

Determining Nitrogen Requirements of Hybrid Hazelnuts for the Upper Midwest

**A Review of the Literature, by Lois Braun,
in partial fulfillment of the requirements of a PhD**

Justification

Hybrid hazelnuts, developed for the Upper Midwest, are a new crop believed to have potential as an alternative to annual row crops. These are hybrids between *Corylus avellana* L., the common European hazel, which is the basis for commercial production worldwide, and two species of native American hazels, *Corylus americana* Walter, the common American hazel, and *Corylus cornuta* Marsh, the beaked hazel. The two American species may confer to the hybrids resistance to Eastern Filbert Blight (EFB), a disease that threatens to decimate the hazelnut industry in the Pacific Northwest, as well as cold hardiness and tolerance to the extreme weather conditions of the Upper Midwest (Rutter and Shepard, 2002).

Because the low economic profitability of conventional row crops has historically justified government payments, and as we become increasingly aware of the environmental costs of growing them, alternatives that combine economic potential with ecological sustainability are needed. The benefits of woody perennials are well appreciated in tropical agroecosystems, but Thevathasan and Gordon (2004) have found similar benefits in Ontario Canada, in the Northern temperate region, as well. They found that hybrid poplars intercropped with row crops increased soil organic carbon, improving N cycling efficiency and thus reducing N leaching and nitrous oxide emissions, compared with annual monocrops. Carbon sequestration was four times higher than for annual crops. Earthworm populations and diversity of beneficial insects and birds were increased. In addition, energy costs for management of woody perennials are lower, primarily because annual tillage is not needed and fertilizer requirements are low. It is likely the same benefits may be realized with hybrid hazelnuts, whether they are grown as field scale cash crops, small scale multi-purpose plantings in field and homestead windbreaks, living snow fences, or as riparian buffers (Josiah, 2001).

Hazelnuts also have economic potential. Currently only 4% of the world crop of hazelnut is produced in the United States (O'Conner, 2006), and only 20% of the hazelnuts consumed in the United States are produced in this country. So there is a large un-met market demand, which is likely to grow as new hazelnut products are developed (Rutter and Shepard, 2002). Recent developments in our

understanding of human health may also help grow demand: the oil in hazelnuts, as in all nuts, is high in healthful monounsaturated fatty acids, which help reduce the risk for heart disease (Richardson, 1997; Willet and Stampfer, 2003). Hazelnut oil also has characteristics desirable for industrial uses, including biodiesel (Xu et al., 2007), which may also increase demand. With current prices up to \$4.75/kg wholesale for unshelled nuts, and \$26.30/kg retail for shelled nuts, there is good economic potential -- if production costs can be kept down.

Although hybrid hazels can grow and be productive with little or no fertilizer, the proper amounts of fertilizers 1) at early establishment may speed up their growth and lead to early nut-bearing, and 2) after maturity may increase their productivity and thus improve their profitability. The former is important because the high up-front cost of establishment is a significant barrier to the adoption of hazelnuts, so if they can be made to produce a marketable crop sooner they will be more economically attractive to growers (Rutter and Shepard, 2002). Subjective observations by Rutter and Shepard and other growers (personal communications) suggest that hybrid hazelnuts are hungry plants: the more fertilizer you apply, particularly N, the faster they will grow and the sooner they will reach reproductive maturity. There is currently no empirically derived information to support these claims, and there are serious negative consequences to overapplication of N. Too much fertilizer N at the wrong time may stress or kill young seedlings, and reduce yield and nut quality (Sanchez et al., 1995), and excess N may become a pollutant and is economically wasteful (Weinbaum et al., 1992). The challenge is figuring out the right amount to apply, with methods and timing that maximize uptake efficiency, so as to balance the needs of the plant for growth and nut production with these environmental and economic concerns.

The objectives of this dissertation were: 1) to evaluate N responses to variable rates of N applications to hybrid hazelnuts in the field; 2) to evaluate leaf and soil analysis as diagnostic tools upon which to make recommendations; and 3) to determine the best timing of N applications for optimal nitrogen use efficiency. Although research has been conducted on the nutrition of European hazelnuts elsewhere, there are several compelling reasons to expect that this research may not be applicable to the hybrid hazelnuts developed for the Upper Midwest.

1) Different region. Most of the early literature on hazelnut nutrition comes from Oregon and from British Columbia, with more recent papers from the Mediterranean hazelnut growing regions (Strabbioli, 1994; Tous et al., 1994; Ferran et al., 1997; Borges et al., 2001; etc). Significant differences between these regions in hazelnut fertilization responses are primarily attributed to

climatic differences. Thus one can expect differences between the Pacific Northwest, which has a Mediterranean climate, and the Upper Midwest, which has a continental climate. Whereas the humid climate in the hazelnut growing areas of the Pacific Northwest are characterized by cool wet winters and hot dry summers, in the Upper Midwest winters are very cold, with frost to 120 cm, and summers are warm and humid, with intense summer rainfall from convective storms. In addition, the growing season for hazelnuts in the Upper Midwest is much shorter. Differences in soil type are also likely to have an influence on response to fertilization. Whereas the soils in the Pacific Northwest are ancient, of volcanic origin, clay-textured, with low to medium organic matter, in the Upper Midwest they are young, of glacial origin, with a wide range of textures and organic matter content. Soils in the Upper Midwest may be very deep with very large pools of mineralizable organic N.

2) Different plants. All the fertilization research on hazelnuts reported in the literature thus far has been on *C. avellana*. Hybrids for the Midwest include two other species besides *C. avellana*. Miljkovic and Jemric (1997) found significant differences in nutritional response among cultivars of *C. avellana*, providing a reason to expect differences between *C. avellana* and hybrid hazelnuts. Moreover, the selection methods used for the Midwestern hybrid hazelnuts have inadvertently selected for vigorous root growth, which is a survival strategy against fire and grazing. This could well have an influence on nutrient uptake.

3) Different system. Because hybrid hazelnuts are being promoted for conservation purposes as well as for production, the system being proposed for growing them differs greatly from the orchard system used in the Pacific Northwest. The two major differences are that 1) the hybrids selected for the Midwest were grown as bushes and planted in hedgerows, as opposed to being pruned into trees grown in open orchard systems as in the Pacific Northwest; and 2) whereas the orchards in the Pacific Northwest are maintained as weed-free monocultures, the system proposed for the Upper Midwest relies on other vegetation growing in the alleys between hedgerows to improve their conservation value. Undoubtedly these differences have an influence on their nutritional requirements, especially due to competition from other vegetation.

4) There has been relatively little research on hazelnut nutrition, compared to other crops. Tous et al. (1994) suggested more research is needed on hazelnut nutrition. They presented a table of fertilizer recommendations from eleven different authors, from both North America and Europe, dating from 1944 to 1987; the apparent discrepancies undoubtedly reflect not just regional differences, but changes in the way we think about soil fertility and crop nutrition. Most notably, a greater awareness

of the consequences of over-application of fertilizers has made it necessary for researchers to figure out ways to balance the objectives of high yield and environmental protection. Since 1994, only about a dozen papers have been published on fertilization of hazelnuts, so the matter has not been resolved.

Note: Because our research is the first that has been done on the nutritional requirements of hybrid hazelnuts, all references to hazelnuts in the following text are to European hazelnuts, unless otherwise noted.

Fundamentals of Nitrogen Nutrition in Woody Plants

The Function of N in Plants

Nitrogen is ubiquitous in plants. Of all mineral nutrients, it is quantitatively the most important nutrient for growth and yield. Nitrogen is essential for growth because it is a component not just of the building blocks of new growth, but also of the enzymes that assemble the building blocks, and the purine and pyrimidine bases in the DNA and RNA needed for cell division. Nitrogen is essential for plant hormones and defense compounds. And N is especially important for photosynthesis because it is also a component of chlorophyll and cytochromes, ATP and H-ATPase pumps, as well as rubisco, the enzyme that catalyses CO₂ fixation and which constitutes over 50% of the protein in leaves (Taiz and Zeiger, 2002).

The Connection between N Uptake and Assimilation and Photosynthesis

Not only is N essential for photosynthesis, but photosynthesis is essential for N uptake and assimilation, because these are energetically demanding processes, whether N is taken up as nitrate or as ammonium (Haynes, 1986). Nitrate uptake is especially energy-demanding because it is absorbed both against a concentration gradient and against the electrochemical gradient, and is thus “thermodynamically uphill.” Once inside plant tissues, nitrate requires additional energy because it must be reduced to ammonium before it can be assimilation. Ammonium uptake does not require metabolic energy directly, because it is “thermodynamically downhill”, but it does require energy indirectly, to pump H⁺ out of the cell to keep electrochemical charges balanced (Engels and Marschner, 1995). And once inside tissues, ammonium must be complexed with fixed carbon from photosynthesis to synthesize the amino acids which are the form in which most N is transported within the plant and which are the building blocks for many N-containing compounds. Because ammonium is toxic to plant cells, it is essential that assimilation occur quickly; thus plants have

various feedback mechanisms to ensure that ammonium does not accumulate (Barker and Mills, 1980). Furthermore, the loading of amino acids for translocation from the roots to the shoots in the xylem, or between different parts of the shoot in the phloem, requires energy (Millard and Nielsen, 1989).

Evidence for the link between photosynthesis and N uptake and assimilation is that the latter are slowed by anything that limits photosynthesis, such as low light, low temperature, deficiency of other nutrients needed for photosynthesis, moisture stress (Haynes, 1986; Engels and Marschner, 1995), or anything that limits the translocation of photosynthates to the roots, such as stem girdling (Malaguti et al., 2001; Jordan et al., 1998). Malaguti et al. (2001) found that girdling reduced nitrate uptake more than ammonium uptake, reflecting the higher energy requirements of nitrate uptake.

Jordan et al. (1998) found that girdling reduced N uptake in peach trees (*Prunus persica*) even when reserves of carbohydrates stored in roots were not depleted, leading them to conclude that N uptake is dependent on the continuous supply of carbohydrates from shoots to roots. However, they maintained that the amount of current photosynthate that is allocated to the roots, which is the result of the competition between sinks, is more important than the photosynthetic activity of the leaves.

Implications for Timing of N Uptake: This connection between N uptake and photosynthesis explains why several researchers have observed that N uptake is highest during the growing season. In a ¹⁵N study on two-year-old prune trees (*Prunus domestica*) grown in sand, Weinbaum et al. (1978) found that N uptake efficiency was minimal during dormancy and bud swell, but increased with shoot elongation and stayed high until leaf fall, after which it declined steeply. The continued ability to take up N into the fall was highly correlated with leaf retention. Titus and Kang (1982) reported similar findings in apples (*Malus domestica*), as did Munoz et al. (1998) in peaches in Spain.

Neither the Weinbaum et al. (1978) study nor the Jordan et al. (1998) study absolutely proves that N uptake depends on the presence of leaves, because there are other explanations for low N uptake, such as low soil temperatures inhibiting root activity. However, Dong et al. (2001a) were able to isolate root temperature from shoot physiological stage, by keeping roots at different temperatures than shoots with insulated planting boxes, to show that both are important determinants of N uptake.

Assertions have been made that N uptake through the dormant season may be maintained at high levels in spite of lack of leaves because of photosynthesis by bark, particularly in species with

chlorophyll-containing bark tissues, such as hazelnuts and aspen (*Populus tremuloides*). For aspen, Foote and Schaedle (1978) found that the contribution of bark photosynthesis to the tree's total carbohydrate balance was 1 to 2%, which offset bark respiration, but did not contribute significantly to growth or reproduction. They concluded, however, that bark photosynthesis could be important to survival in the case of defoliation, and thus could enhance the species' competitiveness with other species. Aschan et al. (2001) came to similar conclusions for aspen, as did Han and Suzaki (1981) for Japanese beech (*Fagus crenata*) and chestnut-leaved oak (*Quercus acutissima*). In conclusion, although bark photosynthesis occurs in some species, it is not likely to be high enough to support N uptake during the winter.

Nitrate versus Ammonium:

Plants roots exude either H^+ or OH^- , or their equivalents, to balance the charges of the N ion taken up. Thus uptake of cations such as ammonium tend to lower soil pH, whereas uptake of anions such as nitrate tend to raise it (Barker and Mills, 1980). Nitrification of ammonium to nitrate also lowers soil pH. Nitrate uptake may either raise or lower soil pH, depending on other factors, but in general it is not as acidifying as ammonium. Ammonium nitrate has a soil reaction that is intermediate between ammonium and nitrate.

In addition, ammonium is toxic to plants in too high a concentration (Haynes, 1986). Herbaceous plants grown in hydroponic solutions in which 100% of the N is provided as ammonium often fail to thrive, whereas in mixes containing both nitrate and ammonium they grow much better (Barker and Mills, 1980). The same appears to be true of woody plants. Peuke and Tischner (1990) found that 100% solutions of ammonium were toxic to poplar (*Populus trichocarpa*), and that the reduction in pH was only part of the reason. Grasmanis and Nicholas (1971), however, successfully grew apples in sand culture with ammonium as their sole source of N, even when the nutrient solution was changed weekly to eliminate the products of nitrification.

Titus and Kang (1982) suggest that supplying N as ammonium is not usually a problem under field conditions, because the same conditions which favor crop uptake also favor the rapid nitrification of ammonium to nitrate. The exception occurs in the spring and fall when nitrification is inhibited in cool soils. But even then, N supplied as ammonium is not usually a problem as long as other factors are not limiting, in particular, as long as photosynthesis is sufficient to supply the carbohydrates needed to assimilate the ammonium into amino acids quickly. Yet there is a cost to ammonium detoxification, for it diverts carbohydrates away from other functions, like growth. On the other hand, when N is supplied as ammonium, it spares the plant the energetic expense of nitrate reduction. This is why Barker and Mills (1980) concluded that "a balance between nitrate and ammonium nutrition gives the best of both regimes" (p. 414).

Regulation of N Uptake

Nitrate uptake into plant roots is mediated by nitrate-specific membrane-bound carrier proteins (Haynes, 1986). Evidence for this is that when a plant not previously exposed to nitrate is first given nitrate, a lag phase occurs before significant uptake commences. This is probably the time required for the transcription and synthesis of nitrate-specific carrier proteins. That its synthesis is not inducible by other anions indicates that it is specific to nitrate. Further evidence for a carrier is that

uptake expends ATP for energy transfer, and that it plateaus with high nitrate supply. This is important because it means that no matter how favorable conditions are, nitrate uptake rates are limited. Ammonium uptake, on the other hand, appears to be passive at high external concentrations, although it may be carrier-mediated at low external concentrations. This explains why ammonium uptake is not as limited as nitrate uptake by low carbohydrate.

Feedback Inhibition of N Uptake: Because both intermediates between nitrate and amino acids (nitrite and ammonium) are toxic to plants, plants have evolved feedback mechanisms to avoid their accumulation: high concentrations of soil ammonium inhibit nitrate uptake, and accumulation of certain amino acids inhibits both nitrate uptake and nitrate reduction. Youssefi et al. (1999) proposed the amino acids glutamine, glutamate, asparagine, and alanine as the regulators. High concentrations of these amino acids in the phloem sap inhibit nitrate uptake by mRNA down-regulation of the nitrate carrier protein. Nitrate reduction may also be down-regulated, which would explain why at high concentrations of soil nitrate, more N is translocated to the leaves as nitrate, instead of first being reduced and assimilated into amino acids in the roots as is normal in most woody plants (Titus and Kang, 1982). Since all of these steps require energy and are thus limited under conditions which limit photosynthesis, it is difficult to discern which one is rate-limiting.

Demand-driven N uptake: Whether it is remobilized from storage or newly absorbed, N is allocated to those plant parts with the greatest demand for it at the time when it is available. In the spring N goes primarily to leaves and flowers; later in the season developing fruit are a dominant sink, especially in mature plants, which have low N requirements for growth. Nuts constitute an especially strong sink for N because of their high protein content. In mature walnuts (*Juglans regia* L.) Weinbaum and van Kessel (1998) found that 78% of applied N was allocated to the nuts. Youssefi et al. (2000a) found that reducing N demand by removing developing nuts reduced N uptake. Likewise, when foliar N applications eased demand, N uptake from the soil also was reduced.

Youssefi et al. (2000b) found that there was a negative correlation between N uptake and prior N status of almond trees (*Prunus dulcis* Mill.). When trees had been given a high rate of N fertilizer previously, they did not take up as much N from a pulse of ¹⁵N labeled fertilizer as trees which had been given a low rate previously. In other words, the more N-deficient the tree, the more N that was taken up from the pulse of labeled fertilizer. These studies together support the concept of demand-driven uptake.

Many fruit and nut trees are alternate bearing, which presents some unique issues for predicting N demand. Rosecrance et al. (1996, 1998) defruited half of the trees in a mature pistachio (*Pistacia vera* L.) orchard in order to establish two groups bearing nuts in alternating years from each other. They found that trees coming out of a bearing year started the next season with depleted reserves, whereas trees coming out of a non-bearing year started the following season with abundant N reserves, due to accumulation without expenditure the previous season. N-uptake in those trees with depleted reserves started earlier in the spring than it did in those trees with abundant reserves, which supports the concept of demand-driven uptake. Non-bearing trees had significantly higher leaf biomass than bearing trees (Brown et al., 1995), suggesting that they used the off year to replenish depleted carbohydrate stores as well. Over the two year cycle N uptake and N export were well matched, with little net accumulation of N. In alternate-bearing hazelnuts, Roversi and Ughini (2006) also found that leaf biomass was higher in non-bearing trees, but uptake of all nutrients was higher in bearing trees.

Internal Nitrogen Cycling

One thing which differentiates perennial plants from annuals is the ability to store nutrients from year to year, that is, to recycle them. Whereas annuals can draw only on the nutrients and carbohydrates stored in their seeds for their initial growth, established perennials have available to them stores in their roots, and in their woody biomass in the case of woody perennials. In older plants these stores may become quite large. The larger the stores, the less dependent the plant on current uptake, and the more the plant will be able to weather periods of low nutrient availability. Stored resources are especially valuable in early spring, when root uptake of N is low, because of cold soils and low root activity, because they enable perennials to leaf out quickly and take advantage of sunlight for a greater part of the year than annuals.

Autumn Storage: In the fall, leaf proteins are degraded to N-rich amino acids, primarily amino acids with 2:1 C:N ratios like arginine and asparagine, or 5:2 glutamine (Beevers, 1976). These are stored in the bark or in roots, either as these same amino acids or as proteins that are rich in them, along with other nutrients and carbohydrates. The longer and harsher the period of winter dormancy, the more likely the amino acids are stored as proteins, and the more likely that they are stored below ground in the roots, though it varies by species (Titus and Kang, 1982).

Some species of woody plants are exceedingly efficient at conserving leaf N. For example, *Juglans regia* may conserve up to 94% of leaf N (Weinbaum and Van Kessel, 1998), and *Populus deltoides*

may conserve 50 to 90% (Coleman et al, 1993). For apples, efficiencies have been measured ranging from 50 to 79% (Millard, 1996). Disruptions in the process of autumn senescence, such as damage to leaves by disease, herbivory or premature killing temperatures, can reduce the efficiency of leaf N translocation to storage at senescence but increasing N supply in the fall does not reduce storage efficiency (Millard and Neilsen, 1989). Rather, foliar N applications in the fall, using urea, can be a very efficient way of building a tree's N reserves because it takes advantage of the reabsorption of nutrients from leaves into storage (Titus and Kang, 1982).

Dong et al. (2002b) found that foliar N applied to apple trees as urea in the fall was assimilated quickly (within 48 hours) and efficiently. If it was applied in September or October, it delayed leaf senescence, which actually enhanced root N uptake, probably by enhancing carbohydrate supply to the roots. N applied in September or October was also translocated to roots for storage, with 60% efficiency, whereas if it was applied in November it was largely lost with leaf abscission, even though it had been absorbed into the leaves.

This conservation of N from year to year makes woody crops "frugal" in the words of Roversi and Ughini (2005, p. 285), who imply that European hazelnuts are even more frugal than other woody crops.

Spring Remobilization: This process is reversed at spring bud-break. The amount of N for spring shoot growth that is derived from storage ranges from 18 to 93% (Millard, 1996), varying by species, age and previous N status of plant. The lower the N status of the plant, the more that will need to be supplied from new uptake. Younger trees have had less time to accumulate storage reserves, and thus are more dependent on new uptake than older plants (Sanchez et al., 1995). Conversely, the larger the tree, the more N it has in reserve, and the less influenced it is by current uptake. In mature, full-canopied walnut trees, Weinbaum and Van Kessel (1998) found that 58% of the annual N used by the plant, both for leaves and for nuts, came from storage, with only 42% coming from new uptake. Increasing N supply to roots does not reduce remobilization of N from storage; it merely increases total growth (Millard and Neilsen, 1989).

It is only later in the season that newly-taken up N reaches shoots in quantities that rival N from storage. In California, Weinbaum and Van Kessel (1998) found that ¹⁵N applied to mature walnuts in February did not appear in leaves until April, with increasing amounts appearing in leaves through October. Some of the N remained in the root system, not to be translocated to shoots until the

second year after application. This explains why species with only one flush of growth per year frequently fail to show a growth response to N fertilization in the year of application (Beevers, 1976). One might surmise that species that continue to put out new growth through the summer, such as hybrid hazelnuts, would be able to respond within the year of application.

Remobilization versus New Uptake: There is some disagreement about the timing of the transition from reliance on remobilized N for spring leaf expansion to reliance on new uptake, which has implications for the efficacy of spring N applications. Deng et al. (1989) addressed this by monitoring the ^{15}N content in xylem sap of mature walnut trees in an orchard. They found that an abrupt decrease in the concentration of storage N in xylem sap preceded a more gradual increase in the concentration of new N, suggesting that the shift to N uptake was stimulated by the depletion of N in the sap. This occurred when N requirements for N for leaf expansion and flower development were very high, further supporting their contention that the initiation of N uptake was driven by demand for N, as opposed to an increase in N availability due to warmer soils or more active roots. Their findings suggest that N fertilization prior to when this shift occurs in the spring is likely to be ineffective.

Grasmanis and Nicholas (1971), however, found that N taken up in the spring contributed significantly to spring growth of young apple trees in sand culture. Using ^{15}N , they determined that stored reserves of N only became important when demand for new N exceeded root uptake capacity. Evidence for this was a marked increase in total plant N content in the early spring. Tagliavini et al. (1996) also found that, in one-year old pears (*Pyrus communis*) in sand culture, active root uptake commenced before remobilization of stored N was complete. They found that, although remobilization provided the majority of N for initial leaf growth, by the end of the season about half of the N content of the trees was from new uptake. The contrast between the findings reported in these two papers on young fruit trees in sand culture and those reported by Deng et al. (1989) in mature walnuts in natural soils support the contention that younger trees rely more on new uptake, and support the practice of applying N in early spring for young trees growing with limited supplies of N.

Allocation of N within Plants: The timing of N fertilization affects how N is distributed. In a 1983 review, Tromp outlines a consistent pattern: N applied in the spring is used for new growth, N applied in summer is more widely dispersed, and N applied in the fall is stored in roots. This was the pattern found by Weinbaum et al. (1984) in 17-year old almond trees in California. They applied ^{15}N at five different times and found that the labeled N moved through successive plant parts as they developed like a wave: N from early applications (March and June) appeared in leaves the year of application,

was stored in dormant twigs over the winter, and then was remobilized in the second year to support flowering, which occurs early in the spring while root uptake is still low, and nut development. N applied in August did not appear in dormant twigs sampled during December, but contributed nearly as much to blossoming as earlier applications, and contributed more than earlier applications to nut development. It is possible that this N was stored in roots instead of twigs over the winter. Finally, N applied in December was not mobilized in time for blossoming, but contributed greatly to leaf and nut development. In black walnuts (*Juglans nigra* L.) in Missouri, there were no yield differences between mid-April and mid-August N application, though nut size was higher for late summer applications (Gray and Garrett, 1999).

Olsen (1997) did a similar experiment with eleven-year old hazelnut trees in Oregon, and found a similar wave-like pattern. He found that March N applications did not appear in leaves until June, whereas fall-applied N did not show up until the following year; it stayed in the roots or bark over the dormant period and appeared in early shoot growth the following year. Even spring applied N is not all used in the season of application; a lot of it appears in the leaves that appear one year later, and some even remains in the roots a year and a half later. Nuts were a strong sink for N, with 7.4% of the N in kernels coming from fertilizer, but buds were an even stronger sink, with 10.6% coming from fertilizer. They concluded that, like for many other woody plants, initial spring growth in European hazelnuts is fueled primarily by stored N reserves.

Implications for N Application Timing: The implication of these results for timing of N applications for maximum N uptake efficiency is unclear. For the hazelnuts in Oregon (Olsen, 1997), N recovery was the same from both fall and spring applications, at about 28%. For almonds in California however (Weinbaum et al., 1984) N uptake efficiency was highest for the March applications (18–24% depending on soil type), followed by August (16%). But contrary to expectation, efficiency was not substantially lower for December (10–15%). For apples in Wisconsin, Aguirre et al. (2001) found that applications before leaf-out in May were more efficiently taken up than applications in October following harvest. Rosecrance et al. (1996) found very little N uptake in pistachios in the post-harvest period. The highest rates of N uptake in pistachios occurred during the period of nut-fill, even in alternate bearing trees in an off year. They recommend N applications during nut fill for highest recovery. Olsen's 1997 advice may be the best that we can come up with: regardless of what time of year they apply N growers should not expect quick results, but should regard them instead as building reserves for long-term crop health and longevity.

Root to Shoot Ratios

Hybrid hazelnut growers have observed that hazelnut seedlings appear to grow very little in their first season or two in the field, but in their third or fourth years they put on very rapid top growth. It is thought that during those first two years most of their growth is underground (M. Demchik, S.J. Josiah, P.A. Rutter, personal communication, 2002), and that this growth is essential for establishing the foundation for strong top growth in later years. A strong root system is thought to be what makes hybrid hazelnuts so resilient to stresses such as drought, fire, flooding, and herbivory. If this idea is true, then fertilizer recommendations need to take root growth into consideration in addition to shoot growth.

In 1922 Turner observed reduced root to shoot ratios with increased N applications in a variety of annual species, raising concerns that small root systems may reduce a plant's resilience to stresses such as drought, soil-borne diseases, and herbivory. Graca and Hamilton (1981) observed that high levels of N slightly reduced root length of *Cotoneaster divaricata* grown in pots fitted with observation windows. Seith et al. (1996) noted that the roots of Norway spruce (*Picea abies*) grown under high N conditions were shorter and thicker, and had fewer root hairs. They were also less colonized by ectomycorrhizae, which has implications for uptake of other nutrients, such as P. They and other foresters (Huttl, 1990; Mohren et al., 1986); blame recent forest decline in Europe in part on increased atmospheric N deposition which has reduced root growth and led to increased P deficiency.

It is not entirely clear whether N actually inhibits root growth, or whether the reduced root:shoot ratios are merely due to stimulation of shoot growth without accompanying root growth. Ericsson (1995) and Andrews et al. (1999) suggest that it is more of the latter. They argue that N increases photosynthetic rates, which allows more translocation of N to shoots, which in turn fuels more leaf growth and higher photosynthesis. The implications are that in the long run overall growth is better with N, because more photosynthates are eventually translocated to the roots as well.

Conversely, with limited N, shoot growth is more limited than root growth, because roots require less N than leaves, so surplus photosynthate is sent to the roots where it is either stored, or used to build more roots, which in turn enhances N uptake, thereby easing the N limitation. Bloom et al., (1985) give an economic analogy to explain plant resource allocation: They "adjust allocation so that their growth is equally limited by all resources." Thus, if nutrients or moisture are most limiting, root growth is most productive; if light is most limiting, leaf or stem growth may be most productive, but only if this

growth investment is successful in attaining the resource sought. Thus, in N deficient conditions alternation in allocation between leaves and roots may allow growth to continue, albeit at a lower level than in high N conditions (Millard and Neilsen, 1989). This kind of alternation of root and shoot growth was observed in Turkish hazelnuts (*Corylus colurna*) by Harris et al. (1995).

P is commonly believed to stimulate root growth. Thus it is thought that supplemental P may ameliorate shoot-root imbalances induced by high N. However, confirmation of this is lacking in the literature. Quite to the contrary, effect of P appears to be the same as the effect of N: high P increases shoot:root ratios; low P decreases the ratio. (Mengel and Kirkby, 1987; Ericsson, 1995; Zhengquan et al., 1999).

Root:shoot ratios may also be affected by competition with other vegetation. DeMontard et al. (1999) found that European hazelnuts intercropped with orchard grass developed higher root:shoot ratios than sole-cropped hazelnuts, enabling them to cope with competition from the grass for soil moisture and nutrients. This will be discussed in further detail in the section on vegetation management below.

General Overview of Hazelnut Nutrition

Nitrogen—a historical perspective: Response to N fertilization is high for all nut crops, for which N is the most commonly deficient nutrient (Proebsting and Serr, 1954). This should be of no surprise given the high protein content of nut kernels. Hazelnuts are no exception. Nitrogen is important both for growth of young plantings and for sustained nut production. The first reports on the importance of N for hazelnuts were by Schuster and Stephenson in 1947. They found that N and P fertilization increased nut yields and profitability, though they did not distinguish between the effects of N and P. The role of N specifically was shown by Painter in the 1950s. In four mature orchards, he found that shoot length, yield, nut size, and percentage nut filling all increased with N application, while % unfilled nuts decreased (Painter, 1951, 1952, 1953, 1955; Painter and Hammar, 1962). Around the same time, however, Crane and McKay (1951, 1995) found no growth rate effects due to N, P and K fertilization, either alone or in combination, in two studies on new plantings of hazelnuts. Instead, they found that N and K increased leaf scorch and mortality, especially in a drought year, whereas P and Mg reduced it. They concluded that it is essential to apply a balance of fertilizers.

Nitrogen—the current perspective: Nitrogen is still considered the nutrient most likely to be deficient, and thus receives the most attention in the Nutrient Management Guide for Hazelnuts in

Oregon (Olsen, 2001a). Current recommendations are to apply no N until two growing seasons have passed since transplanting and then to increase rates with age of plant as follows: 22–29 kg·ha⁻¹ for trees two to five years of age, 29-45 kg·ha⁻¹ for six to seven year-olds, and 45-67 kg·ha⁻¹ for eight to ten year-olds. For mature hazelnuts, N recommendations are based on leaf N as follows: apply no N if leaf N exceeds 2.5%; up to 0.68 kg·plant⁻¹ if leaf N is 2.2-2.5% (optimal); up to 1.36 kg if it is 1.8 - 2.2% (moderately deficient); and 1.36 kg if it is less than 1.8% (severely deficient). From an environmental and nut quality perspective, however, these rates may be too high (A. N. Azarenko, personal communication, 2007). This should be apparent by comparing them with rates that would be needed to replace the N removed in nut harvest: hazelnut shells and kernels are 15% N (Chaplin and Dixon, 1979), so a typical nut harvest of 1.5 kg plant⁻¹ yr⁻¹ would remove only 0.23 kg N plant⁻¹ yr⁻¹. In Italy, Roversi and Ughini (2005) calculated annual N exports from mature hazelnuts to be even less: the sum of N exported in nuts, husks, prunings and leaf drop was only 0.10 to 0.15 kg·plant⁻¹ yr⁻¹.

Other nutrients: Potassium is the second most commonly deficient nutrient in nut crops, though it is generally considered to be important more for maintenance of nut yield and quality than for bush growth (Proebsting and Serr, 1954). This is because the K content of nuts is very high and thus much K is removed with harvest (Crane and McKay, 1955). Painter and Hammar (1963) found that K applications consistently increased hazelnut yield and reduced % blanks, but only inconsistently improved the various components of nut quality. Deficiency symptoms include leaf chlorosis, scorch of leaf margins and tips, and shoot die-back (Proebsting and Serr, 1954), and are most likely to occur when leaf K is lower than 0.8 % (Chaplin and Dixon, 1976).

Olsen (2001a) states that K deficiency is common in Oregon hazelnut orchards, and offers recommendations for K fertilization based on leaf analysis. Growers have to choose between highly soluble K forms, such as KCl, which may burn plants due to chloride toxicity, and less-soluble forms such as K₂SO₄ which are only slowly mobile in the soil. Compounding this, hazelnuts seem to have a poor ability to absorb K from the soil (Kowalenko and Kemplar, 2001). This explains why it took five years of K fertilization before Painter and Hammar (1962) observed increased K in leaves, even in a severely deficient orchard. The low mobility of K in soil is why incorporating K into the soil before planting, according to soil tests, is recommended for all woody crops (Rosen et al., 1998). An alternative is foliar sprays, though only a small amount of K can be absorbed by leaves in each application, so repetitive sprays are needed.

Phosphorus response in any nut species is rare, though not unknown (Proebsting and Serr, 1954). No P is recommended for hazelnuts in Oregon (Olsen, 2001a), except as a starter if soil P is extremely low (Kowalenko, 1996). As with K, the poor mobility of P in the soil is a problem, so incorporating P into the soil before planting according to soil tests is recommended (Rosen et al., 1998).

The calcium requirements of hazelnuts do not seem to be high. Inadequate Ca is only likely to be a problem on low pH soils, in which case liming should solve the problem (Kowalenko, 1996).

Inhibition of Mg uptake with increasing levels of K fertilization has been observed in many plant species (Mengel and Kirkby, 1987). Crane and McKay (1951, 1955) blamed an imbalance between Mg and K for the increased leaf scorch and winter injury they observed in young orchards to which K had been applied. No researchers have reported yield responses to Mg fertilization. Thus Kowalenko (1996) concluded that Mg has more influence on long term plant health and vigor than on immediate yield. Kowalenko and Kemplar (2001) suggested that hazelnuts have a limited ability to take up Mg, and thus that they require more extractable Mg than most other crops. Olsen (2001a) recommends incorporating Mg into the soil at planting if soil test Mg is less than 0.5 me 100g⁻¹, especially if the soil is high in K and Ca. If lime is required, using dolomitic lime will suffice.

Many researchers have reported exceptionally high concentrations of Mn in hazelnut leaves, concentrations that would be toxic in other species (Alkoshab et al., 1988; P.A. Rutter, personal communication, 2002). Typical concentrations of leaf Mn range between 25 and 500 mg·kg⁻¹ (ppm) for production varieties of European hazelnuts, but may be up to 1000 ppm for the ornamental *C. avellana* 'Contorta', and up to 1894 ppm in wild *C. americana* (Mills and Jones, 1996). This compares to typical ranges of 10 to 500 ppm for most other kinds of plants, including most other fruit and nut crops. However, concentrations may be much higher in forest trees and shrubs, up to 5545 ppm in winterberry (*Ilex verticillata*). In domesticated European hazelnuts, Chaplin and Dixon (1979), Kowalenko and Mass (1982a), and Silberman (1983) reported increased concentrations of Mn in response to N fertilization, probably due to the lowering of soil pH and consequent increase in soil extractable Mn. Most authors have concluded that hazelnuts simply have an unusually high rate of Mn uptake and Mn tolerance, and thus it should not be a concern. Indeed, Silberman found no symptoms of Mn toxicity at 1300 ppm Mn, only slight symptoms at 1800 ppm, and severe symptoms at 3700 ppm.

The value of boron sprays on hazelnuts is the subject of much discussion. Research in Oregon (Shrestha et al., 1987; Solar and Stampar, 2001) has found that low rates of foliar and soil-applied B improves hazelnut yields by enhancing nut set at flowering. In the Mediterranean, Ferran et al. (1997) and Borges et al. (2001) found no benefit to B. One explanation for the difference is different cultivars. Another is that B plays a role in nut set under cool spring conditions: Pacific Northwest springs are cool and moist, whereas Mediterranean springs are warmer. This suggests that B would be helpful in Minnesota, where springs are cool.

Soil type: Hazelnuts tolerate a wide range of soils, but prefer lighter ones, according to Farris (2000). Rutter and Shepard (2002) have not yet found a soil on which hazelnuts cannot thrive, from heavy clay to sand, with the exception of compacted soils, which they cannot tolerate. This is consistent with Schuster and Stephenson's 1947 report that hazelnut roots will not grow into a waterlogged soil; hazels grown in areas with a high water table suffer from symptoms similar to drought symptoms.

Soil pH: There is a general agreement that hazelnuts prefer acidic soils. Rutter and Shepard (2002) have observed them doing well on soils from pH 7.0 down to 5.0. 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. However, these soils in Turkey had relatively high organic matter (4-6%), which may have helped buffer the harmful effects of low pH. Silberman (1983) reports that N, K and Ca uptake increase with liming, which also reduces Al uptake, but that liming is probably only cost effective up to pH 5.6 or 5.8. Olsen (2001a) recommends liming only if pH is below 5.6. Nitrogen fertilizers containing ammonium, including ammonium nitrate, tend to lower soil pH, with potentially adverse effects on crop response, as well as on uptake of other nutrients.

Nitrogen Overfertilization of Woody Crops

In recent decades there has been increasing awareness and concern about the problem of overfertilization, particularly of N. This makes it critically important to formulate N recommendations specifically for hybrid hazelnuts in the Upper Midwest, instead of simply adopting the recommendations for European hazelnuts in Oregon.

Weinbaum et al. (1992) state that, under current production practices, orchard crops have the worst record of any commercial crop for the lack of efficiency of nitrogen use. Estimates are that on average fruit orchards take up less than 20% of the nitrogen applied to them. This is compared with

37% nitrogen use efficiency (NUE) for grapes (*Vitis vinifera* L.), about 50% for vegetables, about 55% for row crops, and over 70% for forages (Weinbaum et al., 1992). Table 1 lists values of NUE found for various woody crops under a variety of conditions.

When only 20% of N applied to orchards is taken up, the unused 80% potentially becomes a pollutant, which causes eutrophication of rivers, lakes and oceans (D'Angelo and Reddy, 1993) and contaminates drinking water supplies, which is harmful for human health (Bruning-Fann and Kaneene, 1993). Some N may be lost to the atmosphere either through ammonium volatilization, which contributes to acid rain (ApSimon et al., 1987) and the decline of N sensitive ecosystems (Huttl, 1990; Mohren et al., 1986), or through denitrification, which may produce greenhouse gases (Schlesinger, 1997).

Besides these environmental problems, Weinbaum et al. (1992) state that N overfertilization may lead to production problems. First, N applied to young transplants may burn roots and retard growth as warned against by Baron and Stebbins in their 1981 bulletin for European hazelnuts. Negative responses to N may also be observed if it exacerbates other limitations (Ponder, 1997). Second, excess N increases susceptibility to insects and diseases. Third, in fruit production there is a fine line between not enough N and too much N, for although N may increase fruit yield and fruit size, it is often at the expense of fruit quality. In nuts, N often increases yield by increasing nut number, but it is often at the expense of nut size and nut fill (Sparks, 1987). This is because N increases nut set without proportionately increasing the leaf area required to fill those nuts. In pecans (*Carya illinoensis*), leaf area is more often limited by moisture than by N, so Sparks recommends that growers prioritize irrigation over fertilization. In addition to reduced nut size, excess N can increase the proportion of nuts with adhering husks in pecan (Worley, 1990).

Weinbaum et al. (1992) explain why overfertilization of woody crops is so common. In all crops, NUE is highest when N applications are most closely matched with the N requirements of the crop at the time of application; that is, NUE is highest when N supply matches demand. For annual crops, N budgets have been developed to help growers predict demand. Overfertilization in annual crops is often a result of failure to account for non-fertilizer sources of N, such as N contributed by leguminous intercrops and weeds, N added in irrigation water, or N released by mineralization of soil organic matter, crop residues, or organic mulches. In woody crops, not only must all of these non-fertilizer sources of N be considered, but the N recycled within the plant from year to year must also be accounted for. In woody crops, much N is hidden in the roots and wood, and is moved around as

needed within the plant, making it very difficult to evaluate the N status of the plant. Although leaf analysis can be helpful, it is not ideal because N is moved around between woody tissues and leaves. In a sense, woody plants are N-buffered. The only definitive way of evaluating the N status of woody plants is to harvest the whole plant, but this would be destructive. In conclusion, nitrogen cycling helps to explain why many researchers have observed that N fertilization of woody crops may produce responses that are positive, negative or no responses at all (Crane and McKay, 1951 and 1955) in hazelnuts; Ponder, 1997, in black walnuts).

Weinbaum et al. (1992) further explain that much overapplication of N is due to poor application methods: growers interpret lack of response to fertilization as a sign that more is needed, when really the problem is that a low proportion of what is applied is being taken up by the plant due to low uptake efficiency. Their misperception is reinforced when additional fertilization ultimately produces the response they are looking for. A better solution is to improve application methods. More efficient methods of application will be discussed later in this review, but first we will discuss how better to match applications with crop demand, which is the most important way to improve uptake efficiency. Weinbaum et al. (1992) assert that it is unlikely that accurate N budgets will ever be developed for orchard crops, but they are a start. Soil and leaf analysis are two other tools that can help.

Tools for Formulating Fertilizer Recommendations to Improve NUE

Soil Analysis

Soil sampling is the best tool for making fertilizer recommendations for annual crops but is not so useful for woody crops in which, as Sparks (1977, p. 26) explains, “performance is neither consistently nor highly correlated with soil analysis.” Thus leaf analysis is the preferred tool for woody crops, though leaf analysis is not highly correlated with soil analysis either. One reason for the lack of correlation between soil test results and plant response is the instability of inorganic soil N, which is influenced by variable rates of mineralization of soil organic matter, nitrification of ammonium to nitrate, nitrate leaching, ammonia volatilization, denitrification and microbial immobilization. Although these uncertainties factor in to calculations for annual crops too, perennial crops are present for such longer periods of time, capable of nutrient uptake through much of the year, that soil samples collected just once a year cannot capture what happens for the entire year.

Another reason for the inadequacy of soil samples for woody crops is the mismatch between where feeder roots are distributed and where soil samples are taken. Unlike annuals, which must grow

entirely new root systems each year, woody perennials may, over the years, develop very deep root systems, much deeper than the 0-15 cm depth from which soil samples are typically collected (Worley et al., 1972). The root systems of hybrid hazelnuts in Minnesota may go as deep as 2.8 m (personal observation), but it is not definitively known at what depth hazelnut roots take up most nutrients. Kowalenko (1984) suggests that they take up K from the surface 0-15 cm, P from below 15 cm, and N and Mg from all soil depth increments. However, he concluded that sampling from the surface 15 cm should be sufficient for making recommendations; if there are concerns about nitrate leaching then 0 to 60 cm would be better.

Kowalenko (1984) recommends collecting soil samples in the summer, at the same time as collecting leaf samples, as a complement to them. Soil samples are still important to distinguish between causes of low leaf nutrients. In cases where concentrations of leaf nutrients are low while soil concentrations are adequate, it indicates problems with either nutrient availability or with plant uptake; in either case application of the nutrient in question would be a waste of money (Miletic and Maric, 2001).

Soil tests are also important in establishing new plantings of any kind of woody crop, especially for nutrients which are relatively immobile in the soil, like P, K, and Mg, which are best brought up to moderate levels by incorporation in the soil before planting. Ponder (1997) concluded that, "Fertilization will produce very limited favorable results on unfavorable sites for the species; neither is additional growth (with fertilization) likely on sites where trees are already growing well." Soil testing can help identify the few sites in between where nutrient supply is the only limitation for growth. For all the others, Ponder recommends focusing on cultural practices, such as adequate weed control and moisture, first.

Leaf Analysis

Leaf analysis is more useful than soil analysis for woody plants because leaves, which are the sites of highest metabolic activity in a plant, are very responsive to changes in nutrient supply. Thus, leaf nutrient concentrations are an accurate indicator of how much of a nutrient is actually available to a plant, regardless of how much is present in the soil (Sparks, 1977). Recommended application rates for a nutrient are inversely related to concentrations of that nutrient in the leaves, such as given by Olsen in his 2001 Nutrient Management Guide for Hazelnuts in Oregon. But first, a specific protocol must be followed in collecting leaf samples.

First, leaf nutrient concentrations vary with age of leaf, position on stem, and exposure to sunlight, especially leaf N. That is because plants maximize photosynthesis by continuously redistributing N, which is an essential component of the photosynthetic apparatus, from newly shaded leaves to full sun leaves (DeJong and Doyle, 1985). Thus it is important to collect leaves for analysis from standard positions on each plant. For hazelnuts, the third fully expanded leaf from the apex of a full sun shoot is collected.

Second, leaf nutrient concentrations also vary through the growing season and thus a standard sampling time is usually designated. Nitrogen is generally very high early in the season, when it is needed for rapid growth, and declines due to dilution by carbon compounds as the season progresses. Canali et al. (2005) found that hazelnut leaf concentrations of N, P, K and Mg were highest just before kernels started to widen. The best time to sample is when N has stabilized, after most shoot growth is complete, but before leaves begin to senesce. Kowalenko and Mass (1982b) established that mid-August through early September is the best time for sampling hazelnuts in the Pacific Northwest. In Minnesota, where leaves may begin to show signs of senescence as early as August, an earlier date might be better, as was found for saskatoons in the Prairie Provinces of Canada (Zatylny and St-Pierre, 2006a), in which leaf nutrient concentrations stabilized between late July and mid-August.

Temporal variability may also occur over years. Sentis et al. (2005) found that concentrations of leaf nutrients, including N, were slightly lower in years with high yield, but returned to normal levels in subsequent years. This suggests that developing nuts were strong competitors with leaves for nutrients. It also suggests that low leaf analysis in high yielding years should not be a cause for alarm.

Development of Standard Ranges: Interpreting leaf nutrient concentrations requires comparing them with established standards for that species. Chaplin and Dixon (1979) developed the standards for leaf N of European hazelnuts. Starting with a 30-year old hazelnut orchard that showed visual signs of N deficiency in their leaves, but had adequate concentrations of all other nutrients, they applied N at four rates. Leaf N was linearly or quadratically related to applied N in all six years of the study. Nut yields rose with leaf N up until 2.2%, leveled off, then declined above 2.5%. Below 2.0% N there were visible signs of N deficiency in the leaves. This research established 2.2 to 2.5% as the optimum concentrations for leaf N in hazelnuts. These are the figures still used to make N recommendations for mature hazelnuts in Oregon today (Olsen, 2001a).

Translating target leaf N concentrations into N fertilizer recommendations requires fertilizer response curves, such as developed by Chaplin and Dixon (1979), combined with information about the price of fertilizer and the expected long-term return on the crop. Sometimes a lower fertilizer rate is more profitable. For example, Chaplin and Dixon (1979) found that although their high fertilizer rates increased leaf N to the target concentration within a few years, these rates were not profitable, whereas at their lowest rate, the target was also reached, just slower and more profitably. Likewise, Kowalenko (1996) 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. He thus suggested that the 2.2% N threshold between deficiency and sufficiency be regarded as a goal to be attained rather than to be exceeded. With this reinterpretation, the finding that 44% of hazelnut orchards in Oregon tested below 2.2% leaf N (Olsen, 1997) should not be so alarming; only the 5% testing below 1.8% would be considered to be a serious problem.

Standard ranges for other nutrients besides N were developed by Kowalenko (1984), building on Chaplin and Dixon's work. In a three year survey of seventeen orchards, of diverse ages and management practices, he found consistent correlations between leaf concentrations of N and S, S and Cu, and Cu and Zn. Assuming Chaplin and Dixon's base of 2.2% N to be optimum, he used these ratios to derive optimum concentrations for S, Cu, and Zn. He also found consistent correlations between K and Ca, Ca and Mg, and Mg and K. Assuming an optimum of 0.8% for leaf K, he used these ratios to derive optimum concentrations for Ca and Mg. Attempts to determine the optimal concentration of leaf K definitively, by means of a K response curve, have not been as successful as for determining the N optimum (Kowalenko, 1984), so the concentration adopted in Baron and Stebbin's 1981 bulletin, 0.8% K is still the standard.

Interactions: The effect of soil nutrient applications on leaf nutrient concentrations and their interactions is complex. Applications of some nutrients have been observed to influence leaf concentrations of other nutrients in a wide range of plants. In some cases these effects are due to direct competition between soil ions for sites on the root uptake mechanisms. For example, excessive ammonium may inhibit uptake of other cations such as K^+ , Ca^{2+} and Mg^{2+} and vice versa (Haynes, 1986). In other cases apparent suppression of uptake of some nutrients by others is merely a dilution/concentration effect. Krauss foliar vector diagnosis, as described by Black (1993) describes an array of these kinds of responses. For example, a decline in concentrations of other nutrients in

response to N application may actually be due to dilution of those nutrients in leaves stimulated to grow larger by the additional N. The total amount of those nutrients in the whole plant may be the same, just it is spread out over larger leaves. Conversely, deficiency of some nutrients may result in concentration of others as plant growth is inhibited. Nutrients which stimulate root growth may enhance the uptake of other nutrients. Fertilizers with an acid reaction in the soil, such as ammoniacal forms of N, may make some potentially toxic elements like Mn, Fe and Al more available (Chaplin and Dixon, 1979; Kowalenko and Mass, 1982a; Silberman, 1983; Mills and Jones, 1996).

In hazelnuts, Painter and Hammar (1962) found that N significantly reduced leaf concentrations of K, Mg, B, and P in some years, and K reduced Mg and B in some orchards. Crane and McKay (1951, 1955) found that N and K negatively influenced the concentrations of Mg and P. But Painter and Hammar (1963) also found that K applications increase leaf concentrations of N, Mg, Ca, and Mn. Kowalenko and Maas (1982a) found yet different interactions, none of which had any effect on yield.

For these reasons, leaf nutrient concentrations should not be considered alone in making nutrient recommendations. Plant vigor, leaf color and size, growth and yield all need to be considered together. Sanchez et al. (1995) advise that if growth is vigorous N is probably not needed, regardless of leaf N, but if growth is poor additional N will help only if leaf N is also low. Leaf size is an especially good indicator of N sufficiency: most woody plants (Ran et al., 1994) and many herbaceous ones too (Vos and van der Putten, 1998), maximize photosynthesis by using additional N to increase leaf growth while keeping N per unit leaf area, that is, N concentration, relatively constant.

The Diagnosis and Recommendation Integrated System: A major problem with diagnosing deficiencies and excesses based on how well leaf concentrations match a supposed sufficiency range, is that it is not always clear whether a relative deficiency or the accompanying relative excess is the major problem. (Alkoshab et al., 1988). The Diagnosis and Recommendation Integrated System (DRIS) is intended to overcome this problem. It bases diagnoses of deficiencies and excesses on relative concentration of nutrients (ratios) rather than on the absolute values of a sufficiency range. This minimizes misinterpretation of concentrations that seem low due to dilution (because of other nutrients that are in oversupply) or that seem high due to concentration (because of growth limitation by deficiencies of other nutrients).

Alkoshab et al. (1988) question the value of the hazelnut sufficiency range for N between 2.2 and 2.4 % because it was based on research (Chaplin and Dixon, 1979) in which the correlation between leaf

N concentration and yield was only $R^2 = 0.20$. They assert that this poor correlation may be due to N fertilizer-induced deficiencies or imbalances of other nutrients. To evaluate the potential of DRIS as an alternative method for judging the nutritional status of hazelnuts, they compared the leaf nutrient ratios found in the highest 15% of hazelnuts grown at various Oregon locations with the ratios found in the lowest 15%. If they were statistically different by both of two different methods of calculation, then the ratios found in the highest yielding plants were considered to be the optimal ones. Their DRIS norms for hazelnuts appear in Beverly's 1991 book "A practical guide to the diagnosis and recommendation integrated system (DRIS)". Righetti et al. (1988) used DRIS to identify deficiencies of P, K, Mn, Fe, Cu, and Zn in some Oregon orchards. Excessive concentrations of N, P, K, Mn, Fe, and Cu were found in other orchards. This is significant because some of these deficiencies and excesses had not been diagnosed in hazelnuts before. The authors concluded that although DRIS is a very useful diagnostic approach, it will not detect all deficiencies or excesses. DRIS serves best as a supplement to sufficiency range based interpretation; providing additional information when severe imbalances exist.

Systems for Determining N Fertilization Rates

Applying by Leaf N Thresholds

Worley (1990) proposed a system for prescribing N applications for pecans based on leaf N thresholds. He compared the standard fertilization practice of applying $224 \text{ kg}\cdot\text{ha}^{-1}$ of N annually, with applying half that amount only when leaf N fell below a range of thresholds. He found that growth and nut yield with the half rate applied using a threshold of 2.75 % leaf N were similar to those with the full rate applied annually, and that the higher rate reduced nut size. Moreover, no N application was necessary to meet the 2.75% threshold in some years. Between fertilizer savings and the price premium offered for larger nuts, the economics strongly favored using the threshold.

Basing N Rates on Size of Plant

Many researchers have found that young plantings of woody crops do not respond to N fertilizer. This was found by Proebsting and Serr (1954) for hazelnuts, Sadowski and Jadczyk (2001) for sour cherries (*Prunus cerasus*), in which N responses were only observed starting four years after planting, and Wrona (2006) for apples. Wrona asserts that this is because their N requirements were low enough to be met by the soil. The estimates of Neilsen et al. (2001) that N uptake by three year old apple trees is only $5 \text{ g}\cdot\text{tree}^{-1}\cdot\text{yr}^{-1}$ supports this explanation. Zatylny and St-Pierre (2006b) found that N uptake by young potted saskatoons (*Amelanchier alnifolia*) doubled between their first and

second years, but so did plant biomass. Thus N uptake per unit plant biomass was constant for the two years. Also, N uptake is proportional to root volume, as found by Ran et al. (1994) in almonds. These results are the basis for recommendations commonly seen for woody crops, including for hazelnuts, to increase N application rates with seedling age (Sanchez et al., 1995; Olsen, 2001a).

New plantings: Applying N to new hazelnut transplants is not recommended until one or two growing seasons after planting (Baron and Stebbins, 1981; Olsen, 2001a) not just because N requirements of new transplants is small enough to be met by the soil, but because N at planting time may burn young roots and retard growth. Scorch and winter injury observed by Crane and McKay (1951, 1955) was attributed to applying N before the trees were established. However, neither Farris (2000) nor Rutter and Shepard (2002) mentioned any concern about possible fertilizer burn at planting. Farris watered his seedbeds with 30-20-18 twice a week, with no apparent problem. Rutter and Shepard recommend applying 10-10-10 at or soon after planting. Neither specified concentrations. Presumably they either used very low concentrations, or applied it in such a manner that most of the N did not reach the roots.

Basing N Rates on Crop N Removal

Another approach for improving NUE is to apply N based on anticipated N removal by harvest and pruning. Table 2 gives estimates for crop N removal by various crops. Tous et al. (2005) found that applying N at a rate that matches estimates of hazelnut crop N removal by mature trees in Italy (50 kg N·ha⁻¹, Roversi and Ughini, 2005), hazelnut yields were maintained as well as when higher rates were applied, without reducing leaf N below sufficiency thresholds. Tagliavini et al. (1996) proposed basing N recommendations for orchard crops on N removal, but reminded us that soil inorganic N should be subtracted from recommendations to avoid overapplication. They recommended soil sampling three times a year to account for seasonal fluctuations in soil N availability.

Weinbaum et al. (1987) used labeled N to determine “percent annual depletion” of N from the storage pool, an amount that corresponded with the annual influx from the soil pool. By this method they calculated that in heavily bearing almonds as much as 50% of the N content of the tree may be exported every year with the crop, and must be replaced in order to maintain a constant N content in the plant. This also means that 50% of the N is carried over from year to year, as compared to 0% in annual plants. They suggested fertilizing at rates to replace annual depletion, plus a little more to account for uptake inefficiency.

Other Methods of Improving NUE

Appropriate Timing

One of the most important methods of improving NUE is to apply N when plants are actively growing and thus able to take it up and assimilate it. Weinbaum et al. (1992) and Sanchez et al. (1995) specifically stated that winter, when roots are inactive and when soil conditions are frequently optimal for N leaching and denitrification, is the worst time to apply N (Weinbaum et al., 1992; Sanchez et al., 1995, Kowalenko, 1996). Although some N uptake has been found to occur during the dormant period (Weinbaum et al., 1984, Table 1), it is generally accepted that the efficiency of N uptake declines after leaf senescence (Aguirre et al., 2001). Conversely, the best time to apply N appears to be when plants are fully leafed out and actively growing (Grasmanis and Nicholas, 1971; Weinbaum et al., 1978; Titus and Kang, 1982, Munoz, 1998), both because of the link between photosynthesis and N metabolism and because of high demand for N for developing leaves and fruit at this time. But what is the best time between spring leaf-out and autumn leaf drop?

In the Upper Midwest, the traditionally recommended time to apply N to woody crops is early spring, (Rosen et al, 1998; Rosen and Eliason, 2005). Yet theoretically uptake efficiency should be low then, due to cold wet soil, inactive roots, and lack of substantial photosynthetic tissue. Moreover, it may be a problematic time for growers because of other work demands and because the soil is frequently too wet for them to get into the fields.

On the other end of the season, many growers believe that late summer and early fall applications stimulate late season shoot growth and delay stem hardening, leading to winter damage. Baron and Stebbins' 1981 extension bulletin for Oregon hazelnut growers warned about this, although, in a review of the literature on a wide range of woody plants, Pellet and Carter (1981) showed that this is only true if N concentrations in plants are excessive. If plants are N deficient, late applications may actually help prevent winter damage because some cryoprotectant compounds contain N. However, applications pushed too late into the fall risk not being taken up before root activity starts to slow and leaching conditions start to develop.

On the other hand, post-harvest foliar sprays of urea may be an effective way to build N reserves (Olsen et al., 2001b). Nitrogen applied just before leaves began to translocate nutrients into bark for winter storage, were partitioned to storage in buds and 1 yr old woody tissue, where it could easily be accessed to fuel bud break the following spring. Olsen suggested that foliar sprays may be an

efficient way to supplement ground applications of N in years of high demand due to heavy nut load. But, because large quantities of N cannot be delivered in foliar sprays, they are unlikely to be able to completely replace ground applications.

We do not know the seasonal pattern of root growth of hybrid hazelnuts, but in Turkish tree hazel, *C. colurna*, root growth is strongly concentrated in the early summer, with only a little in the fall, as discovered by Harris et al. (1995), using mini-rhizotrons. Assuming that hybrid hazelnuts are similar, then early summer or soon after might be a good time for ground application of N. However, Rosecrance et al. (1996) found that in pistachios, which have high root growth in the fall, N uptake was not correlated with root growth. It may be that carbohydrates translocated from senescing leaves are used for root growth, but there is not enough to also supply N uptake.

Putting this all together, it is likely that the summer is the best time to apply N, assuming that soil moisture is adequate. Good weed control could alleviate the problem of N stimulation of weeds, which results in increased competition for soil moisture.

Sanchez et al. (1995) state that orchard managers can control the partitioning of N to different plant parts by altering N application timing. N is usually allocated quickly to those plant parts with the highest demand at the time of application. Thus N applied during nut fill, or shortly before, would likely contribute to nut sizing, as found in black walnuts by Gray and Garrett (1999), while avoiding the problem of excessive nut set, which leads to blanks, that may result from applications before flowering. This hypothesis needs to be researched.

Appropriate Application Methods—Placement and Type

Another important way of improving N uptake efficiency is to place fertilizer where the crop roots are located. The recommendation for woody crops is usually to band it along the drip line, where roots are assumed to be concentrated (Weinbaum et al. 1992).

Foliar applications can also be considered a method of targeted fertilizer placement. Foliar sprays are an effective way of getting N to flower buds, to increase fruit set (Sanchez et al., 1995). Lovatt (1999) found that foliar urea applied at critical times in fruit set and fruit development of orange (*Citrus sinensis*) and avocado (*Persea americana*) increased both yield and fruit size. In hazelnuts, foliar sprays at flowering may be especially valuable for boron, because of its specific role in pollination nut set (Shrestha et al., 1987). Weinbaum et al. (1992) state that, although only small amounts of

nutrients can be taken up through leaf cuticles, leaf N applications may supplement soil applications and thus allow for the reduction of soil application rates.

Split applications are another method of improving NUE. Because N uptake is a rate-limited process, it stands to reason that plants can only take up a finite amount at a time, and repeated smaller doses will be more efficiently utilized (Weinbaum et al., 1992)

Fertigation, putting fertilizer in drip irrigation, can be considered to be a method that combines the benefits of split applications with targeted placement. Alva et al. (2003) found that fertilizing oranges with very low concentrations of N in drip irrigation lines, fifteen times per year, improved NUE in oranges relative broadcast applications of a granular fertilizer split between four applications (Table 1).

NUE can also be improved by using other N-forms besides urea, from which N may be lost by ammonia volatilization (Mattos et al., 2003, Table 1). If urea must be used, volatilization losses can be reduced by incorporating it, though that may be difficult in perennial crops; fertigation is a better alternative.

Finally, some of the best improvements of NUE come with use of controlled release fertilizers (Alva et al., 2003). Hangs et al. (2003) found that N uptake from controlled release fertilizer bags buried in the planting holes of spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) seedlings was extremely efficient. These bags were made of standard tea-bag paper and contained polyurethane-coated controlled release urea. Using ^{15}N , they determined that although only 42% of applied N had been taken up by the trees after one season, the remaining N was still present in the bags for future uptake (Table 1). After the second season, 77% of applied N had been taken up, with over 90% of the N still accounted for. That is, 13% was still in the bags, available for uptake, whereas only 10% had been lost from the system. The high efficiency of this system was attributed not just to the controlled release fertilizer, but also to the use of a “point-source” delivery method which minimized losses to competing vegetation and leaching. It is also worth noting that by this method the exceedingly low N rates of $1 \text{ g} \cdot \text{tree}^{-1}$ or $6 \text{ kg} \cdot \text{ha}^{-1}$, were effective at supplying the N needed by the seedlings.

Management Systems for Hybrid Hazelnuts—Implications for N Fertilization

Part of our rationale for believing that research on the N requirements of hybrid hazelnuts in the Upper Midwest is needed is that, not only are they a different plant than grown commercially in other

parts of the world, and not only are the soils and climate in the Upper Midwest different, but we are growing them in a different system than the intensely managed orchards of the Pacific Northwest, the system advocated by Rutter and Shepard (2002). The two major differences between the system most commonly used for hazelnuts in the Upper Midwest and the intensely managed orchard system in the Pacific Northwest are that:

- 1) Hybrid hazelnuts are grown as bushes in closely spaced hedgerows, similar to how they are grown in Europe (Me et al., 2001), instead of pruning them as trees that are planted on a well-spaced grid, as they are grown in the Pacific Northwest. A common spacing is 1.5 m within row, 4.5 m between rows, for a plant population of 1481 bushes·ha⁻¹, as compared with populations of 178 to 494 trees·ha⁻¹ in orchards in Oregon (S.A. Mehlenbacher, personal communication).
- 2) Other vegetation is not controlled closely, except perhaps during the establishment phase, because other vegetation helps conserve soil and provide for a more complex ecosystem that is more resilient against pests. Other reasons for not controlling weeds include that they protect young hazelnuts seedlings from drying winds and they hide them from some kinds of herbivores (Rutter, personal communication).

Bushes in Hedgerows vs Trees in Orchards: Lagerstedt and Painter (1968) compared hazels grown on 4.5 X 4.5 m, 6 X 6 m, and 7.5 X 7.5 m spacing, and found that for a young orchard, which had not yet closed canopy, nut yield increased with increasing plant density. However, Kempler et al. (1994), found that yield reductions due to shading became evident in closer-spaced orchards in as little as five or six years. Pruning to open the canopy was found to be helpful. Lagerstedt and Painter (1973) found that, although European hazelnuts grown as bushes produced slightly fewer nuts than those grown as trees, probably due to shading of fruiting wood in the bushes, the yield advantage of growing them as trees may not sufficiently compensate for the additional costs of pruning required to keep them from reverting to bush form. In addition, they found, the bush form is more resilient in high winds and under heavy snow or ice. They suggested that the advantages of improved microclimate within closer-spaced orchards, even orchards managed as hedgerows as advocated by Rutter and Shepard (2002), may offset the disadvantages of light competition. Rutter and Shepard point out that managing hazels as trees, with the closely-cropped grass orchard floor required for that system of mechanical harvest, would largely negate most of the conservation benefits of growing them as bushes in hedgerows. Which system is better may ultimately come down to the balance between environmental conditions and economics.

Competition from Other Vegetation: Two of the progenitors of these hybrid hazelnuts, *Corylus americana* and *C. cornuta*, have only recently come from wild ecosystems, where they evolved under natural selection with high weed pressure (P.A. Rutter, personal communication, 2002). Thus Rutter asserts that they are good competitors with weeds, at least once they are established. However, many authors (Merwin and Ray, 1997; Hangs 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) found that survival of oak seedlings in a grassland was significantly increased when weeds were removed. Competition for moisture appeared to be the main cause of seedling mortality, whereas competition for light and for N were not so detrimental: seedling survival was actually higher in plots with 80% shade and lower N. Fertilization may actually intensify this competition for moisture by stimulating weed growth (Campbell et al., 1994a and 1994b, De Montard et al., 1999).

De Montard et al. (1999) found that broadcast applications of N to orchard grass (*Dactylis glomerata*) intercropped between rows of European hazelnuts increased competition for moisture, which reduced growth of the hazelnuts, but not of the orchard grass. Competition was both for moisture, as seen in leaf water potential, and for N, as evidenced by the combination of reduced hazel leaf N and reduced hazel canopy growth in the intercropped plots. Spot applications of N to the trees ameliorated this competition, as did root barriers between the trees and grass. They further found that competition was alleviated the fourth year after planting as tree roots extended beneath the rooting zone of the grass. After four years, roots of intercropped hazelnuts had been displaced downwards relative to monocropped hazelnuts, whereas roots of the orchard grass had been restricted to more superficial soil layers relative to monocropped orchard grass. This partitioning of the soil profile between the two species reduced competition for both moisture and N. These findings seem at first to support recommendations to control vegetation during the establishment of woody crops, but to ease up on weed control once they have developed the deep root systems that can tolerate competition. However, it might be that some competition during establishment is necessary to develop those deep root systems, which may be beneficial in the long run, even if it delays canopy growth.

In a review of below ground interactions in agroforestry, Schroth (1999) points out that competition is not necessarily negative for the system as a whole, as total nutrient and water use may be increased. This is why intercropped systems are frequently more productive than the sum of individual monocrops, as found with hazelnuts and orchard grass by DeMontard et al. (1999).

Atkinson (1977) found that 70% of new root growth of young apple trees occurred in the 1.2m wide herbicide strip of the apple rows, as opposed to the grassy row middles, and that N and P uptake was almost exclusively from this area. Besides the obvious explanation of reduced competition for nutrients and moisture in the herbicide strip this could also have been due to the higher soil temperatures. Schroth (1999) points out this downward displacement of the root system of one species by competition with another, although common, is not universal. It depends on the plasticity of the species involved, how competitive their roots are relative to each other, and on the distribution of the limiting resources. If the species do not have plastic root growth patterns, or if they are equally competitive, their roots may intermingle, which may actually be beneficial, such as in the case where one species is an N-fixer (Landgraf, 1993). We observed that roots of a vigorous eleven year old hybrid hazelnuts intermingled with grasses in a pit at Badgersett Research Farm, suggesting that hazelnuts survive competition with weeds by other mechanisms than displacement of roots.

Covercropping in Woody Crops: Although Rutter and Shepard do not explicitly advocate planting cover crops in the alleys between the hedgerows of hybrid hazelnuts, the weeds that are allowed to grow may fulfill some of the same functions as cover crops. For example, deep-rooted weeds may help keep N from leaching (Sicher et al., 1995). There is a large body of literature about cover crops in orchards. Sanchez et al. (2005) found that growth and yield of Gala apple trees was enhanced by perennial legume cover crops such as strawberry clover and an alfalfa/fescue mix, even though the latter became dominated by the fescue after three years. These were better than an annual vetch cover crop, which was better than the traditional management system of disking down the natural vegetation of grasses and legumes in the late winter. It seems that the tillage was harmful to the apple root systems and reduced soil organic matter. However, the legumes did not supply enough N to completely eliminate the need for supplemental N fertilization. Dupraz et al. (1999) found that intercrops of alfalfa (*Medicago sativa* L.) or sainfoin (*Onobrychis sativa* L.) increased both growth and leaf N concentration in black walnut, relative to intercrops of fescue (*Festuca arundinacea* Schr.). Ponder (1988) found that growth of black walnut was significantly enhanced by interplanting with autumn-olive (*Eleagnus umbellata* Thunb.), a N-fixing shrub, in conjunction with weed control. Landgraf (1993) states that leguminous intercrops with pecan can supply in excess of 150 lbs acre⁻¹ N in a single growing season. He recommends fertilizing with P and K to supply the needs of the legumes in order to maximize their N contribution.

Effects of Woodchip Mulch: Another management system proposed for hybrid hazelnuts, especially during the establishment phase, is mulching with woodchips. Zambreno et al. (2005)

found that woodchip mulch increased the growth of young apple trees relative to complete grass cover, with growth in wood chipped plots being similar to growth in herbicided plots. This was probably due to conservation of soil moisture. Woodchips may either tie up soil and fertilizer N, or they may release N, depending on their C:N ratio. Herms et al. (2002) found that N mineralization from a mulch of low C:N ratio (17:1) composted yard trimmings was enough to sustain healthy growth in young river birch (*Betula nigra*) seedlings for two years; additional N made no difference. This was in contrast to the low N mineralization from a mulch of ground wood, which inhibited tree growth unless supplemented with N. This is because the high C:N ratio (125:1) wood stimulated soil bacteria, which then outcompeted the trees for free soil N. A C:N ratio of 30:1 or 20:1 is considered the threshold below which bacterial immobilization of soil N is not a problem. Thus the 17:1 ratio composted yard waste was able not only to increase plant growth, but also to increase N mineralization, and overall nutrient availability. It may be all the N that slow-growing tree crops need (Herms, personal communication).

Organic Fertilizers: Strabbioli (1994) found no differences between organic and conventional fertilizers applied at the same rate of N, P, and K to hazelnuts in Italy, though there were very large differences between fertilized and unfertilized.

Summary and Conclusions

Nitrogen is the most commonly limiting nutrient for growth and productivity of all crops, including hazelnuts. But it cannot be considered in isolation. Plants require a balance of fixed energy (light or fixed carbon), water, and other nutrients, including N, in order to sustain rapid growth (Bloom et al., 1985). In particular, N uptake and metabolism is intricately balanced with photosynthesis and C metabolism because the products of one are needed to build capacity to harvest the other: N uptake requires fixed carbon and energy from photosynthesis, and photosynthesis requires N for chlorophyll and rubisco. Thus feedback mechanisms between roots and shoots exist to keep C and N in equilibrium.

Nitrogen may be the most important soil-derived nutrient quantitatively, but adding it will not enhance growth unless all of the other factors are sufficient. Failure to understand this has led to the use of N to amend problems that were not caused by lack of N, and to overapplication of N, which can lead to serious environmental problems, and to problems for the crop as well.

The primary way to avoid overapplication of N is to match the amount applied with the amount

demanded by the plant, but this is easier said than done. Factors that also must be considered include how much N the soil is capable of supplying; how much N is already stored within the plant; and what other factors may limit the plant's ability to take up and utilize the N, such as levels of light, moisture, and other nutrients. Quantifying these is not simple, especially not in woody plants, due to the large amount of N that may be hidden in storage in roots and woody parts. It is further complicated by competition for resources by weeds and intercrops. Overapplication of N can also be reduced by applying it in ways that improve the efficiency of its uptake. Methods include timing applications for when roots are most active and plant demand is greatest, placing N in close proximity to roots, and applying N in small repeated doses that closely match what the plant can take up at a time.

The first objective of our research was to quantify the N requirements of young hybrid hazelnuts. The first chapter of this dissertation reports on N-rate trials on seedlings from planting through their third year. The second chapter reports on N-rate trials on three plantings from their fourth through six years, and on one planting from its seventh through ninth year. Because hybrid hazelnuts are a new crop, there were no older plantings available with sufficient uniformity on which to conduct N-rate trials on mature bushes, or to determine the effect of nut-bearing on N-demand. Soil and leaf analysis were used in both studies, and their usefulness is discussed in these two chapters. The second objective of our research was to determine the best time to apply N fertilizer to hybrid hazelnuts. The third chapter reports on an N application timing experiment that used ^{15}N to compare the allocation patterns and N uptake efficiency from N applied on five different dates. The overall goal of all three chapters is to improve N application recommendations for hybrid hazelnuts in the Midwest, to balance agronomic requirements with environmental concerns.

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Table 1. Nitrogen Use Efficiency of various crops under a variety of treatments

Crop	Conditions	NUE	Source	
Grapes	Furrow-irrigated	14 %	Cited in Weinbaum et al. 2001	
	Drip-irrigated	42 %		
Oranges	Broadcast 4 times/year	26 %	Alva et al. 2003	
	In irrigation (15 times/year)	35 %		
	Controlled release	47 %		
	¼ recommended rate		Mattos et al. 2003	
	--broadcast as urea	26 %		
--broadcast as ammonium nitrate	40 %			
Apples	N over-applied for age of trees	22 %	Neilsen et al. 2001	
Almond (California)	Sandy soil	-- March	18 %	Weinbaum et al. 1984
		-- December	15 %	
	Clay Soil	-- March	24 %	
		-- December	10 %	
Hazelnut (Oregon)	Spring applied (March)	28 %	Olsen et al. 2001b	
	Applied post-harvest	28 %		
Spruce and Jack Pine	Controlled-release fertilizer bags buried in planting holes			Hangs et al. 2003
	-- taken up after 1 year	42 %		
	-- taken up after 2 years	77 %		
	-- still accounted for after 2 years	90 %		

Table 2. N removed with harvest in various crops.

Source	Crop	Yield (Mt·ha⁻¹)	N removed per ton of crop (kg·Mt)	N removed in crop (kg·ha⁻¹)
Cited in Weinbaum et al. 2001	Apples	45 - 67	0.50	22 - 33
	Peaches	34 - 56	1.28	43 - 72
	Grapes	22 - 34	1.45	32 - 50
	Oranges	28 - 39	2.10	59 - 82
	Almonds	1.7 - 2.8	35.3	60 - 99
	Pistachio	3.4 - 5.6	26.2	89 - 147
	Walnut	4.5 - 6.7	17.9	80 - 120
Roversi et al., 2005	Hazelnut	2.4	18 - 26	43 - 62 ^z

^z Includes nuts, husks, prunings and leaf drop.