfgrass management (7th Ed.). Prentice-Hall, Inc. Englewood Cliffs. N.J.

Vasilas, B.L., J.O. Legg, and D.C. Wolf. 1980. Foliar fertilization of soybeans: absorption and translocation of ^{15}N-labeled urea. *Agron. J.* 72: 271-275.

Wehner, D.J. and J.E. Haley. 1988. Foliar Burn From Turfgrass Fertilization. *Agronomy Abstracts.* p. 157.

Wesly, R.W., R.C. Shearman, and E.J. Kinbacker. 1985. Foliar N-uptake by eight turfgrass grown in controlled environment. *J. Amer. Soc. Hort. Sci.* 110(5): 612-614.

Wesly, RW., R.C. Shearman, E.J. Kinbacher, and S.R. Lowry. 1987. Ammonia volatilization from foliar-applied urea on field-grown Kentucky bluegrass. *HortSci.* 22(6): 1278-1280.

Witte, C.P. and N. Medina-Escobar. 2001. In-gel detection of urease with nitroblue tetrazolium and quantification of the enzyme from different crop plants using the indophenol reaction. *Anal Biochem*. 290: 102-107

Witte, C.P., S.A. Tiller, M.A. Taylor, and H.V. Davies. 2002. Leaf urea metabolism in potato. urease activity profile and patterns of recovery and distribution of ^{15}N after foliar urea application in wild-type and urease-antisense transgenics. *Plant Physiol.* 128: 1129-1136.

Wittwer, S.H. and F.G. Teubner. 1959. Foliar absorption of mineral nutrients. *Annual Review of Plant Physiology.* 10: 13-30.

Xie, S. and Q. Zhang. 2004. Kinetics of uptake and export of foliar-applied radio-labeled phosphorus by leaf and fruit rind of *Satsuma mandarin* during fruit development. *J. of Plant Nutrition.* 27(2): 223-237.

Zhang, X., and R.E. Schmidt. 2000a. Application of trinexapac-ethyl and propiconazole enhances superoxide dismutase and photochemical activity in creeping bentgrass (*Agrostis stoloniferous* var. *palustris*). *J. Am. Soc. Hortic. Sci*. 125:47–51.

Zhang, X., and R.E. Schmidt. 2000b. Hormone-containing products' impact on antioxidant status of tall fescue and creeping bentgrass subjected to drought. *Crop Sci.* 40:1344–1349.

Zhang, X., and E.H. Ervin. 2004. Cytokinin-containing seaweed and humic acid extracts associated with creeping bentgrass leaf cytokinins and drought resistance. *Crop Sci.* 44:1737–1745.

Table 1. Foliar nutrient uptake efficiencies of selected agricultural and horticultural crops, woody plants, and turfgrass species by using different labeled isotopes.

Crop	***Compounds with radioactive labeled-element foliarly applied***	***Percentage of recovery of the foliar-applied nutrient***	***References***
apple (*Malus domestica* Borkh. cv. Golden Delicious)	^{45}CaCl	80-99%	Schlegel and Schonherr, 2002.
blue lake bean (*Phaseolus vulgaris* L. cv. Bros, Twin Falls, and Idaho)	^{32}P, ^{42}K, ^{35}S, ^{45}Ca, $^{55\text{-}59}$Fe, $^{52\text{-}54}$Mn, , ^{65}Zn, ^{36}Cl, and ^{99}Mo	51, 61, 70, 69, 17, 35, 68, 90, and 6% corresponding to the left cell's isotopes, respectively.	Bukovac and Wittwer. 1957
broad bean (*Vicia faba* L. cv. Hang Down)	^{45}CaCl	28%	Schlegel and Schonherr, 2002.
Corn (*Zea mays* L.)	^{45}CaCl	37-42%	Schlegel and Schonherr, 2002.
Corn (*Zea mays* L.)	^{15}N-urea	29-30%	Below et al., 1985.
cotton (*Gossypium hirsutum* L.	^{15}N-urea	80%	Bondada et al., 1997.
cowpea (*Vigna unguiculata* L.)	^{32}P	43%	Adedipe and Ormrod, 1975
creeping bentgrass (*Agrostis palustris* Huds.)	^{15}N-urea	55%	Bowman and Paul, 1990
Kentucky bluegrass (*Poa pratensis* L.)	^{15}N-urea	50%	Bowman and Paul, 1989
Pear (*Pyrus communis* L. cv. Conference)	^{45}CaCl	60-69%	Schlegel and Schonherr, 2002.
perennial ryegrass (*Lolium perenne* L.)	^{15}N-urea, ^{15}N-NH_4^+, and ^{15}N-NO_3^-	35% - 40%	Bowman and Paul, 1992
radish (*Raphanus sativus* L. cv. 18 days)	^{10}B	74.2%	Chamel, et al., 1981
Satsuma mandarin (*Citrus unshiu*	^{32}P	74.8%	Xie and Zhang, 2004

Marc.)			
slash pine (*Pinus elliottii* Engelm.)	^{15}N-urea	71%	Eberhardt and Pritchett, 1971
soybeans [*Glycine max* (L.) Merr.]	^{15}N-urea	44-67%	Vasilas and Wolf, 1980
tall fescue (*Festuca arundinacea* Schreb.)	^{15}N-urea	55%	Bowman and Paul, 1990
tomato (*Lycopersicon esculentum* Mill.)	^{15}N-urea	76.9 to 99%	Nicoulaud and Bloom, 1996; Tan et al., 1999
wheat [*Triticum aestivum* (L.)]	^{15}N-urea	44%	Altman et al., 1983