REDUCED RATES OF CONTROLLED-RELEASE FERTILIZER LOWER POTENTIAL NITROGEN LEACHING FROM A WISCONSIN BARE-ROOT TREE NURSERY

Ryosuke Fujinuma, Nick J. Balster, and Hyung-Kyung Lee[1]

Abstract.—Controlled-release fertilizer (CRF) typically increases nitrogen (N) fertilizer uptake and lowers N lost from the rooting zone via leaching. However, questions remain as to whether lower rates of CRF could further increase this efficiency, especially in sandy bare-root nurseries in Wisconsin. We hypothesized that: 1) a reduced CRF application at 60 percent of the conventional rate (CRF60) would yield similar seedling morphology and biomass compared to a conventional application (CONV) and CRF at 100 percent of the conventional rate (CRF100); and 2) the CRF60 would result in significantly reduced potential N leaching (total N inputs minus plant N uptake) relative to the conventional rate. To test these hypotheses, we conducted a 2-year experiment in northern red oak (*Quercus rubra* L.) (NRO) at the largest bare-root nursery in Wisconsin. We applied a total of 259 kg N ha-1 to the CONV (ammonium sulfate) and CRF100 (coated urea) and 157 kg N ha^{-1} to CRF60 (coated urea) using standard application schedules. After two growing seasons, there was no significant difference in morphology (height, diameter, first-order lateral roots), biomass (stem, roots, total), and N content (stem, root) between treatments. However, the potential N leaching decreased significantly in the CRF treatments (30 percent under CRF100, 88 percent under CRF60) compared to CONV. Net N mineralization also decreased significantly under CRF (59 percent under CRF100, 32 percent under CRF60) compared to CONV. Overall, we conclude the CRF60 treatment would maintain seedling production goals for NRO relative to conventional levels but would significantly reduce potential N leaching at a bare-root nursery in Wisconsin.

INTRODUCTION

Producing large numbers of high-quality northern red oak (*Quercus rubra* L.) (NRO) seedlings in nursery soils characterized by rapid drainage and low nutrient retention requires large annual inputs of nitrogen (N) fertilizer. This condition is exemplified in Wisconsin state nurseries, which produce more than 475,000 NRO seedlings (bare-root) annually on coarse sandy soils (Wisconsin State Nursery 2008). Thus, nursery managers work to maximize N fertilizer uptake and minimize potential N leaching to the environment when N supply exceeds seedling demand (Paramasivam and Alva 1997, Landis and van Steenis 2004, U.S. Environmental Protection Agency 2006). Therefore, the need for efficient N management within these systems is critical to meet production goals while reducing the economic and environmental costs of excess N (Vande Hey 2007).

Controlled-release fertilizer (CRF), a type of enhanced-efficiency fertilizer, typically increases plant N uptake by matching N-release patterns from CRF prills (plastic-coated synthetic granules) with plant N demand

[1]Graduate Research Assistant (RF), Assistant Professor (NJB), and Undergraduate Research Scholar (HKL), Department of Soil Science, University of Wisconsin-Madison, 1525 Observatory Dr., Madison, WI, 53706-1299. RF is corresponding author: to contact, call (608) 215-0920 or email at rfujinuma@gmail.com.

(Shoji and others 1991). This synchronized N-release from CRF has been shown to be effective for seedling production in sandy nursery soils, as CRF increases the residence time of fertilizer-N in the soil relative to conventional fertilization (Dobrahner and others 2007, Zotarelli and others 2008). For example, in sandy arable fields, potatoes and citrus trees grown under CRF management showed larger N uptake compared with the plants grown with conventional fertilization (Dou and Alva 1998, Alva and others 2003, Zvomuya and others 2003). Consequently, increasing plant N uptake with CRF could reduce potential N leaching and thus provide an advantageous management option for nursery managers seeking to increase N fertilizer use efficiency.

Despite the benefits of CRF to nursery management, finding the most efficient CRF fertilization regime continues to challenge nursery managers in Wisconsin. Although improved modeling has been shown to provide more accurate estimates of N release from CRF (Fujinuma and others 2009), questions remain as to whether reduced rates of CRF will satisfy morphological grading criteria such as stem height, root collar diameter, and number of first-order lateral roots (FOLR) (Stroempl 1985, Clark and others 2000). In a study with white pine (*Pinus strobus*) seedlings, reduced CRF applications resulted in N uptake and morphology similar to those of a conventional N fertilization regime (Dobrahner and others 2007). However, few studies have examined similar reductions of CRF in deciduous tree seedlings such as NRO.

The objectives of this study were to determine whether a reduced rate of CRF application would maintain NRO production criteria and minimize potential N leaching within a bare-root tree nursery in southwest Wisconsin. We hypothesized that: 1) reducing the CRF application to 60 percent of the current conventional rate (CRF60) would yield seedling morphology and biomass similar to those with a conventional (CONV) application and CRF at 100 percent of conventional rates (CRF100); and 2) the CRF60 application would result in less potential N leaching than with the CONV and CRF100 applications. To test these hypotheses, we quantified changes in seedling morphology, biomass allocation, N uptake, and potential N leaching in 2-year-old (2-0) NRO seedlings. All hypotheses were tested relative to the end of a typical 2-year production cycle for NRO in Wisconsin.

MATERIALS AND METHODS

This study was conducted at H.G. Wilson State Nursery in Boscobel, WI (43°13' N, 90°70' W). A typical growing season for Wilson Nursery extends from May to October with the 30-year mean air temperature of 18 °C and cumulative precipitation of 487 mm (National Oceanic and Atmospheric Administration [NOAA] 2009). The soil was classified as a loamy sand Entic Hapludoll (U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NCRS] 2008) (90 percent sand) that was slightly acidic (pH 5.9-6.1). NRO seedlings are grown over a 2-year production cycle to maximize root biomass and caliper for increased survivability when transplanted into field conditions (Vande Hey 2007). Prior to this study, the nursery received an organic matter amendment in fall 2004 to increase soil organic matter content to approximately 2 percent; no additional organic matter was applied over the course of this study. The nursery used irrigation water from the nearby Wisconsin River as needed throughout the 2005 and 2006 growing seasons observed in this study.

This study used a complete randomized design of three fertilizer treatments. Each treatment was replicated three times, where each replicate was established as a randomly selected row (1.2 m by 167 m) within the nursery; each row consisted of 46 contiguous beds (1.2 m by 3.6 m). In an effort to capture the spatial variability within each row, we first excluded three beds from each end (to avoid edge effects) and then randomly selected three beds (subplot) from the remaining 40 beds to represent the average of each row (replicated). This design yielded a sample size of nine subplots (beds) per treatment. To avoid cross contamination from adjacent rows, seedlings within a 15-cm side buffer were excluded from sampling. Seedlings were planted in fall 2004 from acorns collected from Hayward, WI, yielding a seedling density of approximately 86 seedlings per square meter.

The three fertilizer treatments were as follows: a conventional fertilization (CONV) of 259 kg N ha^{-1} (approximately 300 mg N $seedling^{-1}$), CRF100 (N application rate equivalent to that of the CONV), and CRF60 (157 kg N ha^{-1}, 60 percent of the CONV N-application rate). Each treatment was applied to the entire row. Ammonium sulfate (21-0-0, 24 percent sulfur) was used in the CONV treatment. The CRF consisted of coated urea (Multicote®, 42-0-0, Haifa Chemical Ltd., Haifa Bay, Israel), which was rated to release 80 percent of fertilizer N within 2 months under constant temperature conditions of 27 °C. Applications of ammonium sulfate were evenly divided 11 times over the course of the 2-year production cycle; each individual fertilizer application amounted to 23.5 kg N ha^{-1}. Eight fertilizer applications were applied at 10-day intervals during the first growing season (2005; June to August) and another three applications at 30-day intervals during the second growing season (2006; May to July). The CRF treatments were divided into two applications; 73 percent of the total application was applied in May 2005 and 27 percent of the total application was applied in May 2006. Thus the seedlings under the CRF100 received 188 kg N ha^{-1} in 2005 and 71 kg N ha^{-1} in 2006; the seedlings under the CRF60 received 113 kg N ha^{-1} in 2005 and 43 kg N ha^{-1} in 2006.

Seedling morphology and biomass were sampled at 2-week intervals from June through October in both the 2005 and 2006 growing seasons. Three seedlings were randomly collected from each subplot using a destructive method. Stem height and root-collar diameter of each seedling were measured on site. In the laboratory, the number of FOLR were counted and then the seedlings were partitioned into leaves, stems, and roots, dried at a constant temperature of 65 °C for 10 days, and weighed (Wilde and others 1979). Each component (leaves, stems, roots) was ground to pass through a 250-µm mesh sieve and homogenized for further chemical analysis. Total N concentration of each component was analyzed using a combustion method with auto-analyzer (Flash EA 1112 CN analyzer, CE Elantech, NJ).

Precipitation plus irrigation water (ml) was summed monthly during the 2005 and 2006 growing seasons (June-September); precipitation and irrigation waters were not measured separately in this study. This volume of water was recorded with a tipping bucket connected to a data logger (HOBO Data Logging Rain Gauge, Onset Computer Corporation, Bourne, MA), which was positioned 90 cm from the ground surface. Three additional funnels (20-cm diameter) were randomly placed at 90 cm from the ground surface within the study area to collect liquid samples for chemical analysis. Each funnel was connected to a 3.6-L reservoir, which contained a drop of 40 g L^{-1} sodium bromate to suppress microbial activity in the sample. Solution volumes in the reservoir were recorded at 2-week intervals during the 2005 and 2006 growing seasons, and then subsamples were taken for further chemical analyses. Water loss due to evaporation was minimized by using containers painted with a reflective coating and looping the input tube from the funnel. The concentration of inorganic-N (ammonium-N and nitrate-N) in each sub-sample was analyzed using colorimetric methods (4D10a1a for ammonium-N and 4D9a1a for nitrate-N) (USDA-NRCS 2004) with a Lachat QC-8100 auto-analyzer (Lachat Instruments Inc., Loveland, CO).

Net N mineralization rate was estimated using an open-top *in-situ* soil core method described in Brye and others (2002). Two PVC tubes (20 cm long by 5 cm in diameter) were placed in randomly selected beds within each replicate (row). Each PVC tube was first inserted into the soil and then removed along with the soil contained within each core. Bags of cation and anion exchange resins (10 g of Dowex 1X8-100 and 10 g of Dowex 50W8-100) were then stuffed into the bottom of each PVC tube followed by a bag of silica sand (20 g) to deter the adsorption of N from the soil below the tube. The tubes were then reinserted into their respective holes. The resin bags within each PVC tube were replaced with new bags monthly to avoid saturation. To maintain the integrity of the hole, the PVC tubes were carefully removed and reinserted when the soil was moist. The inorganic N stored in the resin bags was extracted using 40 ml of 2-M potassium chloride. The concentration of inorganic N in the extracts was also analyzed using the aforementioned colorimetric methods.

The N retained by woody biomass (U; mg N seedling^{-1}) was estimated as N in the stem and roots at the end of the second growing season (after leaf drop) plus the N retained in leaf litterfall in 2005 and 2006:

$$U = [SN + RN] + [(LN1 + LN2) \times 0.4] \quad [1]$$

where SN is stem N content (mg N seedling^{-1}), RN is root N content (mg N seedling^{-1}), LN1 is leaf N content (g seedling^{-1}) at the end of August 2005, and LN2 is leaf N content (g seedling^{-1}) at the end of August 2006, with 40 percent retained in the litterfall based on published literature for oak species (Aerts 1996, Kolb and Evans 2002).

The potential N leaching (PNL) was estimated by a N mass-balance equation;

$$PNL = WN + F + M - U \times 0.86 \quad [2]$$

where PNL is an estimate of the potential N leaching (kg N ha^{-1}) summed over two growing seasons, WN is the N content of water input (precipitation and irrigation, kg N ha^{-1}), F is the fertilizer-N (kg N ha^{-1}), M is net N mineralization (kg N ha^{-1}), U is the N uptake from Eq.[1], and 0.86 is a parameter to convert units from mg N per seedling to kg N ha^{-1} given the 86 seedlings m^{-2} of seedling density.

Differences in seedling morphology (stem height, root-collar diameter, FOLR) and biomass (stem biomass, root biomass) were evaluated by treatment means per sampling date (every 2 weeks) and at the end of the 2-year production cycle. The N balance in NRO seedlings was also calculated at the end of the 2-year production cycle. The data were analyzed by one-way analysis of variance (ANOVA) using a completely randomized design to evaluate the treatment effects on seedling morphology, biomass and N allocation, net N mineralization, and potential N leaching. Significant differences in means comparisons were identified by using Fisher's least significant difference (LSD) test at $p < 0.05$. All statistical analyses were conducted with JMP 7.0 (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

In support of our first hypothesis, seedling morphology and biomass of NRO seedlings did not differ by fertilization treatment (Table 1). All fertilization treatments yielded seedlings within acceptable morphological grading criteria (35-50 cm height; >6 mm root-collar diameter; >8 FOLR) for 2-0 NRO in the central United States (Stroempl 1985, Clark and others 2000). In addition, all fertilization treatments yielded a similar range in total seedling biomass, between 41-46 g at the end of the 2-year production cycle ($p = 0.470$) (Table 1). Many studies also report similar stem height, root-collar diameter, and total biomass between

Table 1.—Morphology and biomass of northern red oak seedlings at the end of the 2-year production cycle in Wilson State Nursery, Boscobel, WI. Values are given as means plus one standard error. There was no significant difference between treatments in Fisher's LSD test at $p < 0.05$.

Fertilizer treatment	Stem height (cm)	Root collar diameter (mm)	Number of FOLR†	Stem biomass (g)	Root biomass (g)	Leaf biomass (g)‡	Total biomass (g)
CONV	57.5 (3.2)	7.4 (0.3)	16 (1)	8.57 (0.68)	13.60 (2.15)	11.48 (1.36)	43.69 (2.45)
CRF100	50.2 (3.6)	6.8 (0.3)	14 (1)	7.11 (0.66)	12.67 (1.32)	8.73 (0.51)	41.05 (1.20)
CRF60	46.3 (5.1)	6.4 (0.7)	16 (2)	6.11 (1.24)	12.68 (2.81)	10.22 (1.00)	45.98 (3.73)

†FOLR = first-order lateral root with diameter greater than 1 mm.
‡Leaf biomass = sum of leaf biomass at summer 2005 and 2006.

seedlings under CRF applications compared to conventional fertilization (Guertal 2000, Boman and Battikhi 2007, Dobrahner and others 2007). By showing a 60-percent reduction in the rate of CRF does not change the morphology or biomass of the NRO seedlings compared to a CRF100 or conventional treatment, our results suggest that the conventional fertilizer rates over the 2-year management cycle likely exceeded production requirements.

The temporal change in height, diameter, and biomass followed similar trends regardless of the fertilization treatments over the 2-year production cycle (Fig. 1). During the first growing season, stem heights increased from June through August, in contrast to root-collar diameters, which increased threefold from mid-August until the end of the 2005 growing season. This pattern was consistent with general growth curves reported for seedlings in bare-root nurseries (Landis and van Steenis 2004). By the end of July 2006 (year 2), NRO seedlings met the morphological grading criteria previously described (Stroempl 1985), which have been used as a reliable indicator of relative growth potential and outplanting success (Von Althen 1980, Grossnickle 2005). Despite the minimal change in height and diameter growth during the second growing season, the belowground biomass continued to increase regardless of treatment during both growing seasons. Thus, a CRF treatment at 60 percent of the conventional rate also did not alter the temporal dynamics of NRO morphology or biomass allocation.

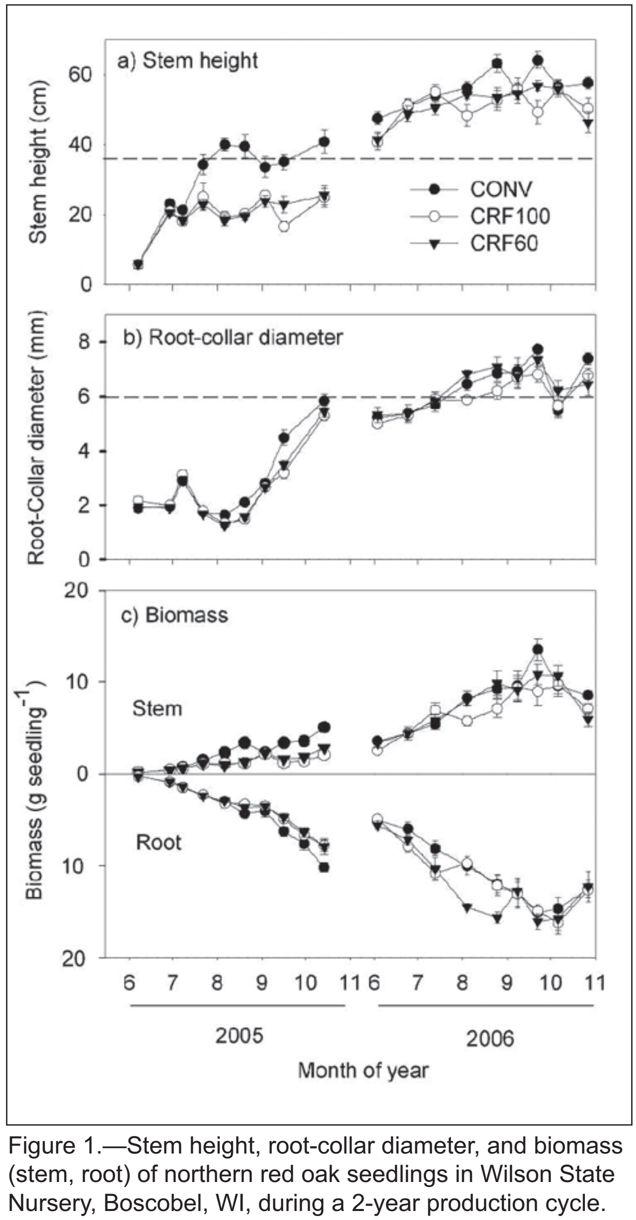

Figure 1.—Stem height, root-collar diameter, and biomass (stem, root) of northern red oak seedlings in Wilson State Nursery, Boscobel, WI, during a 2-year production cycle. The dashed horizontal lines on the graphs of stem height (a) and root-collar diameter (b) refer to morphological grading requirements (Stroempl 1985). Each point indicates a mean plus one standard error.

Similar to the lack of treatment effect on temporal growth dynamics, there was no significant differences in stem and root biomass between treatments, $p = 0.232$ and $p = 0.942$, respectively (Table 1). However, biomass was preferentially allocated to roots relative to stems throughout this study (Table 1; Fig. 1), which concurred with findings from other studies of NRO seedlings grown under a range of N fertilization rates (Salifu and Jacobs 2006, Salifu and others 2009). This pattern of allocation was also observed in N content, where approximately twice the N was allocated to root tissue relative to stems regardless of fertilization treatment (Table 2); similar results have been found in recent studies of NRO seedlings in bare-root nurseries (Salifu and others 2009, Fujinuma and Balster *in review*). Therefore, the reduced amount of N fertilization does not appear to change the preferential allocation of biomass in the roots of NRO seedlings relative to stems within this nursery. Because field trials have shown a competitive advantage of larger seedlings (Grossnickle 2005), we speculate that these larger root systems with proportionally high N content may increase the survival and subsequent growth after transplant into competitive growth environments.

Both CRF treatments significantly decreased potential N leaching compared to the CONV treatment, supporting the second hypothesis in this study ($p < 0.05$). Under the same rate of fertilizer-N, CRF100 decreased potential N leaching by 30 percent compared to CONV. However, CRF60 further decreased potential N leaching by 88 percent relative to CONV (Fig. 2). The contribution of a significantly lower net mineralization and lower fertilizer N inputs from CRF likely explains this additional reduction in potential

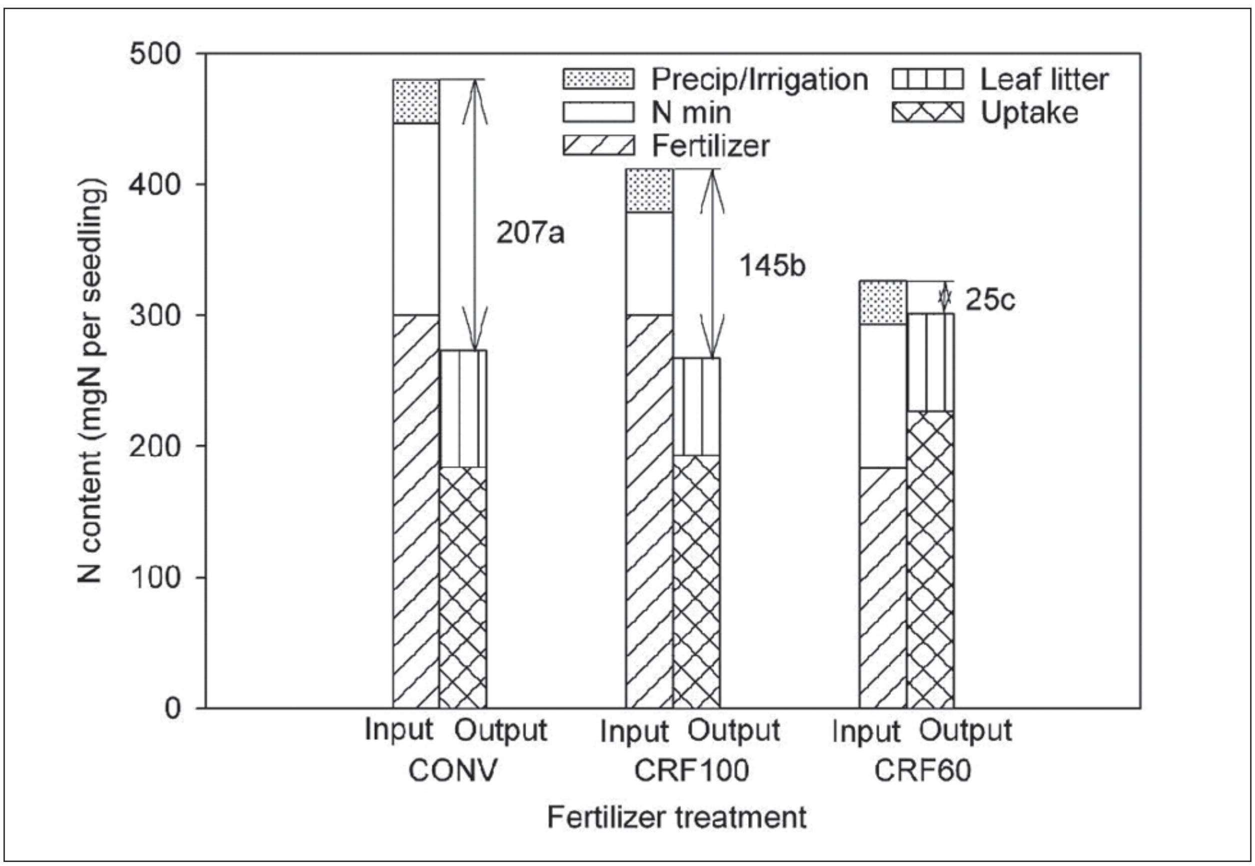

Figure 2.—Potential nitrogen leaching, total inputs, and outputs of N in Wilson State Nursery in Boscobel, WI, over a 2-year production cycle of northern red oak seedlings. Inputs represent total N contributions from fertilization, mineralization, precipitation, and irrigation water. Nitrogen outputs represent seedling N (sum of root N and stem N), as well as leaf litter (maximum leaf N content multiplied by mean retranslocation, 40 percent). Significant differences ($p < 0.05$) are represented by different letters.

N leaching under CRF60 (Köhler and others 2006, Li and others 2007). Although a reduction in N leaching from CRF applications is not a new discovery (Shoji and Kanno 1994, Guillard and Kopp 2004), our results suggest that reductions in the rate of CRF can effect even greater reductions in potential N leaching from the rooting zone without sacrificing production goals in this Wisconsin bareroot nursery.

Differences in fertilization regime appear to change the rate of net N mineralization. In this study, net N mineralization in the CONV treatment at the end of the 2-year production cycle was significantly greater relative to both CRF treatments ($p < 0.05$) (Fig. 2). Results vary by year, however. Net N mineralization under the CRF treatments averaged 34-54 percent lower relative to the CONV treatment in the 2005 growing season, but was not significantly different between treatments in 2006 ($p = 0.39$) (Table 2). Although this lack of significance during the second growing season was not large enough to nullify a difference over the 2-year production cycle, it could be explained by the fact that plots received no organic matter amendments during the study period. Alternatively, the reduced input of N from the CRF treatments may have increased the soil carbon:nitrogen ratio, effectively lowering the contribution of N from the turnover of soil microorganisms (Li and others 2002, McAndrew and Malhi 2002, Chu and others 2005). It should be noted that the N collected in the resin beads may have included the input of soluble N from the fertilizer prills, as N mineralization was measured *in situ* over the course of this study. Based on literature reports of typical N mineralization rates (Köhler and others 2006), however, this artifact of the experiment was likely negligible.

Finally, given the sandy texture of the nursery soil examined in this study, the timing of N leaching loss (and thus fertilization) may be of greatest importance when considering the type of fertilizer used. In other words, despite the higher potential N leaching we measured from the conventional treatments, this leachate may not have reached the water table during the 2005 and 2006 growing seasons within this nursery. By first approximation, the field capacity of a loamy sand soil is approximately 0.13 $m^3\ m^{-3}$ (Campbell and Norman 1998). Therefore, given a dry soil, in order for fertilizer N to reach soil water pools at a 100-cm depth (Dobrahner and others 2007), input from precipitation and irrigation must exceed 130 mm. During this study, monthly cumulative precipitation and irrigation ranged from 100 to 250 mm during the 2005 growing season and 100 to 150 mm during the 2006 growing season (Fig. 3), and there were no heavy storm events (>100 mm hr^{-1}). If we subtract the average in cumulative monthly potential evapotransipration (148 mm) over the two growing seasons examined in this study (Bland 2009), N leached from the rooting zone (15-20 cm) likely did not reach a meter into this soil profile from June through September in 2005 and 2006. Thus, any excess N stored in the upper soil profile may be susceptible to greater seasonal loss during early spring with the relatively large input of melt water from winter snowmelt in Wisconsin; the 30-year

Table 2.—Nitrogen content in northern red oak seedlings, nitrogen input from fertilizer, net N mineralization, and irrigation/precipitation in Wilson State Nursery, Boscobel, WI. Values are given as means plus one standard error. Different letters within a column indicate significant differences in Fisher's LSD test at p < 0.05.

Fertilizer treatment	Stem N (mg N)	Root N (mg N)	Maximum Leaf N (mg N)		Fert. N (kg ha^{-1})	Net N mineralization (kg ha^{-1})		N in (P+I) (kg N ha^{-1})	
			2005	2006	2005-2006	2005	2006	2005	2006
CONV	63a (7)	121a (12)	106a (10)	116a (5)	259	68a (19)	30a (8)	13	15
CRF100	63a (5)	130a (11)	55b (4)	131a (5)	259	23b (8)	17a (3)	13	15
CRF60	72a (8)	155a (17)	56b (7)	129a (23)	157	37ab (8)	30a (14)	13	15

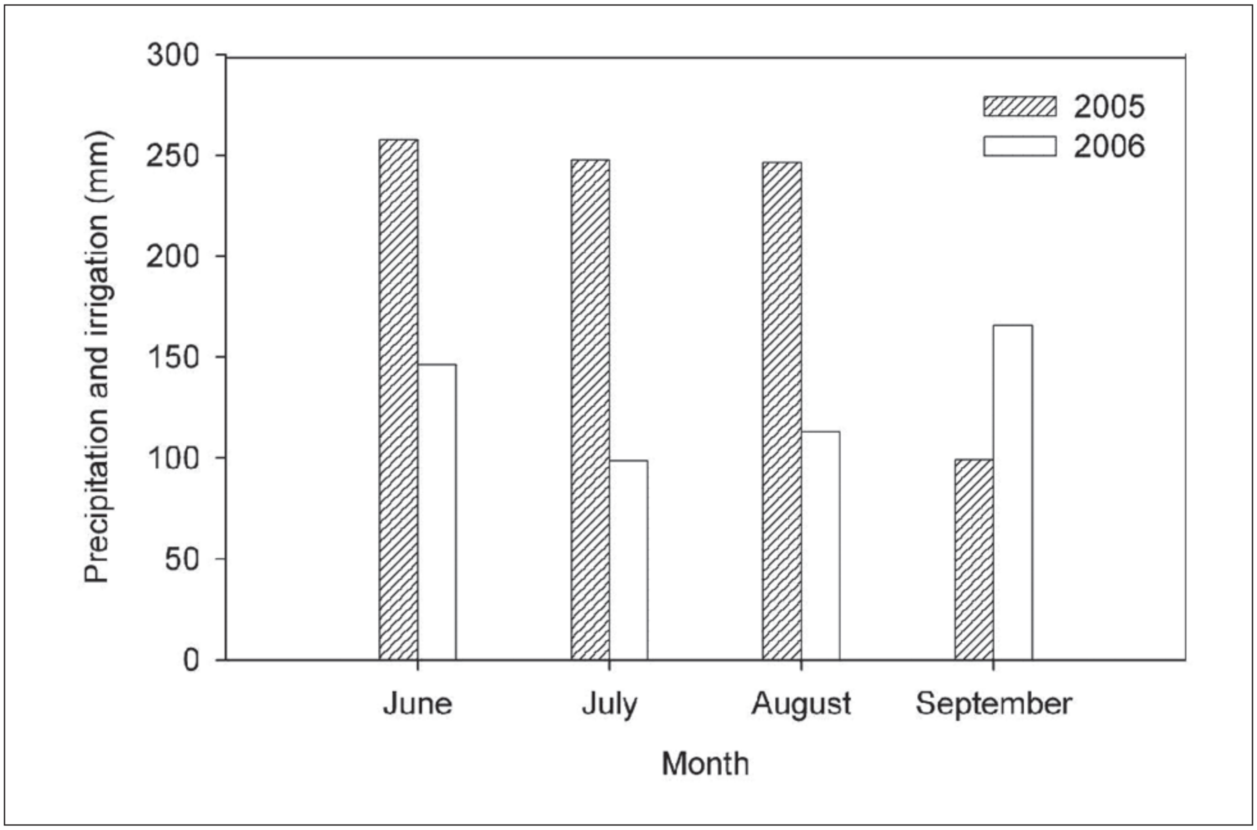

Figure 3.—Sum of monthly precipitation and irrigation at Wilson State Nursery, Boscobel, WI, during 2005 and 2006 growing seasons.

average cumulative precipitation from November to April is 254 mm at this site (NOAA 2009). Given these estimations, we hypothesize that the impact of excess N fertilization on deep groundwater pools within this nursery may be underestimated by measurements that do not quantify soil water dynamics over the entire growing season. Direct measurements of these fluxes, including the capture of soil leachate, would test this hypothesis.

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