Nitrogen fertilization for new plantings of hybrid hazelnuts in the Upper Midwest of the United States of America

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Braun, L. C., Gillman, J. H., Hoover, E. E. and Russelle, M. P. 2011. **Nitrogen fertilization for new plantings of hybrid hazelnuts in the Upper Midwest of the United States of America**. Can. J. Plant Sci. **91**: xxx–xxx. Seed-propagated hybrids of *Corylus avellana* and *C. americana* are a potential crop for the Upper Midwest. Current N recommendations for hazelnuts are based on research on clonally propagated *C. avellana* in Oregon and may not be applicable in the Upper Midwest due to differing soils, climate, and plant genetics. We established three field plots in 2003 to test N fertilization rates on new plantings, with rates up to 33 g N plant^{-1} as ammonium nitrate applied annually in the spring, starting 2 wk after transplanting. We observed a strong negative linear effect of N rate on plant survival. In the second year we added trials on same-aged plants that had not previously been fertilized and found no N effect on survival. We concluded that waiting 1 yr after transplanting before fertilizing increases plant survival, but even then N requirements during establishment years are very low for hybrid hazelnuts. Standard leaf N concentrations for *C. avellana* in Oregon are roughly applicable to hybrid hazelnuts, except that the threshold between deficiency and sufficiency should be raised slightly to 1.9% N. The current threshold between deficient and sufficient, 2.2%, should be regarded as a target, rather than as a threshold to be exceeded.

Key words: *Corylus*, filbert, leaf analysis, nutrient recommendations

Braun, L. C., Gillman, J. H., Hoover, E. E. et Russelle, M. P. 2011. **Amendements azotés pour la plantation de noisetiers hybrides dans le nord du Midwest américain**. Can. J. Plant Sci. **91**: xxx–xxx. Les hybrides de *Corylus avellana* et de *C. americana* multipliés à partir de semences pourraient devenir une culture dans le nord du Midwest. Les recommandations actuelles relatives à la fertilisation des noisetiers avec des engrais azotés s'appuient sur la recherche sur les plants de *C. avellana* multipliés par clonage dans l'Oregon et pourraient ne pas convenir au nord du Midwest, où les sols, le climat et la génétique des plantes diffèrent. En 2003, les auteurs ont aménagé trois parcelles pour vérifier le taux de fertilisation N des nouvelles plantations, jusqu'à concurrence de 33 g de N par plant, sous forme de nitrate d'ammonium, appliqué annuellement au printemps, deux semaines après le repiquage. Les auteurs ont observé une forte réaction linéaire négative entre le taux d'application des engrais N et le taux de survie des plants. La deuxième année, ils ont procédé à des essais supplémentaires sur des plants de même âge qui n'avaient pas encore été fertilisés et ont constaté que les engrais N n'avaient aucune incidence sur leur taux de survie. Ils en concluent qu'attendre un an avant la fertilisation, après le repiquage, hausse la survie des plants, mais les besoins en engrais N des noisetiers hybrides demeurent très faibles pendant les années d'établissement. La concentration normale de N dans les feuilles de *C. avellana* en Oregon s'applique grossièrement aux noisetiers hybrides, si ce n'est qu'on doit légèrement augmenter le seuil entre la carence et l'équilibre à 1,9 % de N. Le seuil actuel de 2,2 % devrait être considéré comme un objectif plutôt qu'un seuil à dépasser.

Mots clés: *Corylus*, aveline, dosage des feuilles, recommandations de fertilization

Hybrid hazelnuts are a potential new crop for the Upper Midwest of the United States of America. These are seed-propagated, putative hybrids between the European hazelnut, *Corylus avellana* L., which is the basis for commercial production worldwide, and the common American hazelnut, *Corylus americana* Walter, which is native to the region. Some genetic lines may also include genes from *Corylus cornuta* Marsh, the beaked hazelnut, which is also native to the region. The American species may confer genetic resistance to eastern filbert blight (EFB), and provide the cold hardiness needed in the Upper Midwest (Rutter and Shepard 2002). Woody perennial crops, such as hazelnuts, may reduce soil erosion, improve soil and water quality, sequester soil carbon, and reduce agricultural energy use, while enhancing wildlife habitat and ecosystem diversity (Josiah 2001; Thevathasan and Gordon 2004). A viable hazelnut industry in the Upper Midwest would help farmers diversify economically, while also enhancing ecological sustainability in the region.

Because hybrid hazelnuts reputedly have a high demand for N, their proponents have been recommending high rates of N fertilization. Their N requirements have not, however, been substantiated. According to Weinbaum et al. (1992) N is overapplied in woody crops

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Abbreviation: **EFB**, eastern filbert blight more often than in any other kind of crop, resulting in stress to young seedlings, reductions in fruit and nut quality, economic waste, and environmental contamination. Thus, the development of empirically derived N recommendations, specific to hybrid hazelnuts in the Upper Midwest, is necessary to attain high productivity without compromising the environmental benefits for which they are being promoted.

Current recommendations for N fertilization of young European hazelnut trees in Oregon are based on age of plant (Olsen 2001). No N is recommended from transplanting through the second season. Starting in the third season, 113–149 g plant^{-1} N are recommended, with rates increasing incrementally each year up to 341 g plant^{-1} in the 10th season. Nitrogen recommendations for mature hazelnuts are based on comparing the N concentrations of leaf tissues to optimal levels, which are 2.2 to 2.5% N, as determined by Chaplin and Dixon (1979). However, these N recommendations may not be applicable to hybrids developed for the conditions of the Upper Midwest, due to differing climate, soils, genetics, and growing systems. The most important difference is likely to be initial plant size: whereas most European hazelnuts in the Pacific Northwest are transplanted as 1- or 2-yr-old rooted layers that are up to 1 m tall, with root volumes from 2000 to 6000 cm^3 (D. C. Smith 2007, personal communication), the hybrids in the Upper Midwest currently are transplanted as 2- to 3-mo-old seedlings one-fifth as tall with a root volume of less than 200 cm^3. Ran et al. (1994) found that N uptake is proportional to root volume, so these small seedlings are not likely to be able to take up as much N as young hazelnuts in the Pacific Northwest. Also, whereas European hazelnuts are pruned as single-trunk trees, hybrid hazelnuts remain as bushes.

The objectives of our research were (1) to evaluate responses of newly transplanted hybrid hazelnut seedlings to variable rates of N in the field and (2) to evaluate leaf and soil analysis as diagnostic tools upon which to make recommendations, for the ultimate goal of developing N fertilization rate recommendations for growers.

MATERIALS AND METHODS

Experiment 1

We conducted N rate trials from 2003 through 2005 in three new hybrid hazelnut plantings in Minnesota. All three sites were located at University of Minnesota Experiment Stations on three different soil types: a loam (Chanhassen), a loamy sand (Becker), and a silt loam with disturbed horizons (Rosemount). Details on soils, site history and management are given in Table 1. These sites had relatively low soil organic matter and were amended with P and K as needed before planting, based on rates recommended for woody crops in Minnesota (Rosen and Eliason 2005).

Planting material consisted of four genetic lines of half-sib seedling hybrid hazelnut bushes purchased from Badgersett Research Corporation in Canton, Minnesota. They had been grown in plug containers measuring 13 cm tall by 4 cm wide in an artificial medium fertilized with a 12-mo slow-release complete fertilizer at a rate supplying 0.06 g N container^{-1}. Two weeks before transplanting, all shoots were trimmed to 15 cm tall. At transplanting, seedlings were 49 to 79 d old and actively growing.

Treatments were six N rates: 0, 2.75, 5.5, 11, 22, and 33 g plant^{-1}. They were replicated five times at each site, in a randomized complete block design. That is, each of five blocks contained six plots, one for each treatment. At Becker, three additional blocks were

Table 1. Characteristics of research sites

University of Minnesota Facility	Soil series and texture (soil type)	pH	Organic matter (g kg^{-1})	Bray P (mg kg^{-1})	K (mg kg^{-1})
Rosemount Dakota County, Lat. 44°76′N, Long. 93°12′W.	Urban-land Waukegan silt-loam complex fine-silty over sandy mixed, mesic Typic Hapludoll *(horizons unidentifiable due to human activity)*	5.1	27 L	30 MH	84 MH
Becker Sherburne County, Lat. 45°38′N’, Long. 93°11′W.	Hubbard loamy sand sandy, mixed, frigid Entic Haploboroll	6.3	19 L	28 MH	93 MH
Chanhassen Carver County, Lat. 44°85′N, Long. 93°56′W.	Hayden loam fine-loamy, mixed, mesic, Typic Hapludalf	5.9	26 L	16 ML	99 MH

[z]H, M, L = high, medium, and low levels of these nutrients as defined for fruit crops in Minnesota (Rosen and Eliason 2005).

planted for destructive sampling. Plots consisted of six plants in a row, one of each of four half-sib lines of seedlings, plus an additional plant on each end as a buffer. Each plant in a plot, including the buffers, received the same N treatment, but data were not collected from buffer plants. Individual plants were treated as experimental units. Plants were spaced 1.5 m apart within rows and 3.8 m between rows. The buffers were planted in mid-May 2003 at 49 d of age, and the others were planted in late June at 79 d of age. All were planted by hand.

Plants were watered immediately after planting, and as needed for the first 2 yr. Perennial ryegrass (*Lolium perenne* L.) was seeded between rows at around the same time hazelnuts were planted, and was kept mowed during the study. A 60-cm-diameter weed-free circle was maintained around each plant by hoeing shallowly as needed for all 3 yr.

Ammonium nitrate (NH_4NO_3) was applied once a year from 2003 through 2005, with the same N rate repeated on each plot all 3 yr. The first N application was made to all sites in mid-July 2003, about 2 wk after planting. In 2004 and 2005, it was applied in early spring. Fertilizer was applied in a circle about 15 cm from the main stem of each plant and was hoed shallowly to incorporate it.

Data Collection

Soil sampling. Soil samples were collected at all sites to a depth of 30 cm, 2 to 4 wk after fertilizer application in all 3 yr. Additional soil samples were collected in late August 2003 and in November 2005. Samples were collected 8 to 15 cm from the main stem of each plant in a plot, composited by plot, dried at 35°C for a minimum of 48 h, and ground. Soil samples from 2003 and 2005 were extracted with 2 M KCl and analyzed by flow injection with a Lachat Quik Chem 8000 (Lachat Instruments, Milwaukee, WI) for nitrate (Knepel 2001) and ammonium (Switala 1993). In 2004, soil was analyzed on an Orion 29A meter with a 9307 nitrate half cell electrode and a 90-02 double junction reference electrode (Gelderman and Beegle 1998); in 2004 soil ammonium was not measured. A subset of the 2003 samples was analyzed for pH by the method of Watson and Brown (1998), using a Beckman pH meter, and for salinity by measuring the electrical conductance in the filtrate from a 1:1 saturated paste (Whitney 1998).

Leaf sampling. Leaf samples were collected in late July/early August in 2004 and 2005. The third fully expanded leaf from the apex of stems growing in full sun was sampled, with four to six leaves collected per plant. Leaves were consolidated by plot, for a total of at least 20 leaves per sample. They were dried at 60°C for at least 48 h and ground. Leaf N concentration was determined by Dumas combustion with a Vario El in 2004, and with a Vario Max in 2005 (Elementar Americas Inc., Mt. Laurel, NJ).

Plant measurements. Plant height and width was measured every fall after leaf drop from 2003 through 2005 at all sites, and again in 2006 at Becker and Chanhassen. Height was measured from the ground to the highest live bud. Width was recorded as the average of two perpendicular measurements taken at the top of the plants. Stem caliper and stem number were measured about 5 cm above the soil surface. The presence or absence of leaf chlorosis was recorded in 2005. In 2007, at Chanhassen only, the number of nut clusters was recorded on each bush, if any.

Root excavations. In August 2005 all the surviving plants in the three blocks planted for destructive sampling at Becker were excavated. Only two plants in the 33 g plant^{-1} N rate were excavated, because the others had died, but seven to ten plants were excavated for each of the other treatments. We used a jet of water to wash the soil from the roots of each plant in situ, gently working the roots free from depths down to 70 cm, and lifted them out intact. We dried the plants in paper bags at 60°C until their mass stabilized, removed their leaves, divided them into above- and below-ground portions, weighed them, and calculated gravimetric root:shoot ratios.

Experiment 2

Twenty-four seedlings had been planted at Becker in 2003, with the same planting material and planting methods, but not included in the initial trials. In 2004 we initiated N trials on them to evaluate the effects of delaying applications for a year after planting. Individual plants were treated as experimental units, arranged in a randomized complete block design with four blocks and six N treatments. Four of the treatments consisted of constant annual rates of 0, 2.75, 5.5, or 11 g plant^{-1} applied in mid-July 2004 and late April 2005. In two additional treatments, 5.5 g plant^{-1} was applied in 2004 and increased to 22 g plant^{-1} in 2005. In one of these treatments the 2005 application of 22 g was applied at one time in late April; in the second treatment it was split into two 11-g applications, one applied in late April and the other in early July. Plot management and N application methods were the same as for the trials started in 2003. Plant height was measured before N application in 2004 and again after leaf drop in 2005 and 2006.

Experiment 3

In August 2005 at Becker, we initiated a third N rate trial on 120 plants that had been planted in late June 2004. At transplanting these seedlings were 180 d old, twice as old as the seedlings planted in 2003, and they had larger root systems, because they had been grown in larger containers. Individual plants were treated as experimental units and were arranged in a complete block design with 24 blocks and five N treatments: 0, 5.5, 11, 22, and 33 g plant^{-1}. Nitrogen was first applied in August 2005, which was over a year after planting, and again in June 2006. Plant height was measured before N application in 2005 and again after leaf drop in 2005 and 2006.

Statistical Analysis

Data were analyzed by regression analysis, using ARC software (XLISP-PLUS version 3.04). Individual plants were the experimental units for growth parameters, whereas the leaf N response was analyzed with plot as the experimental unit. Predictors were block, genetic line, and either N rate or leaf N. Two statistical approaches were used: the predictor N rate was used as either a continuous variable or as a discrete variable. Plant size at the time of first N applications was used as a covariate for exps. 2 and 3, in which the first N applications were a year or more after planting. Sigma Plot 2000 Version 6.00 (copyright 1986–2000 SPSS Inc.) was used for graphing and for determining higher order regression models.

RESULTS

Soil

Soil inorganic N, both as nitrate and as ammonium, was highly correlated with N application rates on all sampling dates and at all sites ($P<0.001$), although the slopes differed among sites and sampling dates. In July 2003, 2 wk after N application, soil total inorganic N at Chanhassen and Rosemount rose linearly with increasing N rates, to about 250 mg kg^{-1}, whereas soil N at Becker rose to about 350 mg kg^{-1}. One month later, in August, soil N at Becker had declined to concentrations similar to those at Chanhassen, whereas concentrations at Rosemount had risen to 412 mg kg^{-1} (Fig. 1A, Table 2). Soil inorganic N in 2004 and 2005 did not reach such high concentrations; the highest concentration measured was at Rosemount, at 182 mg kg^{-1} in June, where it declined to 52 mg kg^{-1} by November.

Soil pH, which was measured only in late August 2003, declined with increasing N application rates at all sites (Fig. 1B, Table 2). pH was lowest across all treatments at Rosemount, where mean pH for the control plots was lower than the mean pH for any treatment at the other two sites. Salinity, which was measured 2 and 6 wk after N application, increased with increasing N rate (Fig. 1C, Table 2). The highest conductance observed, 2.22 mmhos cm^{-1}, measured 2 wk after N application in 2003 at Becker, is in the slightly saline range for sandy soils (Whitney 1998). The levels observed at the other sites, and at Becker 6 wk after N application, were all in the non-saline range.

Transplant Survival

In exp. 1, in which N had been applied 2 wk after planting, survival declined with increasing N rates at all three sites at $P<0.003$, $R^2>0.91$ (Fig. 2, Table 3). Survival was negatively correlated with soil ammonium ($P<0.0006$) and conductivity ($P<0.0001$), but positively correlated with soil pH ($P<0.0007$). The symptoms that preceded seedling death, marginal leaf necrosis followed by leaf death and abscission, were observed within 2 wk of N application at Becker, and by fall at the other two sites. Even the lowest N rate, 2.75 g plant^{-1}, significantly reduced survival at Becker and Chanhassen ($P<0.05$), but the lowest rate to significantly reduce survival at Rosemount was 11 g plant^{-1} ($P<0.05$). In contrast, in exp. 2 and exp. 3, in which N

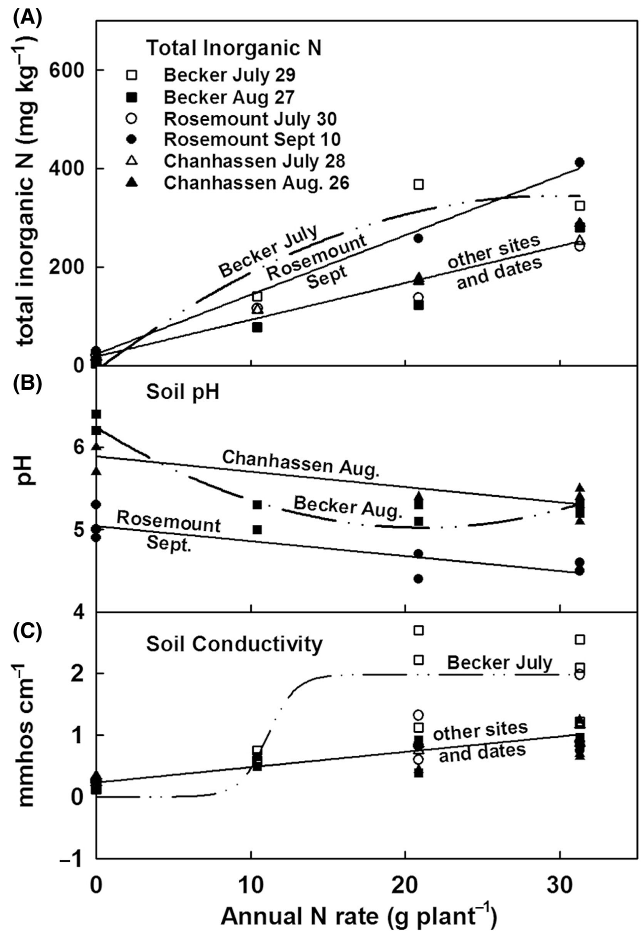

Fig. 1. Soil responses (0–30 cm) to applied N fertilizer measured in late July and again in late August or September of 2003. Open symbols are for late July; closed symbols are for late August or early September. (A) Means of total inorganic soil N (ammonium plus nitrate). Slopes for Becker in August, Rosemount in July, and Chanhassen on both dates were similar and were combined into one regression. (B) Soil pH measured in late August or early September only, based on data from selected samples. (C) Soil electrical conductivity, data from selected samples. Slopes for Becker in August, and Rosemount and Chanhassen on both dates were similar and were combined into one regression. Coefficient estimates and statistics for the lines are given in Table 2.

Table 2. Coefficients and statistics for Fig. 1, soil responses to applied N fertilizer in 2003

	Site	Sampling date (DAF)[z]	Model	x_0	y_0	a	b	R^2	P value
(A) Total Inorganic N	Becker	Jul. 29 (12)	Quadratic	–	−11 NS	24**	−0.40*	0.69	<0.0001
	Rosemount	Sep. 10 (57)	Linear	–	23 NS	12***	–	0.93	<0.0001
	Combined[y]	Various	Linear	–	18 NS	7.5***	–	0.64	<0.0001
(B) Soil pH	Becker	Aug. 27 (41)	Quadratic	–	6.2***	−0.01**	0.003*	0.83	0.0052
	Rosemount	Sep. 10 (57)	Linear	–	5.0***	−0.02*	–	0.65	0.0182
	Chanhassen	Aug. 26 (43)	Quadratic	–	5.9***	−0.02**	–	0.74	0.0034
(C) Soil electrical conductivity	Becker	Jul. 29 (12)	Sigmoidal	11 NS	–	2.0***	0.91 NS	0.69	0.0039
	Combined[x]	Various	Linear	–	0.23**	0.02***	–	0.64	<0.0001

[z]DAF = days after fertilization.
[y]Slopes of total inorganic N for Becker in August, Rosemount in July, and Chanhassen on both dates were similar and were combined into one regression.
[x]Slopes of conductivity for Becker in August, and Rosemount and Chanhassen on both dates were similar and were combined into one regression.
*, **, *** Designate coefficient estimates that are significant at $P<0.05$, $P<0.01$, and $P<0.001$, respectively. NS designates estimates that are not significant. The linear function is $y=y_0+a\cdot x$. The quadratic function is $y=y_0+a\cdot x+b\cdot x^2$. The sigmoidal function is $y=a/(1+\exp[-(x-x_0)/b]$.

applications were postponed until a year after planting, there was no mortality attributable to N fertilizer.

Plant Growth

Experiment 1

Above-ground responses. High N rates significantly inhibited growth of the surviving seedlings, as measured by height (Fig. 3, Table 4), at Rosemount and Becker, where at the end of the third year the surviving plants in the 33 g plant^{-1} N rate were significantly shorter than the controls ($P=0.03$). At Rosemount, the height response through 2005 fit a negative linear model ($P<0.0001$, $R^2=0.32$). The only N rate that did not significantly reduce height at Rosemount was the lowest rate of 2.75 g plant^{-1}.

There were no positive growth responses to N apparent at any site by the end of the first year, but positive responses appeared at Becker at the end of the third year. At the end of 2005, there was a strong

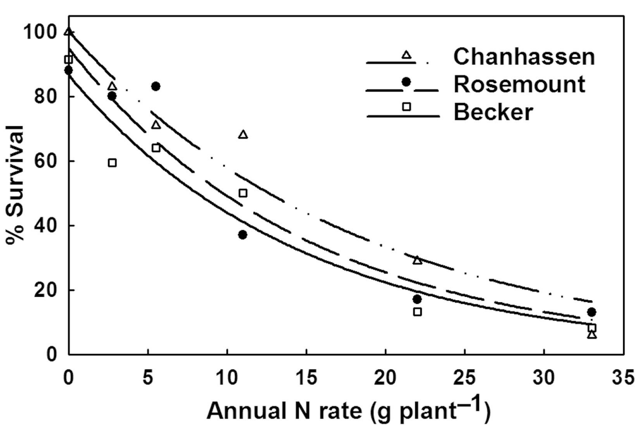

Fig. 2. Survival at the end of 2004 in response to N applied in 2003 at three sites in Minnesota. Means and lines are predicted by the exponential decay function $y=ae^{-bx}$. Coefficient estimates and statistics for the lines are given in Table 3.

quadratic height response to applied N at Becker ($P=0.0027$, $R^2=0.36$). Plant height was significantly greater in the plots that received 11 g plant^{-1} than in the control plots ($P<0.05$), whereas height declined with higher rates ($P<0.06$ and $P<0.03$ for the 22 and 3 g plant^{-1} N rates, respectively). The Gaussian peak function indicated maximum height at about 8 g plant^{-1} N at Becker, amounting to about 10 cm more height than the control. Although these models fit the data, they fail to account for much of the variability, as illustrated by the low R^2 value; most likely this is due to the genetic variation within the half-sib groups.

The growth response to applied N was flat at Chanhassen, where plants grew taller than at the other sites, regardless of treatment (Table 5). When nuts started to be produced there in 2007, plants in control plots had as many nut clusters as plants in fertilized plots.

Above-ground plant height was not closely related to soil inorganic N at any site. The exceptions were all negative linear, showing a slight inhibition of growth by high levels of inorganic N (data not presented).

Root responses. Whole plants excavated at Becker after three growing seasons showed the same growth patterns as were found for the shoots. Total dry weight increased for the 2.75 g plant^{-1} N rate, but declined for higher

Table 3. Coefficients and statistics for Fig. 2, models of 2004 survival in response to applied N fit by the exponential decay function $y=ae^{-bx}$, as determined in Sigma Plot

	Regression coefficients		Statistics	
	a	b	Adj. R^2	P
Becker	86.68***	0.0678**	0.92	0.0015
Chanhassen	100.33***	0.0553**	0.93	0.0009
Rosemount	95.04***	0.0660*	0.91	0.0021

*, **, *** Designate coefficient estimates that are significant at $P<0.05$, $P<0.01$, and $P<0.001$, respectively.

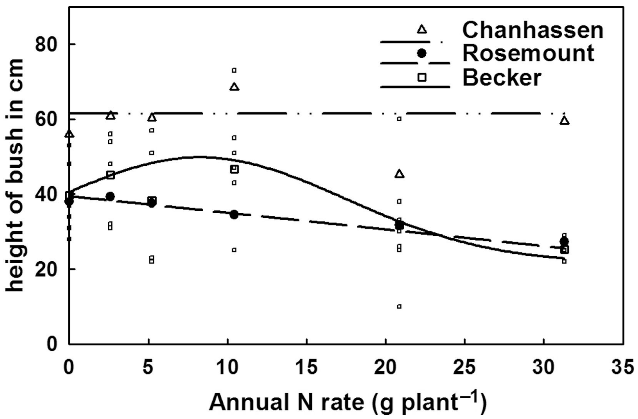

Fig. 3. 2005 hybrid hazelnut plant height in response to applied N at three sites in Minnesota. Large symbols are treatment means. Small squares are plot means for Becker, to give the reader a sense of the variation. The line for Chanhassen is flat, the line for Becker is the four-parameter Gaussian peak function, and the line for Rosemount is the negative linear regression. Coefficient estimates and statistics for the lines are given in Table 4.

rates (data not shown). However, only the reduction in dry weight for plants to which 22 g plant^{-1} or more of N had been applied was statistically significant ($P<0.05$). High N supply inhibited shoot growth and root growth equally; thus, N fertilization had no effect on root:shoot ratios. Roots comprised an average of 67% (SE = 1%) of total woody biomass, regardless of N rate.

Experiment 2

There was a negative growth response to N applied one growing season after transplanting, even at the 2.75 g N rate ($P<0.05$). At the end of two growing seasons there were no significant N rate responses (data not shown).

Experiment 3

There were no significant differences in plant response among N rates one season after fertilizing these seedlings, which were first fertilized one growing season after transplanting. But, after two growing seasons, bush height increased with N applications up to 11 g N plant^{-1}, but decreased at higher rates. However, only plants in the 5.5 and 11 g plant^{-1} N rates were significantly taller than the controls at the end of 2006 ($P<0.09$, data not shown).

Leaf N Responses

The Gaussian peak function approximated the increase in leaf N concentration with applied N at all sites in both years it was measured ($P<0.006$, $R^2>0.33$), with the exception of Chanhassen in 2005 (Fig. 4, Table 6). Leaf N concentration also increased with soil inorganic N at all sites in both years except for Chanhassen in 2005. At Becker in 2004 and Rosemount in 2005, mean leaf N concentration declined for the lowest N rate before it increased with higher rates.

Leaf chlorosis was common in control plots and in low-N plots at all sites in 2005, but was not observed in plots fertilized with more than 5.5 g plant^{-1} of N. Average leaf N concentration in plots with chlorotic leaves was much lower than 2.2% N, the threshold to the deficiency range by standards for Oregon (Olsen 2001).

Average leaf N concentration exceeded 2.5%, the threshold for ‘‘above normal’’ by standards for Oregon, in plots fertilized with 11 g N plant^{-1} or more, at Chanhassen and Rosemount in 2004. Most leaves in these plots were small, distorted, and very dark green. The highest concentrations observed at the two sites were 3.2 and 3.4% N, in 22 g plant^{-1} plots at Chanhassen and Rosemount, respectively, both of which had 83% mortality. In 2005, however, leaf N did not exceed the toxicity threshold for any treatment at either site.

Growth correlations with leaf N. In general, leaf N concentration was not correlated with plant growth. The exceptions, at Rosemount in both 2004 and 2005, and at Becker in 2005, were all negative linear, suggesting either dilution of leaf N by growth or inhibition of growth by high concentrations of leaf N.

DISCUSSION

Mortality

The mortality observed with the higher rates of fertilizer N could have been caused by high soil ammonium concentration, by salinity, or by the soil acidifying effect

Table 4. Coefficients and statistics for Fig. 3, models of 2005 plant height response to applied N, as determined in Sigma Plot

	Model	Coefficients				Adj. R^2_{model}	P_{model}
		a	b	x_0	y_0		
Chanhassen	Gaussian peak	15 NS	6 NS	12***	56***	0.01	0.2004
Becker	Gaussian peak	28**	9**	8***	22*	0.11	0.0012
Rosemount	Negative linear	−0.4***	–	–	39***	0.15	<0.0001

*, **, *** Designate coefficient estimates that are significant at $P<0.05$, $P<0.01$, and $P<0.001$, respectively. The Gaussian peak function is $y=y_0+a\cdot\exp[-0.5\cdot((x-x_0)/b)^2]$. The negative linear function is $y=y_0+a\cdot x$. (Because Sigma Plot cannot include other factors, such as blocking and genetic source, these statistics may differ from those reported in the text, which were done with ARC.)

Table 5. Mean (and maximum in parentheses) heights of bushes at three sites in 2003, 2004, 2005 and 2006

	2003	2004	2005	2006
		(cm)		
Rosemount	14 (26)	24 (37)	36 (58)	–
Becker	9 (38)	30 (69)	42 (97)	48 (102)
Chanhassen	19 (34)	34 (87)	62 (114)	82 (144)

of ammonium nitrate. Although mortality was highly correlated with all three of these, they also were autocorrelated so it is difficult to separate their effects. Backward stepwise regression results showed that pH explained the least amount of variation, and salinity explained the most.

We are reasonably confident that soil acidification was not an important cause of mortality because the 5.1 pH in the control plots at Rosemount, where survival was 88%, was similar to the 5.3 pH in the high N rate plots at Becker, where survival was only 9%. Moreover, Adiloglu and Adiloglu (2005) reported that hazelnuts in Turkey are grown on soils with pH as low as 4.3, with no apparent problems other than low leaf Ca concentration.

The first symptoms observed, marginal chlorosis and necrosis, could have been due to either salt damage or ammonia toxicity. The few plants that survived the high N rates into the second year had small, dark-green leaves that were misshapen, cupped, or wrinkled, which are symptoms of ammonium toxicity (Pilon 2006). Nitrogen concentration in these leaves in 2004 was 2.5% or higher, which is considered above normal (Olsen 2001). This does not, however, exclude the possibility that salinity contributed to the mortality.

That the mortality was first observed at Becker, where soluble salts in samples collected 2 wk after N application were in the slightly saline range, supports salinity as a significant cause. It is possible that soluble salts had been above the slightly saline level earlier, but had been leached out of the soil by irrigation water before we sampled.

Three reasons for the high mortality may be that fertilizer was concentrated near the plants instead of broadcast, that it was applied only 2 wk after transplanting, and that a highly soluble form of fertilizer, ammonium nitrate, was used. The buffer seedlings, that were transplanted a month earlier than the others died at a similar rate as later-planted seedlings, so waiting one and a half months before fertilizing is not long enough for young seedlings.

Although fertilizing 1-yr-old transplants, as in exps. 2 and 3, did not reduce survival, there was no benefit to it, so our findings support Olsen's (2001) recommendation to avoid N fertilization in the first year.

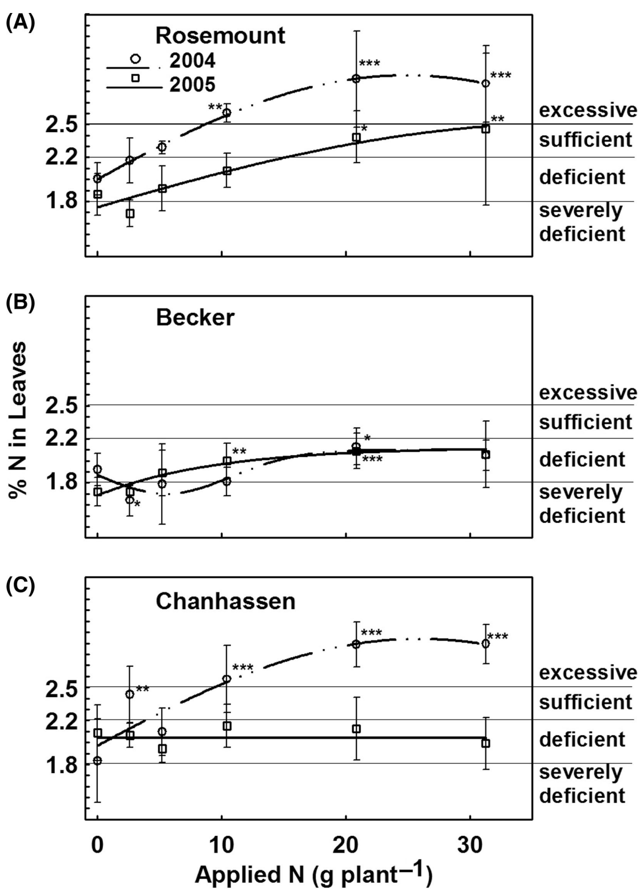

Fig. 4. Hazelnut leaf N concentration response to applied N over 3 yr. Sufficiency and deficiency labels are based on Oregon leaf standards (Olsen 2001). Symbols are treatment means; error bars are standard deviations. *, **, *** designate treatments that are significantly larger or smaller than the controls in that year at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. Coefficients and statistics for regression models are given in Table 6.

Growth Responses

The low numbers of surviving plants in the 22 and 33 g plant^{-1} N treatments of exp. 1 significantly compromised our ability to evaluate the effects of these N rates on growth in later years of the experiment. The surviving plants in these treatments were stunted, and thus were not an accurate indicator of whether the 22 and 33 g plant^{-1} N rates would have been beneficial if applications at these rates were delayed until the plants were 2 or 3 yr old.

We can conclude that application of no N or very low N is best for the first 2 yr. For plants fertilized the year of transplanting, there were no positive N responses at Rosemount, even after 3 yr, whereas at Becker and Chanhassen the best response at the end of 3 yr occurred with only 8 to 12 g plant^{-1} N. For plants fertilized for the first time in the second season after transplanting, we conclude that N is still not beneficial, at least initially, and may even be harmful. However, in the third year the plants in exp. 3 started to show responses

Table 6. Coefficients and statistics for Fig. 4, models of 2004 and 2005 leaf N response to applied N, as determined by Sigma Plot. (Because Sigma Plot cannot include other factors, such as blocking and genetic source, these statistics may differ from those reported in the text, which were done with ARC)

			Regression Coefficients					
		Model	*a*	*b*	x_0	y_0	Adj. R^2_{model}	P_{model}
Rosemount	2004	Peak (3)	2.94***	28***	25***	–	0.72	<0.0001
	2005	Peak (3)	2.5***	45 NS	38 NS	–	0.43	0.0009
Becker	2004	Peak (4)	−0.40***	5.3*	5.5***	2.1***	0.33	0.0061
	2005	Peak (3)	2.1***	35***	23***	–	0.47	<0.0001
Chanhassen	2004	Peak (3)	2.9***	29***	26***	–	0.55	0.0002
	2005	Flat	–	–	–	–	–	–

The three-parameter Gaussian peak function is $y = a \cdot \exp[-0.5 \cdot ((x - x_0)/b)^2]$, and the four-parameter Gaussian peak function is $y = y_0 + a \cdot \exp[-0.5 \cdot ((x - x_0)/b)^2]$.
*, **, *** Designate coefficient estimates that are significant at $P<0.05$, $P<0.01$, and $P<0.001$, respectively.

to N rates of 5.5 and 11 g plant^{-1}, but not to higher rates. These results support the recommendations given for many other woody crops to incrementally increase N application rates each year according to size or age of plant (Sanchez et al. 1995). The low N rates indicated by our results are consistent with those found by Neilsen et al. (2001) for 3-yr-old apple (*Malus domestica*) trees, which took up only 5 g N tree^{-1} yr^{-1}. Application at rates in excess of demand merely reduces N uptake efficiency (Weinbaum et al. 1992).

Our root-to-shoot ratio data do not support concerns about N fertilization stimulating shoot growth at the expense of root growth, leading to plants less able to withstand stresses such as drought and herbivory, as reported for *Cotoneaster divaricata* (Graca and Hamilton 1981), apple (Millard and Neilsen 1989), and *Betula pendula* (Ericsson 1995). These concerns may still be valid in situations conducive to strong positive shoot growth responses, which did not occur in our experiment.

Leaf Responses

Our results demonstrate the complexity in interpreting leaf nutrient concentrations. Krauss foliar vector diagnosis, as described by Black (1993), describes an array of different responses that can occur when a nutrient is applied: if the applied nutrient was limiting growth, a growth response may occur with or without an increase in leaf concentration of that nutrient, depending on whether other factors then also become limiting. Increased leaf N concentration without growth signifies that some factor other than N, such as other nutrients or moisture, was limiting to growth, as appears to have been the case at Rosemount in both 2004 and 2005.

Conversely, at Chanhassen in 2004, increased leaf N concentration accompanied by growth suggests that N was initially limiting, but that other factors became limiting at higher levels of N. The decline in leaf N concentration from 2004 to 2005 at Chanhassen in all treatments except for the control, suggests dilution by growth that occurred in that time interval. Nitrogen deficiency in the controls at Chanhassen abated from 2004 to 2005, suggesting that the controls were able to access additional non-fertilizer N, possibly by allocating photosynthate to root growth (Ericsson 1995), while maintaining strong shoot growth. Finally, the relatively low concentrations of leaf N at Becker, even with the high N rates, suggest that something was interfering with N-uptake there (Weinbaum 1992). Perhaps the N was leached out of the sandy soils before substantial uptake.

The growth responses at all three sites illustrate why leaf nutrient concentration should not be interpreted in isolation. Ran et al. (1994) observed that trees maintain relatively constant N concentrations in their various plant parts by adjusting growth instead of concentration.

Evaluating Standard Leaf N Ranges

Our objective in doing leaf analysis was to determine appropriate concentrations of leaf N in hybrid hazelnuts, and to determine whether the standard leaf N ranges developed for hazelnuts in Oregon (Olsen 2001) are applicable to hybrid hazelnuts in the Upper Midwest. The threshold for above normal concentrations, 2.5% N, appears to be valid, because plants with leaves containing more than 2.5% N were clearly stunted and unhealthy.

The threshold between moderately deficient and severely deficient, 1.8% N, may be low. Plots with average leaf N less than 1.8% had a large proportion of highly chlorotic plants, so 1.8% is clearly deficient. Thus, we suggest that the threshold should be closer to 1.9%, if we accept the Piper-Steenbjerg effect (Black 1993). This rule states that if the nutrient in question is strongly deficient in the control plants, the lowest levels of nutrient application will result in a decline in leaf concentration relative to the controls, due to dilution by growth, while higher ones will result in increased concentrations. This was the case at Becker in 2004, where there was a statistically significant growth response to the lowest rates of N, and at Rosemount in 2005, where, although the overall growth response to applied N was negative, trends suggested that a growth response to low N rates may have developed in subsequent years. Since the leaf N in the controls at both sites was about 1.9%, this level should be considered as the threshold between moderately deficient and severely deficient.

A more important question is whether the 2.2% N threshold between N deficiency and sufficiency is applicable to hybrid hazelnuts. Olsen (1997) found that 44% of established hazelnuts orchards in Oregon tested below 2.2% N, and 5% were below 1.8% N. Hybrid hazelnuts in the Upper Midwest do not appear much different. Our data suggest that the N rates required to raise leaf N to 2.2% may be higher than the rates that produce the greatest growth response. Kowalenko (1996) observed the same in British Columbia, and concluded that attempts to surpass 2.2% leaf N may lead to over-application relative to environmental concerns. Our results from another study in Minnesota with 4- to 6-yr-old hybrid hazelnuts (Braun et al. 2011) suggest that leaf N concentrations below 2.2% N should not be a cause for concern as long as new shoot growth is vigorous. Thus, the relatively low leaf N recorded at Chanhassen in 2005, around 2.0%, may be acceptable, considering that the plants were growing vigorously and did not respond to fertilizer N. Alternatively, leaf N concentrations in the same range at Becker possibly do represent deficiency because growth was slow at Becker. However, applying more N is not necessarily the solution on sandy irrigated soils with a high leaching potential such as at Becker.

Therefore, based on our results at the different sites, we suggest for hybrid hazelnuts that less than 1.9% leaf N be considered severely deficient, 1.9 to 2.0% be considered borderline deficient, 2.0 to 2.5% should be considered sufficient, and above 2.5% should be considered excessive. Because leaf nutrient concentrations are only one factor amongst several to be considered when making fertility recommendations, our suggestions should be viewed as guidelines rather than rigid thresholds. Olsen's work suggests the same is true in Oregon (Olsen 1997).

CONCLUSIONS

Our plant mortality data strongly support recommendations from Oregon to postpone N fertilization until the second or third year after transplanting. Although applying N in the second year may not be harmful, there are no clear benefits to it. Our plant growth data suggest that very little N is required by young hybrid hazelnuts in the Upper Midwest. Our leaf N data suggest that for hybrid hazelnuts less than 1.9% leaf N be considered severely deficient, 1.9 to 2.0% be considered borderline deficient, 2.0 to 2.5% be considered sufficient, and above 2.5% be considered excessive. Factors such as deficiencies of other nutrients, soil moisture, and weed management system must also be considered in making N recommendations.

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