Communications in Soil Science and Plant Analysis, 36: 1465–1477, 2005

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1081/CSS-200058491

Method of Nitrogen Application in Summer Affects Plant Growth and Nitrogen Uptake in Autumn in Young Fuji/M.26 Apple Trees

Shufu Dong
Department of Horticulture, Oregon State University, Corvallis, OR, USA

Lailiang Cheng
Department of Horticulture, Cornell University, Ithaca, NY, USA

Carolyn F. Scagel
USDA-ARS, Horticultural Crops Research Laboratory, Corvallis, OR, USA

Leslie H. Fuchigami
Department of Horticulture, Oregon State University, Corvallis, OR, USA

Abstract: Effects of foliar vs. soil nitrogen (N) application during the summer and the autumn were studied in young Fuji apple trees (*Malus domestica* Borkh) on Malling 26 (M.26) rootstock. One-year-old bench-grafted trees were potted in 3.8-liter pots in a mix of perlite, peat moss, and loam soil (1:1:1 by volume) and were treated weekly from late June to early September with 0.5% urea either by foliar or soil application or soil application of water (control). At the end of September, five trees from each treatment were harvested, and shoot and root growth and leaf N concentration were determined. In mid-October of the same year, trees from each treatment were randomly divided into three subgroups. One group received soil application of water (control), and the other groups received either a foliar or soil application of 3% ^{15}N-urea. After natural leaf defoliation, trees were harvested, and total N and ^{15}N

Received 3 November 2003, Accepted 7 September 2004
Address correspondence to Shufu Dong, Department of Biology, Okanagan University College, 3333 University Way, Kelowna, BC V1V 1V7, Canada. Fax: 250-470-6005; E-mail: sdong@ouc.bc.ca

concentration of stems (all aboveground tissue) and roots was determined. Regardless of application method, N application during the summer promoted plant growth and increased leaf N concentration. Soil N application during the summer stimulated more shoot and extension root growth than foliar N application. In contrast, the foliar N application in the summer promoted more feeder root growth than soil N application. Regardless of application method, autumn N application after terminal bud set had little effect on current-year growth but increased total plant N concentration. In the autumn, trees that received soil N applications in the summer had more ^{15}N uptake by leaves, while trees receiving foliar N applications in the summer had more ^{15}N uptake by root. These results suggest that the differential influence of N application methods during the summer on growth and partitioning of trees affects tree responsiveness to autumn N applications. The use efficiency of autumn-applied N depends on the method of N application in the summer.

Keywords: *Malus domestica*, N, spray, soil application

INTRODUCTION

Nitrogen (N) is the most important element for plant growth and development. Consequently, application of N fertilizers has had the most significant effect in increasing crop production (Mengel and Kirby 1987). Because of its importance in crop production, N fertilizer is often used as an "insurance policy" to achieve maximum productivity (Sanchez et al. 1995). However, some fruit tree growers often apply too much N in their orchards in order to ensure maximum productivity. This overapplication of N not only increases production costs, but may also affect fruit quality (Fallahi and Simons 1996) and result in N contamination of the environment. Therefore, methods of increasing N use efficiency and reducing N loss is important for fertilization management in orchards and nurseries.

Application of N to soil is the traditional method to supply N to plants. While it effectively improves plant growth, soil N application usually has a low recovery and high risk of losses to leaching (Dinnes et al. 2002). Several researches have shown that applications of N to foliage (foliar N applications) have a higher recovery rate than soil applications (Klein and Weinbaum 1984; Rosecrance, Johnson, and Weinbaum 1998; Shim, Titus, and Splittstoesser 1972; Tagliavini, Millard, and Quartieri 1998; Weinbaum 1988). However, it is still believed that soil N applications cannot be completely substituted for by foliar N applications (Mengel 2002). It is possible that the combination of soil and foliar N applications may be a more efficient use of N and reduces N loss (Fallahi and Simons 1996; Khemira, Righetti, and Azarenko 1998).

Seasonal changes in the amount and kinetics of N uptake are important in guiding N fertilization practices (Khemira et al. 1998; Niederholzer et al. 2001; Policarpo et al. 2002). The timing and method of N application (e.g., soil versus foliar N application) during the growing season may influence N uptake as well as plant growth and function. Recently, researches have shown that N foliar application in the autumn can increase the amount of N reserves in the plant that are used for the initial growth in the following season for deciduous fruit trees (Cheng, Dong, and Fuchigami 2002; Dong et al. 2002; Rosecrance et al. 1998). The method of fertilizer application during the summer may affect the uptake and efficient use of autumn applied N. There is little information on this aspect cited in the literature. However, this information would be useful in the optimum management of N fertilizers in orchards.

The objective of this study is to determine the (1) effect of soil versus foliar N applications during the summer on tree growth, and (2) effect of soil versus foliar N applications during summer on N uptake in the autumn in young apple trees.

MATERIALS AND METHODS

One-year-old bench-grafted Fuji apple trees on Malling 26 (M.26) rootstock were used in this study. The trees were planted in 3.8-liter pots in a mix of perlite, peat moss, and loam soil (1:1:1 by volume) and were randomly divided into three groups with 30 trees in each group. Trees were treated weekly from late June to early September with either 0.5% urea foliar applications, 0.5% urea soil applications, or water applications to soil (control). The pots of trees that received foliar applications were covered with plastic film during application to prevent entry of the N into the soil and trees were sprayed until runoff with the urea solution. For the soil applications, the same volume of urea solution or water as used in the foliar application was applied to the soil of each tree. All trees were well watered, and we assumed that there should be no significant difference between different methods of water application (soil vs. foliar) for control; therefore, the control trees in the experiment received only soil applications of water.

At the end of September, five trees from each treatment were harvested, and growth performance (shoot length, biomass, leaf color, and new root growth) was measured. Nitrogen concentration in leaves was also determined by Kjeldahl analysis (Schuman, Stanley, and Knudsen 1973). The new roots were divided into two categories mainly based on their morphology: extension roots (>0.8 mm in diameter) and feeder roots (<0.8 mm in diameter) (Shu, Wang, and Dong 1993).

In mid-October of the same year, three subgroups from each treatment were randomly divided, and two of them were treated with 3% ^{15}N-urea (10% ^{15}N atom abundance, ICON, Mt. Marison, NY, USA) by either foliar or soil application, and the third group received the same volume of water applied to soil as a control. After leaf defoliation, trees were harvested and separated into stems (aboveground part) and roots (underground part). All samples were immediately washed in doubled distilled (DD) water, placed into a −80°C freezer for prefreezing, and then freeze-dried. Samples were ground through 60 mesh screen prior to analysis for total N and ^{15}N.

Total N (mg kg^{-1} dry weight) was determined using Kjeldahl analysis (Schuman et al. 1973) by the Central Analysis Laboratory of Oregon State University. The amount of ^{15}N in samples was determined from the gas evolved from combustion of powdered tissue in an elemental analyzer coupled with a mass spectrometer by the laboratory of Isotope Services, Inc. (Los Alamos, New Mexico, USA). The ^{15}N abundance in control samples is similar to the natural ^{15}N abundance, and so the natural abundance was used to calculate the percentage of N derived from urea fertilizer in each tissue (NDFF%):

$$NDFF\% = \frac{(atom\%^{15}N)_{tissue} - (atom\%^{15}N)_{natural \cdot abundance}}{(atom\%^{15}N)_{fertilizer} - (atom\%^{15}N)_{natural \cdot abundance}} \times 100\%$$

The concentration of ^{15}N was calculated from NDFF% and the N concentration in each tissue. The amount of ^{15}N (mg) in each tissue type was calculated by multiplying ^{15}N concentration with the dry weight of the tissue. Uptake of ^{15}N per plant was calculated by adding the amount of ^{15}N in the different tissues.

The experiment was a nested design with three fall treatments (no ^{15}N, foliar ^{15}N, and soil ^{15}N application) within three summer treatments (control, foliar, and soil N application). Data of shoot length, biomass, total N, and ^{15}N content were subjected to analysis of variance (GLM-ANOVA) procedures. Differences between means were assessed by using the Fisher Protected LSD test ($p = 0.05$). The correlations between the amount of ^{15}N translocation from soil application in autumn and root N content were calculated using Pearson's correlation coefficient (r). All statistical analyses were performed with NCSS Statistical System Software (NCSS Statistical Analysis Software, Kaysville, UT, USA).

RESULTS AND DISCUSSION

Plant Growth

Shoots of trees treated with soil or foliar N applications in the summer were significantly longer than shoots on control trees, and soil N applications promoted greater shoot growth than foliar N applications (Figure 1A). Autumn N treatments after terminal buds set had no effect on shoot length. The same trend was found on total tree biomass (Figure 1B). Summer soil N applications resulted in trees with the highest plant biomass, followed by trees that received the summer foliar N applications, then control trees. Autumn N treatments did not affect the total biomass of the plant. It is well known that the availability of N is one of the most important factors

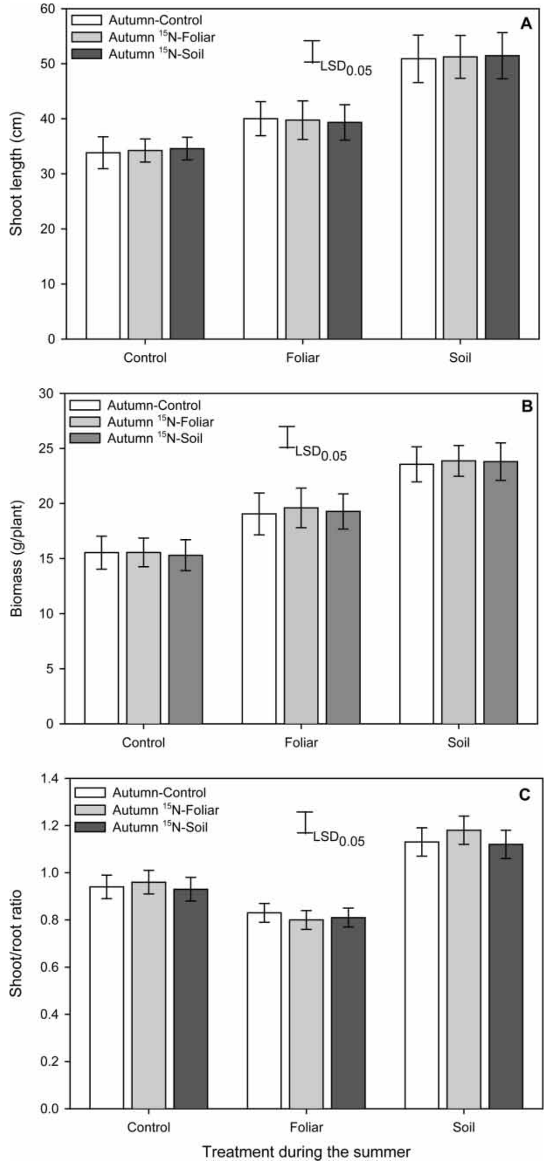

Figure 1. Shoot length (A), total biomass (B), and shoot/root ratio (C) of young Fuji/M26 apple trees treated with soil and foliar nitrogen (N) applications during the summer (June to early September) and autumn (mid-October). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Autumn treatments: no N (water application to soil: Autumn-Control), 3% ^{15}N urea as foliar application (Autumn ^{15}N-Foliar), and 3%^{15}N urea as soil application (Autumn ^{15}N-Soil). Bars on columns represent standard errors of the mean of five replicates.

affecting plant growth (Mengel and Kirby 1987). Both shoot length and total biomass of young apple trees in this experiment were affected by the N fertilization and by the method of N application during the summer. Trees receiving soil N applications during the summer grew more (shoot length and tree biomass) than trees that received foliar N applications, which is similar to results reported by Fallahi and Simons (1996).

The method of N application during the summer affected biomass partitioning in trees. Trees receiving soil N applications during the summer partitioned more biomass to shoots resulting in a higher shoot/root ratio than trees in other treatments (Figure 1C). In contrast, trees receiving the foliar N applications in summer partitioned more biomass to roots resulting in a lower shoot/root ratio than trees in other treatments. Autumn N treatments did not significantly affect the shoot/root ratio.

Different methods of N application during the summer affected initiation and growth of different types of new roots (Figure 2). Trees receiving soil N applications during the summer had significantly more extension roots than trees in other treatments, whereas trees that received foliar N applications in the summer had significantly more feeder roots than trees in other treatments. Extension roots are known to have higher IAA synthesis ability than feeder roots (Shu et al. 1993); therefore, a greater amount of extension roots may

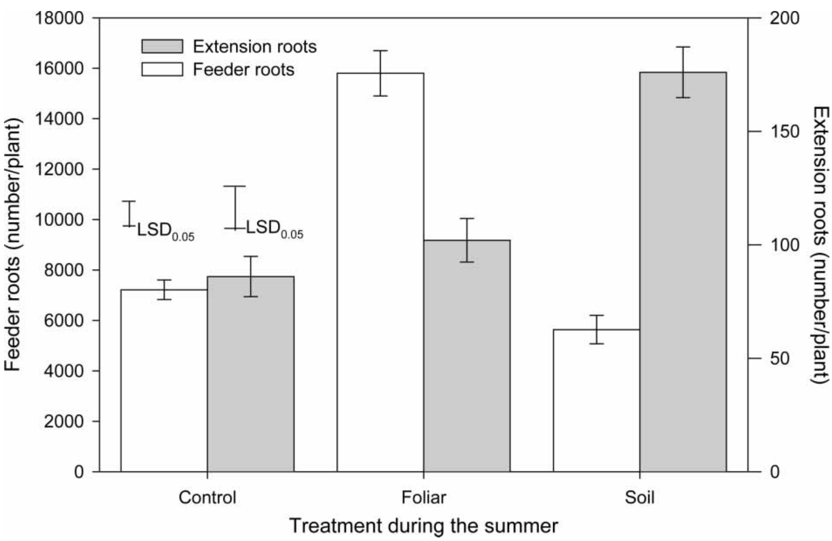

Figure 2. Extension and feeder root initiation of young Fuji/M26 apple trees at the end of September after treatment with soil and foliar nitrogen (N) applications during the summer (June to early September). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Bars on columns represent standard errors of the mean of five replicates.

result in more IAA synthesis, which could promote more aboveground vegetative growth and result in a high shoot/root ratio in trees receiving soil N application in summer.

It has been reported that N taken up from the soil application during the growing season can be quickly translocated to aboveground and directly used for the production of new growth (Gu, Shu, and Zhou 1987), while the N absorbed by leaves from foliar N applications in the summer remains mostly in the leaves (Hill-Cottingham and Lloyd-Jones 1975). This may also partially explain the growth-promoting effects found by soil N applications during the summer. Lack of N translocation from foliar N applications in the summer to the roots of the developing trees may make the roots N "deficient" and result in more root proliferation. This may account for the lower shoot/root ratios and higher number of feeder roots we found in trees that received foliar N compared to trees that received soil N applications during the summer.

After terminal bud set, most N taken up by the tree is translocated to storage for the next season (Titus and Kang 1982). It is not surprising that autumn N applications did not influence aboveground growth in our experiment, since applications of N in the autumn were done after trees had set their terminal and lateral bud (October). At this point, the only aboveground growth that occurs in apple would be an increase in stem diameter and the peak growth of wood diameter has passed (Rom 1994). Therefore, the radial growth of shoots/trunk of young apple trees in late autumn would not account for a large increase in aboveground biomass. In deciduous fruit trees, such as apple, root growth usually exhibits a peak in May–June, June–July, and September (Faust 1989). Thereafter, root growth will be limited, and any difference in root growth during this period is not influenced by the method of N application in the autumn (October).

Tree Nitrogen Status

The concentration of N in leaves in September was significantly higher in trees that received either soil or foliar N applications than in controls, but there was no significant difference in leaf N concentrations between trees that received soil and foliar N applications during the summer (Figure 3). The N concentration in stem and roots at dormant stage was affected by the method of N application during the summer as well as in the autumn (Figure 4). Trees that received either soil or foliar N applications during the summer had higher stem and root N concentrations than controls, and this effect was more apparent when the trees received ^{15}N application in the autumn. Trees that received no N during the summer but received soil ^{15}N application in the autumn had higher N concentrations in stems and roots than trees that received foliar ^{15}N application in the autumn. When trees received either soil or foliar applications of N during the summer, there was no difference

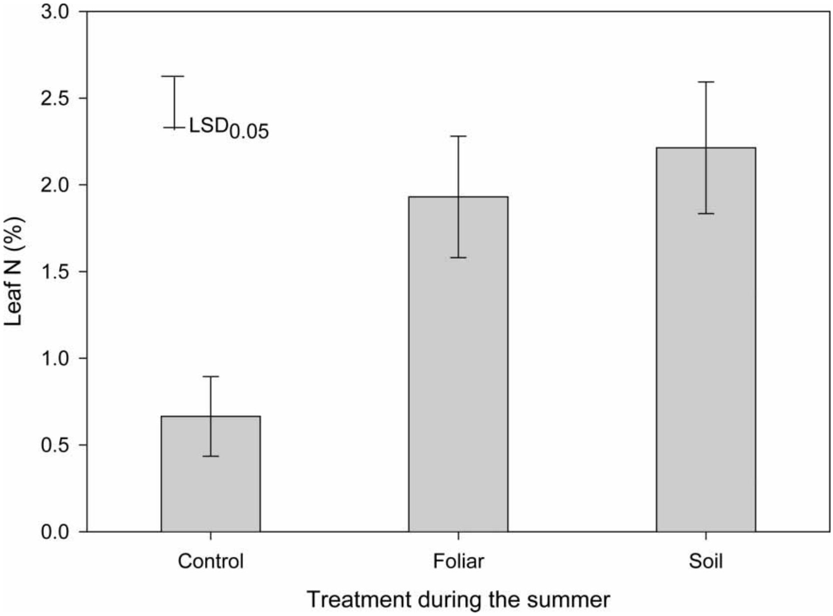

Figure 3. Nitrogen (N) concentration of leaves from young Fuji/M26 apple trees at the end of September after treatment with soil and foliar N applications during the summer (June to early September). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Bars on columns represent standard errors of the mean of five replicates.

in stem and root N concentrations between plants that received foliar or soil ^{15}N application in the autumn.

^{15}N Uptake in Autumn

The method of N application during the summer affected the amount of ^{15}N uptake by trees in the autumn. Trees that received foliar N applications in the summer took up more ^{15}N in the autumn than trees that received soil N applications in the summer or in controls (Figure 5). Trees that received either foliar N applications or no N (control) during the summer took up more ^{15}N from soil ^{15}N application in the autumn than from foliar ^{15}N application in the autumn. In contrast, trees that received soil N applications during the summer took up more ^{15}N from foliar ^{15}N application in the autumn than from soil ^{15}N application in the autumn.

Summer foliar N applications promoted root growth and significantly increased feeder root initiation (Figure 2). Feeder roots had high ability of

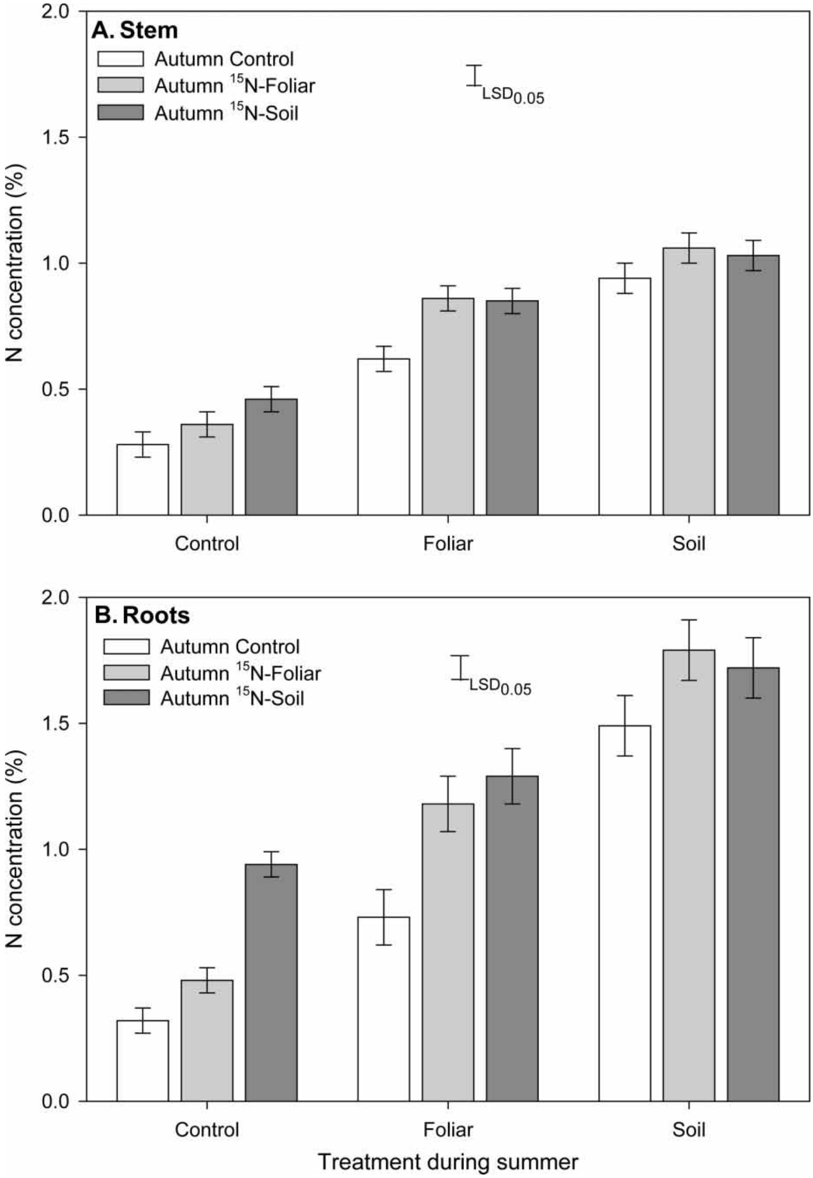

Figure 4. Nitrogen (N) concentration in stem A and roots B of young Fuji/M26 apple trees treated with soil and foliar N applications during the summer (June to early September) and autumn (mid-October). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Autumn treatments: no N (water application to soil: Autumn-Control), 3%^{15}N urea as foliar application (Autumn ^{15}N-Foliar), and 3%^{15}N urea as soil application (Autumn ^{15}N-Soil). Bars on columns represent standard errors of the mean of five replicates.

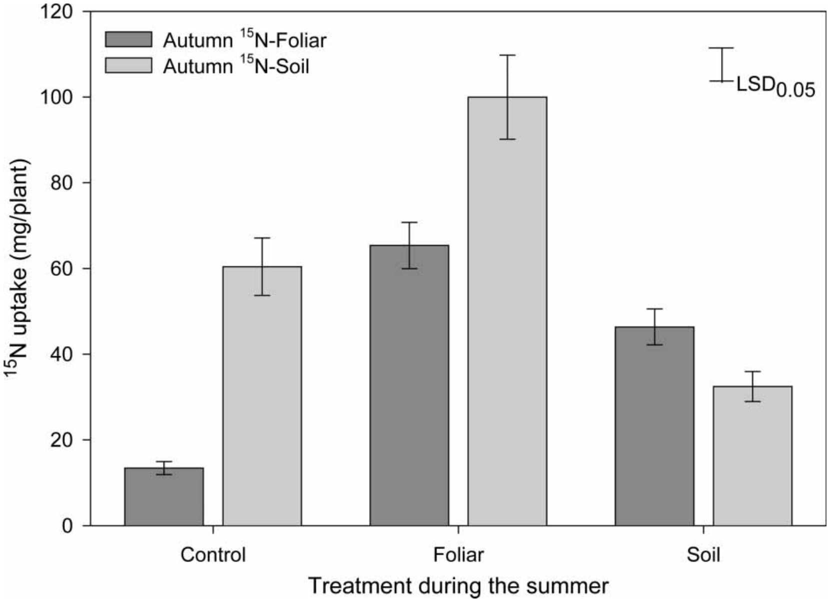

Figure 5. Total amount of labeled nitrogen (^{15}N) taken up in the autumn by young Fuji/M26 apple trees treated with soil and foliar N applications during the summer (June to early September) and autumn (mid-October). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Autumn treatments: no N (water application to soil: Autumn-Control), 3%^{15}N urea as foliar application (Autumn ^{15}N-Foliar), and 3%^{15}N urea as soil application (Autumn ^{15}N-Soil). Bars on columns represent standard errors of the mean of five replicates.

nutrient absorption (Dong, Cheng, and Fuchigami 1999), which may explain why the trees that received foliar N applications during the summer absorbed more soil-applied ^{15}N in the autumn than trees that received soil N applications in the summer. Trees receiving soil N application during the summer developed more aboveground part and less roots (Figure 1C), and therefore, they absorbed more ^{15}N through leaves and less ^{15}N by roots after the autumn application.

Although the method of N application during the summer had no influence on leaf nitrogen concentrations prior to N application in the autumn (Figure 3), we found that the uptake and distribution of ^{15}N from autumn application was influenced by the method of application. The ^{15}N from foliar N application in the autumn was almost evenly distributed between stems and roots, and this distribution was not affected by N application methods during the summer (Figure 6). The ^{15}N from soil N application in the autumn remained mainly in the roots, and its distribution was affected by N application methods during the summer. More of the ^{15}N uptake by roots

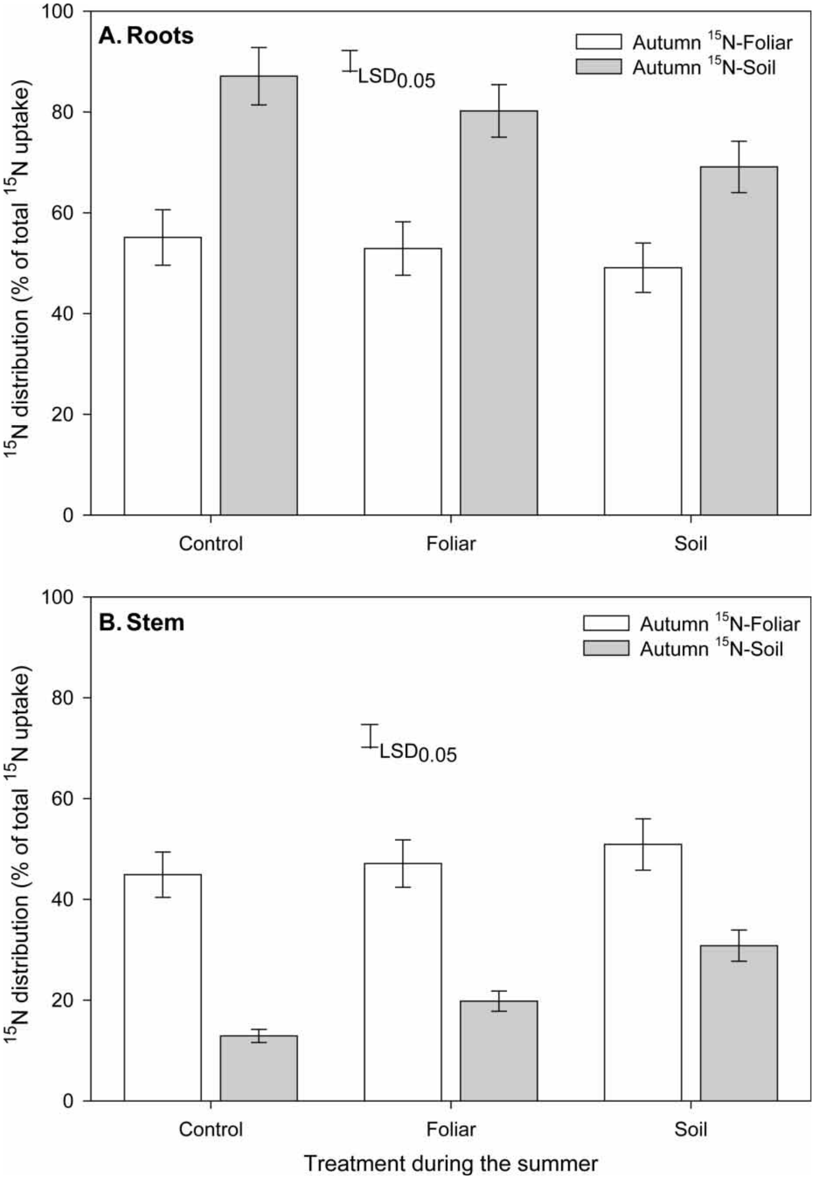

Figure 6. Distribution of labeled nitrogen (^{15}N) absorbed in autumn to roots (A) and stems (B) of young Fuji/M26 apple trees treated with soil and foliar N applications during the summer (June to early September) and autumn (mid-October). Summer treatments: weekly application of no N (water application to soil: Control), 0.5% urea as foliar application (Foliar), and 0.5% urea as soil application (Soil). Autumn treatments: no N (water application to soil: Autumn-Control), 3%^{15}N urea as foliar application (Autumn ^{15}N-Foliar), and 3%^{15}N urea as soil application (Autumn ^{15}N-Soil).

in autumn was translocated to stems in trees receiving either soil or foliar N applications during the summer than in the control trees (Figure 6). A significant correlation was found between the translocation of ^{15}N from soil application in the autumn and the concentration of N in roots ($r = 0.73$, $p = 0.0018$). The higher the N concentration in the roots, the more ^{15}N was translocated to the stem. Other researchers also reported that most of ^{15}N absorbed by roots late in the season was kept in the roots (Hill-Cottingham et al. 1975; Tagliavini et al. 1999), but they did not relate this distribution with root N status. Our results indicated that the distribution ^{15}N from root uptake in the autumn depended on root N status.

In summary, the method of N application during the growing season significantly influences the growth and biomass partitioning of young apple trees. During the summer, soil N applications promote more shoot growth and extension root initiation than foliar N applications, while foliar N applications promoted more root growth and feeder root initiation than soil N applications. Trees receiving foliar N applications during the summer are able to take up more N from soil applications in the autumn, while trees receiving soil N applications during the summer appear to benefit more from foliar N uptake in the autumn. These results suggest that (1) the differential effect of N application methods during the summer on growth and partitioning of trees influences tree responsiveness to autumn N applications; and (2) the efficiency of N uptake and use in autumn depends on the method of N application during the summer. It must be pointed out that this experiment was carried out with young potted trees, and the results may change in mature orchards with crop loads.

REFERENCES

Cheng, L., Dong, S., and Fuchigami, L.H. (2002) Urea uptake and nitrogen mobilization by apple leaves in relation to tree nitrogen status in autumn. *J. Horticultural Sci. Biotechnol.*, 77: 13–18.

Dinnes, D.L., Karlen, L., Jaynes, D.B., Kaspar, T.K., Hatfield, J.L., Colvin, T.S., and Cambardella, C.A (2002) Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.*, 94: 153–171.

Dong, S., Cheng, L., and Fuchigami, L.H. (1999) Ammonium ion uptake by feeder and extension roots of MM106 apple rootstock. *HortScience.*, 34: 492.

Dong, S., Cheng, L., Scagel, C.F., and Fuchigami, L.H. (2002) Nitrogen absorption, translocation and distribution from urea applied in autumn to leaves of young potted apple (*Malus domestica*) trees. *Tree Physiol.*, 22: 1305–1310.

Fallahi, E. and Simons, B.R. (1996) Interrelations among leaf and fruit mineral nutrients and fruit quality in 'Delicious' apples. *J. Tree Fruit Production.*, 1: 15–25.

Faust, M. (1989) *Physiology of Temperate Zone Fruit Trees*; John Wiley & Sons: New York, 55–61.

Gu, M., Shu, H., and Zhou, H. (1987) Studies of nitrogen nutrition in apple trees. V. Characteristics of uptake and translocation of ^{15}N in different forms. *J. Shandong Agricultural University.*, 17: 45–52.

Hill-Cottingham, D.G. and Lloyd-Jones, C.P. (1975) Nitrogen-15 in apple nutrition investigation. *J. Sci. Food Agric.*, 26: 165–173.

Khemira, H., Righetti, T.L., and Azarenko, A.N. (1998) Nitrogen partitioning in apple as affected by timing and tree growth habit. *J. Horticultural Sci. Biotechnol.*, 73: 217–223.

Klein, I. and Weinbaum, S.A. (1984) Foliar application of urea to olive: Translocation of urea nitrogen as influenced by sink demand and nitrogen deficiency. *J. Am. Soc. Horticultural Sci.*, 109: 356–360.

Mengel, K. (2002) Alternative or complementary role of foliar supply in mineral nutrition of plants. *Acta Horticulturae.*, 594: 33–47.

Mengel, K. and Kirby, E.A. (1987) *Principles of Plant Nutrition*; International Potash Institute: Bern, Switzerland, 1–50.

Niederholzer, F.J.A., DeJong, T.M., Saenz, J.L., Muraoka, T.T., and Weinbaum, S.A. (2001) Effectiveness of fall versus spring soil fertilization of field-grown peach trees. *J. Am. Soc. Horticultural Sci.*, 126: 644–648.

Policarpo, M., Marco, L.D., Caruso, T., Gioacchini, P., and Tagliavini, M. (2002) Dynamics of nitrogen uptake and partitioning in early and late fruit ripening peach (*Prunus persica*) tree genotypes under a Mediterranean climate. *Plant Soil*, 239: 207–214.

Rom, C. (1994) Fruit tree growth and development. In *Tree Fruit Nutrition*; Peterson, A.B. and Stevens, R.G., eds.; Good Fruit Grower: Yakima, Washington, 1–18.

Rosecrance, R.C., Johnson, R.S., and Weinbaum, S.A. (1998) The effect of timing of post-harvest foliar urea sprays on nitrogen absorption and partitioning in peach and nectarine trees. *J. Horticultural Sci. Biotechnol.*, 73: 856–861.

Sanchez, E.E., Khemira, H., Sugar, D., and Righeti, T.L. (1995) Nitrogen management in Orchards. In *Nitrogen Fertilization in the Environment*; Bacon, P.E., ed.; Marcel Dekker: New York, 327–380.

Schuman, G.E., Stanley, M.A., and Knudsen, D. (1973) Automated total nitrogen analysis of soil and plant samples. *Soil Sci. Soc. Am. Proc.*, 37: 480–481.

Shim, K., Titus, J.S., and Splittstoesser, W.E. (1972) The utilization of post-harvest urea sprays by senescing apple leaves. *J. Am. Soc. Horticultural Sci.*, 97: 592–596.

Shu, H., Wang, L., and Dong, S. (1993) *Study on Root Systems and Soil Nutrition Space of Young Apple Trees*; Shandong Agricultural University: Taian, Shandong, P.R. China, 2–48.

Tagliavini, M., Millard, P., and Quartieri, M. (1998) Storage of foliar-absorbed nitrogen and remobilization for spring growth in young nectarine (*Prunus persica* var. *nectarina*) trees. *Tree Physiology.*, 18: 203–207.

Tagliavini, M., Millard, P., Quartieri, M., and Marangoni, B. (1999) Timing of nitrogen uptake affects winter storage and spring remobilization of nitrogen in nectarine (*Prunus persica* var. *nectarina*) trees. *Plant Soil*, 211: 149–153.

Titus, J.S. and Kang, S. (1982) Nitrogen metabolism, translocation and recycling in apple trees. *Horticultural Review*, 4: 204–246.

Weinbaum, S.A. (1988) Foliar nutrition of fruit crops. In *Plant Growth and Leaf Applied Chemicals*; Neuman, P.E., ed.; CRC Press: Boca Raton, Florida, 81–100.