Nitrogen fertilization for young established 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 young established hybrid hazelnuts in the Upper Midwest of the USA. Can. J. Plant Sci. 91: 907–918. Hybrids of Corylus avellana, C. americana and C. cornuta are proposed as a new crop for the Upper Midwest. Anecdotal information from midwestern growers suggests that these hybrid hazelnuts have high N requirements, but this has not been confirmed in replicated trials. Current nitrogen (N) recommendations for hazelnut production are based on research from the Pacific Northwest and may not be applicable to these hybrids in the Upper Midwest due to differing soils, climate, genetics, and growing systems. Three years of N rate trials on four plantings, that were 3 to 6 yr old at the start, showed that N responses of hybrid hazelnuts fit patterns for other woody crops: no N responses were found on soils with high organic matter, nor on soils with suspected P or K deficiencies. Where N responses were observed, they suggested that the N requirements of hybrid hazelnuts in the Upper Midwest are relatively low compared with those of European hazelnuts in the Pacific Northwest. Leaf N concentrations were within the expected ranges established for European hazelnuts in Oregon, suggesting that Oregon’s standards may be applied to hybrid hazelnuts, except that 2.2% leaf N should be considered adequate, rather than a threshold to sufficiency.

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

Braun, L. C., Gillman, J. H., Hoover, E. E. and Russelle, M. P. 2011. Amendements azotés pour les jeunes noisetiers hybrides plantés dans le nord du Midwest américain. Can. J. Plant Sci. 91: 907–918. On envisage les hybrides de Corylus avellana, de C. americana et de C. cornuta comme nouvelle culture pour le nord du Midwest. Les données recueillies ici et là des producteurs de la région laissent croire que les noisetiers hybrides exigent beaucoup d’azote (N), mais la chose n’a pas été confirmée par des essais répétés. Actuellement, les recommandations relatives à l’application d’engrais N pour la production d’avelines s’appuient sur les recherches effectuées dans le nord-ouest, sur la côte du Pacifique, et pourraient ne pas convenir à la culture des hybrides dans le Midwest, en raison de différences au niveau des sols, du climat, de la génétique et des systèmes culturaux. Trois années de fertilisation expérimentale dans quatre plantations vieilles de trois à six ans au départ ont révélé que les noisetiers hybrides réagissent aux engrais N comme les autres cultures ligneuses : aucune réaction n’a été relevée sur les sols riches en matière organique, ni sur ceux qu’on soupçonnait être carencés en P ou K. Lorsqu’il y a réaction, celle-ci suggère que les noisetiers hybrides cultivés dans le nord du Midwest ont des exigences en N similaires à celles des noisetiers européens poussant dans la région nord-ouest du Pacifique. La concentration de N dans les feuilles se situant dans la fourchette prévue, c’est-à-dire celle établie pour les noisetiers européens cultivés en Oregon, signe que les normes de cet État pourraient être appliquées aux noisetiers hybrides, si ce n’est qu’on devrait considérer la concentration de 2.2% dans les feuilles comme adéquat plutôt que comme un seuil pour la croissance.

Mots clés: Corylus, aveline, analyse foliaire, recommandations de fertilisation

Hybrid hazelnuts are a potential new crop for the Upper Midwest of the United States of America. These are hybrids between the common European hazel (Corylus avellana L.), which is the basis for commercial production worldwide, and two species of native American hazels: the common American hazel (C. americana Walter), and the beaked hazel (C. cornuta Marsh). The American species may confer genetic resistance to eastern filbert blight (EFB), as well as the cold hardiness needed in the Upper Midwest (Rutter and Shepard 2002). Hybrid hazelnuts are being promoted in the Upper Midwest to increase the diversity of an agricultural landscape dominated by corn and soybeans, with the goal of reducing soil erosion and nutrient loading of surface and ground water.

Because hybrid hazelnuts reputedly have a high demand for N, they have been proposed as possible species for riparian buffer zones to capture N in runoff and subsurface flow from adjacent cornfields. For the same reason, their proponents have been advising people growing them as a cash crop to apply high rates...
of N. Their N requirements have not, however, been substantiated. Nitrogen applied in excess of demand may become a pollutant (Weinbaum et al. 1992), so high N application rates may negate one of the goals for which hybrid hazelnuts are being promoted. Moreover, excess N supply may reduce crop yield or quality, and is economically wasteful. The development of hazelnuts as a viable alternative crop thus requires the development of empirically derived fertilizer recommendations.

Current recommendations for N fertilization of young European hazelnuts are based on research done in the Pacific Northwest, and may not be applicable to hybrids bred for the conditions of the Upper Midwest, due to differing genetics, soils, climate, and growing systems. For example, climatic differences between the Pacific Northwest and the Upper Midwest have an effect not just on the length of the growing season, but also on the size of the mineralizable organic N pool. The most important differences are likely to be due to growing systems. Whereas hazelnuts in Oregon are typically pruned to be trees, and are grown in open, clean-cultivated orchards, in Minnesota, hybrid hazelnuts are typically grown in closely spaced hedgerows, with permanent groundcover between rows for soil conservation. Additionally, whereas hazelnuts in Oregon are transplanted as rooted layers, hybrids are currently transplanted as 2- to 3-mo-old seedlings.

The objectives of our research were: (1) to evaluate N responses to variable rates of N applications to young established hybrid hazelnuts 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. This paper reports results with established plants aged 4 to 10 yr at four sites with diverse soils and diverse management systems. An earlier paper dealt with new transplants through their third or fourth years (Braun et al. 2011). These two age groups differ in that the younger plants have lower reserves of stored nutrients, and thus are presumably more dependent on current uptake (Weinbaum et al. 1978). In addition, the older plants were just beginning to bear nuts, and thus had additional demand for N (Weinbaum and Van Kessel 1998; Youssefi et al. 2000). Finally, whereas the earlier paper described tightly controlled N trials conducted on research stations with plants planted specifically for them, this paper describes N trials that were super-imposed on highly variable plantings that were not planted specifically for them.

METHODS

Nitrogen rate trials were conducted from 2003 through 2005 in four established seed-propagated hybrid hazelnut plantings in Minnesota. All genetic material came from Badgersett Research Corporation in Canton, MN. Two plantings were on-farm, planted in 1997 and 2000, and two were on University of Minnesota experiment station land, planted in 2000. For the latter, the experimental design reflected previous experiments. Table 1 details soil characteristics.

Sites and Maintenance

Chippewa County

Hazelnuts were planted on this sugar beet/corn farm in 2000, with a spacing of 1.5 by 4.5 m. They received no fertilizer until these trials started in 2003. The field was maintained weed-free both in-row and between row with tillage and hoeing.

Staples (Central Lakes Ag Center)

This site was planted in 2000 for an experiment comparing the effects of woodchip mulch and cultivation on transplant growth and survival of three genetic lines. Plants were spaced 1.5 by 4.5 m. No differences were found, so in the fall of 2001 all plots were mulched for ease of maintenance. The mulch was replenished in the summer of 2004. This planting had been fertilized with 4.6 g plant$^{-1}$ N from composted turkey manure in 2001 and 5 g plant$^{-1}$ N from bloodmeal in 2002. This was the only irrigated site: it received overhead irrigation at the same rate and frequency as the adjacent corn field, approximately 25 cm yr$^{-1}$. The irrigation water contained less than 1 mg N L$^{-1}$.

Rosemount

The hazelnuts at Rosemount, where the soil tested low in K, had been planted in 2000 for an experiment to determine the effect of K fertilization on hazelnut transplant growth and survival, with 0, 89 and 178 kg ha$^{-1}$ K applied at planting. This experiment was conducted in a randomized complete block design with three replications and three half-sib genetic lines. Plants were spaced 1.5 by 1.5 m. Although no K-rate effects were observed when this experiment started in 2003, N-rate treatments were applied perpendicularly to the K rates and half-sib lines. Both K-rate and half-sib lines were included as covariates in the final statistical analysis. No N fertilizer had been applied during the previous experiment, but an N credit of approximately 14 g plant$^{-1}$ was assumed for the first year from the N-fixing soybean crop that preceded it (Rehm et al. 1994). Weeds had been controlled with herbicide through spring 2002, but there was no further weed control until 2003, when hoeing beneath the plants and mowing between them was begun.

Fillmore County

Hazelnuts were planted on this homestead in 1997 on Conservation Reserve Program land that had not been in crop production for a decade or more. Plants were spaced 1.8 by 3.8 m. No in-row weed control had been used in recent years; between-row weed control consisted of mowing. Prior to the start of this research in 2003, plants had been fertilized with N at rates of 2.3 g plant$^{-1}$ in 2001 and 65 g plant$^{-1}$ in 2002. For the
N-rate trials, replicated blocks were defined by genetic line and landscape position.

**Plot Layout**
At Chippewa, Fillmore and Staples, N rate treatments were replicated four, eight, and eleven times, respectively, in a randomized complete block design. Plots within blocks consisted of three plants in a row: data were collected only on the middle plant in a plot. At Rosemount, N rates were replicated in three blocks, with nine plants in a row for each treatment-block combination, and every plant was treated as an experimental unit, with previous treatments included as variables. At each site, management practices that had been established by previous managers were continued.

**Nitrogen Treatments**
Treatments were six N rates: 0, 2.75, 5.5, 11, 22, and 33 g plant\(^{-1}\), with additional rates of 1.4 or 44 g plant\(^{-1}\) if enough plants were available. Because plant spacing varied between sites, these rates vary when expressed as kilograms per hectare. However, the intermediate rate, 11 g N plant\(^{-1}\), was approximately 15 kg N ha\(^{-1}\) at all sites, except Rosemount, where it was three times as much due to closer plant spacing. At Chippewa, because of a lack of response in the first years, the rates were increased in 2005 by shifting all plots, except for the control plots, to the next higher rate, up to a top rate of 44 g plant\(^{-1}\). An application error at Rosemount in 2005 resulted in the conversion of the 1.4 g plant\(^{-1}\) rate to 2.75 g plant\(^{-1}\) and the 2.75 g plant\(^{-1}\) rate to 44 g plant\(^{-1}\).

**Timing and Method of N Application**
Nitrogen was applied as NH\(_4\)NO\(_3\) at early leaf expansion in the spring (late April to early May), except in 2003, when it was a month later at Staples and Fillmore. Fertilizer was scattered beneath the drip line of each plant and incorporated with a hoe if possible. At Staples, it was incorporated into the coarse woodchip mulch, whereas at Fillmore it was not possible to incorporate it due to dense perennial weed cover.

**Data Collection**

**Soil Sampling**
Before the start of the experiment one soil sample was collected from every block for the determination of pH, organic matter, extractable P and exchangeable K at a commercial laboratory. After fertilization, soil samples were collected from each plot, to a depth of 30 cm. In 2003 they were collected 6 wk after N fertilization at Staples, 3 mo after fertilization at Rosemount, 4 mo after at Chippewa, and 5 mo after at Fillmore, whereas in 2004 and 2005 they were collected approximately 1 mo after N applications at all sites. Additional soil samples were collected in late October and early November 2005 to determine levels of residual nitrate that could be vulnerable to leaching. Samples were collected from within the drip line of all plants 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

<table>
<thead>
<tr>
<th>Year planted</th>
<th>Soil series and texture (soil type)</th>
<th>PH</th>
<th>Organic matter (%)</th>
<th>Bray P(^z) (mg kg(^{-1}))</th>
<th>K(^z) (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chippewa</td>
<td>Cooperator’s Farm, Chippewa County, Lat. 45°05’N, Long. 95°61’W</td>
<td>2000</td>
<td>Tara silt clay loam (Aquic Hapludolls)</td>
<td>6.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Staples</td>
<td>Central Lakes Ag Center, Wadena County, Lat. 46°36’N, Long. 94°80’W</td>
<td>2000</td>
<td>Verndale sandy loam (Typic Argiudolls)</td>
<td>6.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Rosemount</td>
<td>UMore Park, Dakota County, Lat. 44°75’N, Long. 93°07’W</td>
<td>2000</td>
<td>Waukegan silt loam (Typic Hapludolls)</td>
<td>6.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Fillmore</td>
<td>Cooperator’s Farm, Fillmore County, Lat. 43°76’N, Long. 92°22’W</td>
<td>1997</td>
<td>Renova silt loam, eroded (Typic Hapludalfs)</td>
<td>6.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

\(^z\)H, M, ML, L = high, medium, moderately low, and low levels of these nutrients as defined for fruit crops in Minnesota (Rosen and Eliason 2005).
extracted with 2 M KCl and analyzed by flow injection with a Lachat Quik Chem 8000 (Lachat Instruments, Milwaukee, WI) for nitrate (Knepe 2001) and ammonium (Switala 1993). Soil samples from 2004 soil were 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).

Leaf Sampling
Leaf samples were collected in late August in 2003 and in early August in subsequent years. The third fully expanded leaf from the apex of stems in full sun was sampled. Each sample contained at least 20 leaves. Leaves were composited by plot in 2003, because most plants were too small to supply enough leaves for a sample, but in subsequent years only the middle plant per plot was sampled. Leaves were dried at 60°C for at least 48 h then ground. Leaf N content was determined by Dumas combustion with an Elementar Vario El in 2003 and 2004, and with a Vario Max in 2005 (Elementar Americas Inc., Mt. Laurel, NJ).

Plant Measurements
Plant height and width were measured in early spring 2003 before bud-break, and again every fall through 2005 after leaf drop. Height was measured from the soil surface to the highest live bud. Width was the average of two perpendicular measurements taken at the tops of the plants, from which plant volume was calculated as a cylinder \(V = \pi r^2 h\). Growth was calculated as the increase in plant volume from the initial measurement in spring 2003 to fall 2005.

Weed Biomass and N Uptake
To determine the extent of competition for N by the weeds at Fillmore, which was the only site at which weeds were not controlled at the bases of the hazelnuts, in 2004 weeds were clipped at ground level from within a 0.25-m² ring around plants. Clippings were dried, weighed, and analyzed for total N concentration as described for hazelnut leaves.

Nut Yield
Plants began bearing nuts in 2003 at Fillmore, 2004 at Chippewa and Staples, and 2005 at Rosemount. In 2004 and 2005 at all sites, and in 2006 at Staples and Rosemount only, nuts were hand-harvested, husked, and weighed for in-shell yield on a mass per plant basis. A 20-nut subsample from each plant was shelled to determine the proportion of nut mass comprised by kernel (“percent kernel”) and average mass of individual kernels (“kernel size”). Kernel yield was estimated as the product of in-shell yield and percent kernel.

Statistical Analysis
Data were analyzed by regression analysis, using ARC software (XLISP-PLUS version 3.04). The experimental unit was plot, except at Rosemount, where it was individual plant. Predictors were block, half-sib genetic line (if known), and either N rate, soil inorganic N concentration or leaf N concentration. Initial plant volume was used as a covariate. Block was eliminated from models for Chippewa and Staples, for which it was non-significant. Two statistical approaches were used: N rate was used either as a continuous independent variable for regression or as a discrete variable. The latter approach, which essentially compared slopes of growth rate over time, was more useful because it identified responses that were not linear. Sigma Plot 2000 Version 6.00 (copyright 1986–2000 SPSS Inc.) was used for graphing.

RESULTS
As expected, results were highly variable among the four sites, reflecting differences in management system and soil conditions.

Soil N Responses
Soil inorganic N, both as nitrate and as ammonium, was highly correlated with N application rates at three of the sites in all years, rising to 295, 110 and 102 mg N kg⁻¹ for the highest rates at Rosemount, Chippewa and Fillmore, respectively. However, at Staples total inorganic N never rose above 5 mg N kg⁻¹, even for the highest rates, probably due to leaching from the sandy soil with irrigation. Soil inorganic N in control plots was also roughly correlated with soil organic matter. Based on total inorganic N measured in control plots in summer 2005, the amount of N available to the hazelnuts in the top 30 cm of soil, without fertilization, was estimated to be about 160, 80, 50, and 15 kg ha⁻¹ at Chippewa, Rosemount, Fillmore, and Staples, respectively.

Growth Responses (Fig. 1 and Table 2)
At all sites, growth was exponential for all treatments over the 3 yr, reflecting the rapid above-ground growth of hazelnut plants from their fourth to sixth seasons (seventh to ninth at Fillmore). Dramatic differences in growth rate were observed between sites: over the 3 yr of the study, plant volume increased by 60 and 100 times at Chippewa and Rosemount, respectively, but only by five and ten times at Fillmore and Staples.

Chippewa
Hazelnut plants grew larger, maintained leaves that were larger and darker green, and bore nuts more abundantly at Chippewa than at other sites. At the end of 2005, the plants at Chippewa were over three times larger than the plants at any other site, with an average volume of 4 m³. However, no growth responses to applied N were observed at Chippewa in any year (Fig. 1A and Table 2). Growth was correlated with soil inorganic N only inconsistently (data not presented).
Staples
At the end of the first year (Fig. 1B and Table 2), plants that had been fertilized with 22 g N plant$^{-1}$ were larger than the controls ($P = 0.024$), but it was not until the end of the second year that a positive linear growth response became apparent ($P = 0.0063$). The linear trend was even stronger in the third year ($P = 0.0007$), while plants fertilized with the highest N rate continued to be larger in volume than the controls in the second and third years ($P = 0.010$ and $P = 0.0341$, respectively). Plant volume was correlated with soil inorganic N only inconsistently (data not presented).

Rosemount
The Rosemount hazelnuts were probably K limited, as suggested by an average leaf K of 0.3%, which is below average for hazelnuts. The Rosemount hazelnuts had low K concentrations, which is why they were limited by K.

Table 2. Values and statistics for Fig. 1, models of growth responses to applied N as graphed by Sigma Plot. The linear function is $y = y_0 + a \times x$. The four-parameter Gaussian peak function is $y = y_0 + a \times \exp\left(-0.5\frac{(x-x_0)^2}{b}\right)$. The exponential rise to a max function is $y = y_0 + a(1 - e^{-bx})$. *, **, *** designate coefficient estimates that are significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$ respectively. NS = not significant. (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>
<thead>
<tr>
<th>Model</th>
<th>Year</th>
<th>Type</th>
<th>$a$</th>
<th>$b$</th>
<th>$x_0$</th>
<th>$y_0$</th>
<th>Adj. $R^2_{model}$</th>
<th>$P_{model}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chippewa</td>
<td>2003</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>Linear</td>
<td>0.101</td>
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<td></td>
<td>2004</td>
<td>Linear</td>
<td>0.033</td>
<td>–</td>
<td>0.643</td>
<td>0.13</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>Staples</td>
<td>2003</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Linear</td>
<td>0.303*</td>
<td>–</td>
<td>0.330**</td>
<td>0.283**</td>
<td>0.11</td>
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</tr>
<tr>
<td></td>
<td>2005</td>
<td>Linear</td>
<td>0.033**</td>
<td>–</td>
<td>0.708**</td>
<td>0.13</td>
<td>0.0055</td>
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<tr>
<td>Rosemount</td>
<td>2003</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td></td>
<td>2004</td>
<td>Gaussian peak</td>
<td>0.703NS</td>
<td>1.030*</td>
<td>3.303***</td>
<td>0.283**</td>
<td>0.11</td>
<td>0.0464</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Linear</td>
<td>0.033**</td>
<td>–</td>
<td>0.708**</td>
<td>0.13</td>
<td>0.0055</td>
<td></td>
</tr>
<tr>
<td>Fillmore</td>
<td>2003</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Exponential Rise to a max</td>
<td>1.00*</td>
<td>0.204NS</td>
<td>0.331NS</td>
<td>0.17</td>
<td>0.0425</td>
<td></td>
</tr>
</tbody>
</table>
the 0.5% threshold for severe deficiency by Oregon standards for hazelnuts (Olsen 2001). Although no responses to K fertilization that preceded this research were observed during the first 2 yr, in the third year it became apparent that K was limiting the response to N fertilization. In 2005, a strong interaction was observed between K rate and N rate ($P = 0.0087$). Where no K had been applied at planting no response to applied N occurred, whereas where 178 kg ha$^{-1}$ was observed between K rate and N rate ($P = 0.0008$): in 2005 there was a negative N rate growth response in the four blocks that had low Bray-P (between 15 and 18 mg kg$^{-1}$) ($P = 0.0353$), whereas in the four blocks that had high Bray P (between 21 and 24 mg kg$^{-1}$) a plateau response to applied N was observed ($P = 0.0497$). With adequate levels of P, the response to N reached a plateau at 11 g plant$^{-1}$ N; plants fertilized with 11 g plant$^{-1}$ N or more were significantly larger than the controls at the end of the third year ($P < 0.459$) though no significant differences were observed between the 11 g plant$^{-1}$ N rate and higher rates. The same patterns were observed for growth responses to soil inorganic N, which became evident only in plots with adequate P. No relationship between soil N and growth was observed in low P plots. Yet another factor limiting growth at Fillmore could have been competition from weeds. Rings of darker green weeds were observed around plants fertilized at the higher rates, and weed analysis in 2004 confirmed that weeds were utilizing fertilizer N. Although weed biomass did not increase significantly with N, weed N concentration and thus N content both increased linearly with applied N ($P = 0.0016$ and $P < 0.0001$, respectively).

**Leaf N Responses (Fig. 2 and Table 3)**

**Chippewa**
Leaf N was not correlated with applied N in any year (Fig. 2A and Table 3), and was correlated with soil inorganic N only inconsistently (data not shown).

**Staples**
A positive linear leaf N response to applied N was observed in the first year (Fig. 2B and Table 3, $P = 0.0026$), but none the second or third years. Soil N was not correlated with leaf N at any time (data not shown).

**Rosemount**
In the first year, leaf N showed a plateau response to applied N (Fig. 2C and Table 3), with a peak between 2.0 and 2.1% leaf N, corresponding to the 22 g plant$^{-1}$ N rate ($P = 0.0131$). In the second year, leaf N declined for the three lowest rates (1.38 to 5.5 g plant$^{-1}$; $P < 0.001$), but did not differ between the control and the three higher rates. In the third year, leaf N in the control was higher than in fertilized plants. Leaf N also correlated with soil inorganic N in the first and third years:

- in the first year it was a plateau response ($P = 0.0014$), whereas in the third year it was a negative linear response ($P = 0.0336$, data not shown).
No leaf response to applied N was observed the first year (Fig. 2D and Table 3), but plateau responses occurred in the second and third years ($P < 0.0002$ for both). In the second year leaf N peaked at 2.18% for N applications of 33 g plant$^{-1}$, and in the third year leaf N peaked at 2.26% for N applications of 29 g plant$^{-1}$. In the third year, leaf N for the control plots and the lowest N rate plots, in which growth was stunted, declined well below the 1.8% threshold for severe deficiency in Oregon’s standards. Leaf N at Fillmore was also correlated with soil inorganic N in the third year ($P < 0.0007$, data not shown), and with growth in the last 2 yr ($P = 0.0110$ and $P = 0.0077$, respectively).

### All Sites

Across all sites and all years, leaf N was generally in the deficient range, as defined by Oregon standards (Olsen 2001), except for Chippewa in 2004 and Rosemount.

### Fillmore

No leaf response to applied N was observed the first year (Fig. 2D and Table 3), but plateau responses occurred in the second and third years ($P < 0.0002$ for both). In the second year leaf N peaked at 2.18% for N applications of 33 g plant$^{-1}$, and in the third year leaf N peaked at 2.26% for N applications of 29 g plant$^{-1}$. In the third year, leaf N for the control plots and the lowest N rate plots, in which growth was stunted, declined well below the 1.8% threshold for severe deficiency in Oregon’s standards. Leaf N at Fillmore was also correlated with soil inorganic N in the third year ($P = 0.0007$, data not shown), and with growth in the last 2 yr ($P = 0.0110$ and $P = 0.0077$, respectively).

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**Table 3.** Coefficients and statistics for Fig. 2, models of leaf N responses to applied N as graphed by Sigma Plot. The linear function is $y = y_0 + a \times x$. The quadratic function is $y = y_0 + a \times x + b \times x^2$. The four-parameter Gaussian peak function is $y = y_0 + a \exp\left[-(x-x_0)^2 / b^2\right]$. The exponential rise to a max function is $y = y_0 + \alpha (1 - e^{-bx})$. *, **, *** designate coefficient estimates that are significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$ respectively. n.s. = not significant at $P < 0.10$. (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>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Model</th>
<th>$a$</th>
<th>$b$</th>
<th>$x_0$</th>
<th>$y_0$</th>
<th>Adj. $R^2_{model}$</th>
<th>$P_{model}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chippewa</td>
<td>2003</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Staples</td>
<td>2003</td>
<td>Linear</td>
<td>0.004***</td>
<td>–</td>
<td>–</td>
<td>2.094***</td>
<td>0.09</td>
<td>0.0080</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Linear</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Rosemount</td>
<td>2003</td>
<td>Exponential rise to a max</td>
<td>0.323***</td>
<td>0.149NS</td>
<td>–</td>
<td>1.738***</td>
<td>0.49</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Gaussian peak</td>
<td>–0.228**</td>
<td>1.998**</td>
<td>2.767***</td>
<td>2.283***</td>
<td>0.27</td>
<td>0.0266</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Quadratic</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Fillmore</td>
<td>2003</td>
<td>Flat</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Exponential rise to a max</td>
<td>0.300**</td>
<td>0.112NS</td>
<td>–</td>
<td>1.854***</td>
<td>0.17</td>
<td>0.0097</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Exponential rise to a max</td>
<td>0.027**</td>
<td>–0.0004*</td>
<td>–</td>
<td>1.706***</td>
<td>0.34</td>
<td>&lt;0.0001</td>
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</table>
Responses to Applied N

Nitrogen fertilization, however, did not affect yield or yield increase and nutrients are exported with the harvest (Weinbaum and Van Kessel 1998; Youssefi et al. 2000). At the other three sites, N was limiting to growth, as expected, due to lower organic matter soils, although this limitation did not become apparent until the second or third year after N rate trials began. As expected, the strongest N response was at Staples, due to its sandy, low organic matter soil. Again, based on total inorganic N measured in control plots and assuming root spread equal to canopy spread and a rooting depth of 30 cm, only an estimated 13 kg N ha\(^{-1}\), or 0.9 g N plant\(^{-1}\), would have been available at Staples without fertilization. The linear growth response to N at Staples suggests that there may have been a growth response to N rates higher than those that were applied. Moreover, it may be assumed that, due to the sandy soils and irrigation at Staples, only a fraction of the N that was applied stayed in the plants root zone long enough to be taken up. Thus we cannot confidently base N recommendations on results from there.

At Rosemount, response to applied N apparently was limited by lack of K, whereas at Fillmore it was apparently limited by both P and K. This demonstrates Liebig’s Law of the Minimum (Wallace 1990), which states that no great response can be obtained until the factor in greatest limitation is corrected. Potassium is the second most commonly deficient nutrient in nut crops (Proebsting and Serr 1954), and is commonly deficient in Oregon (Olsen 2001). However, it is surprising that a K limitation was observed, because K is generally considered not to be as important for growth as for maintenance of nut yield and quality, because of the high K content of nuts (Crane and McKay 1951).

The interaction observed between N rate and soil P at Fillmore is also surprising, because P response in nut crops is not common (Proebsting and Serr 1954). Kowalenko (1996) recommended no P for hazelnuts except as a starter or if soil P is extremely low. Moreover, the levels of soil P that appeared to be limiting, 15–18 mg kg\(^{-1}\) Bray-P, are considered only moderately low for other woody crops (Rosen and Eliason 2005). Plants frequently respond to low soil P by
increasing root growth relative to shoot growth, which enables them to extract scarce P from a larger soil volume (Ericsson 1995; Zhengquan 1999). The plants in the lower P soils at Fillmore may have been allocating resources below ground. An above-ground N response may be manifested later, after they have established large root systems to compensate for low P.

At all three sites at which a growth response was observed, it did not occur until the second or third year after fertilization was initiated. A delayed response to fertilization is common in woody plants and has three possible explanations. First, physiological processes, from N assimilation to photosynthesis, are rate-limited, and must occur in sequence before they can result in additional growth (Engels and Marschner 1995). That a leaf N response occurred a year or more before a growth response at all three sites supports this explanation. The disappearance of the leaf N response in the third year at Staples and Rosemount, when the growth response was the strongest, suggests dilution of leaf N by growth, and further supports this explanation. Second, if soil-derived nutrients are limiting, photosynthates may be allocated to roots before shoots, which enables them to overcome the limitation by enhancing capacity for nutrient uptake (Millard and Neilson 1989), as described for P above. Root growth was not measured, so it cannot be confirmed whether high rates of root growth preceded above-ground growth at these sites. Third, N applications prior to the start of this research could have supplied enough N for the first year of the experiment, when plants were still small. Although these rates were generally very low, research by Braun et al. (2011) on new transplants suggests that small plants do not require large amounts of N. The methods of this study did not allow determination of whether responses observed in the third year were responses to fertilizer applied in the third year, which would support this final explanation, or were delayed responses to fertilizer applied in the first year, which would support the first two. However, it is likely that all of these explanations played a role. In conclusion, N fertilization may be effective in the long term, even when results are not immediately observed.

At Rosemount the largest increase in plant volume occurred in the treatment in which N was increased from 2.75 to 44 g N plant$^{-1}$ in the third year. These plants grew twice as much as those in the 22 g N plant$^{-1}$ treatment, even though over the 3 yr they received a total of only 75% as much N as the plants in the 22 g N plant$^{-1}$ treatment. This suggests that the plants in the 22 g N treatment were not able to take up or utilize all the fertilizer supplied to them from this relatively high rate in the first 2 yr, possibly because their root systems were still too small to intercept it. According to Ran et al. (1994), N uptake ability is strongly affected by root volume. These results further support recommendations commonly made for woody plants, to increase N rates with increasing size and age of plant (Sanchez et al. 1995). This is why recommenda-

tions for European hazelnuts in Oregon are based on age of plant (Olsen 2001).

The only site at which N responses reached a plateau was at Fillmore, which has low organic matter soils. Based on inorganic N measured in control plots at Fillmore, only an estimated 48 kg N ha$^{-1}$, or 3.4 g N plant$^{-1}$ yr$^{-1}$ was available without fertilization in the top 30 cm of soil beneath the plant canopy. This is less than half of the 7.1 g N content that Braun et al. (2009) measured in the above-ground biomass of other plants of a similar age in a $^{15}$N tracer study conducted at the same site. Thus, these plants were clearly N limited and an N response was to be expected. That response reached a plateau in the third year at 11 g N plant$^{-1}$. Eleven grams of N per plant is, thus, the maximum rate that we recommend for 8-yr-old hybrid hazelnuts growing under similar conditions. This is much lower than the 226 g N plant$^{-1}$ recommended for 6- to 7-yr-old trees in Oregon (Olsen 2001). This discrepancy is likely due to the facts that the hazelnuts in this study were much smaller than similarly aged trees in Oregon, and that they were not yet exporting significant quantities of N with nut harvests.

N uptake efficiency at Fillmore was exceedingly low, only 5 to 9%, according to the $^{15}$N tracer study Braun et al. (2009) conducted at the site. This means that only 0.6 to 1.0 g out of 11 g N applied was likely to have been absorbed each year. This low efficiency was likely due to competition from weeds growing close to the plants. However, much of the N taken up by weeds the first year should have been released as they died and decomposed in subsequent years. The delay in leaf N response until the second year and the delay in growth response until the third year support this explanation. Sicher et al. (1995) affirmed that deep-rooted weeds may sequester and release N in a similar fashion as cover crops, thus actually enhancing the long-term efficiency of N uptake: after they die, weeds release N slowly, in greater synchrony with the ability of the crop to take it up. As the hazelnuts grow larger and shade out the weeds they should be better able to take advantage of N thus released. However, this should not be taken as justification to ignore weed control. Many researchers (Merwin and Ray 1997; Hanss et al. 2003) have found that weeds close to woody crops delay growth, not so much because of competition for N, but because of competition for moisture (Davis et al. 1999). Fertilization may intensify this competition for moisture by stimulating weed growth (Campbell et al. 1994), as was observed at Fillmore. However, de Montard et al. (1999) found that competition for moisture was alleviated in later years as tree roots colonized soil horizons deeper than the competition. Thus it is likely that N uptake efficiency would improve in future years. That the hazelnuts at Fillmore were able to accumulate 7 g of N over 8 yr with competition and without fertilization demonstrates the ability of woody plants such as hybrid hazelnuts to scavenge and store N as it slowly becomes available over
many years. It demonstrates their “frugality”, in the words of Roversi and Ughini (2005).

Another factor contributing to the low N requirements of hybrid hazelnuts may be the relatively high ability of the soils of the Upper Midwest to supply N to plants without supplemental N. The 3.4 g N plant⁻¹ that was calculated as being available at Fillmore from non-fertilizer sources is significant relative to the 7 g N contained in 8-yr-old plants; soils at Chippewa and Rosemount provided even more N. To prevent over-application of N, fertilizer recommendations should thus consider both the N that is already stored in the plants and the N that is potentially mineralized from soil organic matter.

Leaf N
Nitrogen recommendations for mature European hazelnuts in the Pacific Northwest are based on comparing the N content of leaf tissues to optimal levels (Olsen 2001). The results reported in this paper demonstrate the complexity of this approach. 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 to 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. Growth with increased leaf concentration suggests that the applied nutrient was initially limiting, but that other nutrients became limiting, according to the law of the minimum; whereas increased concentration with no growth signifies that some factor other than the applied nutrient, such as other nutrients or moisture, was limiting to growth. Conversely, the concentration of the applied nutrient may decline by dilution if there are no other limitations and growth is vigorous. Induced deficiency, where application of one nutrient interferes with the uptake of another, further complicates the interpretation.

For these reasons, leaf N concentration should not be considered alone in making N recommendations. Plant vigor, leaf color, growth and yield all need to be considered together. These other factors suggest that the hazelnuts at Chippewa do not need N fertilization in spite of borderline low leaf N concentration. Likewise, the low leaf P and K levels at Chippewa should not be of concern, for they probably reflect dilution by rapid growth. Conversely, the high leaf N concentration at Rosemount suggests that there may be no response to N fertilization until other limits on growth, such as K deficiency, are removed.

Ran et al. (1994) found that most woody plants maximize photosynthesis by using additional N to increase leaf surface area while keeping N per unit leaf area relatively constant. Conversely, if N is limited, leaf area is reduced before leaf N concentration falls. This explains why at Rosemount and Staples the control plants were able to maintain such high leaf N in the third year — they grew less. But, at Fillmore, plants in the control plots were so depleted of N by the third year that reducing leaf area was not enough to maintain leaf N concentrations, which declined to severely deficient levels. Low leaf N combined with no growth indicates a need for N. This is an example of how leaf analysis can still be a useful diagnostic tool.

Evaluating Standard Leaf N Range
One of our objectives was to determine appropriate concentrations of leaf N in hybrid hazelnuts, to determine whether the standard leaf N ranges developed for European hazelnuts in Oregon (Olsen 2001) are applicable to hybrid hazelnuts in the Upper Midwest. Overall, leaf N concentrations were low by the standards of Oregon hazelnuts. Even at Chippewa, where there were no reasons to suspect N deficiency, leaf N averaged below the sufficiency range in 2 years out of 3. The only site with leaf N consistently above the sufficiency threshold, Rosemount, appears to have had high leaf N because another nutrient was limiting. Leaf N was also low, relative to the standards for Oregon hazelnuts, in our N rate trials on newly established hybrid hazelnuts (Braun et al. 2011).

These low leaf N levels may not be atypical, even of European hazelnuts in Oregon: Olsen (1997) found that 44% of hazelnut orchards tested below 2.2% N and 5% of orchards tested below 1.8% N. Similar results were found in British Columbia, leading Kowalenko (1996) to state that 2.2% N should be considered a target to be attained rather than to be surpassed. Kowalenko (1996) further stated that the N rates required to increase leaf N above 2.2% may sometimes be higher than the rates that produce the greatest growth response, and may lead to over application relative to environmental concerns. This would be of concern especially at sandy irrigated sites such as Staples, where leaching of excess N causes groundwater contamination.

Our research suggests that leaf N concentrations in these hybrid hazelnuts are not significantly different from those of European hazelnuts in the Pacific Northwest, but that standard leaf N ranges should be interpreted as guidelines rather than rigid thresholds. As long as leaf nutrient concentrations are understood to be only one factor amongst several to be considered in making nutrient recommendations, then the Oregon leaf N standards may be considered to be roughly applicable to hybrid hazelnuts in the Upper Midwest.

Yield
We were not able to make strong conclusions about the effect of N on nut yield due to the relative immaturity of these plantings. The strongest predictor of nut yield at all sites was plant size, suggesting that soil conditions and management practices that favor plant growth should also favor early nut bearing. That Fillmore was
the only site where N rate had a significant effect on yield probably reflects the relative maturity of this site; we expect that N rate effects are likely to develop at other sites as they mature. The N rate that produced the highest yields at Fillmore, 11 g plant\(^{-1}\), was the same relatively low rate that produced the highest growth, which is contrary to the observation that there is sometimes a trade-off between vegetative growth and reproduction (Weinbaum et al. 1992). However, in some cases a negative relationship was found between N rate and nutrient size, which is consistent with Sparks (1987), who observed that high N rates can stimulate pecans to set more nuts than they are able to fill, leading to smaller nuts and more blanks. Until further research can be done on mature plantings, we recommend that N fertilization rates be based on estimates of N removal with harvest, as recommended by Tagliavini et al. (1996) and Tous et al. (2005).

Responses to Soil Inorganic N

Our results showed highly inconsistent responses to soil inorganic N. This is in keeping with the comments of Sparks (1977, p. 26) that soil analysis is not highly correlated with leaf analysis nor with tree performance. N dynamics in woody crops are more complicated than in annuals for two reasons: first, their roots are present in the soil all year, and can absorb soil N whenever temperatures favor uptake (Dong et al. 2001) and, second, they store N over the winter and reuse it the following season (Titus and Kang 1982; Weinbaum et al. 1992). Soil inorganic N measurements are a snapshot of one instance in time. In contrast, woody plants respond to the N that is available over the course of many seasons. Most soil-testing laboratories in humid regions of the United States make recommendations for annual crops based on soil organic matter or on crop productivity instead of on soil-test N, because of the transient nature of inorganic N in the soil. The rationale for this is even more valid for perennial crops. In this study, measuring soil inorganic N in the control plots provided an estimate of N available from mineralization of soil organic matter. As expected, the two sites with rapid growth, Chippewa and Rosemount, had high organic matter soils and thus had large pools of inorganic N in control plots, relative to the two sites with slower growth, Fillmore and Staples. Yet soil analysis may still be useful, as in the cases of Rosemount and Fillmore, where correlations between growth and soil inorganic N were observed only in plots with high levels of K and P, supporting our hypotheses that K and P were limiting to growth at these sites.

CONCLUSIONS

The N requirements of hybrid hazelnuts vary significantly depending on soil type and management system. Other factors, such as other nutrient deficiencies, moisture, weeds, ground cover, and mulch, must be considered in making N recommendations. Assuming no other limitations to growth, the N requirements of established hybrid hazelnuts that are not yet in full nut production are very low in the Upper Midwest, relative to those of European hazelnuts in the Pacific Northwest. Our leaf N data support standard ranges developed in Oregon in general, but suggest that 2.2% N should be considered an adequate level rather than the lower threshold of sufficiency.

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