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Reduced Nitrogen Fertilizer Rates Maintained Raspberry Growth in an Established Field

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Abstract: Optimizing nitrogen (N) fertilizer rates maintains good red raspberry (*Rubus idaeus* L.) production while alleviating environmental risks. Although raspberry growers in Washington are using the caneberry nutrient management guides derived from western Oregon, these guides may not be appropriate for other production regions given the differences in climate, soil type, and crop productivity. However, limited research has been conducted to observe the impact of the N fertilizer rate on floricane red raspberry growth, yield, and fruit quality in Washington. The aim of this study is to evaluate the response of "Meeker" floricane red raspberries grown in northwest Washington, USA, to different N fertilizer rates in order to provide information for future local nutrient management guides. Treatments of urea (46% nitrogen (N)) were surface-applied to raised beds of established 'Meeker' raspberry plots at controls, low, medium, and high rates (0, 34, 67, and 101 kg N ha^{-1}, respectively) in 2019 and 2020. The experiment was arranged in a randomized complete block with three replications. Fruit yield and quality, plant growth and leaf tissue nutrient concentrations, and soil characteristics were evaluated. There were no N fertilizer rate treatment effects for the yield, fruit quality, plant growth, leaf tissue nutrient concentrations, and soil characteristics, except for fruit titratable acidity and soil ammonium (NH_4-N) concentrations. The lack of a plant response may be due to nutrients mineralized from soil organic matter (3.81–4.0%) and the utilization of plant nutrient reserves. Based on the results, the soil organic matter level and plant nutrient reserves should be considered when making nutrient management suggestions. Fertilizer costs as well as the potential for environmental pollution from excess fertilizers could be reduced through utilizing these two potential sources of nutrients. Furthermore, longer periods of research is warranted to understand how to adjust N fertilizer rates based on plant and soil characteristics while sustaining yields.

Keywords: *Rubus idaeus* L.; nutrients; soil organic matter; plant nutrient reserves; nutrient management; summer-bearing red raspberry

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1. Introduction

Red raspberry (*Rubus idaeus* L.) is a globally important crop, with the Pacific Northwest (PNW) region of the United States of America (USA) leading in the raspberry processing market [1]. The processed market primarily uses floricane ("floricane-fruiting" or "summer-bearing") red raspberry with biennial canes that are vegetative one year and fruiting the following. The distinctive growth habit of the floricane raspberry with biennial canes makes nutrient management more challenging compared to other annual and perennial crops, due to the differences in nutrient uptake timing and partitioning [2,3].

Raspberry growers aim to provide sufficient nutrients in advance of crop demand through the application of fertilizers, which in turn promotes vegetative growth and removes limitations to yield and quality [4]. Most growers in the PNW use granular or a combination of granular and liquid fertilizers in their established plantings [3]. Among all the fertilizers applied, nitrogen (N) is one of the most important given nitrogen serves as a constituent of many plant cell components, such as amino acids that make up structural proteins and enzymes important for metabolism, nucleic acids, and chlorophyll [5]. Growers rely on regional caneberry nutrient management guides that may require adaptation to local conditions. These guides recommend applying N fertilizer based on annual plant tissue tests and periodic soil analyses, as well as observations of annual cane growth and yield to ensure optimal plant growth and productivity. The current regional nutrient management guides recommend 34 to 56 kg N ha^{-1} during the establishment year and 56 to 90 kg N $ha^{-1}year^{-1}$ after establishment [4,6]. This application strategy should maintain current season yields, good primocane growth for next season's crop, and replenish N lost through pruning, leaf senescence, and harvest.

Rempel et al. (2004) and Strik et al. (2006) studied the uptake, partitioning, and storage of N in "Meeker" floricane red raspberry using depleted ^{15}N in Oregon, USA [2,7]. Regarding the N uptake, it was shown that 24–37% of applied N fertilizer is translocated to the above-ground tissues and most of the N fertilizer applied in early Spring (mid-March) is used to support new growth, such as primocanes, fruiting laterals, and fruits. In contrast, most of the fertilizer N applied in late Spring (mid-May) is translocated to primocanes and little goes to floricanes. Kowalenko et al. (2000) concluded that a single early Spring (date not specified) granular N fertilizer application in "Willamette" floricane red raspberry grown in British Columbia, Canada, can ensure good yields for the current season as the main flush of growth occurs early in floricanes [8]. Nutrient partitioning studies estimated 17%, 12%, and 13% of the total N (g $plant^{-1}$) present in floricane raspberry is lost annually through the removal of floricane and fruiting lateral, primocane leaf senescence, and fruit harvest, respectively. In addition, 30% of the total N is stored in over-wintering tissue, while 28% is considered lost or transported to the roots. Stored N in over-wintering primocanes, the crown, and roots is an important long-term N source for the floricane red raspberry [2,3]. Strik (2008) reported that floricane growth is mainly supported by stored N, whereas primocane growth is more dependent on external N sources, such as fertilizer and soil N [6].

Nutrient management trials can help identify optimum fertilizer rates, which may be locally specific. Rempel et al. (2004) observed "Meeker" raspberry plants that received higher rates of N fertilizer took up more fertilizer N but had similar total N uptake compared to plants that received a lower N fertilizer rate. This indicates that the floricane red raspberry may prefer taking up fertilizer N instead of utilizing soil N and stored N when receiving high rates of N fertilizer [2]. Rizzi et al. (2019) found that the "Autumn Bliss" primocane-fruiting red raspberry cultivated in south Brazil had a greater yield when they received either 200 or 300 kg ha^{-1} of N than plants that received 100 kg ha^{-1} of N. However, yields were similar between plants that received 200 and 300 kg ha^{-1} of N, which indicates fertilization beyond plant need may not benefit yields [9]. Field research carried out in western Serbia by Milošević et al. (2018) found greater yields in the "Thornfree" trailing blackberry (*Rubus* L. subgenus *Rubus*, Watson) when plants received high rates of N [10]. Yet, another study carried out in Norway showed that a high N fertilizer rate (178 kg N ha^{-1}) did not increase the yield of the "Veten" floricane red raspberry compared to a low N fertilizer rate (40 kg N ha^{-1}) [11]. The lack of a yield response to the N fertilizer rate was also found by Rempel et al. (2004) in the "Meeker" red raspberry cultivated in Oregon in the first year of the study and by Kowalenko et al. (2000) in the "Willamette" raspberry grown in British Columbia, Canada [2,8]. These findings highlight that optimizing the N fertilizer rate to match crop demand is important for maintaining production. However, the relationship between the N rate and crop performance may be locally specific and more research is required. Optimizing nutrient management is also important for reducing environmental risks, such as eutrophication in water that results from excessive fertilization, and soil toxicity caused by the accumulation of salt ions from fertilizers [12,13].

Current nutrient management recommendations for northwest Washington, an important production region in the PNW, were primarily developed from research and observations made in Oregon [4,14]. The recommended fertilizer rates in these guides are generalized for multiple cultivars, planting ages, soil types, and agricultural management practice. As a result, current recommendations included in these guides may have limited applicability to floricane red raspberry grown in other locations. Both climate and soil type differ between northwest Washington and western Oregon. The average 10-year mean daily air temperature between 2011 and 2020 in western Oregon was 1.73 °C higher than northwest Washington [15,16]. The typical soil type for raspberry production in western Oregon is a fine loam, whereas in northwest Washington it is a coarse loam over sand [17]. The soil cation exchange capacity (CEC) and soil organic matter (SOM) content differ by soil type. Fine loam soil in western Oregon is prone to have more small-sized soil particles, which likely results in a greater CEC and SOM content compared to coarse loam soil in northwest Washington [18]. The average yields between the two states also differs. The 3-year (2015–2017) average yield of red raspberry in Oregon is 4999 kg ha^{-1}, while the average in northwest Washington is almost double at 9098 kg ha^{-1} (Oregon data not available after 2017; [19]). Growers in locations with high productivity, such as northwest Washington, have the potential to lose more N through crop harvest and may need more fertilizer N to replenish these losses. Given how climate, soils, and productivity differ across production regions, there is a need to create more localized nutrient management recommendations.

The objective of this research is to evaluate the response of "Meeker" floricane red raspberry when treated with different N fertilizer rates in northwest Washington, and to monitor for changes in plant growth, productivity, fruit quality, and select soil variables. We hypothesize that improved plant performance will be observed when plants receive high N fertilizer rates. Information from this research provides crop consultants and regional growers with knowledge about the optimization of N fertilizer rates and contributes to creating more localized and relevant nutrient management guidelines.

2. Materials and Methods

2.1. Experimental Site

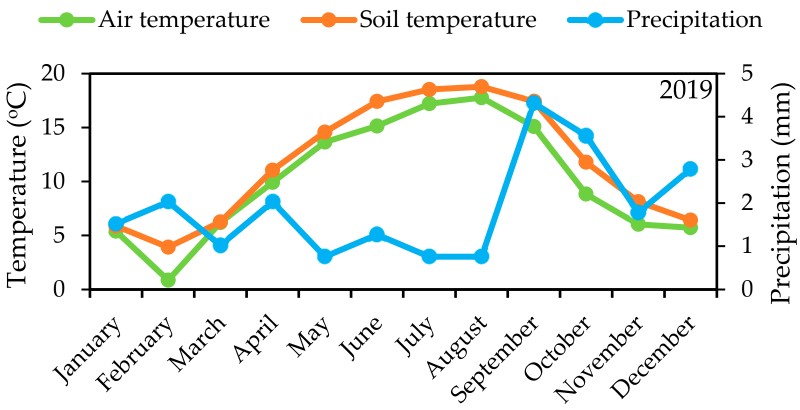
The experiment was carried out in an established field of "Meeker" red raspberry located at the Washington State University Northwestern Washington Research and Extension Center (WSU NWREC) in Mount Vernon, Washington, USA (latitude: 48°44′20″ N/ longitude: −122°39′16″ E) in 2019 and 2020. The field was planted with tissue culture transplants in May 2017 on raised beds approximately 0.61 m wide at the top and 0.25 m tall, following commercial production practices in this region. In-row plant spacing was 0.6 m and between-row spacing was 3 m. The experimental area was 0.03 ha (9 m in width × 37 m in length). There were 12 experimental plots in total and each plot was 3 m in width by 9.25 m in length and contained 11–14 raspberry plants with 8–15 canes per plant.

The soil at the site was a silt loam, characterized as a fine silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts [17], and the soil characteristics are shown in Table 1. The site was managed using commercial standard practices for the region [14]. The average monthly air temperature, soil temperature at a depth of 20 cm, and precipitation of the experimental area in 2019 and 2020 are shown in Figure 1 [16].

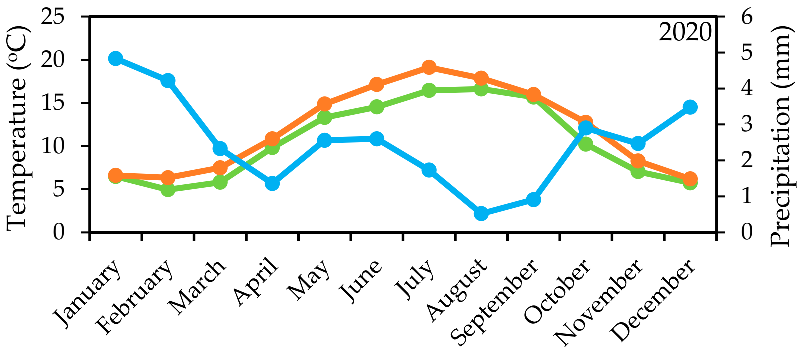
Table 1. Initial soil characteristics of the "Meeker" floricane red raspberry experimental field site, 2019.

pH [z]	Cation Exchange Capacity (meq 100 g^{-1})	Organic Matter (%)	ENR [y] (kg N ha^{-1})	mg kg^{-1}											
				NO_3-N	P [x]	K	Ca	Mg	SO_4-S	Na	Mn	B	Fe	Cu	Zn
6.4	6.7	2.8	96	5	100	202	930	103	3	11	2.0	0.3	69	3.0	1.8

[z] Measured using soil:H_2O at a 1:1 ratio. [y] Estimated nitrogen release (ENR) was estimated based on the percentage of organic matter in the soil. [x] Bray I P.



(**a**)



(**b**)

Figure 1. Average monthly air temperature, soil temperature, and precipitation of the experimental area in 2019 (**a**) and 2020 (**b**). Data provided by WSU AgWeatherNet.

2.2. Experimental Design

The experimental design was a randomized complete block with four treatments replicated three times. Treatment was granular urea (46N-0P-0K) (Wilbur-Ellis company LLC; Yakima, WA, USA) fertilizer applied at low, medium, and high rates (34, 67, and 101 kg N ha^{-1}, respectively), plus a no-fertilizer control (0 kg N ha^{-1}). Fertilizer application was split with the first half applied in mid-April (a week before primocane emergence) and the second half applied in late-May (a month before first harvest) to the same plot in both 2019 and 2020, which was in accordance with nutrient management guides currently applied in Washington [4]. For fertilizer application, urea was uniformly sprinkled over the surface of the raised bed and drip irrigation was immediately applied for at least 2 h to incorporate urea into the soil and reduce volatilization.

2.3. Fruit Yield and Quality

Raspberry fruits were machine-harvested (Littau, #R0012, Littau Harvester Inc.; Lynden, WA, USA) by plot every 3–4 d for a total of 10 times from 29 June to 4 August 2020. No yield data were collected in 2019 due to the unavailability of the harvester. The total yield per plant and per hectare was calculated for the whole harvest season.

A total of 30 ripe berries was randomly collected from each plot on 6, 17, and 28 July to correspond with the early, middle, and late harvest, respectively, in 2020. The berry weight was measured and berry samples were frozen at −15 °C until berry quality analysis. Berry quality (total soluble solids (TSS), pH, titratable acidity (TA), and total soluble solids-to-titratable acidity ratio (TSS/TA)) were measured in September 2020. Berries were thawed at room temperature (22 °C) for 5 h and then the fruits from each treatment plot and time point were crushed in a sample mesh bag (Agdia, Inc., Elkhart, IN, USA) and the juice was strained into a test tube. Percent TSS was measured using a digital refractometer (HI-96801, Hanna Instruments; Woonsocket, RI, USA). Initial juice pH and TA (g L^{-1}) were determined simultaneously with 5 mL juice samples using a digital titrator (HI922 Hanna Instruments; Woonsocket, RI, USA) that titrated to an endpoint of pH 8.2 using a solution of 0.1 N sodium hydroxide. Juice from each treatment plot and time point were measured with three analytical replicates.

2.4. Primocane Growth

Primocane height and number were recorded from three representative plants within the interior of each plot on 15 September 2020. Primocane height was determined by measuring the height of the tallest primocane per plant, starting at the base of the crown and extending to the tallest leaf tip. Primocane number was determined by counting the number of primocanes emerging from the base of the crown per plant.

2.5. Leaf Photosynthesis

Leaf photosynthesis was measured as net CO_2 assimilation (A) (µmol m^{-2} s^{-1}) using a portable photosynthesis system (CIRAS-3, PP Systems; Amesbury, MA, USA). The photosynthetically active radiation, CO_2 reference, and H_2O reference were set at 1200 µmol m^{-2} s^{-1}, 390 µmol mol^{-1}, and 70%, respectively. Photosynthesis measurements were collected from the fourth most recent fully expanded leaflet from three representative primocanes per treatment plot between 10 a.m. and 2 p.m. on 26 August 2020.

2.6. Plant and Soil Sample Collection

In each plot, the 4th most recent, fully expanded whole leaf (approximately 30 cm from the growing point) and petiole were collected from 5 representative primocanes free of damage and disease. Sampling occurred from mid-July to late-August at a 14-day interval such that there were 4 sample collections in both 2019 and 2020. Sample collection and timing was in accordance with the protocol outlined by Hart et al. (2006) who reported that raspberry leaf tissue nutrient concentration is relatively stable during late-July and early-August in western Oregon [4]. During each sampling time, leaf samples were collected between 9 a.m. and 2 p.m. on sunny days. Leaf samples were placed in paper bags and were transported to the laboratory located approximately 1 km from the field site at WSU NWREC after completing all sampling work.

Baseline soil sampling was conducted on 22 March 2019. Soil samples consisting of 30 cores, were randomly selected from the area 5 m around the experimental field, using a standard 2.5 cm-wide soil probe to a 30 cm depth. Soil from all cores was combined and mixed thoroughly as one composite sample. Post-harvest comprehensive soil sampling was conducted on 15 September 2020. Soil samples consisted of 12 cores per plot, with 4 cores collected from each side of the raised raspberry bed at about 1/2 height plus 4 cores collected from the center of the row from representative areas, using a standard 2.5 cm-wide soil probe to a 30 cm depth. Cores from the same plot were combined and mixed thoroughly as one composite sample.

2.7. Plant Leaf Tissue Nutrient Analyses

On each sampling date, the sampled leaves were kept intact, dried at 38 °C for 5 days until constant weight, and then sent to a commercial laboratory (Brookside Laboratories, Inc.; New Bremen, OH, USA) for nutrient analysis using the method described by Miller et al. (2013) [20].

2.8. Soil Properties

Baseline soil samples collected on 22 March 2019 were sent to a commercial laboratory (A&L Western Laboratories; Modesto, CA, USA) for soil pH, cation exchange capacity (CEC), soil organic matter (SOM), estimated nitrogen release (ENR), and nutrient analyses.

Soil samples collected on 15 September 2020 were sent to a commercial laboratory (Brookside Laboratories, Inc.; New Bremen, OH, USA) within 24 h of sampling for soil pH, CEC, SOM, ENR analyses [20,21]. Soil mineral N was extracted using 6 g field-moist soil with 30 mL 2 M KCl, then determined using the colorimetric method [22–24].

2.9. Statistical Analyses

All data were subjected to analysis of variance using linear mixed-effects models with the function lme() in the nlme package built in R (R version 3.6.3; Boston, MA, USA). Block was always treated as a random effect. Assumptions of normality and homogeneity of variance were checked by visual inspection of residual plots. Soil cation exchange capacity was subjected to log transformation to improve the normality and homogeneity.

Leaf tissue nutrient concentration data were first analyzed using a two-way factor analysis with N fertilizer rate and year as the factors with repeated measures for the two-year data. Treatment by year interactions and year effects were tested and data were separated by year when significant ($\alpha = 0.05$). Leaf tissue nutrient concentrations, fruit yield, and fruit quality data within each year were analyzed using a two-way factor analysis with N fertilizer rate and sampling/harvest time as the factors. Treatment by time interactions and time effects were tested and data were separated by sampling time when significant ($\alpha = 0.05$). Lastly, leaf tissue nutrient data within each sampling time point and fruit yield and quality data within each harvest time point were analyzed using a one-way factor analysis with N fertilizer rate as the factor. Given the soil variables, primocane height and number, total yield across the harvest season, and leaf photosynthesis were only collected in 2020; these data were analyzed using a one-way factor analysis and effects for N fertilizer rate were tested. A Tukey's honest significant difference test was used for post hoc comparisons at the 5% level of significance to compare treatment means.

3. Results and Discussion

3.1. Fruit Yield and Average Berry Size

Fruits were harvested a total of 10 times in 2020 with the early, middle, and late harvests corresponding to 29 June–10 July, 11 July–24 July, and 25 July–4 August, respectively. There was no interaction between the N fertilizer rate and harvest time nor N fertilizer rate effects for average plant yield. However, among the three harvest periods, the greatest average plant yield occurred at the middle harvest, followed by late then early harvests (Table 2). No N fertilizer rate effects were found for the average plant yield within each of the three harvest periods (Table S1). The mean total yield was 0.933, 1.15, 0.977, and 1.05 kg plant^{-1} and corresponded to 4611, 5698, 4828, and 5174 kg ha^{-1} (estimation based on 4942 plants ha^{-1} as outlined by Galinato and DeVetter (2015)) for the 0, 34, 67, and 101 kg N ha^{-1} fertilizer rate treatments, respectively [25]. Although no differences were found for the total yield across the N fertilizer rate treatments, the total yield for the low, medium, and high N fertilizer rates were 23.6%, 4.7%, and 12.2% greater than the no-fertilizer control (Table 3). Total yield in the current study was similar to "Meeker" red raspberry yields (1.0–2.2 kg plant^{-1}) treated with different N fertilizer application rates in Oregon, USA [2]. However, the total yield on a per hectare basis in this study was lower than yields of "Meeker" red raspberries (5720–12,580 kg ha^{-1}) treated with different fertilizer sources in western Serbia, which is likely attributed to the 150% higher plant density in Serbia [26]. The lack of a yield response to N fertilizer rate was also observed in "Meeker" and "Veten" red raspberries cultivated in Oregon, USA and Norway, respectively [2,11].

Table 2. Berry weight, average plant yield, and total yield of the "Meeker" floricane red raspberry fertilized with different nitrogen (N) fertilizer rates, 2020.

Treatment	Berry Weight (g)	Average Plant Yield (kg Plant^{-1})	Total Yield (kg Plant^{-1})
N fertilizer rate (A)			
Control (0 kg N ha^{-1})	3.02 ^{z}	0.311	0.933
Low (34 kg N ha^{-1})	3.03	0.385	1.15
Medium (67 kg N ha^{-1})	3.10	0.325	0.977
High (101 kg N ha^{-1})	3.10	0.349	1.05
Harvest time (B)			
Early	3.35 a	0.212 c	- ^{y}
Middle	3.08 b	0.542 a	-
Late	2.75 c	0.274 b	-
Significance ^{x}			
N fertilizer rate (A)	0.78	0.85	0.85
Harvest time (B)	<0.0001	<0.0001	-
Interaction A × B	0.55	0.85	-

^{z} Data are displayed as means; means followed by a different letter within a group are significantly different at $p \leq 0.05$ using a means comparison with a Tukey's honestly significant difference test. ^{y} (-) Not applicable as the total yield was calculated across the whole harvest season. ^{x} Significance was determined at $p < 0.05$.

Table 3. Total soluble solids (TSS), fruit pH, titratable acidity (TA), and total soluble solids-to-titratable acidity ratio (TSS/TA) of the "Meeker" floricane red raspberry fertilized with different nitrogen (N) fertilizer rates, 2020.

Treatment	TSS (°Brix)	pH	TA (g L^{-1})	TSS/TA
N fertilizer rate (A)				
Control (0 kg N ha^{-1})	11.8 ^{z}	3.35	1.64 b	7.21
Low (34 kg N ha^{-1})	11.9	3.31	1.64 b	7.26
Medium (67 kg N ha^{-1})	12.2	3.35	1.76 a	6.90
High (101 kg N ha^{-1})	11.9	3.34	1.64 b	7.27
Harvest time (B)				
Early	10.3 c	3.40 a	1.57 c	6.56 b
Middle	12.3 b	3.30 b	1.68 b	7.32 a
Late	13.3 a	3.30 b	1.75 a	7.60 a
Significance ^{y}				
N fertilizer rate (A)	0.44	0.37	0.03	0.16
Harvest time (B)	<0.0001	<0.0001	<0.0001	<0.0001
Interaction A × B	0.72	0.52	0.38	0.84

^{z} Data are displayed as means; means followed by a different letter within a group are significantly different at $p \leq 0.05$ using a means comparison with a Tukey's honestly significant difference test. ^{y} Significance was determined at $p < 0.05$.

The lack of a yield response to our N fertilizer rates may be due to the plant uptake of non-fertilizer soil N and utilization of plant nutrient reserves [2,3]. In addition, soil organic matter levels (3.8–4.0%) in this study could have provided sufficient plant-available N through mineralization, thus reducing the potential for yield responses to our N fertilizer rates [13]. Rempel et al. (2004) attributed similar "Meeker" red raspberry yields across N fertilizer rates as being due to plants adjusting their N uptake, so that they took up more fertilizer N instead of soil N when fertilized at high N fertilizer rates, while total N uptake was similar across all N fertilizer rate treatments. Plant reserves are also very important long-term N sources for floricane red raspberries, which may obscure potential yield responses to fertilizer treatments [2].

Similarly, there was no N fertilizer rate by harvest time interaction or N fertilizer rate effect on the berry weight. The mean berry weight in this study ranged from 3.02–3.10 g (Table 2). However, the berry weight differed due to the harvest time with berry weight being the greatest during early harvest, followed by middle, then late harvests. The berry weight did not differ across N fertilizer rates within each harvest time (Table S1). Average berry weights in this study were slightly greater than the "Meeker" red raspberry berry weights reported by Rempel et al. (2004) in Oregon, USA, but similar to the "Meeker" red raspberry and greenhouse-grown "Autumn Bliss" red raspberry in western Serbia and northeastern China, respectively [2,26,27]. The lack of a N fertilizer rate effect for the berry weight contrasted with Heiberg (2000) and Rempel et al. (2004), who found that fertilized plants had greater berry weights compared to unfertilized plants [2,11]. The decline in berry weight across the harvest season was in accordance with Zhang et al. (2019), and may be partially explained by the continuous removal of N through harvest and developmental stage of fruiting buds [2,3,28,29].

3.2. Fruit Quality

There was no interaction between the N fertilizer rate and harvest time or N fertilizer rate effects for TSS, pH, and TSS/TA. However, TA was higher when plants were treated with 60 kg N ha^{-1} (Table 3). Harvest time effects were found for all measured fruit quality variables (Table 3). Both TSS and TA were greatest at late harvest and decreased with earlier harvest times. Fruit pH was greater at early harvest compared to middle and late harvests. However, TSS/TA in early harvest was lower than middle and late harvests. No N fertilizer rate differences were found for the TSS content, pH, TA, and TSS/TA within each harvest time (Table S1).

Fruits were in acceptable ranges for TSS, pH, TA, and TSS/TA [30]. Similarly, no differences in TSS content by the N fertilizer source and rate were observed in "Autumn Bliss" red raspberries grown in southern Brazil, "Meeker" red raspberries grown in western Serbia, and "Thornfree" blackberries grown in western Serbia [9,10,26]. However, Papp et al. (1984) found that TSS of "Malling Exploit" floricane red raspberries decreased with high N fertilizer rates in Budapest, Hungary [31]. In addition, Stojanov et al. (2019) reported that pH and TA varied by fertilizer source and rate in "Meeker" red raspberries and Jeppsson (2000) found that the "Viking" black chokeberry TA differed by fertilizer rates, while Rizzi et al. (2019) and Milošević et al. (2018) found no differences in the pH and TA across different fertilization regimes in "Autumn Bliss" red raspberries and "Thornfree" blackberries, respectively [9,10,26,32]. Both Stojanov et al. (2019) and Milošević et al. (2018) observed that TSS/TA differed by fertilization regimes in "Meeker" red raspberries and "Thornfree" blackberries, respectively, whereas Rizzi et al. (2019) reported the similar SS/TA across fertilizer treatments in "Autumn Bliss" red raspberries [9,10,26].

3.3. Plant Growth and Photosynthesis

The primocane length and number and primocane leaf CO_2 assimilation did not differ across N fertilizer rate treatments, although these measured variables were numerically greater than the control (Table 4). "Meeker" raspberry primocane length also did not differ across N fertilizer rates in the first year of a study in Oregon. However, fertilized plants had a greater primocane length than unfertilized plants in the second year, but plants fertilized with either low or high N fertilizer rates had similar primocane lengths in the first year [2]. Similarly, An et al. (2018) and Stojanov et al. (2019) observed fertilized "Autumn Bliss" plants at 34 kg N ha^{-1} and "Meeker" plants (rate not specified) had greater primocane lengths compared to unfertilized plants, respectively, but the primocane number did not differ [26,27]. The lack of differences in the primocane number by N fertilizer rates observed by Rempel et al. (2004) may be explained by the similar plant total N content (g plant^{-1}) across all N fertilizer rate treatments [2]. Similarly, the lack of a primocane growth response to the N fertilizer rates in the current study may be due to the mineralization and subsequent provision of sufficient N from soil organic matter and the utilization of plant reserves [3,6]. The mean leaf CO_2 assimilation values in this study were within the range (3.1–14.8 μmol m^{-2} s^{-1}) of "Meeker" raspberries cultivated with different mulches in Washington, USA [29]. The lack of differences in leaf CO_2 assimilation contrasted with Jafarikouhini et al. (2020), who found that sweetcorn (*Zea mays* L. *saccharata*) fertilized at more than 175 kg N ha^{-1} had higher leaf photosynthesis than those receiving lower N fertilizer rates at vegetative, tasseling, and silking stages. However, there were no differences for sweetcorn leaf photosynthesis across N fertilizer rates at the milking stage [33]. Similarly, the "Golden Delicious" apple (*Malus domestica* Borkh.) receiving higher rates of N (250 kg N ha^{-1}) had higher leaf photosynthesis than those receiving lower rates of N [34].

Table 4. Primocane length, primocane number, and primocane leaf CO_2 assimilation of "Meeker" floricane red raspberries fertilized with different nitrogen (N) fertilizer rates, 2020.

Treatment	Primocane Length (cm)	Primocane Number (No. $Plant^{-1}$)	CO_2 Assimilation (μmol m^{-2} s^{-1})
Control (0 kg N ha^{-1})	279 [z]	8.22	8.27
Low (34 kg N ha^{-1})	276	6.56	7.47
Medium (67 kg N ha^{-1})	258	6.56	7.09
High (101 kg N ha^{-1})	269	7.00	7.29
p-value	0.72	0.11	0.61

[z] Data are displayed as means (n = 3).

3.4. Primocane Leaf Nutrient Levels

The mean leaf tissue N concentrations in this study were 2.90, 2.90, 2.97 and 2.82% for 0, 34, 67, and 101 kg N ha^{-1} fertilizer rate treatments, respectively. These values were within the recommended sufficiency levels (2.3–3.0%) outlined in the caneberry nutrient management guide [4]. There were no N fertilizer rate by year interactions (p = 0.70) nor N fertilizer rate effects (p = 0.65) or year effects (p = 0.11) for leaf tissue N concentrations across the two-year study. The leaf tissue N concentrations in this study were similar to the values of "Autumn Bliss" red raspberries (2.48–2.74%) cultivated in South Brazil, "Meeker" red raspberries cultivated in Washington, USA (2.80–3.58%) and Oregon, USA (2.10–3.30%), and "Willamette" red raspberries (2.10–3.30%) cultivated in British Columbia, Canada [8,9,35,36].

The lack of response of leaf tissue N concentrations to N fertilizer rate was also observed in "Autumn Bliss" red raspberries grown in South Brazil, in "Willamette" red raspberries grown in Nova Scotia, Canada, in "Thornfree" blackberries grown in western Serbia, and in "Thornless Evergreen" blackberries grown in Oregon, USA [9,10,37,38]. In contrast, Heiberg (2002) and Spiers (2002) reported that increasing N fertilizer rate increased leaf tissue N concentrations of "Veten" red raspberries grown in Norway and "Navaho" blackberries grown in Mississippi, USA [11,39]. Interestingly, An et al. (2018) found unfertilized "Autumn Bliss" red raspberries had greater leaf tissue N concentrations than fertilized plants, but this may be due to a "dilution effect" of the leaf tissue N concentration, as fertilized plants had greater leaf biomass compared to unfertilized plants [27]. The dilution effects were not observed in the current study, as plant growth was not impacted by the N fertilizer rate (Table 5). Similar to the lack of plant growth response in this study, the lack of differences in leaf tissue N concentrations may be attributed to the provision of sufficient nutrients from soil organic matter mineralization and plant nutrient reserves [2].

Within each year, there was no treatment by sampling time interactions (p = 0.23 and 0.96 for 2019 and 2020, respectively) nor N fertilizer rate treatment effects (p = 0.47 and 0.79 for 2019 and 2020, respectively) for the leaf tissue N concentrations, while sampling time effects (p = 0.003) were found only in 2019. Within each sampling time, the leaf tissue N concentrations did not differ by N fertilizer rate treatments (p = 0.41, 0.26, 0.68, 0.11 for mid- and late-July and August, respectively in 2019; p = 0.67, 0.99, 0.81, and 0.97 for mid- and late-July and August, respectively in 2020).

Table 5. Soil pH, cation exchange capacity (CEC), organic matter (SOM), estimated nitrogen release (ENR), and mineral nitrogen (NO_3-N and NH_4-N) of "Meeker" floricane red raspberry field fertilized with different nitrogen (N) fertilizer rates, 2020.

Treatment	pH [z]	CEC (meq $100g^{-1}$)	SOM (%)	ENR [y] (kg N ha^{-1})	mg kg^{-1}	
					NO_3-N	NH_4-N
Control (0 kg N ha^{-1})	6.30 [x]	11.1	3.80	98.6	0.565	0.06 b
Low (34 kg N ha^{-1})	6.23	10.3	3.87	99.8	1.322	0.20 a
Medium (67 kg N ha^{-1})	6.33	10.9	4.00	101	0.515	0.08 ab
High (101 kg N ha^{-1})	6.23	11.3	3.95	100	1.570	0.07 ab
p-value	0.77	0.08	0.75	0.86	0.47	0.03

[z] Measured using soil:H_2O at a 1:1 ratio. [y] Nitrogen release was estimated based on the percentage of organic matter in the soil. [x] Data are displayed as means (n = 3); means followed by a different letter within a group are significantly different at $p \leq 0.05$ using a means comparison with a Tukey's honestly significant difference test.

3.5. Soil Properties

Soil pH, CEC, SOM, ENR, and measured nutrient concentrations did not differ across N fertilizer rate treatments, except soil NH_4-N (Table 5). The soil pH was within the recommended range (5.5–6.5) for raspberries [14]. The soil NH_4-N concentration was greater in the 34 kg N ha^{-1} treatment than the no-fertilizer control, but was similar to the other N fertilizer rate treatments. Both soil NO_3-N and NH_4-N concentrations in this study were lower than other published studies (Table 5) [2,27,36,40,41]. One important note is that our extraction reagent (2 M KCl) was contaminated with unknown sources of ammonium by the manufacturer. As the contaminated reagent was applied consistently for all analyzed samples, we assume a treatment effect still exists. The mineral N (NO_3-N + NH_4-N) concentrations from all treatments in this study (estimated 2.81–7.34 kg N ha^{-1}) were lower than the values measured in a "Meeker" red raspberry field (estimated 10–20 kg N ha^{-1}) and trailing and semierect blackberry fields (estimated 21.7–101 kg N ha^{-1}) both in Oregon, USA [2,40]. The difference may also be due to the different caneberry types, fertilizer source, and soil sampling depth. The SOM and ENR in this study were similar to the values reported by Rempel et al. (2004) in "Meeker" red raspberries (3–4% for SOM) cultivated in Oregon, USA, and by Zhang et al. (2019) in "Meeker" red raspberries (107–170 kg N ha^{-1} for ENR) grown with different mulch treatments in Washington, USA [2,29]. The SOM from all the treatments in this study was considered medium to high, according to the grading guidelines created by A&L Western Agricultural Laboratories (A&L Western Laboratories, INC; Portland, OR, USA). The ENR from all treatments in this study, which was estimated based on the percentage of organic matter in the soil, was higher than the recommended annual N fertilizer need (56–90 kg N ha^{-1}) for the floricane-fruiting red raspberry [4,14]. Thus, both the SOM and ENR values in this study indicated that the plants may have had access to an adequate amount of N independent of the applied N fertilizer.

4. Conclusions

There was no N fertilizer rate effect on the established "Meeker" red raspberry yield, growth, photosynthesis, and leaf tissue nutrient concentrations. The fruit quality was also minimally impacted by the N fertilizer rate, with only TA being responsive to N fertilizer rate adjustments. The soil variables, except NH_4-N, did not differ by N fertilizer rate either. The lack of an N fertilizer response for most of the measured variables leads to the rejection of the experimental hypothesis that plants receiving higher N fertilizer rates exhibit an improved performance. Soil organic matter and plant nutrient reserves likely contributed to sufficient N to meet plant demand, which may obscure the effects of the N fertilizer rate. The results of this study highlight the complex dynamics of nutrient management in perennial fruit crop systems, as soil and plant nutrient reserves may provide sufficient nutrients to meet plant demand. Due to this, soil organic matter and plant reserves should be considered as potential nutrient sources when developing a raspberry nutrient management program for N. Adjusting N fertilizer rates based on these characteristics could reduce fertilizer costs and the potential for environmental pollution from excess fertilizers. However, it should be noted that the overall impact of N fertilizer rates on raspberry growth and productivity was limited in this experiment due to the lack of a fertilizer response, despite the application of a no-fertilizer control in addition to regionally recommended rates. Thus, further research with a measurable plant response to N fertilizer rates is warranted to characterize the interplay of soils and plant reserves better, and to create more robust and localized nutrient management guidelines for raspberry growers in northwest Washington. The timing of plant-available N in soil in relation to crop demand also needs to be understood to account for their role in nutrient management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12030672/s1, Table S1: Significance (displayed as *p*-values) of nitrogen fertilizer rate treatments within each harvest time on "Meeker" floricane red raspberry average plant yield, berry weight, total soluble solids (TSS °Brix), fruit pH, titratable acidity (TA g L^{-1}), and total soluble solids-to-titratable acidity ratio (TSS/TA) in 2020.

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