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Abstract approved

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Bernadine C. Strik / Timothy L. Righetti

The effects of ^{15}N-labeled fertilizer applied to mature summer-bearing red raspberry (*Rubus idaeus* L.) plants were measured over two years. Four nitrogen (N) treatments were applied singularly at 0, 40, or 80 $kg \cdot ha^{-1}$ of N in early spring (budbreak), or split with 40 $kg \cdot ha^{-1}$ of N (unlabeled) applied at budbreak and 40 $kg \cdot ha^{-1}$ of N (^{15}N-labeled) applied 8 weeks later. Plants were sampled six times per year to determine N and ^{15}N content in the plant components throughout the growing season. Soil was also sampled seven times per year to determine inorganic N concentrations within the four treatments as well as a bare soil plot. There was a trend for the unfertilized treatment to have the lowest and for the split-N treatment to have the highest yield in both years. N application had no significant effect on plant dry weight or total N content in either year. Dry weight accumulation was 5.5 $t \cdot ha^{-1}$ and total N accumulation was 88-96 $kg \cdot ha^{-1}$ for aboveground biomass in fertilized plots in 2001. Of the total N present averaged over two years, 17% was removed in prunings, 12% was lost through primocane leaf senescence, 13% was removed through fruit harvest, 30% remained in the over-wintering plant, and 28% was considered lost or transported to the roots. Peak fertilizer N uptake occurred by July for the single N

applications and by September for the last application in the split-N treatment. This uptake accounted for 36-37% (single applications) and 24% (split application) of the ^{15}N applied. Plants receiving the highest single rate of fertilizer took up more fertilizer N while plants receiving the lower rate took up more N from the soil and from storage tissues. By mid-harvest, fertilizer N was found primarily in the fruit, fruiting laterals, and primocanes (94%) for all fertilized treatments; however, in the split application, the majority of this fertilizer N was located in the primocanes (60%). Stored fertilizer N distribution was similar in all fertilized treatments. By the end of the second year, 5-12% of the fertilizer acquired in 2001 remained in the fertilized plants. Soil nitrate concentrations increased after fertilization to 10.6 $g \cdot sampled\ volume^{-1}$, but declined to an average of 4.8 $g \cdot sampled\ volume^{-1}$ by fruit harvest. Seasonal soil N decline was partially attributed to plant uptake; however, leaching and immobilization into the organic fraction also contributed to the decline.

Nitrogen Use and Management in Red Raspberry

by
Hannah Gascho Rempel

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NITROGEN USE AND MANAGEMENT IN RED RASPBERRY

Introduction

The Pacific Northwest is one of the major red raspberry (*Rubus idaeus* L.) producers in the world. In 2002, 3.9 million t of raspberries from 4860 ha were harvested in Oregon and Washington (Oregon Agriculture Statistics Service, 2003). The main type of raspberry grown in the Pacific Northwest is the floricane-fruiting red raspberry cv. Meeker. Floricane-fruiting red raspberry plants have a biennial top and a perennial root system. First-year shoots (primocanes) develop from either vegetative buds on the roots or from basal buds of second-year canes (floricanes). The primocanes over-winter, and during their second spring, produce fruiting laterals and become floricanes. Both primocanes and floricanes exist simultaneously on a single plant. After harvest, the floricanes senesce.

During the last century, many fertilization and yield trials were evaluated to determine optimum nitrogen (N) application rates for red raspberry. Results were highly variable with N application recommendations ranging from 50 $kg \cdot ha^{-1}$ to 340 $kg \cdot ha^{-1}$ (Dale, 1989). Current fertilizer N recommendations in Oregon are 70-90 $kg \cdot ha^{-1}$ for established plants depending on crop load, cane vigor, plant age, soil type, and irrigation system (Hart *et al.*, 2000). These studies did not clearly determine the fate of the fertilizer N in the plant or soil, or determine how the portion of N taken up was partitioned within the plant.

Red raspberry is N limited, especially during periods of rapid growth (Kowalenko *et al.*, 2000). However, over-application of N fertilizers is costly to the producer and has negative effects on groundwater, freshwater lakes and ponds (Tisdale *et al.*, 1999). As a result, characterizing N cycling within production agriculture, in order to match fertilizer N application to plant N need, is important for both improved production and decreased environmental risk. Research in other perennial crops has revealed the possibility of maintaining production levels while simultaneously reducing fertilizer N inputs (Ledgard *et al.*, 1992; Sanchez *et al.*, 1991).

Plant N needs depend on the time of year; therefore, N partitioning within the plant varies throughout the growing season. Early in the season, blackberry (*Rubus* sp.) plants preferentially partitioned fertilizer N to new growth such as primocanes and fruit. At the end of the growing season the fertilizer N was stored in roots, crown and over-wintering primocanes (Malik *et al.*, 1991; Mohadjer *et al.*, 2001; Naraguma *et al.*, 1999). Time of application also affects within plant N partitioning. In apple (*Malus domestica* Borkh.) and pear (*Pyrus communis* L.), ^{15}N applied late in the season accumulated primarily in storage organs and was subsequently found in new growth the following spring (Khemira *et al.*, 1998; Sanchez *et al.*, 1992). Plant N need is also influenced by the fertilization history. Under N deficient circumstances, Taylor and van den Ende (1969) found that peach trees (*Prunus persica* L.) partitioned storage N preferentially to reproductive tissues over vegetative growth.

Because of their N storage capacity, mature perennial crops have a lower fertilizer recovery (FR) than that of agronomic crops. For example, mature highbush blueberry plants (*Vaccinium corymbosum* L.) recovered 32% of the applied fertilizer by the end of the growing season (Retamales and Hanson, 1989) compared to approximately 50% for corn (*Zea mays* L.) (Varvel and Peterson, 1990). However, the amount of fertilizer N reported as recovered might not provide a complete picture of overall N use in the plant. Fertilizer N uptake may impact the uptake and use of other forms of plant-available N, such as storage and soil N (Khemira *et al.*, 1998).

N cycling patterns have been studied in blackberry using ^{15}N (Malik *et al.*, 1991; Mohadjer *et al.*, 2001; Naraguma *et al.*, 1999); however, no work has been done with soil-applied ^{15}N in red raspberry. Currently, the only completed ^{15}N research in red raspberry examined the use of foliar ^{15}N applied in late summer to primocane-fruiting raspberry (Reickenberg and Pritts, 1996).

The objectives of this study were 1) to determine the effects of N fertilization rate and timing on N uptake, partitioning and yield in red raspberry using ^{15}N, 2) to determine the amount and partitioning of fertilizer N stored in the plant in the second year, and 3) to estimate the ability of the soil in a mature summer-bearing red raspberry field to supply N to the plant.

Materials and Methods

Experimental site and design

This study was conducted from 2000-2002 in a mature 'Meeker' red raspberry planting (0.13 ha) established in 1993 at the North Willamette Research and Extension Center (NWREC), Oregon State University, Aurora, Ore. The plants were established at 0.75 m within rows and 3.0 m between rows on a Quatama series soil (fine-loamy, mixed, mesic Aqualtic Haploxeralfs) having a pH of 5.8, a P concentration of 143 ppm and a K concentration of 279 ppm. The organic matter content was 3-4%. A 3.0 m within-row space was included after each plot to allow for separation by treatment during machine harvest of fruit. The field received overhead irrigation to supply ~2.5 cm of water per week during the growing season when rainfall was inadequate.

The four treatments in the study differed in rate and timing of N application. 1) No added N (*0N*), 2) 80 $kg\cdot ha^{-1}$ of N (18 $g\cdot plant^{-1}$), after budbreak (17 Mar.), (*80N*), 3) 40 $kg\cdot ha^{-1}$ of N (9 $g\cdot plant^{-1}$) on 17 Mar., (*40N*), 4) 40 $kg\cdot ha^{-1}$ of N (9 $g\cdot plant^{-1}$) on 17 Mar., (unlabeled fertilizer) and 40 $kg\cdot ha^{-1}$ of N (9 $g\cdot plant^{-1}$) on 17 May, (*split-N*). All fertilizer was applied in the form of granular ammonium sulfate. Depleted ^{15}N fertilizer (0.01 atom % ^{15}N) (Icon Isotopes, Summit, N.J.) was applied in 2001, as described above. In 2002, only unlabeled fertilizer was applied on similar dates and at the same rates as in 2001. Fertilizer was broadcast on the soil surface up to 0.3 m away on either side of the row. All treatment plots were fertilized with 35P – 66K each spring.

In the spring of 2000, six additional plots within the field were fertilized with 28 $kg \cdot ha^{-1}$ of N (unlabeled) in April plus 16.8 $kg \cdot ha^{-1}$ of N (unlabeled) and 44.8 $kg \cdot ha^{-1}$ N (5.0 atom % ^{15}N) (Icon Isotopes, Summit, N.J.) in May. These plots were included so that N storage could be observed over a longer period. These plants will be referred to as the "enriched plants" to differentiate them from the rate and timing treatments.

Plant sampling and analysis

Throughout 2001 and 2002, a single plant per replication was destructively harvested on each of 12 dates. In 2001 the destructive harvest schedule was as follows: 12 Apr. (one month after fertilizer application), 14 June (late bloom), 12 July (late fruit maturity), 15 Aug. (floricane senescence), 19 Sept. (prior to leaf senescence), and 10 Dec. (dormancy). Destructive harvest dates in 2002 followed the same phenological pattern as 2001: 18 Apr., 17 June, 11 July, 15 Aug., 18 Sept., and 10 Dec. Plants were excavated to a depth of up to 0.5 m. The southernmost plant in the plot was always sampled, so as not to disturb the growth of the neighboring plants in the row.

On each sampling date, the harvested plants were divided into large roots (greater than 1 cm in diameter), small roots (less than 1 cm in diameter), crown, primocanes, primocane leaves, floricanes, fruiting laterals (including leaves), and green fruit (when present). Due to the difficulty of recovering the whole root system without disturbing the neighboring plant, and the extensive growth habit of raspberry roots, the amount of root tissue recovered was considered to be a sub-sample of the entire root system. The separated plants were dried at 100 °C to a constant dry weight, randomly sub-sampled, and ground to pass a 40-mesh screen. Ground samples were sent to Isotope Services (Los Alamos, N.M.) for analysis of total N concentration and atom percent ^{15}N by mass spectrometry.

Atom percent values were converted to the proportion of the nitrogen derived from fertilizer (NDFF), using standard conversions (Hauck and Bremner, 1976):

$$\%NDFF = \frac{(\text{atom }\%\ ^{15}N_{\text{natural abundance}}) - (\text{atom }\%\ ^{15}N_{\text{sample}})}{(\text{atom }\%\ ^{15}N_{\text{natural abundance}}) - (\text{atom }\%\ ^{15}N_{\text{fertilizer}})} \times 100$$

The ^{15}N natural abundance was assumed equal to 0.366 atom percent.

Fresh fruit were harvested every 2-3 days throughout the harvest season using a Littau over-the-row rotary harvester (Littau Harvesters Inc., Stayton, Ore.). On each harvest date, total fresh yield and average berry weight per treatment (based on the weight of a 25 berry sub-sample per replication per harvest) were recorded. Total yield per plot and per plant were calculated, adjusting for missing plants when necessary. To determine fruit dry weight, a 25 berry sub-sample was collected from an early, middle and late harvest date each year and freeze-dried. The freeze-dried fruit were weighed, ground and analyzed for total N concentration and atom percent ^{15}N as described above. Average fruit N and ^{15}N concentrations were calculated.

Three single plants per replication from the enriched plots were destructively harvested during 2002 on the same six dates listed above and on 7 Feb. 2002 and 11 Feb. 2003. They were divided, dried, ground and analyzed as previously described.

In Sept. 2001 and 2002, the following data on cane growth were collected: the number of plants and primocanes per plot; cane length and cane diameter (0.3 m above ground) on a sub-sample of three floricanes and three primocanes per plot; the number of fruiting sites and lateral length on one lateral from each of the apical, middle and basal section of the cane (n=3 canes/plot); and the total number of nodes and nodes with a lateral(s), and percent budbreak (n=3 canes/plot).

Floricanes were pruned and removed from the field after the September measurements and destructive harvest were completed each year. Primocanes were not suppressed in this study.

To determine the presence of residual ^{15}N remaining in the field between labeled fertilizer application (2001) and unlabeled fertilizer application (2002), soil was removed from a plot that had received a labeled fertilizer application the previous year. Corn seeds were planted in this soil to act as indicator plants for residual ^{15}N. The plants were grown in the greenhouse for five weeks. The corn was harvested, separated into aboveground portion and roots, dried, weighed, ground, and analyzed for N concentration and ^{15}N as previously described for the raspberry plants.

Soil sampling and analysis

Soil samples were taken from each treatment plot within two days of each destructive harvest date in order to determine the amount of plant-available soil N. In addition, soil was sampled in March of each year prior to fertilizer application to establish a baseline amount of soil N. A bare soil plot containing no plants or weeds was also sampled each time. Samples were taken to two depths, 0.15 and 0.30 m, on each date. Sub-samples were taken from within each replication, homogenized, and analyzed at the Central Analytical Lab (Corvallis, Ore.) for ammonium (NH_4-N) and nitrate (NO_3-N) concentrations.

The soil data were converted from ppm to g·sampled volume^{-1} in order to avoid inflating the amount of inorganic N reported in the soil. These units more accurately represented the method of fertilizer application since fertilizer was broadcast within the plant row, but was not applied in the alley between plant rows. The conversion from ppm to g·sampled volume^{-1} was carried out as follows:

$$\text{g}\cdot\text{sampled volume}^{-1} = \left[\text{ppm (mg}\cdot\text{kg}^{-1}) \times (\text{kg}\cdot(1\times10^{6}\text{ mg})^{-1})\right] \times \left[\text{soil bulk density (g}\cdot\text{cm}^{-3})\right] \times \left[\text{fertilized area (cm}^{2}\cdot\text{sample area}^{-1})\right] \times \left[\text{sample depth (cm)}\right]$$

The bulk density of the soil was 1.2 g·cm^{-3}. The area of fertilization per plant was 0.75 m by 0.60 m. While the possibility for error remains in this conversion, it provided a more accurate picture of N in the soil than kg·ha^{-1} for this study.

Soil temperatures were measured within the experimental site to two soil depths (0.15 and 0.30 m) from Apr. 2001 through Nov. 2002 using a Hobo 8K four-channel datalogger (Onset Computer Corp., Bourne, Mass.). Air temperature data were recorded at a weather station at NWREC.

Statistical analyses

The experimental design was completely randomized. The experimental unit was the plot which was replicated three times. Since plants were not randomly chosen for destructive harvest, sample dates were not independent and analysis was not performed between dates. Treatments were the rates and timing of fertilizer N application. Analysis of variance was performed for rate and timing effects using the GLM procedure in SAS (SAS Institute Inc., 1999). Treatment means were compared using a Fisher's protected least significant difference (LSD) test. Contrasts were also performed in SAS (SAS Institute Inc., 1999) to separate the effects of rate and timing for those plots receiving N fertilizer.

Results

Dry weight accumulation

No significant differences were found in total plant dry weight content among treatments in 2001 or 2002, so dry weight values were pooled across treatments (see Appendix A-1). In general, no significant differences were found in dry weight partitioning among treatments. In 2001, whole plant dry weight (excluding roots) increased from a low initial value of 608 $g \cdot plant^{-1}$ in April (one month after N application) to a maximum of 1676 $g \cdot plant^{-1}$ in July (mid-harvest), and then declined throughout the remainder of the growing season (Fig. 1A). In 2002, the first destructive harvest occurred after early spring growth had begun (see Appendix A-2), thereby missing a period of initial growth. As a result, by the first sampling in 2002, pooled floricane dry weights were approximately double the values observed at the end of the first year. Aboveground plant dry weight declined from mid-harvest through December in 2002 as in the previous year.

Floricane tissues increased in dry weight early in the growing season then declined; primocane growth continued past fruit harvest. In 2002, crown dry weight decreased from 391 $g \cdot plant^{-1}$ in April to 187 $g \cdot plant^{-1}$ in July and then increased after the fruiting season was complete (Fig. 1A). Roots are not included as the amount sampled only represented a portion of the total root system of the plant.

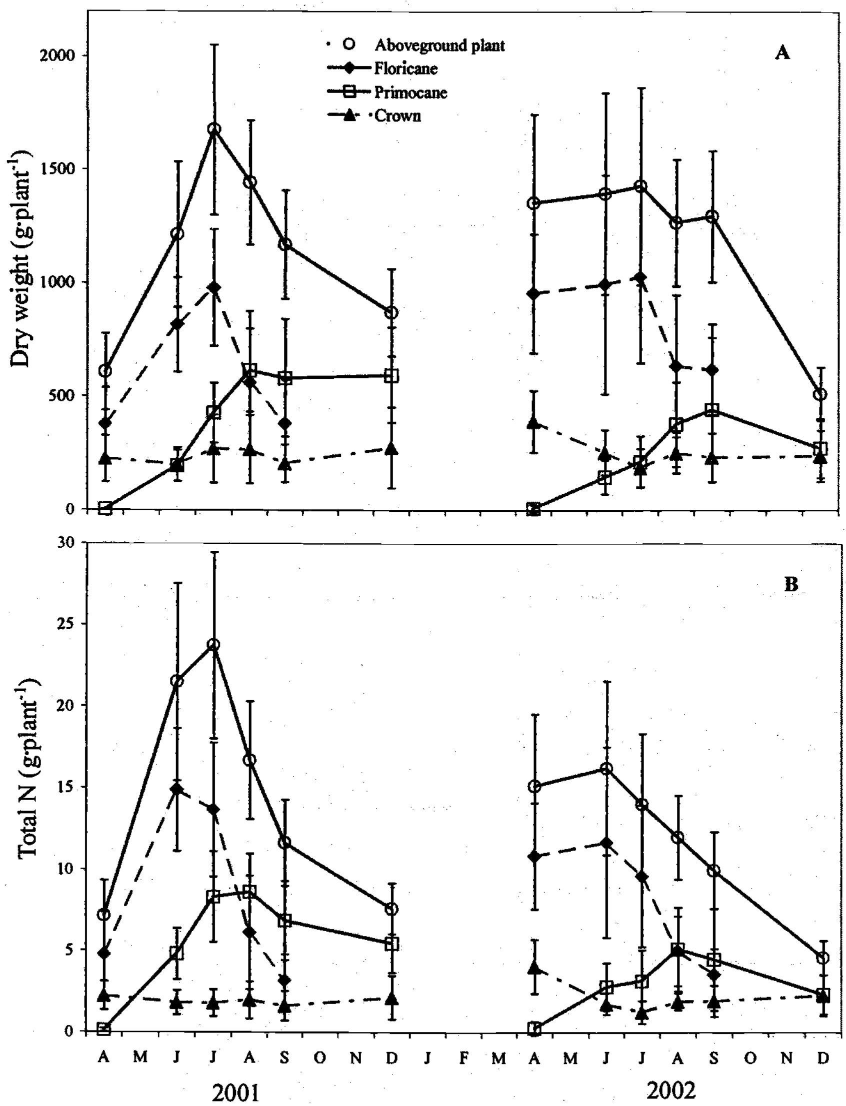

Figure 1. A) Dry weight content and B) total N content pooled across all treatments for 'Meeker' red raspberry plants excavated in Apr. through Dec. of 2001 and 2002. Aboveground plant included all tissues except roots. Floricanes included fruiting laterals, canes, and green and red fruit (when present). Primocanes included canes and leaves. Floricanes were removed annually in late September. Bars indicate standard deviation of the mean (n=3).

Nitrogen accumulation

Total N content was pooled across treatments, as there were generally no significant differences among treatments on a whole plant basis (excluding roots) in

2001 or 2002 (see Appendix A-3). In general, no significant differences were observed in the percentage of total N present in a given tissue (N partitioning) in 2001 or 2002. However, the amount of N removed in the 80N fruit in 2001 was significantly higher than the N removed in the 40N or split-N fruit. In 2002, the most N was removed in the split-N fruit (Table 1).

Patterns of N accumulation were similar to dry matter accumulation with regard to differences between years (Fig. 1B). The period of initial N accumulation occurred prior to the first sampling in 2002. Consequently, total N accumulation at the initial 2002 sampling was nearly double the value observed at the end of the first year.

Total N partitioning did not exactly mirror dry weight partitioning (data not shown). While N partitioning was similar to dry weight partitioning in April and December, once leaf growth commenced, fruiting laterals and primocane leaves had a higher percentage of total plant N than their percentage of whole plant dry weight. N was exported from the crown and floricanes throughout the growing season. Most of this N was remobilized to the fruiting laterals in June. The percentage of total N partitioned to floricanes declined from 55% and 50% in April, to 10% and 26% in September of 2001 and 2002, respectively. In June, fruiting laterals accounted for 50% of the total N in 2001 and 42% in 2002. As floricanes senesced, primocanes and primocane leaves received remobilized N through September. In August, primocane leaves accounted for 32% of the total N in 2001 and 25% in 2002. Primocanes comprised 31% and 28% of the total N in September of 2001 and 2002, respectively. Fourteen percent of the total N was partitioned to red fruit in both years.

Of the total N present, averaged over both years, 17% was removed in September prunings, 12% was lost through primocane leaf senescence, 13% was accounted for in harvested fruit, 30% remained in the over wintering plant, and 28% was considered lost or transported to the roots (Table 1). Average total N removed from the field was approximately 40 kg·ha^{-1} of N.

Table 1. An accounting of the total N in g·plant^{-1} in 'Meeker' red raspberry over two years.

			Total N (g·plant^{-1})			
Treatment[z]	N applied/ accounted for[y]	Harvested fruit[x]	Prunings[w]	Primocane leaf senescence[v]	Over-wintering plant[u]	Transported to roots or lost[t]
			2001			
0N	0	2.4 a[s]	3.7 (8.5)	2.9	9.2	6.0
80N	18	4.7 b	1.9 (3.0)	2.7	6.9	11.4
40N	9	2.7 ac	2.6 (6.1)	2.7	5.3	11.6
Split-N	9+9	3.8 bc	4.5 (6.9)	4.8	8.4	8.3
p-value	-	0.02	0.21 (0.30)	0.22	0.69	0.66
			2002			
0N	11.2	1.0 a	2.2 (5.5)	0.9	3.5	10.1
80N	10.8	1.8 a	4.3 (6.0)	2.3	5.7	5.3
40N	13.5	1.2 a	4.2 (2.6)	2.0	3.5	11.1
Split-N	10.5	3.7 b	3.5 (5.8)	1.6	5.4	13.0
p-value	0.79	0.00	0.38 (0.17)	0.59	0.50	0.10

[z] Treatments applied were 0 kg·ha^{-1} of N (0N), 80 kg·ha^{-1} of N (80N) in Mar. (labeled in 2001), 40 kg·ha^{-1} of N (40N) in Mar. (labeled in 2001), and 40 kg·ha^{-1} of N in Mar. (unlabeled) + 40 kg·ha^{-1} of N (split-N) in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.
[y] N accounted for indicates the amount of N measured in the crown and floricane in Apr. 2002.
[x] Red fruit total N based on the cumulative season's harvest.
[w] Floricane and fruiting lateral tissue removed in either September or August (in parentheses).
[v] An estimate based on the primocane leaves sampled in September.
[u] An estimate based on the primocane and crown sampled in December.
[t] The roots collected represented a subsample of the entire root system; therefore, their total N content was not known.
[s] Means followed by the same letter within year are not significantly different (ANOVA, Fisher's LSD, P>0.05).

N concentration in large and small roots ranged from 0.56% to 2.06% N throughout 2001 and 2002. Large roots decreased to an average low of 0.83% N during fruiting in 2001, then increased after harvest to a high of 1.45% N in Dec. 2001. Trends were similar in 2002. Small roots in the 0N treatment had a significantly lower N concentration than small roots in the 80N treatment from Aug. to Dec. 2001, and from June to Sept. 2002. In addition, the N concentration in primocane leaves sampled in August in the 0N treatment [2.28% N] was significantly lower than that in the higher N treatments (80N and split-N) in both years [3.01% N] (see Appendix A-4).

Uptake of fertilizer nitrogen – Year 1

The effect of N application rate (40N vs. 80N) on fertilizer N uptake was significant on a whole plant basis (excluding roots) in June and September only (see Appendix A-5). However, the 80N treatment generally contained at least a 67% higher mass of nitrogen derived from fertilizer (NDFF) than the 40N treatment throughout the fruiting season. Greater uptake in both primocane and floricane tissues accounted for the higher mass of NDFF in the 80N treatment in June. In September, the difference was due to a higher mass of NDFF in primocane tissues in the 80N than in the 40N treatment (Table 2). Peak NDFF accumulation for the 80N treatment occurred in July at 6.50 $g{\cdot}plant^{-1}$ (Fig. 2A). NDFF uptake for the 80N treatment was rapid from April to July, then declined through December.

Table 2. An accounting of the nitrogen derived from fertilizer (NDFF) in g·plant^{-1} in 'Meeker' red raspberry over two years.

Treatment[z]	NDFF (g·plant^{-1})					
	N applied/ accounted for[y]	Harvested fruit[x]	Prunings[w]	Primocane leaf senescence[v]	Over-wintering plant[u]	Transported to roots or lost[t]
			2001			
80N	18	1.31 a[s]	0.53 (0.88)	1.07 a	1.80	1.79
40N	9	0.25 b	0.32 (0.85)	0.47 b	0.90	1.42
Split-N	9+9	0.19 b	0.34 (0.25)	0.74 ab	0.77	0.12
p-value	-	0.00	0.28 (0.36)	0.02	0.24	-
			2002			
80N	1.74	0.14 a	0.57 (1.05 a)	0.072	0.33 a	1.26
40N	0.96	0.048 b	0.42 (0.18 b)	0.040	0.088 b	0.65
Split-N	0.47	0.15 a	0.36 (0.43 b)	0.049	0.19 ab	0.44
p-value	0.20	0.00	0.73 (0.00)	0.10	0.02	-

[z] Treatments applied were 0 kg·ha^{-1} of N (0N), 80 kg·ha^{-1} of N (80N) in Mar. (labeled in 2001), 40 kg·ha^{-1} of N (40N) in Mar. (labeled in 2001), and 40 kg·ha^{-1} of N in Mar. (unlabeled) + 40 kg·ha^{-1} of N (split-N) in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.
[y] NDFF accounted for indicates the amount of NDFF measured in the crown and floricane in Apr. 2002.
[x] Red fruit NDFF based on the cumulative season's harvest.
[w] Floricane and fruiting lateral tissue removed in either September or August (in parentheses).
[v] An estimate based on the primocane leaves sampled in September.
[u] An estimate based on the primocane and crown sampled in December.
[t] The roots collected represented a subsample of the entire root system; therefore, their NDFF content was not known. Data were calculated by subtracting all NDFF removed from the peak NDFF value during the season.
[s] Means followed by the same letter within year are not significantly different (ANOVA, Fisher's LSD, P>0.05).

Few significant differences were seen in fertilizer N uptake between timing treatments (40N vs. split-N); however, timing of application was significant for whole plant NDFF accumulation (excluding roots) during June (see Appendix A-5). The 40N treatment accumulated 4.5 times as much fertilizer N as the split-N treatment in June. Most of this difference was reflected in fertilizer N uptake in new growth (fruiting laterals, green fruit, primocanes, and primocane leaves); the 40N treatment accumulated 2.24 g·plant^{-1} of fertilizer N in new growth vs. 0.47 g·plant^{-1} in new

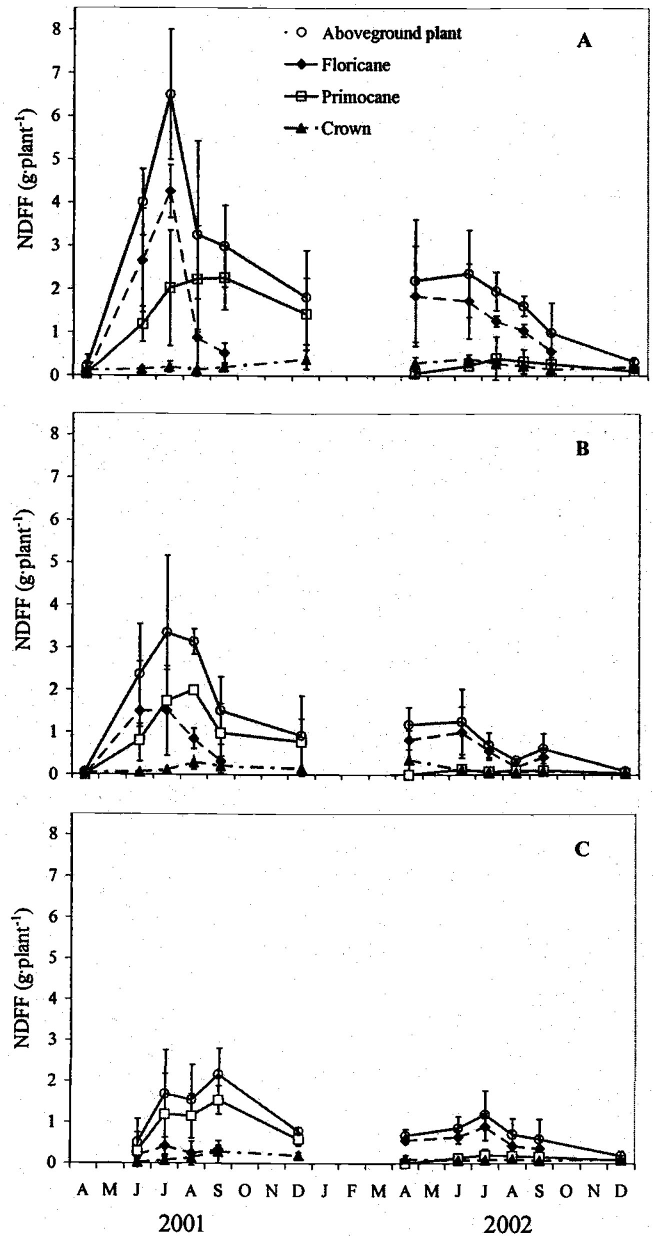

Figure 2. Nitrogen derived from fertilizer (NDFF) content from Apr. through Dec. of 2001 and 2002 for three labeled fertilizer applications, A) 80 kg·ha^{-1} of N, B) 40 kg·ha^{-1} of N, and C) 40 kg·ha^{-1} of N unlabeled fertilizer in Mar. + 40 kg·ha^{-1} of N labeled fertilizer in May. Aboveground plant included all tissues except roots. Floricanes included cane, fruiting laterals, and green and red fruit (when present). Primocanes included canes and leaves. Floricanes were removed annually in September. Bars indicate standard deviation of the mean (n=3).

growth for the split-N treatment in June. However, in the split-N treatment the labeled fertilizer had only been applied in May, whereas the single 40N treatment was applied in March. Peak NDFF accumulation occurred in July at 3.35 $g{\cdot}plant^{-1}$ for the 40N treatment (Fig. 2B). NDFF accumulation was most rapid for the 40N treatment between April and July, uptake plateaued in August, then declined in September and December. Peak fertilizer N accumulation for the split-N treatment was in September at 2.16 $g{\cdot}plant^{-1}$ (Fig. 2C). NDFF accumulation was most rapid for the split-N treatment from June to July, increased again from August to September, and declined in December.

Initial fertilizer N uptake was low for all treatments. Initially the fertilizer N that was taken up moved primarily into the crown. In June, the fruiting laterals were the main sink for fertilizer N for both the 40N and the 80N treatments. In the split-N treatment, much of the May-applied fertilizer N was allocated to the primocane leaves in June. In July, fruiting tissues were still an important sink for fertilizer N, especially for the 80N treatment (Table 2); however, allocation of fertilizer N to primocane tissues was increasing. Fertilizer N in primocanes continued to increase through leaf senescence. Floricanes took up little fertilizer N, especially from the last half of the split-N treatment (Fig. 2C).

The 80N plants took up more fertilizer N than did the 40N and split-N plants, often containing between 67% to 100% more %NDFF (the percentage of total N that came from labeled fertilizer) than the 40N plants on a whole plant basis (Fig. 3). Red fruit in the 80N treatment contained three times more %NDFF than red fruit in any other treatment (Table 3). By December, the 80N treatment had the highest %NDFF in storage tissues of any treatment. For example, the small roots of the 80N, 40N, and split-N treatments contained 29%, 20%, and 12% NDFF, respectively.

Labeled fertilizer N recovery at peak NDFF accumulation was 36%, 37%, and 24% for the 80N, 40N, and split-N treatments, respectively. In July at the 80N treatment's peak NDFF accumulation, 38% of the fertilizer recovered was found in the floricane tissues, 31% was in the primocane tissues, and 20% was in red fruit. For the 40N treatment in July, 32% of the fertilizer recovered was found in the floricane tissues, 52% was in the primocane tissues and 8% was in the red fruit. The split-N treatment's peak NDFF uptake was in September at which point primocane tissues contained 71% of the fertilizer recovered.

Corn grown in ^{15}N-labeled soil the year after labeled fertilizer application contained less than 0.9 %NDFF. Therefore it was assumed, based on these data and previous work at this experimental site (Mohadjer *et al.*, 2001), that the uptake of residual labeled fertilizer in the second year was minimal.

<u>Stored fertilizer nitrogen – Year 2</u>

The amount of fertilizer N accounted for in Apr. 2002 was similar to that measured in Dec. 2001 (Table 2). Stored fertilizer N distribution was similar in all three treatments (Fig. 2). NDFF content slowly declined throughout the 2002 growing season to a low of 0.1 to 0.3 g·plant^{-1} of NDFF (Table 2). By Dec. 2002, 7% of the

NDFF acquired in 2001 remained in the 80N treatment, 4% remained in the 40N treatment and 8% remained in the split-N treatment (Table 2).

In 2002, floricanes and fruiting laterals (formerly primocanes in 2001) retained the highest mass of NDFF in all treatments and did not remobilize this N to other plant parts (Fig. 2). In September, floricane tissues still contained an average of 62% of the mass of NDFF in the plant. The 80N and split-N treatments had significantly more NDFF removed in fruit than did the 40N treatment (Table 2).

Overall the NDFF concentration remained constant or declined slightly during 2002 for all treatments to a low of 3-6% NDFF per plant (Fig. 3). However, the 80N treatment maintained a significantly higher %NDFF per plant than either the 40N or split-N treatments from Apr. to Aug. 2002 (see Appendix A-6).

NDFF concentration in the plant parts varied throughout the season, and was generally highest in the 80N treatment and lowest in the split-N treatment (see Appendix A-6). In April, %NDFF in the 80N floricane tissues [20%] was significantly higher than in the other treatments [7% for the 40N treatment, and 6% for the split-N treatment]. Also in April, roots contained 7% to 14% NDFF, a concentration as high or higher than in all other tissues at this time, except for floricane tissues. In general, roots in the 80N treatment contained approximately twice as much %NDFF as the other treatments. Overall the %NDFF in most tissues slowly declined throughout the season in all treatments. By September, no significant differences in %NDFF between treatments were found (see Appendix A-6).

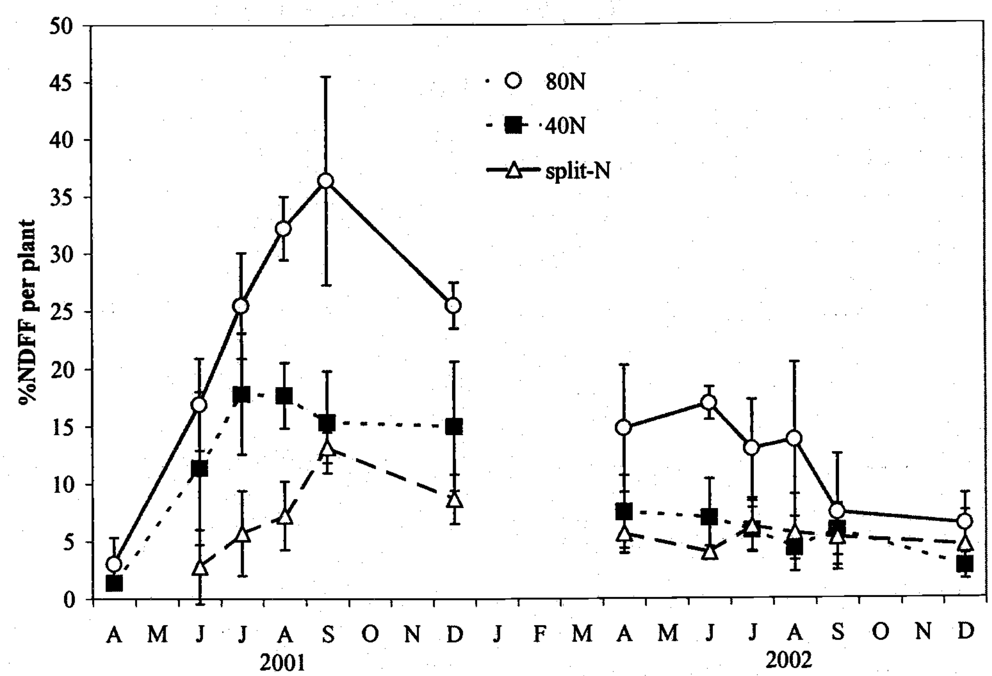

Figure 3. Percentage of nitrogen derived from the fertilizer (NDFF) of aboveground plants in Apr. through Dec. of 2001 and 2002 for three labeled fertilizer applications, 80 kg·ha^{-1} of N (80N), 40 kg·ha^{-1} of N (40N), and 40 kg·ha^{-1} of N unlabeled fertilizer in Mar. + 40 kg·ha^{-1} of N labeled fertilizer in May (split-N). Bars indicate standard deviation of the mean (n=3).

The enriched plants were sampled two years after labeled (5.0 atom % ^{15}N) N was applied. In Feb. 2002, whole plant NDFF content (excluding roots) was 0.8 g·plant^{-1} (see Appendix A-7). NDFF content peaked in June 2002 at 1.4 g·plant^{-1} and declined throughout the remainder of the season to 0.2 g·plant^{-1}. Most of the increase in June was due to increased NDFF remobilization to floricane tissues. Crown NDFF content declined from an initial 0.3 g·plant^{-1} through fruiting, then increased as fertilizer N was remobilized throughout the fall reaching 0.2 g·plant^{-1} in December. Except for a peak of 7% NDFF during June, %NDFF remained at approximately 4% throughout 2002 and declined to 3% in Feb. 2003 (see Appendix A-8).

Fruit yield and plant growth parameters

In 2001 and 2002, the 0N treatment tended to have the lowest yield and the split-N treatment had the highest yield (Table 3). The 80N treatment had a significantly higher %NDFF in the fruit than the other fertilized treatments in both years (Table 3). Average N concentration in the fruit was higher for all fertilized treatments than for the 0N treatment in 2002. Berry weight in the fertilized treatments in 2002 was significantly higher than in the 0N treatment (Table 3).

Table 3. Effect of nitrogen fertilizer application on yield per plant and nitrogen partitioning to fruit of 'Meeker' red raspberry.

Nitrogen application ($kg{\cdot}ha^{-1}$)	Total fresh yield ($kg{\cdot}plant^{-1}$)	Yield dry weight ($g{\cdot}plant^{-1}$)	Fruit weight (g)	Cull weight ($g{\cdot}plant^{-1}$)	Fruit N[z] (%)[y]	Fruit NDFF[z] (%)
			2001			
0N[x]	1.4	230	2.5 a[w]	63.8	1.02	NA
80N	1.9	312	2.6 ac	78.3	1.43	29.4 a
40N	1.7	263	2.7 bc	66.3	1.05	9.2 b
Split-N	2.2	359	2.7 bc	70.4	1.06	5.0 b
p-value	0.16	0.14	0.02	0.29	0.00	0.00
			2002			
0N	1.0 a	181 a	2.1 a	116.2 a	0.53 a	NA
80N	1.4 a	251 a	2.3 b	165.2 bc	0.74 b	7.7 a
40N	1.1 a	218 a	2.2 b	154.3 ac	0.63 c	3.5 b
Split-N	2.1 b	388 b	2.3 b	195.1 bc	0.92 d	4.2 b
p-value	0.03	0.03	0.02	0.03	0.00	0.00

[z]Average for three sample dates – early, middle and late harvest. NDFF = Nitrogen derived from fertilizer.
[y]%N based on dry weight.
[x]Treatments applied were 0 $kg{\cdot}ha^{-1}$ of N (0N), 80 $kg{\cdot}ha^{-1}$ of N (80N) in Mar. (labeled in 2001), 40 $kg{\cdot}ha^{-1}$ of N (40N) in Mar. (labeled in 2001), and 40 $kg{\cdot}ha^{-1}$ of N in Mar. (unlabeled) + 40 $kg{\cdot}ha^{-1}$ of N (split-N) in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.
[w]Means followed by the same letter within years are not significantly different (ANOVA, Fisher's LSD, P>0.05).

A trend was observed in 2001, which became significant in 2002, for primocanes to be longer in the fertilized treatments than in the 0N treatment (Table 4). Canes in the fertilized treatments were an average of 0.2 to 0.4 m longer in 2001 and 0.6 to 0.8 m longer in 2002 than in the 0N treatment. The decrease in primocane length over time revealed the general decline in vigor experienced by the 0N treatment.

Table 4. Cane characteristics of 'Meeker' red raspberry (n=3, with 3 canes sub-sampled per plot). Measurements were taken in Sept. 2001 and 2002.

Nitrogen application (kg·ha^{-1})	Primocane length (cm)	Floricane length (cm)	Primocane internode length (cm)	Budbreak (%)	Plants per plot[z]	Primo-canes per plot[z]
			2001			
0N[y]	296	264	5.1	42 a[x]	11.3	129.7
80N	325	289	5.4	39 a	12.0	126.0
40N	320	280	5.1	40 a	11.7	119.3
Split-N	345	268	5.4	56 b	11.7	174.7
p-value	0.34	0.51	0.45	0.03	0.94	0.17
			2002			
0N	224 a	318	4.5	39	6.7	45.7
80N	297 b	332	4.6	45	7.0	54.3
40N	281 b	319	4.6	36	7.0	48.7
Split-N	303 b	352	5.2	36	6.7	58.3
p-value	0.00	0.27	0.21	0.58	0.98	0.68

[z]Six destructive harvests took place between the 2001 and 2002 measurements, thus there were fewer plants and canes in 2002.
[y]Treatments applied were 0 kg·ha^{-1} of N (0N), 80 kg·ha^{-1} of N (80N) in Mar. (labeled in 2001), 40 kg·ha^{-1} of N (40N) in Mar. (labeled in 2001), and 40 kg·ha^{-1} of N in Mar. (unlabeled) + 40 kg·ha^{-1} of N (split-N) in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.
[x]Means followed by the same letter within years are not significantly different (ANOVA, Fisher's LSD, P>0.05).

Soil nitrogen concentration

The same patterns were seen in the 0-0.30 m data (Fig. 4) as in the 0-0.15 m data in both years (see Appendix A-9). In the bare soil and 0N treatment, NO_3-N concentrations remained below 3.5 g·sampled volume^{-1} throughout both years, whereas in the fertilized plots, N application caused a sharp increase in NO_3-N which then declined throughout the growing season (Fig. 4a).

Fertilizer uptake by the plants was small in April, while soil N levels were still high. The difference between NO_3-N levels in the bare soil and fertilized plots in Apr. 2001 was approximately 12 g·sampled volume^{-1}.

In 2001, NO_3-N levels in the top 0.3 m declined between April and September (Fig. 4a) at which point all fertilized plots fell below NO_3-N levels considered excessive (<30 ppm) (Marx *et al.*, 1999). In 2002, NO_3-N levels in the top 0.3 m declined rapidly between April and July (Fig. 4a). By June 2002, the 40N treatment fell below excessive NO_3-N levels. The remaining fertilizer treatments also fell below excessive NO_3-N levels by July 2002. Nitrate levels in the fertilized plots showed no significant difference from the bare soil plots by July 2001 and 2002 (Fig. 4a). While irrigation practices were similar both years, rainfall accumulation was greater in 2002 than in 2001 (see Appendix A-10).

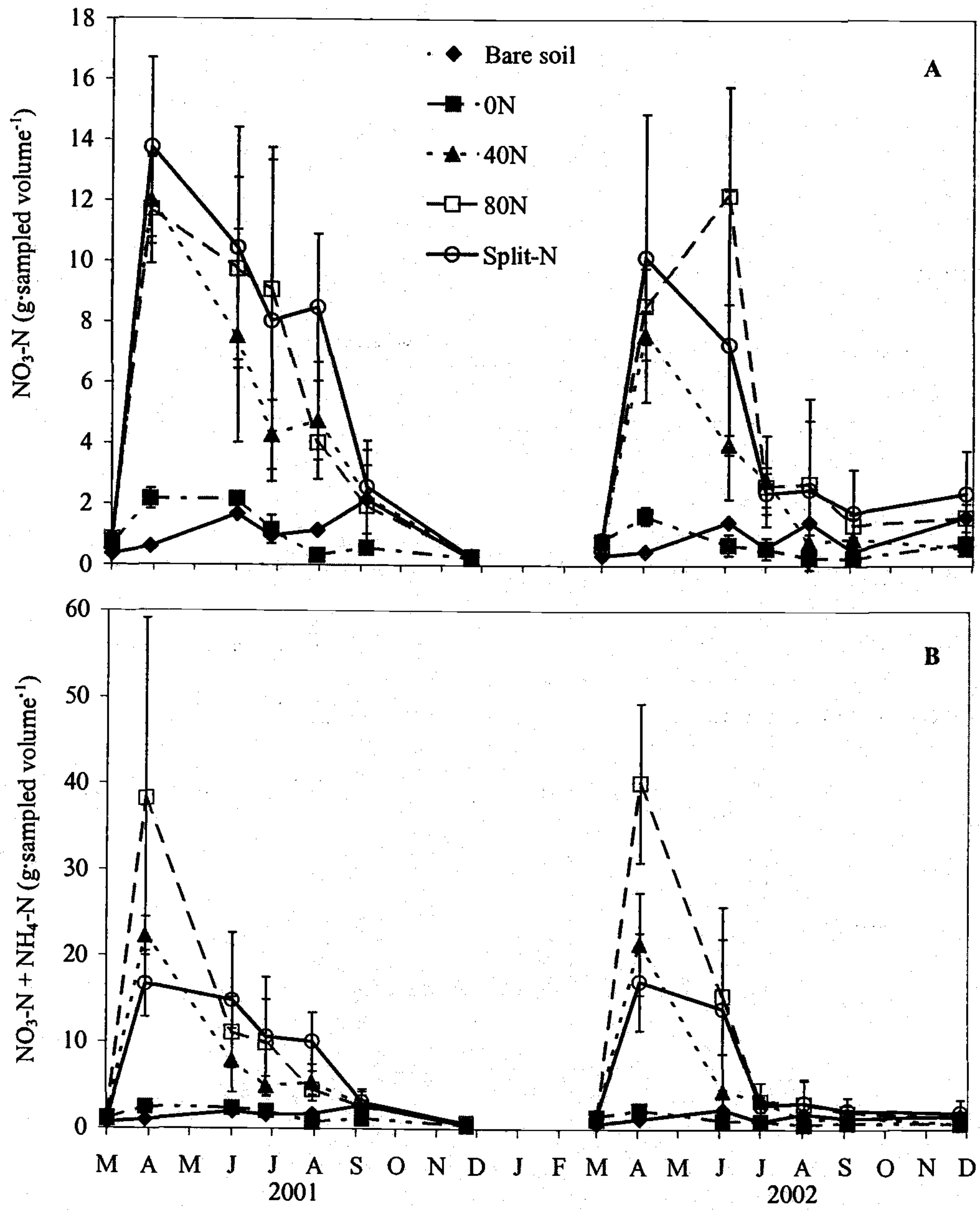

Figure 4. a) Soil NO_3-N and b) total inorganic N content (NO_3-N + NH_4-N) for the sum of two incremental depth (0-15 cm + 15-30 cm) measurements for four N applications, 0 kg·ha^{-1} of N (0N), 80 kg·ha^{-1} of N (80N), 40 kg·ha^{-1} of N (40N), and 40 kg·ha^{-1} of N in Mar. + 40 kg·ha^{-1} of N in May (split-N), as well as a bare soil plot. Measurements were made at the experimental site from Mar. through Dec. of 2001 and 2002. The sampled volume was 0.14 m^3, equivalent to the estimated volume occupied by a raspberry plant. Bars indicate standard deviation of the mean (n=3).

Discussion

Dry weight and total N accumulation

Dry weight and N accumulation in this study were consistent with previous research in red raspberry (Dean *et al.*, 2000; Kowalenko, 1994; Wright and Waister, 1980). Dry weight accumulation of aboveground plants was 5.5 $t \cdot ha^{-1}$ in 2001. N accumulation was 88-96 $kg \cdot ha^{-1}$ for aboveground biomass in fertilized plots in 2001.

Dry weight and N accumulation did not follow expected patterns in 2002. Floricane dry weights pooled across treatments in Apr. 2002 were approximately double the values from the end of the previous year. Red raspberry growth has been shown to vary annually based on differences in temperature and precipitation (Kowalenko, 1994). In the present study, temperatures and precipitation during the spring of 2002 were higher than in 2001 (see Appendices A-1 & A-2), possibly causing increased root growth earlier in the season and subsequent early increases in aboveground growth.

Most caneberries have relatively low dry weight and N accumulation values on a $kg \cdot ha^{-1}$ basis (Dean *et al.*, 2000; Mohadjer *et al.*, 2001). This fact is attributed to the wide inter-row spacings required for machine harvest. In addition, raspberry plant size is smaller and yield is lower compared to other caneberries. For example, the average cumulative total dry-matter yield of 'Kotata' trailing blackberry fruit was 1.6 $kg \cdot plant^{-1}$ (Mohadjer *et al.*, 2001), whereas the average cumulative dry-matter yield of 'Meeker' red raspberry fruit in this study and 'Willamette' red raspberry in a previous study (Kowalenko, 1994) was 0.3 kg·plant^{-1}. N removal in fruit averaged 3.2 g·plant^{-1} in this study and in 'Willamette' red raspberry (Kowalenko, 1994) while 23.8 g·plant^{-1} of N were removed in 'Kotata' trailing blackberry (Mohadjer *et al.*, 2001). Annual total N accumulation (excluding roots) was 16 g·plant^{-1} in this study, 19 g·plant^{-1} in 'Willamette' red raspberry (Kowalenko, 1994), and 27 g·plant^{-1} in 'Kotata' trailing blackberry (Mohadjer *et al.*, 2001). The lower fruit yield and N content suggests a reduced N requirement for raspberry plants in comparison to trailing blackberry.

No significant differences in dry weight or N content were observed among treatments. The raspberry plants in this study showed high variability in size within treatments, which accounted for much of the variability in total N among treatments. However, a trend was observed of less N accumulation in the unfertilized treatment.

Floricane removal or pruning typically occurs any time after harvest throughout the fall. Less N is available to be remobilized within the plant if the floricanes are removed too early. In this study, pruned floricanes were removed from the field; however, typical grower practice is to flail the prunings in the field, thereby returning some of the N to the soil through decomposition. In kiwifruit (*Actinidia deliciosa* 'Hayward'), 9% of the ^{15}N in prunings were recovered by the plants within two years (Ledgard *et al.*, 1992). In this study, average N losses through floricane removal for 2001 and 2002 were 25.6 kg·ha^{-1} of N if pruning was performed in mid-August. However, if pruning was done in mid-September, allowing more time for floricane N to be remobilized to storage tissues, losses were reduced to 15.5 $kg \cdot ha^{-1}$ of N.

A limited yield response was seen by treatment. A lack of yield response to fertilizer rate has been observed in previous red raspberry research in the Pacific Northwest (Chaplin and Martin, 1980; Kowalenko, 1994). Observed yield increases due to higher fertilizer rates were sometimes directly related to an increase in berry weight (Kowalenko, 1981), although this was not always the case (Chaplin and Martin, 1980). In this study, a significant increase in berry weight in the fertilized treatments compared to the unfertilized treatment was observed in the second year.

A trend was observed in 2001 of increased primocane length in fertilized plants compared to the unfertilized plants. This trend became significant in 2002. Most studies examining the N requirements of raspberry have pruned excess primocanes and topped the remaining primocanes during the winter (Dean *et al.*, 2000; Kowalenko, 1994; Kowalenko *et al.*, 2000). While some growers follow this practice, the removal may have masked trends of a decrease in primocane length due to insufficient N. When the removed prunings were measured, their dry weight was found to increase with increasing N rate (Kowalenko *et al.*, 2000). Strik and Cahn (1999) showed, in two out of three years, that topping primocanes resulted in lower yields per plant. The decrease in primocane length in the unfertilized plots mimicked the practice of topping and contributed to an overall decline in plant vigor in this treatment.

The N concentration in primocane leaves sampled in August in the unfertilized treatment was lower than that of the fertilized treatments in both years, and fell below the recommended concentration in 2002 also revealing an overall decline in plant health for the unfertilized treatment (Hart *et al.*, 2000).

Distribution of fertilizer N

Labeled fertilizer N uptake was low compared to blackberry (Mohadjer *et al.*, 2001) and other perennial crops (Feigenbaum *et al.*, 1987; Khemira *et al.*, 1998). During the on-year in 'Kotata' trailing blackberry, the maximum NDFF content was 13.9 $g{\cdot}plant^{-1}$ (excluding roots) (Mohadjer *et al.*, 2001). In the current study, maximum fertilizer N uptake was 6.5 $g{\cdot}plant^{-1}$ (excluding roots). This difference can probably be attributed to raspberry's smaller plant size and lower yield.

However, when fertilizer N was considered as a percentage of total N in the plant, %NDFF averaged 26% and 18% at peak growth (July) for the 80N and 40N treatments, respectively. By September, when primocane growth neared its peak, the 80N treatment averaged 36% NDFF on a whole plant basis, and the split-N and 40N treatments had 13% and 15% NDFF, respectively. So while fertilizer N uptake was lower than in other perennial crops, the relative amount of fertilizer N within the plant was high and increased with increasing N application rate.

Even though the 80N plants had a much higher %NDFF than the 40N plants, total N uptake was similar. For example, the average %NDFF from August to December 2001 was 16% for 40N plants and 31% for 80N plants, while average total

N content in this period was 12.2 g·plant^{-1} for 40N plants and 9.0 g·plant^{-1} for 80N plants. This suggests that the high %NDFF in the 80N plants was luxury uptake in a N saturated system. Uptake of fertilizer N simply replaced soil N that would have been taken up otherwise. This trend has also been observed in kiwifruit; when 200 kg·ha^{-1} of fertilizer N was added, total N in the plant was increased by only 50 kg· ha^{-1} of N, even though fertilizer N accounted for 100 kg·ha^{-1} of the total N in the plants (Ledgard and Smith, 1992). This suggests that in kiwifruit in a N saturated system, additional fertilizer N replaced 50 kg·ha^{-1} of N that would have been taken up from the soil.

Fertilizer N recovery (FR), as a percentage of the ^{15}N added, was similar to other small fruit crops. Recovery was 32% to 45% in blackberry and 32% in mature highbush blueberry (Mohadjer *et al.*, 2001; Naraguma *et al.*, 1999; Retamales and Hanson, 1989). Overall FR in this study ranged from 24% to 37% at the peak of fertilizer N uptake. The lowest application rate had the highest FR, a trend also observed in kiwifruit (Ledgard *et al.*, 1992). The relatively low fertilizer N uptake (compared to agronomic crops) was attributed to plant size and subsequent N need, the amount of labile N available in the soil, and the presence of storage N already in the plant.

Research in blueberry has shown that split N applications result in a 10% higher yield by providing N when plant growth was highest, thereby improving FR (Retamales and Hanson, 1992). However, yield in kiwifruit was not affected by a split vs. a single application of N (Ledgard *et al.*, 1992). Research in British Columbia indicated that the main flush of growth in red raspberry occurs early in floricanes; therefore, yields may be highest with a single early N application (Kowalenko *et al.*, 2000).

In this study, in June of the uptake year, significantly more fertilizer N was in the plants receiving labeled fertilizer in March (40N) than in plants receiving labeled fertilizer in May (split-N). Little labeled fertilizer N was partitioned to floricane tissues with the May application in 2001, but rather went to primocane growth. However, the NDFF content in the primocane tissues of split-N plants was not different than that of 40N plants. Since the split-N treatment also received unlabeled fertilizer in March, the March fertilizer N may have already fulfilled the N needs of the current year's floricane tissues. The %NDFF in split-N roots was lower than the percentage in 40N roots, suggesting that the later N application did not increase NDFF content in storage tissues as occurs in late N applications in fruit trees (Khemira *et al.*, 1998; Sanchez *et al.*, 1992). However, in 2002 significantly more fertilizer N was found in the split-N vs. 40N fruit, indicating that some of the second half of the split application assisted in fruit growth the second year. While a single N application resulted in higher yields when the first application was made in May (Kowalenko *et al.*, 2000), in this study the split N application resulted in higher yields in the second year, even though no advantage was observed in increased availability of stored fertilizer N. This trend may follow the observation by Ljones (1969) that fertilization benefits growth the year after fertilizer is applied.

Stored plant N is an important resource for perennial plant growth in the spring. Sixty percent of the N uptake by new growth in kiwifruit was from remobilization of N stored in the vines (Ledgard and Smith, 1992). In the current study, an average of 60% of fertilizer N present in December was available for use the following April. A similar storage pattern was observed in the rate of decline of %NDFF in the enriched plants. This level of available stored N is much higher than the 10% estimated for red raspberry by Dean *et al.* (2000), but is consistent with work in other perennial crops such as apples and pears (Neilsen *et al.*, 2001; Sanchez *et al.*, 1991). Little loss was seen in NDFF content between dormancy and budbreak indicating the labeled N was conserved during this period; however, this also suggests that little fertilizer N was reallocated from the roots to the crown and floricanes during this time.

A pot study using 'Chester Thornless' blackberry concluded that primocanes were a large reserve of fertilizer N; however, this N was not remobilized to other plant parts the following season (Malik *et al.*, 1991). The same pattern was observed in this study. Primocanes ended the 2001 season with approximately 75% of the NDFF content present in the plant (excluding roots). In 2002, only a small amount of this stored fertilizer N (now in floricanes) was remobilized to current season primocane growth. This partitioning strategy ensures reproduction is continued with stored N and vegetative growth is supported by exogenous N. The decline in stored fertilizer N throughout the season was primarily attributed to removal through fruit harvest and leaf loss.

While the roots in this study represented a sub-sample of the total root system, the high concentration of NDFF in the roots may reflect trends in their fertilizer allocation. In 2002, roots in the 80N treatment generally had about twice as much %NDFF as the other fertilized treatments. The roots were probably a sizable sink for fertilizer N, particularly for the 80N treatment which received an excess of N. If it had been possible to retrieve all the roots, fertilizer recovery would probably have increased.

Soil N availability

Bare soil N values in this study were lower than those seen previously at this experimental site (Mohadjer *et al.*, 2001). This is most likely because in the previous study (Mohadjer *et al.*, 2001), plots received irrigation throughout the growing season while the bare soil in this study did not. Soil N values for fertilized plots in this study were also lower than those measured in British Columbia due to high rates of atmospheric deposition and high levels of N in their irrigation water (Dean *et al.*, 2000). However, the magnitude and timing of the soil inorganic N response to fertilization was the same as that observed in kiwifruit (Ledgard *et al.*, 1992).

Little inorganic N was present in the soil by December and thus at risk for leaching during the Pacific Northwest's rainiest season. However, some of the decline in NO_3-N levels observed throughout the growing season was probably due to irrigation-driven leaching. Some of the labile N may have become immobilized into the organic matter fraction since the plants clearly were not taking up the large difference in soil N values between April and December. In studies where labeled fertilizer N has been tracked in the soil, 93% and 99% of the fertilizer N recovered in the topsoil was found in the organic fraction (Naraguma *et al.*, 1999; Retamales and Hanson, 1989). Ledgard *et al.* (1992) concluded that most of the fertilizer N would remain in stable humus forms.

When comparing the soil graphs (Fig. 4) to the NDFF uptake graphs (Fig. 2), it is clear that when plants had taken up the maximum amount of fertilizer N in July 2001 (6.5 g·plant^{-1} for the 80N treatment) there were still high levels of inorganic N in the top 0.15 m of soil (approximately 5 g·sampled volume^{-1} for fertilized plots). Therefore, when the plant reached its N uptake saturation point, the roots in the fertilized plots were still exposed to high levels of soil N.

Conclusions

Plants in the 0N treatment showed no significant differences in dry weight or total N compared to the fertilized treatments. The lack of differences may have been because the 0N treatment was buffered against a drop in dry weight and total N for the length of this study, because of reserves accumulated before this study began. A maximum of 2.2 g·sampled volume^{-1} of N was available in the 0N plots from the soil. The soil and storage N pools were not adequate to provide for N needs over time. If this study proceeded for a longer period of time, quantitative differences in total N and dry weight would probably be observed between the 0N treatment and the fertilized treatments. This study suggests that skipping a year of fertilization or consistently applying no N is not advisable, as raspberry plants in a production system need some form of fertilizer N to appropriately account for their N needs.

The 80N treatment had a 67% higher NDFF content than the 40N treatment on a per plant basis at peak uptake. However, no significant differences were observed in total N between treatments. The increased fertilizer N uptake by the 80N treatment probably represents luxury consumption at the expense of soil N uptake. When comparing the 80N and 40N treatments, significantly more fertilizer N was present in all reproductive tissues (fruiting laterals, floricanes, green and red fruit) for the 80N treatment at the point of highest fertilizer N uptake. While some of this fertilizer N was remobilized to storage tissues, much of the N in the floricane tissues was lost to fruit removal and pruning.

Little fertilizer N was partitioned to reproductive tissues and partitioning to storage tissues was not increased with the second half of the split-N treatment in the year of labeled application. However, fertilizer N content in the fruit of the split-N vs. the 40N treatment was higher in the second year. Either a single early application or a split application of 40 $kg \cdot ha^{-1}$ of N, depending on management practices, is probably sufficient to maintain production and to maximize fertilizer recovery in mature red raspberry in the Pacific Northwest.

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APPENDIX

Table A-1. Average dry weight (g·plant^{-1}) per plant part and for the aboveground plant on the date the plant was destructively harvested.

Sample Date
Tissue[z]
(g·plant^{-1})

April 12, 2001

N application (kg·ha^{-1})	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N[y]	159.3	25.6	360.0	0.7	2.1a[x]	547.8
80N	256.2	14.0	328.9	3.0	5.2b	607.3
40N	162.8	26.8	291.0	-	0.6a	481.2
Split-N	326.4	20.1	445.1	2.2	2.2a	796.0
p-value	0.11	0.14	0.73	0.27	0.02	0.30

June 14, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
0N	140.7	394.5	324.3	80.4	67.5	119.1	1126.6
80N	240.9	488.8	306.6	92.1	71.0	116.4	1315.8
40N	229.8	384.9	264.1	95.0	126.4	122.8	1223.0
Split-N	195.8	422.6	338.0	71.1	60.5	98.3	1186.2
p-value	0.38	0.73	0.86	0.78	0.07	0.88	0.92

July 12, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit[w]	Primocane Leaves	Primo-cane	Aboveground Plant
0N	242.3	415.8	303.7	104.8	230.5	146.0	271.6	1714.7
80N	227.5	408.8	218.3	90.7	335.3	145.1	221.2	1647.0
40N	173.7	223.1	194.6	59.4	263.3	155.6	232.4	1302.0
Split-N	434.4	376.7	237.6	91.2	359.0	219.1	321.9	2039.9
p-value	0.14	0.12	0.54	0.30	0.10	0.32	0.57	0.28

August 15, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	332.8	431.7	414.3	200.8	491.9	1871.5
80N	96.9	135.7	101.7	131.9	229.6	695.8
40N	309.1	354.5	254.3	224.8	489.4	1632.0
Split-N	327.0	313.3	243.3	239.4	450.1	1573.0
p-value	0.15	0.10	0.11	0.29	0.18	0.10

September 19, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	260.0a	236.0	276.6	137.9	516.9	1427.4
80N	104.0bc	89.2	133.1	116.8	364.0	807.0
40N	196.7ac	126.2	171.1	104.7	350.0	948.8
Split-N	262.6a	245.8	249.1	188.2	545.0	1490.7
p-value	0.03	0.11	0.22	0.36	0.24	0.07

Table A-1 (Continued)

December 10, 2001	Crown	Primocane Leaves	Primocane	Aboveground Plant
0N	372.8	6.9	776.3	1156.1
80N	195.7	2.7	498.9	697.3
40N	171.8	6.9	435.5	614.3
Split-N	361.3	5.3	644.6	1011.2
p-value	0.40	0.68	0.65	0.56

April 18, 2002	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	376.0	95.2	855.6	1.2	1.1	1329.1
80N	458.0	89.5	839.6	28.7	1.8	1417.6
40N	315.1	85.9	912.2	2.9	2.1	1318.3
Split-N	416.3	82.5	856.7	0.7	0.7	1356.9
p-value	0.68	0.97	0.99	0.45	0.63	0.98

June 17, 2002	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
0N	223.0	262.3	396.1	96.8	47.0	61.2	1086.3
80N	221.5	259.9	414.3	77.4	42.2	50.5	1065.9
40N	247.9	447.1	633.3	136.4	66.2	111.2	1641.9
Split-N	324.6	487.7	639.4	126.6	80.5	126.2	1784.9
p-value	0.60	0.36	0.49	0.60	0.37	0.15	0.33

July 11, 2002	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Aboveground Plant
0N	171.6	190.1	332.0	48.1	180.6	47.9	92.9	1063.2
80N	249.9	215.5	462.3	58.5	251.3	82.7	132.5	1452.7
40N	130.5	251.6	385.3	67.5	218.1	64.8	121.8	1239.6
Split-N	197.1	317.5	656.2	77.6	394.9	113.0	199.5	1955.7
p-value	0.41	0.55	0.24	0.76	0.03	0.35	0.31	0.15

August 15, 2002	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	354.2a	251.1	607.0	130.0	227.7	1570.0
80N	207.9bc	224.9	422.5	104.3	307.6	1267.2
40N	174.8bc	76.2	229.9	88.0	229.7	798.5
Split-N	275.2ac	224.0	501.7	120.4	306.9	1428.1
p-value	0.03	0.26	0.17	0.82	0.86	0.27

Table A-1 (Continued)

September 18, 2002						
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	181.1	90.5	399.8	39.3	177.6	888.3
80N	261.1	137.2	489.3	98.4	561.6	1547.5
40N	231.0	145.3	534.2	90.9	371.1	1372.4
Split-N	258.5	147.2	533.5	76.7	352.3	1368.2
p-value	0.83	0.66	0.76	0.62	0.41	0.59

December 10, 2002				
	Crown	Primocane Leaves	Primocane	Aboveground Plant
0N	262.2	0.9	204.0	467.1
80N	279.9	4.0	303.1	587.0
40N	146.8	2.6	257.0	406.4
Split-N	265.6	4.9	313.9	584.4
p-value	0.50	0.66	0.77	0.76

[z]n=3

[y]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[x]Means in the same column followed by the same letter are not significantly different (ANOVA, Fisher's LSD, p>0.05). Means are compared within dates only, not among dates.

[w]Red fruit dry weight based on the cumulative season.

Table A-2. Air and soil temperatures in Aurora, Oregon from March 2001 to December 2002. Air temperatures based on a weather station at the North Willamette Research and Extension Center. Soil temperatures based on measurements made within the experimental plot. The soil received summer irrigation.

	Temperature (°C)								
	Air			Bare soil 0-15 cm			Bare soil to 15-30 cm		
Date	Min.	Max.	Mean	Min.[z]	Max.[z]	Mean[z]	Min.[z]	Max.[z]	Mean[z]
Mar-01	3.8	13.7	8.6						
Apr-01	4.2	14.3	9.1	8.4	22.5	13.8	9.5	21.6	13.4
May-01	7.3	22.1	14.7	10.5	22.7	15.8	11.1	20.6	15.9
Jun-01	9.3	21.3	15.4	13.3	21.3	16.9	13.5	24.2	16.2
Jul-01	12.4	25.7	18.8	16.4	22.6	19.2	16.5	22.7	18.8
Aug-01	12.7	27.1	19.6	16.6	23.3	20.2	16.9	23.2	19.5
Sep-01	10.6	25.0	17.2	13.1	22.4	18.0	14.6	19.8	19.9
Oct-01	6.1	16.9	11.3	8.1	20.4	13.1	9.4	17.8	16.2
Nov-01	5.6	12.2	8.6	9.4	13.2	11.2	10.5	12.0	13.4
Dec-01	2.8	8.6	5.5	2.9	8.2	5.7			11.5
Jan-02	2.6	8.0	5.3	2.5	9.4				
Feb-02	2.6	11.4	6.9	3.3	11.4				
Mar-02	2.9	11.2	6.8	4.2	11.8	11.6			11.9
Apr-02	5.8	16.2	10.7	6.3	17.3	14.5	8.6	19.6	14.8
May-02	7.1	18.2	12.6	8.9	20.8	18.2	10.0	18.7	18.4
Jun-02	10.7	23.6	17.1	13.2	23.7	20.9	13.5	21.1	21.1
Jul-02	12.7	28.2	20.3	16.3	28.8	20.8	16.4	27.1	20.9
Aug-02	11.6	27.9	19.5	16.6	23.6	19.9	19.8	24.0	19.9
Sep-02	10.1	25.0	17.1	14.4	21.3	12.4	20.6	21.7	12.4
Oct-02	6.9	18.2	11.9			7.9			8.1
Nov-02	3.7	13.7	8.1			4.3			5.0
Dec-02	3.0	9.8	6.2						

[z]Dataloggers placed in field in April of each year. All of the dataloggers except for one were removed in November 2001.

Table A-3. Average total N (mg·plant^{-1}) per plant part and for the aboveground plant on the date the plant was destructively harvested.

Sample Date
Tissue
(mg·plant^{-1})

April 12, 2001

N application (kg·ha^{-1})	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N[y]	1910	994	6648	21	70a[v]	9636
80N	2367	563	2998	98	167b	6193
40N	1669	1081	2340	-	20a	5102
Split-N	2992	734	3723	80	69a	7576
p-value	0.28	0.31	0.12	0.26	0.01	0.41

June 14, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
0N	1111	9985	2836	1799	1660a	1762	18631
80N	2009	13365	2105	2185	2958ab	2342	24733
40N	2257	8713	1592	2237	4694b	2294	21342
Split-N	1857	11095	1856	1707	1925a	1612	19863
p-value	0.30	0.50	0.44	0.78	0.03	0.41	0.57

July 12, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Aboveground Plant
0N	1534	8245	1505	1389	2398a	4490	1614	21174
80N	1619	9159	1182	1492	4653b	5239	1937	25281
40N	1224	5153	936	1314	2740ac	5478	3238	20082
Split-N	2751	7692	1145	1749	3827bc	7588	3623	28374
p-value	0.08	0.38	0.58	0.80	0.02	0.18	0.42	0.41

August 15, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	2018	6188	2273	4709	2857	18044
80N	718	2513	506	3929	2376	10042
40N	2371	4836	1263	5666	3748	17884
Split-N	2731	5466	1400	7142	4019	20759
p-value	0.12	0.40	0.17	0.20	0.42	0.23

September 19, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	1472	2118	1587	2926	3923	12027
80N	789	1085	780	2726	2828	8209
40N	1627	1768	850	2661	2877	9783
Split-N	2568	3216	1244	4764	4672	16465
p-value	0.09	0.16	0.29	0.22	0.22	0.10

Table A-3 (Continued)

December 10, 2001				
	Crown	Primocane Leaves	Primocane	Aboveground Plant
0N	2725	139	6525	9388
80N	1765	58	5147	6969
40N	1223	144	4079	5446
Split-N	2804	113	5634	8551
p-value	0.44	0.68	0.79	0.77

April 18, 2002						
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	3865	3751	7378	44	36	15073
80N	4225	2948	6543	732	51	14256
40N	4365	3469	9172	125	88	17177
Split-N	3667	3220	6854	25	23	13781
p-value	0.97	0.89	0.68	0.37	0.57	0.93

June 17, 2002							
	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
0N	1304	4125	2247	1743	1130	452	11001
80N	2061	4548	2862	1741	1614	958	13785
40N	1473	7850	2710	2682	1801	1049	17565
Split-N	2166	10423	3016	2721	2681	1472	22479
p-value	0.29	0.16	0.82	0.66	0.25	0.19	0.16

July 11, 2002								
	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Aboveground Plant
0N	896a	2139	1482	666	967a	1240	460	7850a
80N	2090b	4349	3012	1003	1849a	2492	1201	15995ac
40N	789a	4520	1890	1127	1189a	1625	871	12011a
Split-N	1215ac	5931	3207	1307	3744b	3266	1496	20167bc
p-value	0.04	0.18	0.27	0.62	0.00	0.26	0.12	0.04

August 15, 2002						
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	2290	2519	2990	2794	1372	11965
80N	1935	3172	2803	3260	2750	13979
40N	1324	1222	1413	2307	1791	8058
Split-N	2027	3076	2767	3633	2477	13980
p-value	0.10	0.29	0.31	0.75	0.54	0.34

Table A-3 (Continued)

September 18, 2002						
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
0N	1244	510	1699	888	1164	5505
80N	2404	1090	3223	2260	4449	13426
40N	1875	1337	2821	2036	2669	10739
Split-N	2171	1079	2425	1590	2869	10134
p-value	0.55	0.35	0.43	0.59	0.26	0.33

December 10, 2002				
	Crown	Primocane Leaves	Primocane	Aboveground Plant
0N	1993	10	1498	3491
80N	2951	30	2736	5688
40N	1442	43	2092	3534
Split-N	2634	87	2740	5375
p-value	0.51	0.53	0.56	0.53

[z]n=3

[y]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[x]Means in the same column followed by the same letter are not significantly different (ANOVA, Fisher's LSD, p>0.05). Means are compared within dates only, not among dates.

[w]Red fruit total N based on the cumulative season.

Table A-4. Average N concentration (%) per plant part on the date the plant was destructively harvested.

Sample Date
Tissue[z]
(%)

April 12, 2001

N application ($kg \cdot ha^{-1}$)	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots[x]	Small Roots[w]
0N[y]	1.26a[v]	3.61	1.82a	2.61	3.29	2.06	1.28
80N	0.91bc	3.99	0.91b	3.40	3.30	1.74	1.21
40N	1.03ac	4.04	0.82b	3.21	3.86	1.84	1.24
Split-N	0.91bc	3.66	0.83b	3.92	3.05	1.79	1.16
p-value	0.03	0.74	0.01	0.67	0.23	0.62	0.82

June 14, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.80	2.50	1.09	2.22	2.50	1.48	0.98	1.26
80N	0.82	2.78	0.69	2.39	4.11	2.02	1.13	1.62
40N	0.96	2.23	0.59	2.36	3.75	1.94	1.01	1.41
Split-N	0.95	2.62	0.56	2.37	3.37	1.66	0.99	1.43
p-value	0.10	0.39	0.56	0.53	0.15	0.17	0.17	0.47

July 12, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit[u]	Primocane Leaves	Primo-cane	Large Roots	Small Roots
0N	0.63	1.92	0.49	1.35	1.03a	3.07	0.59	0.59	1.18
80N	0.72	2.22	0.56	1.75	1.43b	3.63	0.92	0.95	1.43
40N	0.69	2.25	0.48	2.24	1.04a	3.61	1.54	0.87	1.33
Split-N	0.68	2.04	0.48	1.91	1.06a	3.51	1.10	0.89	1.23
p-value	0.86	0.58	0.40	0.18	0.00	0.22	0.46	0.09	0.08

August 15, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.60	1.37	0.53	2.35a	0.57a	0.75	1.02a
80N	0.74	1.69	0.48	3.05bc	1.02bc	1.00	1.43b
40N	0.77	1.37	0.50	2.53ac	0.77ac	0.90	1.43b
Split-N	0.86	1.70	0.56	2.98bc	0.89bc	0.78	1.36b
p-value	0.16	0.31	0.63	0.04	0.02	0.15	0.03

September 19, 2001

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.57a	0.85a	0.56	2.13a	0.74	0.77	0.97a
80N	0.76b	1.23ac	0.57	2.34ac	0.79	0.92	1.28b
40N	0.81b	1.34bc	0.50	2.63bc	0.81	0.93	1.39b
Split-N	0.74b	1.62bc	0.50	2.58bc	0.87	0.99	1.28b
p-value	0.03	0.04	0.58	0.03	0.34	0.05	0.01

Table A-4 (Continued)

December 10, 2001

	Crown	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.72	2.05	0.87	1.08	1.18a
80N	0.92	2.10	1.06	1.02	1.52b
40N	0.67	2.14	0.95	2.04	3.68c
Split-N	0.78	2.09	0.89	1.65	1.43ab
p-value	0.15	0.79	0.29	0.21	0.00

April 18, 2002

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	1.04	3.86	0.88	3.82	3.23	1.27	1.83
80N	0.92	3.35	0.77	2.81	3.01	1.25	1.62
40N	1.39	4.22	1.04	3.63	3.92	1.37	1.86
Split-N	0.91	3.89	0.79	3.73	3.20	1.37	1.81
p-value	0.62	0.36	0.50	0.59	0.32	0.89	0.81

June 17, 2002

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.59a	1.58	0.57a	1.81a	2.32a	0.78a	0.60a	1.04a
80N	0.93b	2.05	0.72b	2.34b	3.79b	1.88b	1.05b	1.58bc
40N	0.59a	1.77	0.42c	1.93ac	2.83ac	0.94ac	0.68a	1.09a
Split-N	0.70a	2.18	0.51ac	2.12bc	3.28bc	1.13c	0.74a	1.30ac
p-value	0.00	0.23	0.01	0.01	0.01	0.00	0.00	0.02

July 11, 2002

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Large Roots	Small Roots
0N	0.54a	1.08a	0.43a	1.38a	0.53	2.50	0.51a	0.56	0.84a
80N	0.83b	2.14b	0.63bc	1.78b	0.74	3.10	0.97bc	0.80	1.30b
40N	0.60a	1.84b	0.50ac	1.66b	0.63	2.51	0.74ac	0.63	0.99a
Split-N	0.63a	1.84b	0.49a	1.66b	0.92	2.92	0.76ac	0.95	1.47b
p-value	0.00	0.00	0.04	0.01	0.00	0.15	0.03	0.26	0.00

August 15, 2002

	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.65a	1.10	0.49	2.21a	0.62a	0.75	1.08a
80N	0.93bc	1.45	0.66	2.97bc	0.91b	1.01	1.55b
40N	0.77ac	1.65	0.62	2.72ac	0.82b	0.87	1.27ac
Split-N	0.74a	1.37	0.56	3.03bc	0.81b	0.66	1.35bc
p-value	0.03	0.34	0.27	0.03	0.01	0.18	0.02

Table A-4 (Continued)

	September 18, 2002						
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.68	0.57	0.43	2.22	0.66	0.90	1.14a
80N	0.91	0.78	0.64	2.33	0.85	1.23	1.61b
40N	0.84	0.91	0.53	2.21	0.72	1.00	1.19a
Split-N	0.84	0.75	0.45	2.00	0.83	0.89	1.40ab
p-value	0.08	0.37	0.22	0.54	0.20	0.21	0.04

	December 10, 2002				
	Crown	Primocane Leaves	Primocane	Large Roots	Small Roots
0N	0.79	1.07	0.74	1.03	1.42
80N	1.03	1.04	0.91	1.15	1.66
40N	0.97	1.65	0.84	1.01	1.55
Split-N	0.96	1.74	0.86	1.21	1.68
p-value	0.40	0.38	0.22	0.27	0.21

[z]n=3

[y]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[x]Large roots have a diameter greater than 1 cm.

[w]Small roots have a diameter less than 1 cm.

[v]Means in the same column followed by the same letter are not significantly different (ANOVA, Fisher's LSD, p>0.05). Means are compared within dates only, not among dates.

[u]Red fruit values are based on an average of 3 sample dates – early, mid, and late harvest.

Table A-5. Average nitrogen derived from fertilizer per plant part ($mg{\cdot}plant^{-1}$) and for the aboveground plant on the date the plant was destructively harvested.

Sample Date
Tissue[z]
($mg{\cdot}plant^{-1}$)

April 12, 2001

N application ($kg{\cdot}ha^{-1}$)	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
80N[y]	120	36	15	23	28	227
40N	43	18	4	-	3	67
Split-N	-	-	-	-	-	-
p-value[x]	0.24	0.11	0.42	0.00	0.00	0.05
Contrasts[w]						
80N vs 40N	NS	NS	NS	-	**	NS
80N vs split-N	-	-	-	-	-	-
40N vs split-N	-	-	-	-	-	-

June 14, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
80N	158	2000	142	523	587	605	4015
40N	69	1163	60	273	471	337	2372
Split-N	25	130	14	42	217	80	507
p-value	0.00	0.07	0.00	0.00	0.13	0.00	0.00
Contrasts							
80N vs 40N	**	NS	*	*	NS	*	*
80N vs split-N	***	*	**	**	NS	***	***
40N vs split-N	NS	NS	NS	*	NS	*	*

July 12, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit[v]	Primocane Leaves	Primo-cane	Aboveground Plant
80N	210	2395	104	457	1306	1484	546	6503
40N	111	1017	52	186	253	920	816	3355
Split-N	74	190	21	22	191	1011	180	1687
p-value	0.07	0.00	0.01	0.00	0.00	0.27	0.36	0.01
Contrasts								
80N vs 40N	NS	**	*	*	***	NS	NS	NS
80N vs split-N	NS	***	**	**	***	NS	NS	**
40N vs split-N	NS	NS	NS	NS	NS	NS	NS	NS

Table A-5 (Continued)

August 15, 2001	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
80N	139	830	51	1368	866	3254
40N	296	766	89	1254	740	3144
Split-N	145	211	37	680	471	1544
p-value	0.03	0.16	0.03	0.00	0.05	0.03
Contrasts						
80N vs 40N	NS	NS	NS	NS	NS	NS
80N vs split-N	NS	NS	NS	*	NS	NS
40N vs split-N	NS	NS	*	NS	NS	NS

September 19, 2001	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
80N	199	419	111	1068	1200	2996
40N	212	246	69	468	516	1512
Split-N	286	274	60	736	805	2162
p-value	0.28	0.03	0.01	0.02	0.00	0.00
Contrasts						
80N vs 40N	NS	NS	NS	*	*	*
80N vs split-N	NS	NS	*	NS	NS	NS
40N vs split-N	NS	NS	NS	NS	NS	NS

December 10, 2001	Crown	Primocane Leaves	Primocane	Aboveground Plant
80N	387	15	1416	1818
40N	148	31	748	927
Split-N	195	13	576	785
p-value	0.07	0.31	0.05	0.05
Contrasts				
80N vs 40N	NS	NS	NS	NS
80N vs split-N	NS	NS	NS	NS
40N vs split-N	NS	NS	NS	NS

Table A-5 (Continued)

N Application (kg·ha⁻¹)	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
			April 18, 2002			
80N	298	403	1446	54	5	2187
40N	353	213	609	6	3	1182
Split-N	110	196	364	2	2	673
p-value	0.11	0.00	0.07	0.41	0.05	0.02
Contrasts						
80N vs 40N	NS	**	NS	NS	NS	NS
80N vs split-N	NS	**	*	NS	NS	*
40N vs split-N	NS	NS	NS	NS	NS	NS

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Aboveground Plant
			June 17, 2002				
80N	404	653	872	203	135	100	2366
40N	114	477	379	151	88	46	1254
Split-N	78	301	243	101	86	5	858
p-value	0.00	0.06	0.03	0.14	0.00	0.02	0.01
Contrasts							
80N vs 40N	***	NS	NS	NS	NS	NS	NS
80N vs split-N	***	NS	*	NS	NS	NS	*
40N vs split-N	NS	NS	NS	NS	NS	NS	NS

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Aboveground Plant
				July 11, 2002				
80N	282	459	603	64	141	299	109	1957
40N	61	222	250	42	48	49	31	703
Split-N	90	431	260	56	150	147	58	1192
p-value	0.00	0.02	0.01	0.19	0.00	0.35	0.16	0.00
Contrasts								
80N vs 40N	***	NS	*	NS	***	NS	NS	**
80N vs split-N	**	NS	*	NS	NS	NS	NS	*
40N vs split-N	NS	NS	NS	NS	***	NS	NS	NS

Table A-5 (continued)

August 15, 2002	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
80N	230	312	739	167	169	1616
40N	61	46	132	61	43	343
Split-N	103	167	257	87	94	709
p-value	0.00	0.02	0.01	0.13	0.10	0.00
Contrasts						
80N vs 40N	***	*	**	NS	NS	***
80N vs split-N	***	NS	*	NS	NS	***
40N vs split-N	NS	NS	NS	NS	NS	NS

September 18, 2002	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Aboveground Plant
80N	154	150	417	72	203	996
40N	92	74	347	40	69	621
Split-N	73	54	303	49	113	591
p-value	0.06	0.34	0.14	0.10	0.06	0.11
Contrasts						
80N vs 40N	NS	NS	NS	NS	NS	NS
80N vs split-N	NS	NS	NS	NS	NS	NS
40N vs split-N	NS	NS	NS	NS	NS	NS

December 10, 2002	Crown	Primocane Leaves	Primocane	Aboveground Plant
80N	212	1	114	326
40N	44	1	44	88
Split-N	103	1	90	192
p-value	0.00	0.07	0.01	0.00
Contrasts				
80N vs 40N	***	NS	*	NS
80N vs split-N	**	NS	NS	NS
40N vs split-N	NS	*	NS	NS

[z]n=3

[y]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[x]p-values are taken from an ANOVA table which included the 0N treatment. Means are compared within dates only, not among dates.

[w]NS, *, **, *** - Nonsignificant or significant at $p<0.05$, 0.01, or 0.001, respectively.

[v]Red fruit NDFF (mg) based on the cumulative season.

Table A-6. Average percent of nitrogen derived from fertilizer per plant part, and for the aboveground plant on the date the plant was destructively harvested.

Sampling Date
Tissue[z]
(%)

April 12, 2001

N application (kg·ha⁻¹)	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots[x]	Small Roots[w]	Aboveground Plant
80N[y]	5.24	5.53	0.93	17.25	17.99	2.23	2.07	3.06
40N	2.63	1.67	0.33	14.40	9.43	1.59	1.25	1.42
Split-N	-	-	-	-	-	-	-	-
p-value[v]	0.08	0.06	0.01	0.25	0.04	0.01	0.22	0.03
Contrasts[u]								
80N vs 40N	NS	NS	*	NS	NS	NS	NS	NS
80N vs split-N	-	-	-	-	-	-	-	-
40N vs split-N	-	-	-	-	-	-	-	-

June 14, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Large Roots	Small Roots	Above-ground Plant
80N	9.77	13.83	7.89	25.92	22.95	28.87	8.37	17.34	16.9
40N	3.46	12.16	4.51	14.69	10.10	14.82	4.35	8.16	11.4
Split-N	1.34	1.22	0.84	2.81	11.83	5.12	1.02	4.60	2.8
p-value	0.06	0.03	0.04	0.03	0.30	0.01	0.42	0.02	0.00
Contrasts									
80N vs 40N	NS	NS	NS	NS	NS	NS	NS	NS	NS
80N vs split-N	*	*	*	*	NS	**	NS	*	**
40N vs split-N	NS	*	NS	NS	NS	NS	NS	NS	*

July 12, 2001

	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Large Roots	Small Roots	Above-ground Plant t
80N	15.03	29.13	9.95	35.20	29.31	25.52	28.89	14.23	26.46	25.54
40N	9.25	18.27	6.20	14.33	10.37	18.05	19.16	5.62	12.29	17.74
Split-N	2.55	2.50	1.61	1.48	4.87	12.55	4.36	1.03	6.07	5.70
p-value	0.01	0.01	0.04	0.01	0.00	0.12	0.00	0.01	0.00	0.00
Contrasts										
80N vs 40N	NS	NS	NS	*	***	NS	NS	*	*	*
80N vs split-N	**	**	*	**	***	NS	**	**	**	***
40N vs split-N	NS	*	NS	NS	NS	NS	*	NS	NS	**

Table A-6 (Continued)

August 15, 2001								
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots	Aboveground Plant
80N	21.62	35.48	11.19	34.74	34.60	21.37	34.37	32.22
40N	11.85	16.21	7.10	22.70	19.71	10.87	18.23	17.69
Split-N	5.15	2.98	2.36	9.75	12.07	4.76	14.51	7.25
p-value	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Contrasts								
80N vs 40N	NS	***	*	**	*	NS	***	***
80N vs split-N	**	***	***	***	**	**	***	***
40N vs split-N	NS	**	*	**	NS	NS	NS	***

September 19, 2001								
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots	Above-ground Plant
80N	26.04	36.95	14.67	40.00	42.37	30.14	34.35	36.40
40N	11.47	14.52	8.11	18.53	18.04	10.57	20.07	15.37
Split-N	9.65	9.25	4.60	14.97	17.32	11.52	23.89	13.15
p-value	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Contrasts								
80N vs 40N	*	**	***	**	**	*	NS	***
80N vs split-N	**	***	***	**	**	*	NS	***
40N vs split-N	NS	NS	**	NS	NS	NS	NS	NS

December 10, 2001						
	Crown	Primocane Leaves	Primocane	Large Roots	Small Roots	Aboveground Plant
80N	22.06	24.18	27.51	16.99	28.62	25.51
40N	11.66	16.75	16.31	12.27	20.21	15.02
Split-N	7.17	11.54	10.21	5.03	11.86	8.69
p-value	0.00	0.06	0.00	0.00	0.00	0.00
Contrasts						
80N vs 40N	**	NS	*	NS	*	**
80N vs split-N	***	NS	**	**	***	***
40N vs split-N	NS	NS	NS	*	*	*

April 18, 2002								
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots	Aboveground Plant
80N	7.15	13.66	20.36	7.95	9.29	12.28	17.05	14.81
40N	7.53	6.48	7.93	5.77	5.28	7.99	8.95	7.55
Split-N	3.32	6.33	6.06	7.67	6.06	2.90	13.96	5.68
p-value	0.00	0.00	0.01	0.00	0.03	0.02	0.05	0.00
Contrasts								
80N vs 40N	NS	**	*	NS	NS	NS	NS	*
80N vs split-N	*	**	**	NS	NS	*	NS	**
40N vs split-N	*	NS	NS	NS	NS	NS	NS	NS

Table A-6 (Continued)

June 17, 2002									
N Application (kg·ha^{-1})	Crown	Fruiting Laterals	Floricane	Green Fruit	Primocane Leaves	Primocane	Large Roots	Small Roots	Above-ground Plant
80N	19.58	15.09	29.72	13.14	8.34	9.99	16.03	19.54	16.95
40N	7.46	5.96	12.43	5.76	4.89	4.51	7.94	9.38	7.04
Split-N	3.79	2.96	8.83	3.40	3.22	3.32	2.18	8.72	4.00
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Contrasts									
80N vs 40N	***	***	**	**	**	**	**	***	***
80N vs split-N	***	***	***	***	***	***	***	***	***
40N vs split-N	NS	NS	NS	NS	NS	NS	*	NS	NS

July 11, 2002										
	Crown	Fruiting Laterals	Floricane	Green Fruit	Red Fruit	Primocane Leaves	Primo-cane	Large Roots	Small Roots	Above-ground Plant
80N	13.64	13.17	21.09	9.79	7.77	8.78	7.74	10.21	16.69	13.04
40N	7.99	4.77	13.32	3.43	3.66	3.02	3.81	6.59	9.76	6.05
Split-N	7.09	6.97	9.14	3.83	4.34	4.35	3.99	6.92	10.34	6.39
p-value	0.00	0.03	0.00	0.19	0.00	0.10	0.01	0.00	0.01	0.00
Contrasts										
80N vs 40N	*	NS	*	NS	**	NS	NS	NS	NS	**
80N vs split-N	*	NS	**	NS	**	NS	NS	NS	NS	*
40N vs split-N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

August 15, 2002								
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots	Above-ground Plant
80N	12.06	9.77	25.76	6.57	7.61	12.55	15.72	13.77
40N	4.57	3.83	8.85	2.56	2.41	5.08	4.83	4.37
Split-N	5.70	6.52	12.44	2.46	3.95	9.23	6.93	5.67
p-value	0.00	0.00	0.01	0.00	0.00	0.22	0.00	0.01
Contrasts								
80N vs 40N	**	*	*	*	**	NS	***	*
80N vs split-N	**	NS	*	*	*	NS	**	*
40N vs split-N	NS	NS	NS	NS	NS	NS	NS	NS

September 18, 2002								
	Crown	Fruiting Laterals	Floricane	Primocane Leaves	Primocane	Large Roots	Small Roots	Above-ground Plant
80N	6.62	12.13	12.54	3.53	4.90	8.52	10.27	7.46
40N	4.94	5.10	11.80	2.42	3.07	5.44	5.27	5.95
Split-N	3.25	4.77	10.50	3.04	3.69	4.05	5.85	5.27
p-value	0.05	0.26	0.02	0.02	0.07	0.09	0.10	0.06
Contrasts								
80N vs 40N	NS	NS	NS	NS	NS	NS	NS	NS
80N vs split-N	NS	NS	NS	NS	NS	NS	NS	NS
40N vs split-N	NS	NS	NS	NS	NS	NS	NS	NS

Table A-6 (Continued)

	December 10, 2002					
	Crown	Primocane Leaves	Primocane	Large Roots	Small Roots	Aboveground Plant
80N	8.15	2.33	4.52	5.93	7.06	6.43
40N	2.87	1.07	2.12	2.63	3.42	2.75
Split-N	5.03	2.71	3.94	4.12	5.93	4.59
p-value	0.03	0.35	0.03	0.01	0.03	0.02
Contrasts						
80N vs 40N	*	NS	NS	*	NS	NS
80N vs split-N	NS	NS	NS	NS	NS	NS
40N vs split-N	NS	NS	NS	NS	NS	NS

[z]n=3

[y]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[x]Large roots have a diameter greater than 1 cm.

[w]Small roots have a diameter less than 1 cm.

[v]p-values are taken from an ANOVA table which included the 0N treatment. Means are compared within dates only, not among dates.

[u]NS, *, **, *** - Nonsignificant or significant at $p<0.05$, 0.01, or 0.001, respectively.

Table A-7. Average nitrogen derived from fertilizer (NDFF) in mg per part and for the aboveground plant for plots receiving enriched ^{15}N in 2000.

	NDFF ($mg \cdot plant^{-1}$)						
	Tissue[z]						
Sample Date	Crown	Fruiting Laterals	Floricanes	Green Fruit	Primocane Leaves	Primo-canes	Above-ground Plant
7 Feb. 2002	261	-	533	-	-	-	857
18 Apr. 2002	227	247	547	-	1	1	1080
17 June 2002	133	522	315	195	117	85	1400
11 July 2002	88	262	223	75	130	62	864
15 Aug. 2002	106	97	111	-	95	78	516
18 Sept. 2002	158	123	239	-	73	151	766
10 Dec. 2002	163	-	-	-	2	139	397
11 Feb. 2003	154	-	68	-	-	-	242

[z]n=3

Table A-8. Average percent nitrogen derived from fertilizer (NDFF) per part and for the aboveground plant for plots receiving enriched ^{15}N in 2000.

	NDFF (%)								
	Tissue[z]								
Sample Date	Crown	Fruiting Laterals	Floricanes	Green Fruit	Primocane Leaves	Primo-canes	Large Roots[y]	Small Roots[x]	Above-ground Plant
7 Feb. 2002	5.37	-	5.01	-	-	-	4.56	4.59	5.08
18 Apr. 2002	7.02	6.42	7.56	-	3.90	5.50	5.29	2.97	6.88
17 June 2002	5.75	3.89	6.96	4.43	3.37	3.80	4.60	5.10	4.51
11 July 2002	4.44	3.83	6.41	3.33	3.30	3.41	5.20	4.54	4.16
15 Aug. 2002	4.30	3.90	5.31	-	2.91	2.59	5.41	4.54	3.70
18 Sept. 2002	4.65	5.38	7.31	-	3.20	3.48	0.98	4.06	4.70
10 Dec. 2002	4.13	-	-	-	2.45	3.02	4.01	3.68	3.58
11 Feb. 2003	3.58	-	2.22	-	-	-	4.63	2.68	2.97

[z]n=3.
[y]Large roots have a diameter greater than 1 cm.
[x]Small roots have a diameter less than 1 cm.

Table A-9. Soil nitrate and ammonium concentration per sampled volume for four fertilizer applications and a bare soil plot. Samples were collected in a 'Meeker' red raspberry field in 2001 and 2002.

Sample Date
Inorganic N
(g sampled volume^{-1})
Sample Depth
(cm)

March 15, 2001

N application (kg·ha^{-1})	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N[z]	0.32	0.40	0.72	0.20	0.21	0.40	1.12
80N	0.49	0.37	0.86	0.24	0.16	0.41	1.26
40N	0.41	0.39	0.79	0.19	0.23	0.43	1.22
Split-N	0.45	0.36	0.81	0.17	0.12	0.29	1.10
Bare soil	0.46	0.61	1.07	0.15	0.20	0.36	1.43
p-value	0.36	0.38	0.60	0.61	0.34	0.61	0.78

April 12, 2001

	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	1.11a[y]	1.06a	2.16a	0.16ac	0.17	0.33	2.50a
80N	7.81b	3.89b	11.70b	20.44b	6.09	26.53	38.23bc
40N	8.34b	3.64b	11.98b	8.44bc	1.85	10.3	22.27ac
Split-N	9.33b	4.41b	13.74b	2.18ac	0.79	2.97	16.71a
Bare soil	0.24a	0.36a	0.60a	0.20ac	0.21	0.41	1.01a
p-value	0.00	0.00	0.00	0.03	0.31	0.06	0.03

June 15, 2001

	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.93	1.24	2.17a	0.11	0.09	0.21	2.38
80N	5.49	4.25	9.74bcd	0.55	0.84	1.39	11.13
40N	3.71	3.82	7.53acd	0.16	0.15	0.31	7.84
Split-N	5.48	4.95	10.44bd	1.62	2.75	4.37	14.80
Bare soil	1.01	0.66	1.68ac	0.16	0.12	0.28	1.96
p-value	0.05	0.08	0.04	0.23	0.16	0.18	0.07

Table A-9 (Continued)

July 10, 2001							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.75	0.42	1.17	0.47	0.38	0.85	2.02
80N	4.41	4.65	9.06	0.52	0.33	0.85	9.91
40N	1.30	2.97	4.27	0.36	0.28	0.64	4.91
Split-N	4.34	3.68	8.03	1.34	1.23	2.57	10.60
Bare soil	0.62	0.35	0.96	0.32	0.28	0.59	1.56
p-value	0.10	0.17	0.11	0.17	0.43	0.28	0.14

August 13, 2001							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.18a	0.14a	0.32a	0.22	0.19	0.42	0.73a
80N	0.83a	3.18b	4.02bc	0.25	0.24	0.48	4.50ac
40N	1.43a	3.32b	4.75bc	0.32	0.24	0.56	5.31bc
Split-N	4.13b	4.35b	8.48d	1.05	0.51	1.56	10.03d
Bare soil	0.66a	0.47a	1.13ac	0.25	0.26	0.51	1.64a
p-value	0.02	0.00	0.00	0.25	0.13	0.20	0.01

September 19, 2001							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.31	0.27	0.58	0.27	0.31	0.58	1.16
80N	0.65	1.31	1.96	0.30	0.27	0.57	2.53
40N	0.64	1.62	2.26	0.30	0.26	0.57	2.83
Split-N	1.31	1.25	2.56	0.29	0.24	0.53	3.10
Bare soil	0.99	1.17	2.17	0.25	0.31	0.56	2.73
p-value	0.24	0.57	0.42	0.34	0.17	0.54	0.42

Table A-9 (Continued)

December 7, 2001							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.14	0.10	0.23	0.09	0.08	0.16	0.40
80N	0.16	0.13	0.29	0.28	0.14	0.42	0.70
40N	0.17	0.15	0.32	0.18	0.11	0.29	0.60
Split-N	0.15	0.12	0.28	0.15	0.16	0.31	0.59
Bare soil	0.06	0.14	0.20	0.10	0.09	0.19	0.39
p-value	0.29	0.50	0.49	0.34	0.47	0.27	0.20

March 15, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.38	0.42	0.79	0.35	0.26	0.61	1.40
80N	0.35	0.32	0.67	0.24	0.19	0.42	1.10
40N	0.48	0.36	0.83	0.29	0.15	0.44	1.27
Split-N	0.47	0.37	0.84	0.33	0.25	0.58	1.41
Bare soil	0.16	0.16	0.32	0.12	0.15	0.28	0.60
p-value	0.29	0.11	0.18	0.54	0.68	0.56	0.30

April 16, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	1.03a	0.61	1.64a	0.33a	0.27a	0.60a	2.24a
80N	7.13b	1.42	8.55b	22.68b	8.89b	31.57b	40.12b
40N	5.24b	2.35	7.59b	10.58c	3.28a	13.87c	21.46c
Split-N	7.67b	2.46	10.13b	4.67ac	2.28a	6.94ac	17.07cd
Bare soil	0.24a	0.21	0.45a	0.50a	0.22a	0.72ac	1.17ad
p-value	0.01	0.09	0.01	0.00	0.00	0.00	0.00

Table A-9 (Continued)

June 17, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.42	0.25a	0.68a	0.18	0.15	0.33	1.01
80N	7.18	5.01b	12.19b	1.99	1.23	3.22	15.40
40N	2.01	1.97ac	3.98ac	0.26	0.14	0.40	4.38
Split-N	4.65	2.62c	7.27bc	4.23	2.42	6.65	13.92
Bare soil	0.87	0.57ac	1.43ac	0.33	0.50	0.83	2.27
p-value	0.06	0.00	0.02	0.32	0.30	0.31	0.11

July 15, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.35	0.22a	0.56	0.17	0.18	0.35	0.92
80N	0.96	1.65bc	2.60	0.35	0.34	0.69	3.29
40N	1.32	1.47bc	2.79	0.50	0.16	0.66	3.45
Split-N	1.41	0.97ac	2.39	0.22	0.16	0.38	2.77
Bare soil	0.41	0.19a	0.60	0.20	0.11	0.31	0.91
p-value	0.11	0.03	0.06	0.60	0.24	0.49	0.08

August 16, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.12	0.14	0.26	0.14	0.12	0.26	0.52
80N	1.29	1.40	2.69	0.17	0.11	0.28	2.97
40N	0.33	0.43	0.77	0.12	0.12	0.24	1.01
Split-N	1.37	1.13	2.50	0.26	0.28	0.55	3.05
Bare soil	0.90	0.53	1.43	0.17	0.16	0.33	1.77
p-value	0.34	0.55	0.45	0.15	0.47	0.27	0.44

Table A-9 (Continued)

September 19, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.14	0.10	0.24	0.27	0.22	0.49	0.73
80N	0.71	0.63	1.35	0.25	0.36	0.60	1.95
40N	0.50	0.40	0.90	0.25	0.30	0.55	1.44
Split-N	0.96	0.79	1.75	0.23	0.21	0.44	2.18
Bare soil	0.29	0.18	0.47	0.38	0.42	0.80	1.27
p-value	0.18	0.47	0.31	0.38	0.20	0.06	0.38

December 10, 2002							
	Nitrate			Ammonium			Total Inorganic N
	0-15 cm	15-30 cm	0-30 cm	0-15 cm	15-30 cm	0-30 cm	0-30 cm
0N	0.25	0.22	0.47	0.12	0.10a	0.22	0.69
80N	0.33	0.68	1.02	0.17	0.12ab	0.29	1.30
40N	0.26	0.10	0.37	0.14	0.12ab	0.26	0.63
Split-N	1.04	0.46	1.51	0.22	0.14b	0.37	1.88
Bare soil	0.53	0.49	1.02	0.28	0.23c	0.51	1.53
p-value	0.36	0.20	0.40	0.18	0.01	0.07	0.38

[z]Treatments applied were 0 kg·ha of N, 80 kg·ha of N in March (labeled in 2001), 40 kg·ha of N in March (labeled in 2001), and 40 kg·ha of N in March (unlabeled) + 40 kg·ha of N in May (labeled in 2001). The same rates of unlabeled N were applied in 2002.

[y]Means in the same column followed by the same letter are not significantly different (ANOVA, Fisher's LSD, p>0.05). Means are compared within dates only, not among dates.

Table A-10. Monthly average of daily precipitation (mm) measured at the North Willamette Research and Extension Center weather station in Aurora, Ore.

	Monthly Average of Daily Precipitation (mm)	
	Year	
Month	2001	2002
March	89.2	142.0
April	61.7	62.0
May	26.7	34.3
June	42.4	46.5
July	18.5	1.8
August	30.2	6.1
September	17.5	49.5
October	96.5	14.2
November	183.9	81.8
December	206.0	116.1