Response of Highbush Blueberry to Nitrogen Fertilizer during Field Establishment—II. Plant Nutrient Requirements in Relation to Nitrogen Fertilizer Supply

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***Abstract*. A study was done to determine the macro- and micronutrient requirements of young northern highbush blueberry plants (*Vaccinium corymbosum* L. 'Bluecrop') during the first 2 years of establishment and to examine how these requirements were affected by the amount of nitrogen (N) fertilizer applied. The plants were spaced 1.2×3.0 m apart and fertilized with 0, 50, or 100 kg·ha⁻¹ of N, 35 kg·ha⁻¹ of phosphorus (P), and 66 kg·ha⁻¹ of potassium (K) each spring. A light fruit crop was harvested during the second year after planting. Plants were excavated and parts sampled for complete nutrient analysis at six key stages of development, from leaf budbreak after planting to fruit harvest the next year. The concentration of several nutrients in the leaves, including N, P, calcium (Ca), sulfur (S), and manganese (Mn), increased with N fertilizer application, whereas leaf boron (B) concentration decreased. In most cases, the concentration of nutrients was within or above the range considered normal for mature blueberry plants, although leaf N was below normal in plants grown without fertilizer in Year 1, and leaf B was below normal in plants fertilized with 50 or 100 kg·ha⁻¹ N in Year 2. Plants fertilized with 50 kg·ha⁻¹ N were largest, producing 22% to 32% more dry weight (DW) the first season and 78% to 90% more DW the second season than unfertilized plants or plants fertilized with 100 kg·ha⁻¹ N. Most DW accumulated in new shoots, leaves, and roots in both years as well as in fruit the second year. New shoot and leaf DW was much greater each year when plants were fertilized with 50 or 100 kg·ha⁻¹ N, whereas root DW was only greater at fruit harvest and only when 50 kg·ha⁻¹ N was applied. Application of 50 kg·ha⁻¹ N also increased DW of woody stems by fruit harvest, but neither 50 nor 100 kg·ha⁻¹ N had a significant effect on crown, flower, or fruit DW. Depending on treatment, plants lost 16% to 29% of total biomass at leaf abscission, 3% to 16% when pruned in winter, and 13% to 32% at fruit harvest. The content of most nutrients in the plant followed the same patterns of accumulation and loss as plant DW. However, unlike DW, magnesium (Mg), iron (Fe), and zinc (Zn) content in new shoots and leaves was similar among N treatments the first year, and N fertilizer increased N and S content in woody stems much earlier than it increased biomass of the stems. Likewise, N, P, S, and Zn content in the crown were greater at times when N fertilizer was applied, whereas K and Ca content were sometimes lower. Overall, plants fertilized with 50 kg·ha⁻¹ N produced the most growth and, from planting to first fruit harvest, required 34.8 kg·ha⁻¹ N, 2.3 kg·ha⁻¹ P, 12.5 kg·ha⁻¹ K, 8.4 kg·ha⁻¹ Ca, 3.8 kg·ha⁻¹ Mg, 5.9 kg·ha⁻¹ S, 295 g·ha⁻¹ Fe, 40 g·ha⁻¹ B, 23 g·ha⁻¹ copper (Cu), 1273 g·ha⁻¹ Mn, and 65 g·ha⁻¹ Zn. Thus, of the total amount of fertilizer applied over 2 years, only 21% of the N, 3% of the P, and 9% of the K were used by plants during establishment.**

Like many crops, fertilizer practices in blueberry (*Vaccinium* sp.) are routinely adjusted by comparing the results of leaf nutrient analysis at a standard time against the known optimal ranges of leaf nutrient concentrations. Effective fertilizer management, however, also requires a good understanding of plant nutritional demands both in terms of the nutrient amount (Santos, 2011) and the timing in which each nutrient is most needed (Mattson and van Iersel, 2011). Biomass determination through sequential plant excavation, coupled with nutrient analysis of each tissue type, is presently the most reliable way to obtain the amounts and seasonal patterns of plant nutrient uptake (Weinbaum et al., 2001). Nutrient analysis of entire plants at multiple times during annual cycles of growth and development is difficult and expensive, and only N has been examined in detail in highbush blueberry (Bañados et al., 2012; Hanson and Retamales, 1992; Retamales and Hanson, 1989; Throop and Hanson, 1997).

Nitrogen is the predominant nutrient applied to blueberry for successful commercial growth and production. Although the blueberry plant is relatively small and slow-growing compared with many temperate fruit tree crops, the amount of N fertilizer applied to the crop each year is comparable (Stiles and Reid, 1991). Typical rates in Oregon, for example, average 50 to 100 kg·ha⁻¹ of N per year during planting establishment and 100 to 300 kg·ha⁻¹ of N per year once the field matures. Other nutrients are also applied, largely based on soil tests and general recommendations from plant and soil testing laboratories. Hart et al. (2006) developed more stringent guidelines for nutrient management of blueberry based on leaf tissue and soil analysis. However, with the exception of N, the defined ranges of nutrient sufficiency were based on experience and not on controlled studies of each nutrient.

Nutrient requirements in perennial fruit crops such as blueberry depend on new biomass production in vegetative and reproductive tissues, the nutrients needed for production of the new tissue, and the amount of nutrients reallocated from existing plant tissues. Mature northern highbush blueberry plants produce most new shoots and leaves in the spring and early summer, before or during fruit development, and most new roots in early spring, before budbreak, and mid- to late summer after fruit harvest (Abbott and Gough, 1987). Most N is acquired during shoot and fruit development (Throop and Hanson, 1997), and therefore split applications of granular N fertilizer are recommended in the spring (April to June in the northern hemisphere) for blueberry (Hart et al., 2006). Reallocation of nutrients in woody plants occurs internally, especially in early spring from storage tissues such as the crown and woody stems and in the fall from senescing leaves (Mohadjer et al., 2001; Rempel et al., 2004; Strik et al., 2004) and externally from decomposition of plant tissues such as senesced leaves and roots and pruned wood (Strik et al., 2006).

We previously found that 50 kg·ha⁻¹ N per year promoted more growth and yield than no N fertilizer during establishment of highbush blueberry, whereas rates 100 kg·ha⁻¹ N or greater were excessive and resulted in salt stress and plant mortality in the young planting (Bañados et al., 2012). Through destructive

harvests and the use of depleted ^{15}N fertilizer, we estimated that unfertilized plants gained 1.6 g/plant of N from soil sources, whereas fertilized plants accumulated 2.3 g/plant of N, on average, 60% of which was from fertilizer N and 40% was from the soil. The objectives of the present study were to determine the requirements of N and other macro- and micronutrients in the young plants and to examine how the requirements were affected by the amount of N fertilizer applied. Plants were excavated, separated into relevant plant parts, and analyzed for nutrients on six key dates from leaf budbreak immediately after planting to the first fruit harvest the next year.

Materials and Methods

Two-year-old 'Bluecrop' blueberry plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Lowell, OR) and transplanted on 27 Mar. 2002 to a field located at the North Willamette Research and Extension Center in Aurora, OR. The plants were delivered from the nursery in 4-L pots filled with a mix of peat, bark, and pumice. Both roots and the soil mix were placed in the planting hole and packed firmly in place with surrounding soil. Soil at the site was a Quantama fine loam (mixed, mesic Aquatic Haploxeralfs) with a pH 5.0 and 3.0% organic matter content. The soil was amended before planting with a 10-cm deep layer of Douglas fir (*Pseudotsuga menziesii* Franco) sawdust and 66 kg·ha^{-1} of N [21N–0P–0K (NH$_4$)$_2$SO$_4$]. The sawdust and fertilizer was incorporated 0.2 m deep by cultivation in ≈1-m wide strips to form five 50-m-long rows of planting beds. Plants were spaced 1.2 m apart within rows and 3.0 m apart between rows (equal to a density of 2778 plants/ha). Grass alleyways (1.1 m wide) were planted and maintained between the rows. The field was irrigated as needed (≈25 to 38 mm/week) from May to September each year using overhead sprinklers.

Three N fertilizer treatments were applied to plants during the first 2 years after planting. The treatments were arranged in a randomized complete block design with three replicates per treatment. Each treatment plot consisted of one row of 12 plants. The N fertilizer used was granular ammonium sulfate (21N–0P–0K). Three equal applications of the fertilizer were sprinkled around the base of the plants each spring at a total rate equivalent to 0 (no additional fertilizer N), 50, or 100 kg·ha^{-1} N per year. A fourth set of plants was fertilized at a rate of 150 kg·ha^{-1} N but was not used in the present study as a result of severe problems in the treatment with salt injury and plant death (Bañados et al., 2012). The fertilizer was applied on 11 Apr., 20 May, and 27 June in 2002 (Year 1) and on 24 Mar., 8 Apr., and 23 June in 2003 (Year 2). Each plant was also fertilized with 35 kg·ha^{-1} P and 66 kg·ha^{-1} K each spring. Plants were winter-pruned in Feb. 2003 and lightly cropped the second year after planting.

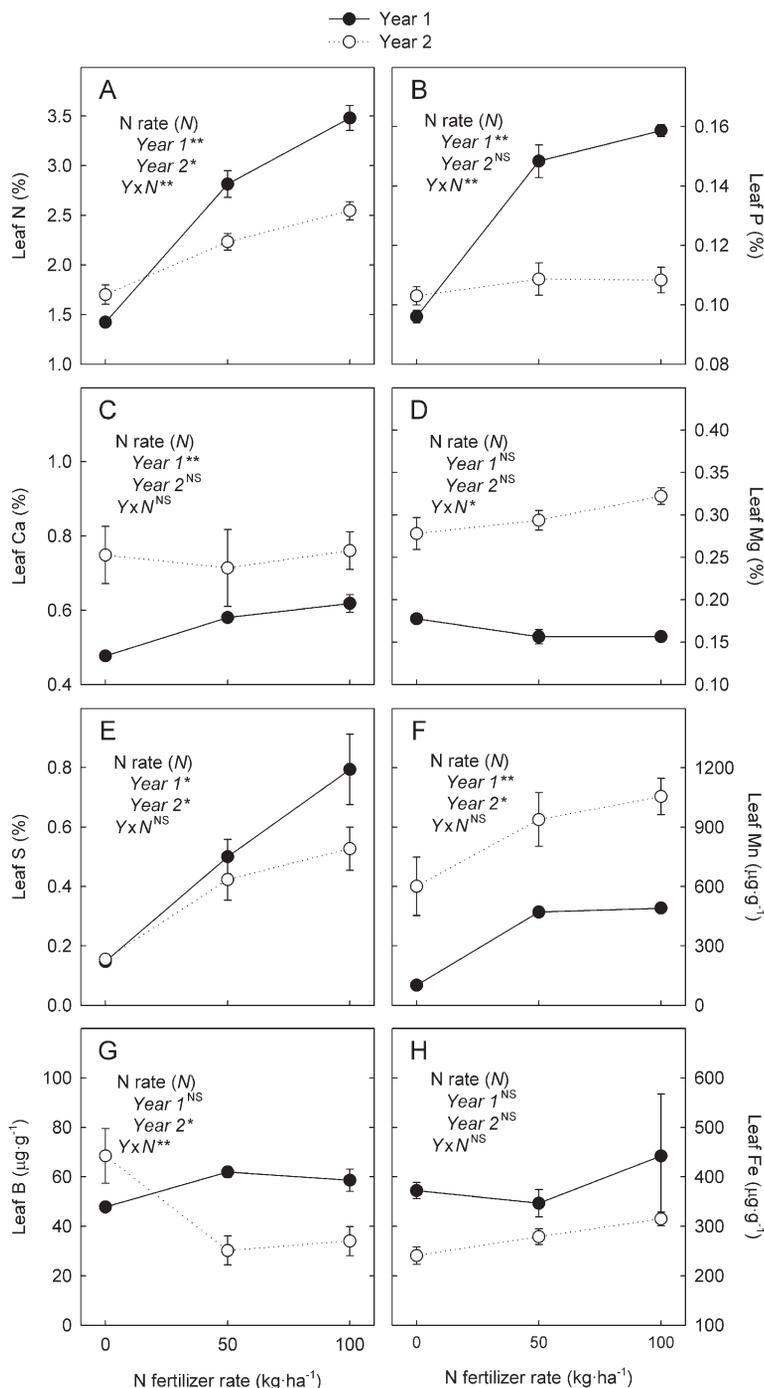One randomly selected plant from each treatment plot was excavated and sampled

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Fig. 1. Leaf (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) calcium (Ca), (**D**) magnesium (Mg), (**E**) sulfur (S), (**F**) manganese (Mn), (**G**) boron (B), and (**H**) iron (Fe) concentrations in response to N fertilizer rate in 'Bluecrop' blueberry during the first and the second year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha^{-1} N and leaves were collected 24 July 2002 (Year 1) and 25 July 2003 (Year 2). Results from individual and combined analysis of variance are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates and error bars represent ± 1 SE.

destructively on six key dates: leaf budbreak (29 Apr. 2002), late July when leaf sampling is recommended for nutrient analysis (24 July 2002; see Hart et al., 2006), and just before leaf abscission (29 Oct. 2002) in Year 1; and just before winter pruning (7 Feb. 2003), leaf budbreak (22 Apr. 2003), and late July when fruit were first harvested (25 July 2003) in Year 2. Each plant was dug up from the entire width of the planting bed to a depth of 0.3 m to recover as much of the root system as possible. Roots were washed after digging to remove the soil, and the plants were partitioned into new shoots, leaves, flowers and fruit (Year 2 only), 1-year-old wood, 2-year-old wood (Year 2 only), the crown, and roots. Each part was then oven-dried at 70 °C, and dry weights were recorded after the samples reached a constant weight. New shoots and 1-year-old wood produced in 2002 were reclassified as 1- and 2-year-old wood, respectively, in Feb. 2003.

All dried plant parts were ground to pass through a 40-mesh (425-μm) screen and analyzed for N using a combustion analyzer (CN-2000; Leco Inc., St. Louis, MO) and for P, K, Ca, Mg, S, Fe, B, Cu, Mn, and Zn using inductively coupled plasma–optical emission spectroscopy (Optima 3000DV; Perkin Elmer, Wellesley, MA) after acid-digestion (Jones and Case, 1990). Fruit samples were analyzed for N but were unavailable for analysis of other nutrients, and root samples were not analyzed for Fe as a result of potential issues with soil contamination.

Data were analyzed by analysis of variance using SAS Version 9.2 software (SAS Institute, Cary, NC) and square-root transformed when needed as determined by the heterogeneity of variance. Any transformed data were back-transformed for presentation. Means were separated at the 0.05 level using Duncan's new multiple range test.

Results and Discussion

Leaf nutrient status. The concentration of N in leaf samples taken in late July increased with N fertilizer application as has been shown by others in northern highbush (Ballinger and Kushman, 1966; Bishop et al., 1971; Cummings, 1978; Cummings et al., 1971) and rabbiteye (*V. virgatum* Ait.) (Spiers, 1983) blueberry. The leaf N concentrations in this study, however, were higher than what is considered normal (1.76% to 2.00%; Hart et al., 2006) for northern highbush blueberry in Oregon, especially during the first year after planting when levels averaged 2.82% in plants fertilized with 50 kg·ha^{-1} N and 3.48% in those fertilized with 100 kg·ha^{-1} N (Fig. 1A). By the second year, leaf N concentrations were lower in N-fertilized plants but again were still higher than normal, averaging 2.23% with 50 kg·ha^{-1} N and 2.57% with 100 kg·ha^{-1} N. Without N fertilizer, leaf N concentrations averaged only 1.42% the first year after planting but increased to 1.76% the second year. It is possible that current recommendations for sufficiency of leaf N concentration (Hart et al., 2006), generally

used for producing plants, may need to be increased for young, establishing plants. Leaf N concentration has been shown to decrease with planting age (Cummings, 1978).

The concentration of several other leaf nutrients also increased significantly with N fertilizer application, including P and Ca during the first year after planting (Fig. 1B–C), Mg during the second year after planting ($P < 0.10$;

Fig. 1D), and S and Mn during both the first and the second year after planting (Fig. 1E–F). Others have found little effect of N fertilizer rate on leaf P (Ballinger and Kushman, 1966; Bishop et al., 1971; Cummings et al., 1971) in establishing northern highbush blueberry, although variability in response has differed with site (Cummings et al., 1971). The effect of N fertilization on leaf Ca has likewise been shown
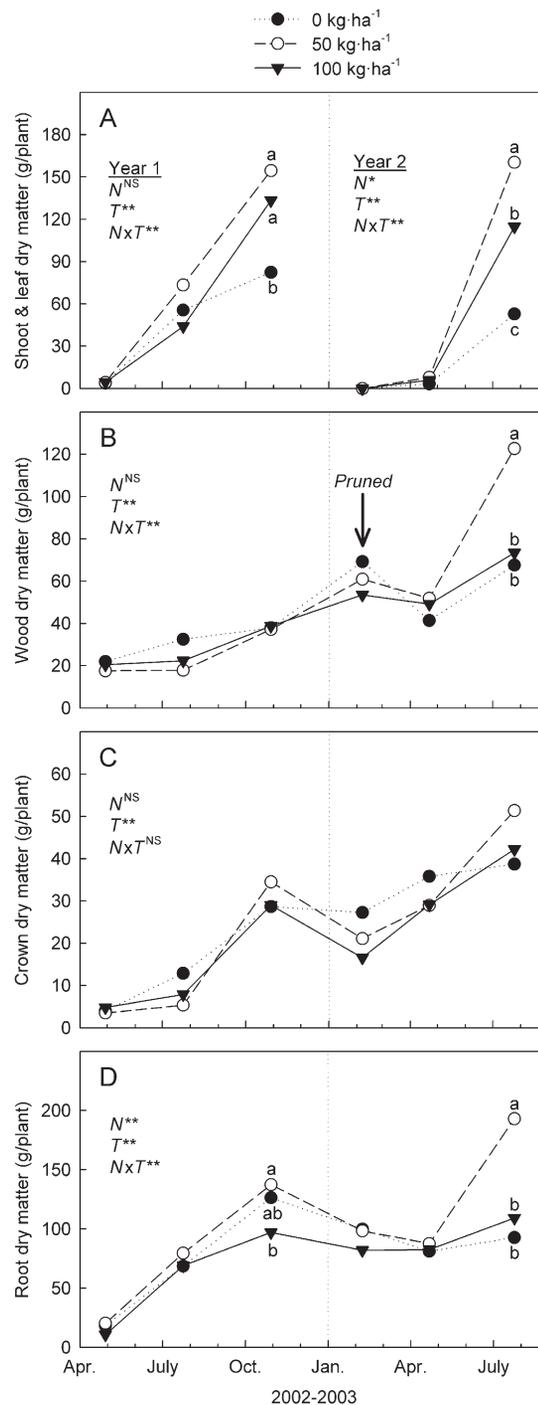

Fig. 2. Dry weight of (**A**) new shoots and leaves, (**B**) woody stems, (**C**) crown, and (**D**) roots of 'Bluecrop' blueberry during the first (2002) and second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha^{-1} nitrogen (N) and pruned 7 Feb. 2003. Results from two-way analysis of variance [N rate (*N*) × time (*T*)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test).

to vary by site as well as cultivar within a region (Cummings et al., 1971). Bishop et al. (1971) and Ballinger and Kushman (1966) found that Ca decreased with increasing N rates in mature 'Bluecrop' and 'Wolcott' blueberry, whereas Cummings (1978) reported little effect of N rate on leaf Ca in the first growing season and a decrease with N rate in the second year. Leaf Mg was affected little by N rate in our study, as has been reported by others (Ballinger and Kushman, 1966; Bishop et al., 1971; Cummings et al., 1971). Leaf Mn concentration increased with N fertilization, which was likely related to a decline in soil pH (Bañados et al., 2012), also observed by Townsend (1973) in a 6-year study in 'Blueray' blueberry.

In general, P and S concentrations were lower in the N-fertilized plants in the second year than they were in the first, declining by an average of 0.4 to 0.5 mg·g^{-1} and 0.8 to 2.6 mg·g^{-1}, respectively, whereas Ca, Mg, and Mn concentrations were higher the second year after planting, increasing by an average of 1.3 to 1.4 mg·g^{-1}, 1.3 to 1.6 mg·g^{-1}, and 468 to 564 µg·g^{-1}, respectively. An increase in leaf Mg, Ca, and Mn over time has been reported by others (Cummings, 1978; Townsend, 1973). In our study, only leaf P and Ca concentrations were within the range each year considered optimum for blueberry (i.e., 0.10% to 0.40% for P and 0.41% to 0.80% for Ca; Hart et al., 2006), and this was the case whether plants were fertilized with N or not. Leaf Mg and Mn concentrations, on the other hand, were higher than recommended (i.e., 0.13% to 0.25% for Mg and 30 to 350 µg·g^{-1} for Mn; Hart et al., 2006) the second year after planting, regardless of N treatment, and leaf S concentrations were higher than recommended (0.11% to 0.16%; Hart et al., 2006) in both years but only when N fertilizer was applied [as $(NH_4)_2SO_4$].

Leaf B concentration was also significantly affected by N fertilizer application, but in this case, the response differed between years ($P < 0.05$; Fig. 1G). In the first year after planting, leaf B concentrations increased from 48 µg·g^{-1} without N fertilizer to 62 µg·g^{-1} with 50 kg·ha^{-1} N and 59 µg·g^{-1} with 100 kg·ha^{-1} N. The next year, the opposite was true, and leaf B decreased from

68 µg·g^{-1} with no N to 30 µg·g^{-1} with 50 kg·ha^{-1} N and 28 µg·g^{-1} with 100 kg·ha^{-1} N. Leaf B was not deficient (less than 20 µg·g^{-1}) in either year, whether plants were fertilized with N or not, but levels were slightly less than optimum (i.e., 31 to 80 µg·g^{-1}; Hart et al., 2006) the second year after planting when N fertilizer was added.

Leaf concentrations of the remaining nutrients, including K, Fe, Cu, and Zn, were unaffected by N fertilizer application and, with the exception of Fe (Fig. 1H), remained more or less the same during the first 2 years after planting. Leaf K concentration averaged 0.78% over each treatment and year, and leaf Fe, Cu, and Zn concentrations averaged 333, 5, and 9 µg·g^{-1}, respectively. Both Cu and Zn were within a range considered adequate for these nutrients (5 to 15 µg·g^{-1} for Cu and 8 to 30 for µg·g^{-1} for Zn; Hart et al., 2006), whereas K and Fe were higher than adequate (i.e., 0.41% to 0.70% for K and 61 to 200 µg·g^{-1} for Fe; Hart et al., 2006). Although others have reported an increase in leaf K concentration with N fertilization in highbush blueberry (Bishop et al., 1971; Cummings, 1978; Cummings et al., 1971; Townsend, 1973) and an increase in leaf K as plants aged (Cummings, 1978), fluctuations in leaf K are often associated with fruiting; these plants produced no fruit in Year 1 and only a small crop in Year 2.

Accumulation and partitioning of plant biomass. Plants fertilized with 50 kg·ha^{-1} N were the largest among the three N treatments and, by the end of the first growing season, produced 0.36 kg of total DW and weighed 22% more than plants fertilized with 100 kg·ha^{-1} N and 32% more than unfertilized plants. By fruit harvest the next season, the difference was even greater as plants fertilized with 50 kg·ha^{-1} N averaged 0.70 kg of total DW per plant, whereas those with 100 kg·ha^{-1} N or no fertilizer averaged only 0.39 and 0.37 kg/plant, respectively. Clearly, soil N was limited at the site, but adding 100 kg·ha^{-1} N was excessive for this planting density and resulted in reduced plant growth [see Bañados et al. (2012) for further details and additional harvest dates]. Reduced growth with excessive N fertilization

in blueberry has been previously reported (Cummings, 1978).

Most DW accumulated in new shoots, leaves, and roots in both years (Fig. 2) as well as in fruit the second year (Table 1). The total of these parts combined represented 76% to 80% of the total DW by the end of the first season and 71% to 75% by fruit harvest of the second season. New shoot and leaf DW was much higher each year with N fertilizer (Fig. 2A), whereas root DW was only higher at harvest and only when 50 kg·ha^{-1} N was applied (Fig. 2D). Application of 50 kg·ha^{-1} N also increased DW of woody stems by fruit harvest (Fig. 2B), but neither 50 nor 100 kg·ha^{-1} N had any significant effect on crown (Fig. 2C) or flower and fruit DW (Table 1). Not surprisingly, unfertilized plants allocated relatively more biomass to roots and less biomass to shoots than fertilized plants, but only during the first growing season. By the end of the first year, the root-to-shoot ratio in unfertilized plants averaged 0.85 g of root DW per gram of shoot DW (including all aboveground parts plus the crown), whereas in plants fertilized with 50 and 100 kg·ha^{-1} N, the ratio averaged 0.61 and 0.48 g·g^{-1}, respectively. By contrast, the second year, the ratio was similar among treatments, averaging 0.34 to 0.39 g·g^{-1} at fruit harvest. Root-to-shoot ratios often decline with N fertilizer application and plant age (Gregory, 2006); however, excavation of the root system also becomes more difficult as the plants grow and mature. Such difficulty likely reduced the percentage of roots recovered in the present study and perhaps partly accounted for the lower root-to-shoot ratios and the lack of treatment differences observed during the second year after planting.

Three major losses of DW occurred during the first 2 years after planting. The first was at leaf abscission in early to mid-Nov. 2002. Leaf abscission resulted in a net loss of 43 g of DW or 16% of the total biomass in unfertilized plants, 92 g or 25% of the total biomass in plants fertilized with 50 kg·ha^{-1} N, and 86 g or 29% of the total biomass in plants fertilized with 100 kg·ha^{-1} N. At this point, fertilization with more N resulted in a greater allocation of biomass to leaves and therefore

Table 1. Effects of nitrogen (N) fertilizer rate on flower and fruit dry weight and macro- and micronutrient content in 'Bluecrop' blueberry during the second year after planting.[z]

N rate (kg·ha^{-1})	Dry wt (g/plant)	Macronutrient content (g/plant)						Micronutrient content (mg/plant)				
		N	Phosphorus	Potassium	Calcium	Magnesium	Sulfur	Iron	Boron	Copper	Manganese	Zinc
Flowers												
0	4.1	0.13	0.02	0.06	0.02	0.01	0.01	0.8	0.4	0.2	1.1	0.3
50	4.2	0.21	0.03	0.08	0.02	0.01	0.02	1.4	0.2	0.1	3.9	0.3
100	3.1	0.16	0.02	0.06	0.01	0.01	0.01	1.0	0.3	0.1	2.7	0.2
Significance[y]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fruit[x]												
0	116	0.88	0.10	0.80	0.05	0.04	0.08	3.8	0.9	0.3	4.2	0.7
50	171	2.34	0.15	1.19	0.07	0.07	0.12	5.6	1.4	0.4	6.1	1.0
100	55	0.88	0.05	0.37	0.02	0.02	0.04	1.7	0.4	0.1	1.9	0.3
Significance[y]	§	§	—	—	—	—	—	—	—	—	—	—

[z]Flowers were collected on 22 Apr. 2003, and fruit were harvested on 25 July 2003.
[y]Results from one-way analysis of variance: NS and § = nonsignificant and $P < 0.10$, respectively.
[x]All fruit nutrient content except N was calculated using the average of 2 years of data collected from mature 'Bluecrop' plants fertilized each year with 0, 100, and 200 kg·ha^{-1} N (unpublished results). The plants were growing at the same site and sampled the same years as those used in the present study.

a relatively greater loss of total biomass at leaf abscission. The next loss of DW occurred during winter pruning in which 28 g of wood was removed from unfertilized plants, but only 9 and 4 g of wood were removed from plants fertilized with 50 and 100 kg·ha⁻¹ N, respectively. Unfertilized plants required more pruning than fertilized plants because this treatment had a lot of weak and twiggy wood. Twiggy wood typically has thinner and shorter new growth and produces small berries and therefore is often removed during pruning (Strik et al., 1993). The final loss of DW occurred at harvest when an average of 55 to 171 g of fruit per plant was picked (Table 1). Although production was variable, plants fertilized with 50 kg·ha⁻¹ N tended to produce more fruit than those fertilized with 100 kg·ha⁻¹ N. Plants also lost a small amount of DW (less than 3 to 4 g/plant) at fruit set as the flower petals senesced (Table 1).

Accumulation and partitioning of nutrients. In most cases, nutrient content in each plant part followed the same pattern of accumulation as DW (Figs. 3 to 6). Thus, many differences among N treatments were similar. For example, nutrient content in new shoots
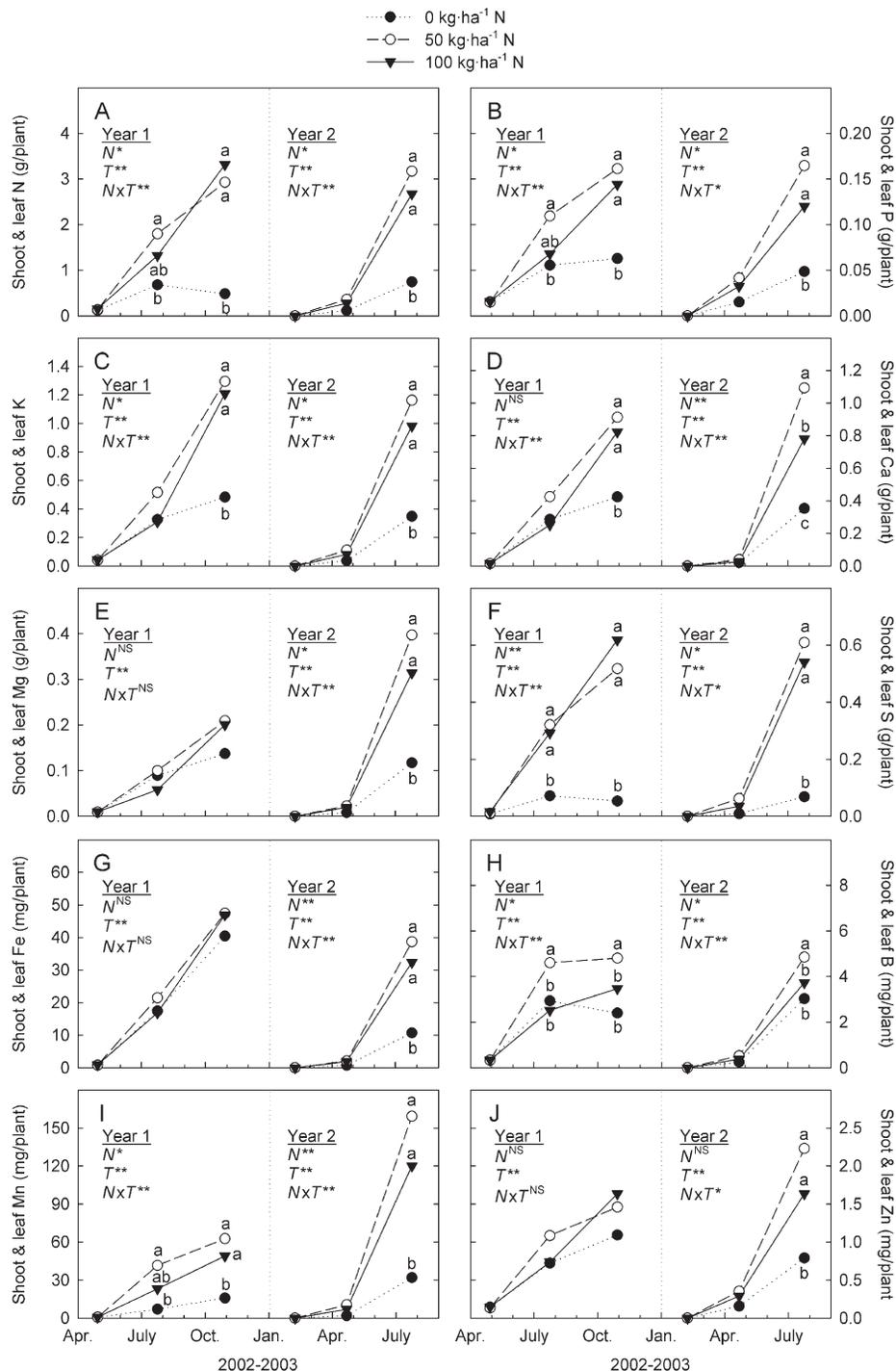

Fig. 3. New shoot and leaf (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) potassium (K), (**D**) calcium (Ca), (**E**) magnesium (Mg), (**F**) sulfur (S), (**G**) iron (Fe), (**H**) boron (B), (**I**) manganese (Mn), and (**J**) zinc (Zn) content in 'Bluecrop' blueberry during the first (2002) and the second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha⁻¹ N. Results from two-way analysis of variance [N rate (N) × time (T)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test). Shoot and leaf copper (Cu) content increased to an average of 0.6 g/plant in Year 1 and 0.7 g/plant in Year 2 but was unaffected either year by N or $N \times T$.

and leaves was generally higher each year in fertilized plants than in unfertilized plants (Fig. 3). Likewise, like with DW, the content of many nutrients in wood and roots was often highest in fertilized plants (Figs. 4 and 6). However, there were a number of exceptions. New shoot and leaf Mg, Fe, and Zn contents, for example, were similar among treatments the first year after planting (Figs. 3E, 3G, and 3J), largely as a result of a higher concentration of each in unfertilized plants ($P \leq 0.05$). Another exception was that wood N and S content was higher in fertilized plants much earlier than DW, and this occurred whether 50 or 100 kg·ha^{-1} N was applied (Figs. 4A and 4F). Wood K, Cu, and Mn content also differed among treatments before harvest and, in one instance, wood had a higher Cu content when no fertilizer was applied (Figs. 4C, 4H, and 4I). In addition, the content of several nutrients in the crown differed among N treatments, in which N, P, S, and Zn content was higher at times with N fertilizer (Figs. 5A, 5B, 5F, and 5J), whereas K and Ca content was sometimes lower (Fig. 5C–D). Basically, differences in root N, P, K, Mg, S, Cu, and Mn content were similar to differences in root
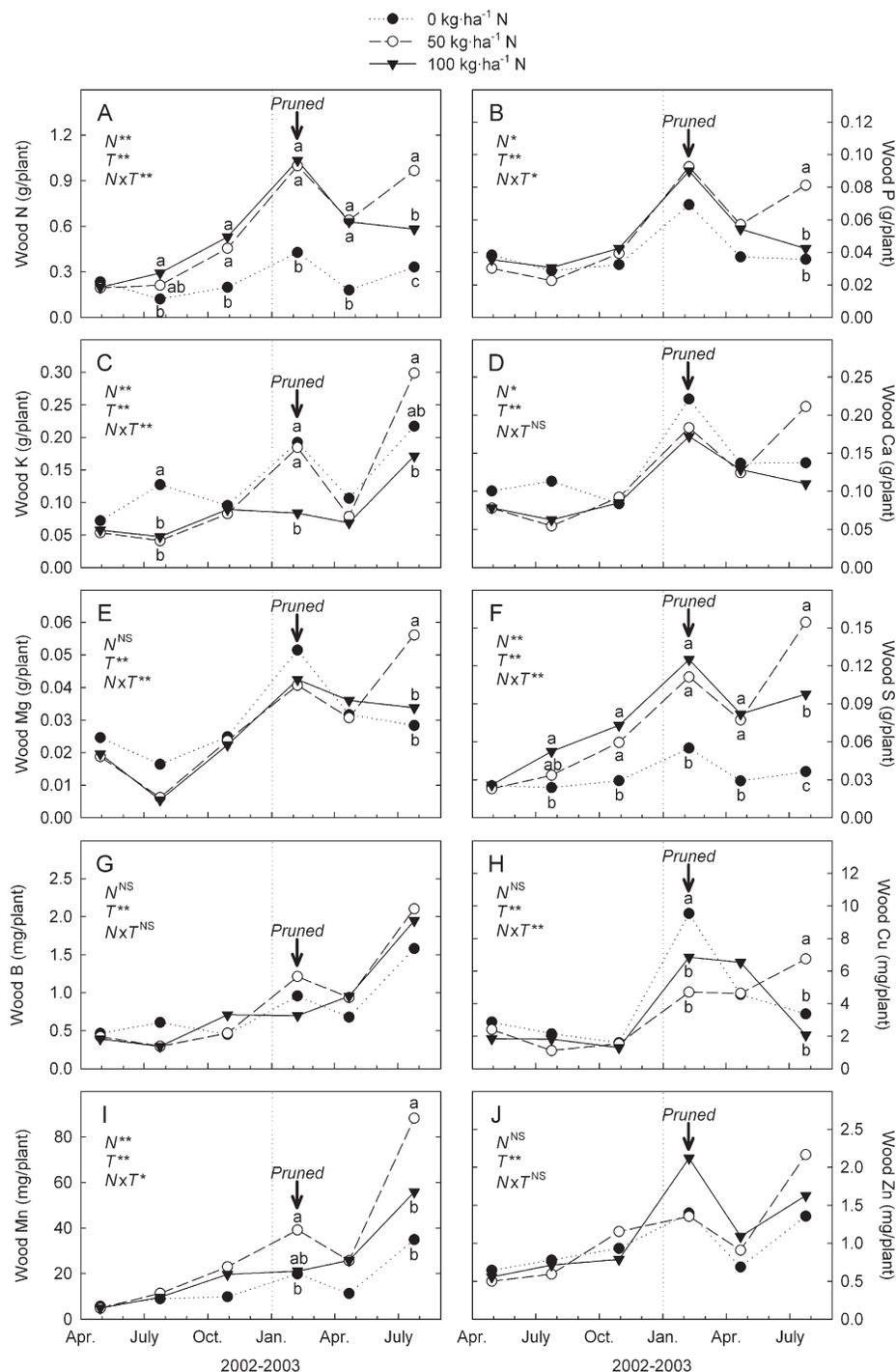

Fig. 4. Woody stem (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) potassium (K), (**D**) calcium (Ca), (**E**) magnesium (Mg), (**F**) sulfur (S), (**G**) boron (B), (**H**) copper (Cu), (**I**) manganese (Mn), and (**J**) zinc (Zn) content in 'Bluecrop' blueberry during the first (2002) and the second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha^{-1} N. Results from two-way analysis of variance [N rate (N) × time (T)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test). Wood iron (Fe) content ranged from 4 to 17 mg/plant but was unaffected by N or $N \times T$.
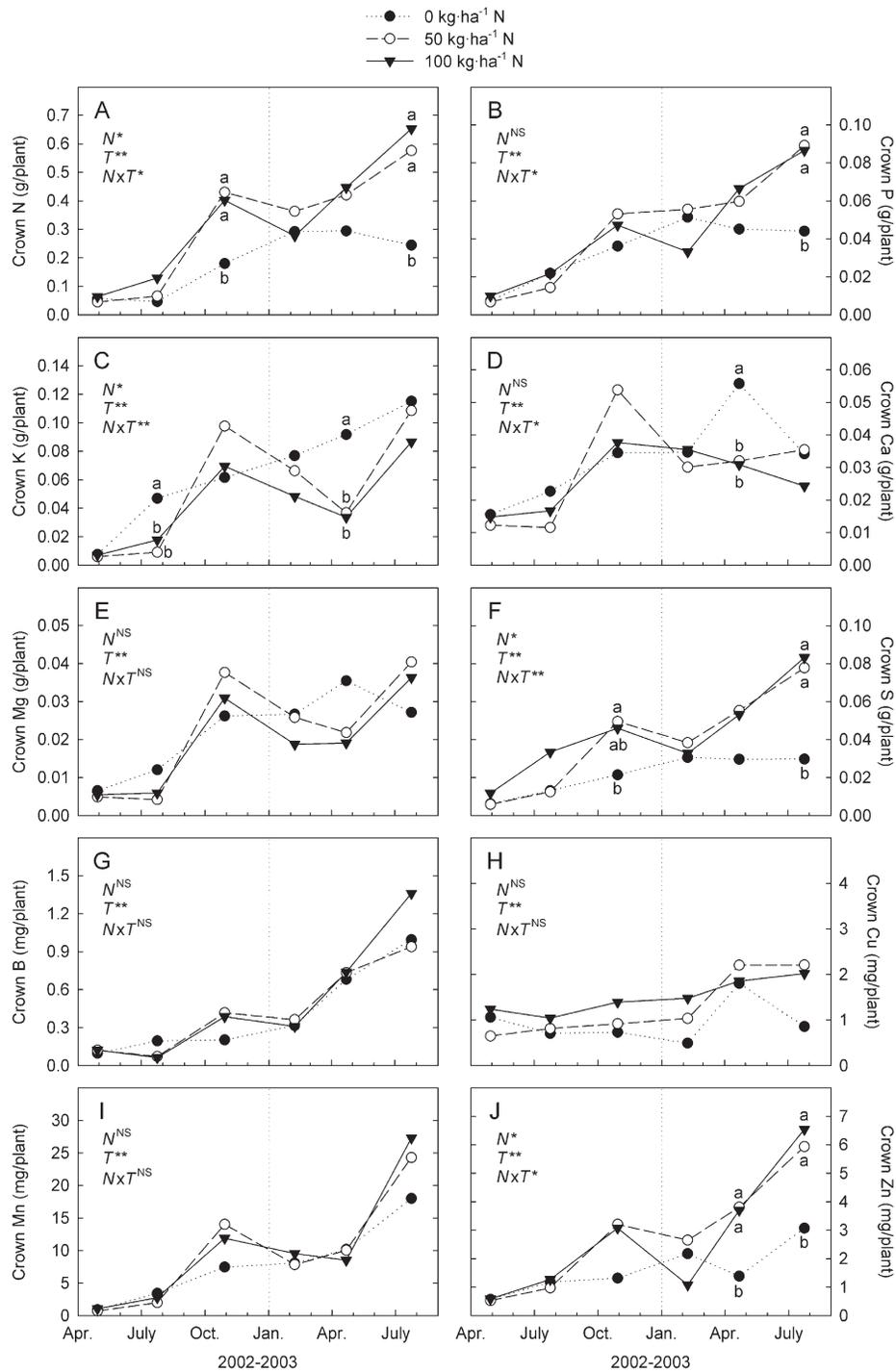
Fig. 5. Crown (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) potassium (K), (**D**) calcium (Ca), (**E**) magnesium (Mg), (**F**) sulfur (S), (**G**) boron (B), (**H**) copper (Cu), (**I**) manganese (Mn), and (**J**) zinc (Zn) content in 'Bluecrop' blueberry during the first (2002) and the second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha⁻¹ N. Results from two-way analysis of variance [N rate (N) × time (T)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \le 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test). Crown iron (Fe) content ranged from 3 to 29 mg/plant but was unaffected by N or $N \times T$.

DW, although sometimes the differences occurred in the 50 and 100 kg·ha⁻¹ N treatments and, unlike root DW, usually occurred more often than just at fruit harvest (Figs. 6A–C, 6E, 6F, 6H, and 6I).

The content of many nutrients in the woody stems increased over fall and winter (29 Oct. 2002 to 7 Feb. 2003; Fig. 4A–J). The increase of N, P, K, and Mg in almost all treatments from fall to late winter may have

been a result of remobilization of nutrients from senescing leaves or additional plant uptake during this time period. Copper content likely increased as a result of a copper sulfate fungicide (see subsequently). The content of Ca in the woody stems increased over fall/winter; because this nutrient is not mobile, it is unlikely this increase was from remobilization before leaf abscission. In the crown tissues, only N, P, and K

content in the unfertilized plants increased over winter, perhaps a result of added nutrient uptake during this period. In the roots, N content increased in the unfertilized plants and P in those fertilized with 100 kg·ha⁻¹ N, perhaps a result of the lower soil pH in this treatment (Bañados et al., 2012), which would have increased availability of soil P. Losses in nutrient content over this time period may have been caused by a reduction in efficiency
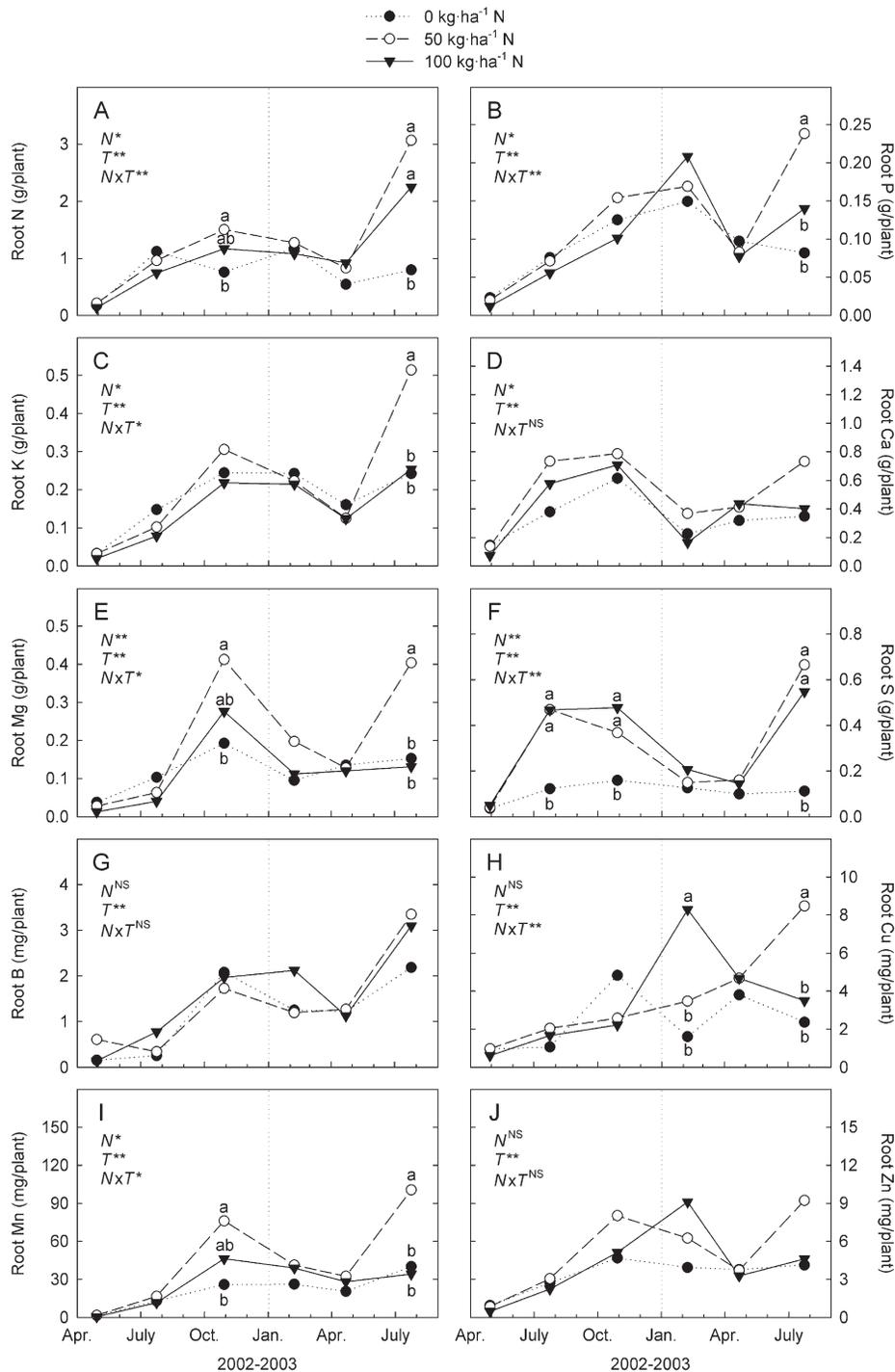
Fig. 6. Root (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) potassium (K), (**D**) calcium (Ca), (**E**) magnesium (Mg), (**F**) sulfur (S), (**G**) boron (B), (**H**) copper (Cu), (**I**) manganese (Mn), and (**J**) zinc (Zn) content in 'Bluecrop' blueberry during the first (2002) and the second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha^{-1} N. Results from two-way analysis of variance [N rate (N) × time (T)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test).

of harvesting the entire root system as plants aged.

Like DW, plants fertilized with 50 kg·ha^{-1} N tended to have a higher fruit N content (Table 1). As mentioned earlier, other fruit nutrients were not measured, but measurements done on fruit from mature 'Bluecrop' plants growing at the same site and fertilized with 0, 100, and 200 kg·ha^{-1} N indicated that N treatment had no effect on fruit nutrient

concentrations beyond fruit N [which increased with N fertilization (1.02% to 1.28% N; Bañados, 2006), as previously reported by others (Ballinger and Kushman, 1966; Bishop et al., 1971)]. In this case, fruit averaged 0.09% P, 0.69% K, 0.04% Ca and Mg, 0.07% S, 33 µg·g^{-1} Fe, 8 µg·g^{-1} B, 2 µg·g^{-1} Cu, 36 µg·g^{-1} Mn, and 6 µg·g^{-1} Zn (Strik et al., unpublished data). Assuming nutrient concentrations were similar in the present study, the fruit would

have contained 0.9 to 2.3 g/plant of N; 0.4 to 1.2 g/plant of K; less than 0.2 g/plant of P, Ca, Mg, and S; 2 to 6 mg/plant of Fe and Mn; and less than 2 mg/plant of B, Cu, and Zn (Table 1).

With the exception of Cu, total nutrient uptake by the plants increased from leaf budbreak to leaf abscission (Year 1) or fruit harvest (Year 2) and was higher in many cases when plants were fertilized with N (Fig. 7). With N fertilizer, uptake of some nutrients
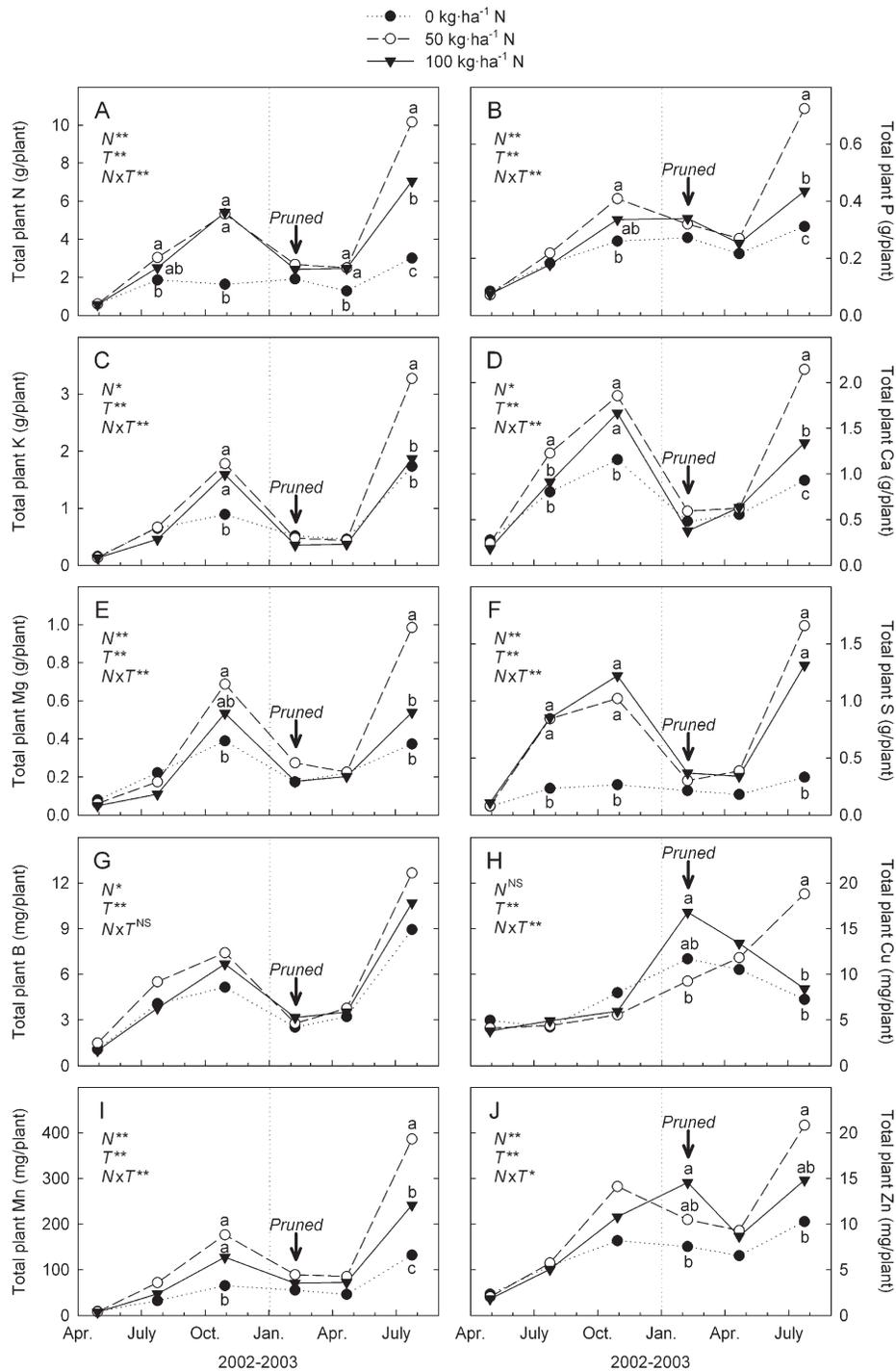
Fig. 7. Total plant (**A**) nitrogen (N), (**B**) phosphorus (P), (**C**) potassium (K), (**D**) calcium (Ca), (**E**) magnesium (Mg), (**F**) sulfur (S), (**G**) boron (B), (**H**) copper (Cu), (**I**) manganese (Mn), and (**J**) zinc (Zn) content in 'Bluecrop' blueberry during the first (2002) and the second (2003) year after planting. The plants were fertilized each spring with 0, 50, or 100 kg·ha^{-1} N. Results from two-way analysis of variance [N rate (N) × time (T)] are inset in each graph: NS, *, ** = nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively. Each symbol represents the mean of three replicates; means without letters or with a common letter on a given date are not significantly different at the 5% level (Duncan's new multiple range test).

such as Ca, S, and B was generally higher in Year 1 at the beginning of the growing season (April to July) than later in the season (July to October), whereas uptake of other nutrients such as K, Mg, Mn, and Zn was higher later in the season. However, when no N fertilizer was applied, plant growth was limited later in the season (Fig. 2), and uptake of many nutrients, including N, P, K, Ca, S, and B, was reduced, and only Cu uptake was higher. Unlike other nutrients, Cu uptake also increased

over winter between the first 2 years after planting, whether N was applied or not (Figs. 4 and 7). The plants were sprayed with copper sulfate fungicide (Bordeaux) after pruning, a common practice in blueberry to control bacterial canker (Strik et al., 1993).

Loss and net gain of nutrients. Loss and net gain of nutrients in plants fertilized with 50 kg·ha^{-1} N are summarized in Table 2. Total nutrient losses, including leaf abscission, pruning, and fruit harvest, averaged 4.85,

0.28, 2.38, 0.82, 0.25, and 0.54 g/plant of N, P, K, Ca, Mg, and S, respectively, and 51.1, 5.20, 0.57, 42.4, and 1.71 mg/plant of Fe, B, Cu, Mn, and Zn, respectively. At a density of 2691 plants/ha, each loss was equivalent to 13.1 kg·ha^{-1} N, 0.8 kg·ha^{-1} P, 6.4 kg·ha^{-1} K, 2.2 kg·ha^{-1} Ca, 0.7 kg·ha^{-1} Mg, 1.5 kg·ha^{-1} S, 138 g·ha^{-1} Fe, 14 g·ha^{-1} B, 1.5 g·ha^{-1} Cu, 114 g·ha^{-1} Mn, and 4.6 g·ha^{-1} Zn. More than half the N, P, K, Cu, and Zn was removed during fruit harvest, whereas most Ca, Mg, S, Fe, Mn,

Table 2. Loss and net gain of macro- and micronutrients in 'Bluecrop' blueberry during the first 2 years after planting.[z]

	Macronutrients (g/plant)						Micronutrients (mg/plant)				
	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur	Iron[y]	Boron	Copper	Manganese	Zinc
Loss											
Leaf abscission[x]	2.18	0.10	1.09	0.69	0.17	0.39	38.2	3.55	0.09	24.1	0.31
Pruning[w]	0.33	0.04	0.10	0.06	0.01	0.03	7.3	0.25	0.07	12.2	0.40
Fruit harvest	2.34	0.15	1.19	0.07	0.07	0.12	5.6	1.40	0.40	6.1	1.00
Gain											
Bud break to leaf abscission (Year 1)[v]	2.55	0.24	0.56	0.92	0.46	0.50	39.2	2.38	1.36	145	11.8
Bud break to harvest (Year 2)[u]	5.54	0.33	1.69	1.40	0.69	1.16	19.3	7.36	6.64	285	10.5

[z]Plants were fertilized each spring with 50 kg·ha^{-1} nitrogen.
[y]Net iron gain does not include iron in the roots.
[x]Estimated from leaves collected on 29 Oct. 2002.
[w]Calculated as the difference in wood sampled just before pruning (7 Feb. 2003) and wood sampled at budbreak (22 Apr. 2003).
[v]Calculated as the difference in nutrients of whole plants (minus any leaf nutrients) sampled just before leaf abscission (29 Oct. 2002) and whole plants sampled at budbreak (29 Apr. 2002).
[u]Calculated as the difference in nutrients of whole plants (minus any fruit nutrients) sampled at harvest (25 July 2003) and whole plants (minus any flower nutrients) sampled at budbreak (22 Apr. 2003).

and B was lost during leaf abscission. Although the nutrients in senesced leaves may be lost from plants in the short term, if leaves drop into the row, the nutrients would likely be available to plants again once leaves decompose (Strik et al., 2006).

The relative losses of nutrients were similar in plants fertilized with 0 and 100 kg·ha^{-1} N, although unfertilized plants (which allocated 32% total biomass to fruit) tended to lose proportionally more nutrients during harvest, whereas plants fertilized with 100 kg·ha^{-1} (which allocated only 13% total biomass to fruit) lost most nutrients during leaf abscission (data not shown).

Net nutrient gains averaged 8.09, 0.57, 2.25, 2.32, 1.15, and 1.66 g/plant of N, P, K, Ca, Mg, and S, respectively, and 58.5, 9.74, 8.00, 431, and 22.3 mg/plant of Fe (not including roots), B, Cu, Mn, and Zn, respectively (Table 2). When combined with the losses, plants fertilized with 50 kg·ha^{-1} N required the equivalent of 34.8 kg·ha^{-1} N, 2.3 kg·ha^{-1} P, 12.5 kg·ha^{-1} K, 8.4 kg·ha^{-1} Ca, 3.8 kg·ha^{-1} Mg, 5.9 kg·ha^{-1} S, 295 g·ha^{-1} Fe, 40 g·ha^{-1} B, 23 g·ha^{-1} Cu, 1273 g·ha^{-1} Mn, and 65 g·ha^{-1} Zn over 2 years. Thus, the relative amount of N, P, and K fertilizer used during establishment, including the N added during sawdust incorporation and in the nursery potting media at planting, was 21%, 3%, and 9%, respectively. Because plants were smaller, fewer nutrients were required when 0 or 100 kg·ha^{-1} N was applied and therefore percent fertilizer used in these treatments was even less.

This study has generated the first comprehensive nutrient accumulation data set from planting to fruit harvest for establishing highbush blueberry. The information was used to determine nutrient requirements of the young plants, a useful tool for developing efficient fertilizer management practices during the critical stage of field establishment. Plant uptake of most nutrients increased throughout the growing season, indicating that it is best to apply the majority of fertilizers in the spring; however, K, Mg, Mn, and Zn uptake was higher later in the season and therefore it may be better to apply these nutrients, if needed, in early or midsummer. Next, we plan to evaluate nutrient requirements in relation to N supply in mature plants.

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