Long-term Effects of Pre-plant Incorporation with Sawdust, Sawdust Mulch, and Nitrogen Fertilizer Rate on ‘Elliott’ Highbush Blueberry

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Abstract. Soil amendment, mulching, and fertilization practices are key components of blueberry production, yet grower practices range widely and long-term impacts are not commonly studied. ‘Elliott’ northern highbush blueberry (*Vaccinium corymbosum* L.) was evaluated from establishment to maturity (2003–18) to investigate the impacts of pre-plant sawdust incorporation (with or without 141 m³·ha⁻¹ sawdust incorporated into the bed area), sawdust mulch (with or without an 8-cm-deep layer on soil surface), and N fertilizer rate (low, medium, and high, increased incrementally from 22, 67, and 112 kg·ha⁻¹ in 2004, respectively, to 56, 168, and 269 kg·ha⁻¹ of N from 2010 to 2018). Soil with sawdust incorporated had 4.3% soil organic matter at the end of the study in 2018 compared with 3.4% for nonincorporated soil. Soil pH was higher with sawdust incorporation and mulch when plants were young, but by 2011 these treatments were similar. High rates of N fertilization decreased soil pH by 0.3 to 0.4 throughout the study compared with the low rate, but all treatments were within or above the recommended pH range (4.5–5.5) throughout the study. Low levels of N fertilization were associated with higher soil pH and lower leaf N in most years, but higher leaf Ca and often any impacts of the low N rate were mitigated when sawdust was incorporated. Soil and leaf Ca increased when sawdust was incorporated and used as a mulch and when fertilizing with the low rate of N, but fruit Ca concentration only increased with mulch and the low N rate, whereas levels decreased with incorporation. When sawdust was not incorporated before planting, N fertilization rate affected leaf N, Ca, S, and Mn concentration, whereas this was not found when soil was amended with sawdust. Unmulched plants generally had higher leaf N, K, Fe, and Al but lower leaf Ca compared with mulched. Sawdust incorporation increased yield 4% and produced fruit with higher total soluble solids (TSS), but similar firmness, on average (2008–13), than for unamended soil. There was no main effect of mulch on yield or berry traits; however, plants grown with sawdust incorporated and no mulch had 7% greater yield per plant (averaged over 2006–13) compared with incorporated with mulch or nonincorporated with or without mulch. Nitrogen fertilization rate had no effect on yield, but berry weight was greater with low or medium N rates, particularly when sawdust was not incorporated. Net returns from higher yield with sawdust incorporation more than compensated for the materials and labor costs. Berry firmness and TSS were similar among incorporation, mulch, and fertilizer treatments for most years. Incorporating sawdust before planting resulted in an estimated \$7680/ha greater net profit from fruit sales during the study period, more than compensating for the initial materials and application cost (\$3150/ha). Use of the low rate of N from 2004 to 2018 saved \$2680/ha and \$5152/ha compared with the medium and high rates, respectively.

Blueberries are a long-lived perennial crop with a high cost of establishment requiring ≈7 years to reach maturity and full production (Sutton and Sterns, 2020). Over the past 2

decades, research has been conducted on best management practices for establishment of both conventional and organic northern highbush blueberry (*Vaccinium corymbosum* L.), including incorporating or amending with organic matter before planting, mulching, and fertilization (Bañados et al., 2012; Cox, 2009; Krewer et al., 2009; Strik et al., 2017a, 2017b, 2019). In the early 2000s, common practice in the Pacific northwestern United States was to incorporate and mulch with Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*] sawdust and to apply 100 to 140 kg·ha⁻¹ N in mature plantings with some growers fertilizing at much higher rates. At that time, sawdust was readily available at a relatively

low cost, but has since increased in cost (Julian et al., 2012; Sutton and Sterns, 2020), emphasizing the need for research on the long-term effects on plant productivity, and if these practices should continue to be used.

Soil amendments such as sawdust are typically used to improve soil organic matter (SOM) and aeration without the concern of raising soil pH above the optimum of 4.5 to 5.5 (Hart et al., 2006), as compared with using composts that typically have a high pH (Sullivan et al., 2018). However, incorporating sawdust and other organic amendments into soil adds to establishment costs, and past research has shown mixed results for plant productivity (Lareau, 1989; Nemeth et al., 2017; Strik et al., 2017b; Townsend, 1973; White, 2006) even though amendment does increase SOM compared with pre-amendment levels (Strik et al., 2020b; White, 2006). In the first years after planting, beds with sawdust incorporated required 5- to 6-fold irrigation water volume to maintain similar levels of soil moisture to unamended soil (White, 2006). In addition, the high C:N ratio in sawdust can bind N and reduce plant-available N (Hart et al., 2006). Sawdust and other wood-based mulches can be a useful tool in blueberry production for reducing weed pressure (DeVetter et al., 2015; Krewer et al., 2009; Tertuliano et al., 2012). These organic mulches also reduce daily soil temperature fluctuation compared with bare soil or woven polypropylene weed mat (Cox, 2009; Strik et al., 2017a, 2020a), which may be beneficial because blueberry plants have a relatively narrow temperature range (≈14 to 18 °C) for optimum root growth (Abbott and Gough, 1987; Spiers, 1995). Mulching has also led to higher yield and plant growth compared with bare soil in several cases (Clark and Moore, 1991; Karp et al., 2006; Kozinski, 2006; Krewer et al., 2009).

Several studies have shown that high rates of N fertilization are either detrimental or have no impact on yield compared with lower rates. In ‘Bluecrop’, moderate rates of N fertilization (50 kg·ha⁻¹) promoted more growth and yield in young plants than when no fertilizer was used, and increased fertilizer use efficiency while reducing salt stress and plant mortality compared with higher N rates (100 or 150 kg·ha⁻¹; Bañados et al., 2012). In ‘Duke’ and ‘Liberty’ produced organically, using a low N rate (73 kg·ha⁻¹) resulted in 4% higher yield over a 10-year period compared with a high N rate (140 kg·ha⁻¹; Strik et al., 2017a), and in conventional blueberry no differences were found when N rates were doubled and tripled (Lareau, 1989). Goulart et al. (1997) found that increasing N rates did not affect yield when plants were mulched with sawdust but decreased yield when no mulch was used; however, increasing N rates above recommended levels increased yield of ‘Duke’ in the second and third harvest years (Ehret et al., 2014). Excessive N fertilization can reduce soil pH, particularly with fertilizers such as ammonium sulfate, thus requiring mitigation using applications of lime

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(calcium carbonate) to stay within the desired range for blueberry (Hart et al., 2006).

The objective of this study was to follow the effects of sawdust incorporation and mulching and three different N fertilization rates on soil characteristics; nutrient concentration of soil, leaf, and fruit; and fruit yield and quality. Effects were assessed through maturity and up to 15 years after planting to better understand the long-term effects of these production practices and the associated economic costs and benefits of the treatments.

Materials and Methods

The study site was a 0.3-ha block established in Oct. 2003 at Oregon State University's North Willamette Research and Extension Center (Aurora, OR; lat. 45°16'47"N, long. 122°45'23"W). Soil is mapped as a Willamette silt loam (fine-silty, mixed, mesic pachic ultic argixerolls) with an average pH of 5.4 and 4% organic matter content before planting. Two-year-old 'Elliott' northern highbush blueberry plants, growing in 3.8-L containers, were transplanted to raised beds ≈0.30 m high with 0.75 m between plants in the row and 3.1 m between rows.

The experimental design was a split-plot with four replications. Pre-plant incorporation of douglas fir sawdust was the main plot (with or without incorporation) effect. Sawdust was applied at 141 m³·ha⁻¹ with 16-16-16 fertilizer (16N-7P-13K) added to each incorporated treatment row at a rate of 45 kg·ha⁻¹ of N to help facilitate decomposition of sawdust. Nonincorporated rows did not receive the supplemental fertilizer. Subplots consisted of combinations of surface mulching (with or without sawdust mulch; applied in an 8-cm-deep layer; 155 m³·ha⁻¹ and replenished as required during the study in 2005, 2008, and 2010) and N fertilization rate (low, medium, and high rates, increased incrementally until 2010 when plants were considered mature; Table 1). Nitrogen fertilizer was surface applied as a granular product (Table 1) with the total rate divided into thirds, applied in mid-April, May, and June of each year. In 2004 and 2005, an additional 35 kg·ha⁻¹ of P and 66 kg·ha⁻¹ of K were applied in spring. Weeds were controlled, as needed, in all treatments. In 2018, sawdust mulch was added to the entire planting with a goal of improving weed control and an additional 28 kg·ha⁻¹ N (urea) was applied, divided equally between the second and third fertilizer applications.

At planting, each treatment plot consisted of 20 plants with a 3-m unplanted buffer between plots within the row to separate the N rate treatments and to allow for clearing of the machine harvester between plots. Some plants were removed for earlier research trials as detailed by White (2006), leaving 13 to 16 plants per plot depending on treatment. Guard rows flanked the planting. Plants were irrigated by overhead sprinklers until Aug. 2004 when drip tubing was installed and used for all irrigation needs. The planting was otherwise maintained according to standard commercial practice; further details on establishment are provided by White (2006) and Strik and Buller (2014).

Flower buds were removed at pruning before the 2004 and 2005 growing seasons to remove the fruit crop and encourage plant growth. Plants were harvested by hand for the first two fruiting seasons (2006 and 2007) and by machine (Littau Harvesters Inc., Stayton, OR) from 2008 through 2013 and in 2018. Fruit were harvested as they reached commercially acceptable ripeness, typically requiring two to three harvests per year at 7- to 14-d intervals between mid-August and early September. Fruit were weighed and divided by the number of plants per plot to calculate yield per plant. The percentage of total yield at each harvest was calculated. A random subsample of 25 berries was taken on every harvest date to determine average berry weight (a weighted seasonal average mass was then calculated) and berry firmness and diameter, using a FirmTech II (BioWorks, Inc., Wamego, KS; maximum and minimum compression forces of 250 and 25 g). The subsamples were then homogenized by hand in a zippered plastic bag and measured for percent TSS using a temperature-compensating digital refractometer (Atago, Bellevue, WA). Berry diameter, firmness, and TSS are reported as seasonal averages.

Plant tissue (most-recent fully expanded leaves sampled in late July to early August in 2004, 2005, 2009–12, and 2018) and soil (late October to early November in 2004, 2005, 2011, and 2018) samples were collected. Soil was sampled between plants to a depth of 0.2 m at the center of the row using a 2.4-cm-diameter chrome-plated steel soil probe (Soil Sampler Model Hoffer; JBK Manufacturing, Dayton, OH). Mulch, when present, was removed from the soil surface before taking the samples and replaced afterward. Ripe fruit were subsampled from the second harvest in 2011 and 2012 for nutrient analysis. Soil (including SOM and pH)

and tissue samples were analyzed for macro- and micronutrients by a commercial testing laboratory (Brookside Laboratories, New Bremen, OH). Leaf N was determined using a combustion analyzer with an induction furnace and thermal conductivity detector (Gavlak et al., 1994). Other leaf nutrients, including P, K, Ca, Mg, Al, B, Cu, Mn, Fe, and Zn, were determined using an inductively coupled plasma (ICP) spectrophotometer after wet ashing the samples in nitric/perchloric acid (Gavlak et al., 1994). Extractable soil K, Ca, Mg, Na, B, Cu, Mn, Zn, and Al were determined by ICP after extraction of the nutrients using the Mehlich 3 method (Mehlich, 1984). Soil P was extracted with the Bray-1 method and then determined by ICP. Soil NO₃-N and NH₄-N were determined using automated colorimetric methods after extraction with 1 M KCl (Dahnke, 1990). SOM and pH were measured using Loss-On-Ignition at 360 °C (Nelson and Sommers, 1996) and the 1:1 soil:water method (McLean, 1982), respectively.

Treatment cost comparison. Costs of materials (sawdust and fertilizer) were calculated from prices quoted in 2021 and may have been lower if purchased in larger quantities for a commercial field of increased size. Sawdust mulch included product (\$12.28/m³) and custom installation with an estimated labor and equipment cost of \$1050/ha. Fertilizer costs used were \$0.66/kg for ammonium sulfate and \$0.86/kg for urea. Net returns were based on actual fruit yield harvested per plot, extrapolated to a per-hectare basis, at an estimated price of \$1.54/kg fruit paid to a grower for machine-harvested 'Elliott' for the processed market in the midharvest-season. Other management costs such as for pruning and harvest were not considered but were expected to be similar among the treatments. Although weed management costs would be higher for bare soil compared with sawdust mulch due to increased presence of weeds in the row requiring hand pulling or hoeing and greater use of pre- and postemergent herbicides, these differences were not measured and are thus not included.

Statistical analyses were performed with SAS version 9.4 (SAS Institute, Cary, NC) using PROC MIXED, and means were separated at the 5% level using Tukey's honestly significant difference test. PROC UNIVARIATE was used to ensure a normal distribution of data before analysis, and log transformations were applied as necessary. Treatment effects on yield and fruit quality (2006–13, 2018) were analyzed by year due to expected changes as plants matured during the study. Yield and quality from 2018 were analyzed separately due to the gap in available data since 2013. Soil test results were analyzed by year as data were only available from select years during the study period. The effect of treatment and year on leaf tissue nutrients was analyzed as a split-split-plot as well as by year to assess overall effects and treatment effects in younger vs. mature plantings. The effect of year and treatments on fruit nutrients (2011 and 2012) was analyzed as a split-split-plot design.

Table 1. Nitrogen fertilization rates and sources applied from 2004 to 2018 in 'Elliott' northern highbush blueberry grown at Oregon State University's North Willamette Research and Extension Center in Aurora, OR.

N rate treatment	N fertilizer rate (kg·ha ⁻¹)						
	Ammonium sulfate		Urea				
	2004	2005	2006	2007	2008	2009	2010–18
Low	22	22	31	31	39	39	56
Medium	67	67	95	95	112	112	168
High	112	112	153	153	185	185	269

Results and Discussion

SOM and pH

Incorporation of sawdust resulted in a long-term increase in SOM compared with unamended soil, as has been found in other studies (Strik et al., 2020b). Although not as dramatic as in the first year after planting (2004), where incorporated plots had 8.3% SOM compared with 5.1% in unamended plots (White, 2006), incorporated plots still had higher SOM in 2018 (4.3% and 3.4%, respectively). Fluctuation in SOM from year to year is not unusual due to sampling method and natural year-to-year variation (Strik et al., 2019). Mulch and N rate had no effect on SOM in the first two growing seasons (White, 2006) or over the longer term (data not shown). Sawdust mulch did not increase SOM during establishment of 'Duke' as compared with weed mat over bare soil (Strik et al., 2020b), but was intermediate for SOM when compared with a mulch of compost topped with sawdust (highest SOM) and weed mat over bare soil (lowest SOM) after more than 8 years (Strik et al., 2019).

Soil pH increased from the early years of the study (White, 2006) to above the recommended level (4.5–5.5; Horneck et al., 2011) in 2011 and 2018, averaging 6.0 across all treatments in both years. An increase in soil pH from ≈ 5.0 to 6.0 between 2016 and 2018 was also found in organic blueberry, although with different mulching systems (Davis and Strik, 2021). Adding sawdust as a pre-plant amendment increased soil pH compared with unamended soil in 2004 (5.1 vs. 4.8, respectively) and 2005 (4.9 vs. 4.6), as did mulch compared with bare soil in 2004 and 2005 (5.1 vs. 4.8, respectively, in 2004; 4.9 vs. 4.6 in 2005) (White, 2006). However, starting in 2011 there were few effects of amendment or mulch on soil pH (averaged 6.0). In contrast, by 2018, soil pH was reduced when applying the high rate of N (5.9) compared with the medium- and low-rate treatments (6.2, on average). High rates of N reduce soil pH relative to lower rates (Hart et al., 2006; Strik et al., 2019) when ammonium forms of N are used due to nitrification and resulting acidification of the soil; acidification occurs to a lesser extent when using urea as a fertilizer source, as in our study from 2006 to 2018; however, the difference in soil pH between the N rates studied was less than expected for a long-term study (expectation for a drop of 1 unit in pH over 10 years with urea; Hart et al., 2006). Bañados et al. (2012) found that fertilization with ammonium sulfate reduced soil pH relative to no fertilizer, but rates ranging from 50 to 150 kg·ha⁻¹ N did not differ in soil pH over their 2-year study. In organic production systems, Strik et al. (2019) found significantly lower soil pH when fertilizing with 140 kg·ha⁻¹ N (5.1) as compared with 73 kg·ha⁻¹ N (5.3), on average, after 10 years of using either fish solubles or feather meal sources. However, soil pH increased thereafter in various mulching treatments once fertilized with the same rate of N (to as high as 5.9; Davis and Strik, 2021).

Soil nutrients

Soil NO₃-N and NH₄-N were analyzed only in 2011 and 2018. These nutrients tend to be variable, and the treatments had no effect on NO₃-N (ranged from <0.5–6.3 ppm) or NH₄-N (0.6–5.1 ppm). Low levels of both forms of N are expected, as no fertilizer was applied after mid-June and samples were not taken until late October (after fall rains began, which would also reduce N in soil). Our results are similar to those reported in organic production, where higher than needed N rates had little effect on soil N levels at the end of the growing season (Strik et al., 2019).

Soil P (Bray I) was not tested in 2004 and 2005, but later in the study was higher with bare soil (176 ppm and 138 ppm in 2011 and 2018, respectively) than with sawdust mulch (148 ppm and 116 ppm) and was unaffected by incorporation or fertilizer rate treatment. Strik et al. (2019) reported lower soil P with sawdust mulch than with weed mat over bare soil.

Soil S was not tested in 2004 or 2005, but in 2018 was higher in plots fertilized with the high rate of N (15 ppm) compared with either of the lower rates (averaged 12 ppm). Only urea fertilizer was applied from 2006 to 2018 (Table 1), so this is not a direct response to applications of more fertilizer, but soil S is affected by rainfall.

In 2005, plots fertilized with the high rate of N had significantly lower soil K (197 ppm) than those receiving the low rate of N (221 ppm; White, 2006). In 2018, fertilization with the low rate of N still led to the highest soil K (155 ppm) compared with either the medium or high rates (averaged 127 ppm). Soil K was lower by the end of the study with little additional K fertilizer applied, as we have noted in our other studies (Davis and Strik, 2021), but was still above recommended soil sufficiency levels (Hart et al., 2006).

Soil Ca was higher with both sawdust incorporation and mulch in all years except 2011 and increased throughout the study. In 2004, soil Ca was 804 ppm and 689 ppm with or without pre-plant incorporation, respectively, and 715 ppm and 778 ppm for bare soil and sawdust mulch, respectively (White, 2006). By 2018, soil Ca increased to 1154 ppm and 1060 ppm with or without pre-plant incorporation, respectively, and 1063 ppm and 1151 ppm for bare soil and sawdust mulch, respectively. Although no fertilizers containing Ca were applied during the study, soil Ca likely increased with decomposition of sawdust over time. A douglas fir sawdust used as a mulch applied to a similar depth as the present study was shown to contain 30 to 92 kg·ha⁻¹ Ca depending on the year (Strik et al., 2019). The low rate of N fertilization led to higher soil Ca than the high N rate in 2005 (White, 2006), and both medium and high N rates in 2018 (an average of 1223 ppm for the low rate and 1049 ppm for the higher rate).

The impact of pre-plant amendment with sawdust was variable for soil Mg with higher and lower levels with incorporation in 2004 and 2005, respectively (White, 2006), and no effect in the later years. Mulch only had an

effect on soil Mg in 2018 with higher levels with sawdust mulch (340 ppm) than for bare soil (307 ppm). In soil that was not amended before planting, sawdust mulch decreased soil Ca and Mg compared with weed mat over bare soil in a long-term study by Strik et al. (2019). Compared with fertilizing with the high rate of N, applying a low rate of N resulted in higher soil Mg in 2005 (White, 2006) and 2018 (354 ppm for low, 301 ppm for high).

Although soil B (in 2004) and Cu (in 2005) were higher with incorporation soon after planting (White, 2006), there was no effect of incorporation, mulch, or N rate on these nutrients later in the study. Soil Mn was higher with sawdust incorporation from the first growing season (White, 2006) through 2018, with 37 ppm and 26 ppm Mn for incorporated and nonincorporated, respectively. Soil Mn was lower with the low rate of N fertilizer (25 ppm) than the other N rates (averaged 37 ppm) in 2005 (White, 2006), but there was no treatment effect in the later years (data not shown).

Leaf nutrients

Leaf N. Leaf N concentration was higher in 2011 and 2012 than the other years (Table 2). There was a year $\times$ incorporation $\times$ mulch interaction, because leaf N was considerably lower for plants where sawdust was incorporated and used as a mulch in 2004 and 2005, whereas treatment effects were relatively small in subsequent years (data not shown). The demand of soil microbes actively decomposing the sawdust applied at planting and as a mulch may have reduced the N available to the plant (Hart et al., 2006), despite the addition of N fertilizer in sawdust-incorporated rows. The effect of N fertilization rate on leaf N was much more pronounced in the establishment years also, with the lowest levels found in plants fertilized with the low rate of N, particularly in sawdust-amended soil. As plants matured, the larger root systems likely increased fertilizer uptake efficiency (Strik et al., 2020b). On average, leaf N was highest where sawdust was not incorporated before planting, with no mulch (bare soil), and plants were fertilized with the high rate of N (Table 2). Although leaf N was below sufficiency levels reported by Hart et al. (2006), regardless of N rate, on average, they were within the newly revised sufficiency levels we recommended based on more recent research (Strik and Davis, 2022).

When data were analyzed by year, incorporating sawdust reduced leaf N the first 2 years after planting (1.47% and 1.63% in 2004 and 2005, respectively) compared with plants grown without incorporation (1.70% and 1.73%). Soil amendment had less impact on leaf N as the planting matured, but there was an interaction between incorporation and N rate in 2009 and 2018 wherein plants grown without sawdust incorporation had lower leaf N with the low N rate (1.54% in 2018) compared with the high N rate (1.72%), whereas when sawdust was incorporated, N rate had no effect (averaged 1.63% N). Leaf N was also higher with bare soil

Table 2. Effects of year, with or without pre-plant incorporation of sawdust, bare soil compared with sawdust mulch, and N fertilization rate on leaf nutrient concentration in 'Elliott' blueberry grown at Oregon State University's North Willamette Research and Extension Center in Aurora, OR.

	Leaf macronutrient concn (%)						Leaf micronutrient concn (ppm)				
	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn
Year (Yr)											
2004	1.58b ^z	0.10d	0.60a	0.85a	0.24a	NA ^y	27c	163b	314a	7.4a	11ab
2005	1.68b	0.14a	0.52b	0.53c	0.17c	NA	13e	43e	87b	3.1c	12a
2009	1.58b	0.09e	0.36d	0.65b	0.16c	0.112c	41a	110c	173b	1.2d	8b
2010	1.69b	0.13b	0.51b	0.51c	0.17c	0.125a	18d	100c	83b	4.4b	10ab
2011	1.86a	0.10cd	0.52b	0.41d	0.14d	0.119abc	20d	64de	88b	4.0b	9ab
2012	1.85a	0.11c	0.51b	0.51c	0.14d	0.122ab	18d	86cd	116b	3.0c	10ab
2018	1.62b	0.09e	0.46c	0.60b	0.19b	0.115bc	32b	194a	100b	3.1c	11ab
Incorporation (I)											
Incorporated	1.67b	0.11	0.51	0.61a	0.18a	0.12	25a	113	145	3.9	11
Nonincorporated	1.71a	0.11	0.50	0.57b	0.17b	0.12	23b	110	138	3.8	10
Mulch (M)											
Bare	1.71a	0.11	0.52a	0.58b	0.18	0.12	24	115a	145	3.9	10
Sawdust	1.66b	0.11	0.49b	0.60a	0.18	0.12	24	108b	137	3.9	10
N rate (N) ^x											
Low	1.64c	0.11	0.49b	0.61a	0.18	0.12	26a	112	127b	4.1a	11
Med	1.69b	0.11	0.50ab	0.58b	0.18	0.12	24 b	112	143a	3.8b	10
High	1.74a	0.11	0.51 a	0.57b	0.18	0.12	22c	111	152a	3.7b	10
Significance ^w											
Yr	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0039	<0.0001	<0.0001	0.0002	<0.0001	0.0377
I	0.0216	NS	NS	0.0138	<0.0001	NS	0.021	NS	NS	NS	NS
Yr × I	<0.0001	NS	0.0001	NS	<0.0001	NS	NS	NS	NS	NS	NS
M	<0.0001	NS	<0.0001	<.0001	NS	NS	NS	0.0063	NS	NS	NS
Yr × M	<0.0001	<0.0001	<0.0001	NS	NS	0.0019	<0.0001	0.0044	NS	NS	NS
I × M	0.0014	NS	NS	0.0021	0.001	NS	0.0083	NS	NS	NS	NS
Yr × I × M	<0.0001	<0.0001	NS	<0.0001	0.0016	NS	<0.0001	NS	0.0137	NS	NS
N	<0.0001	NS	0.0006	<0.0001	NS	NS	<0.0001	NS	<0.0001	0.0013	NS
Yr × N	<0.0001	0.0002	0.0033	NS	NS	NS	<0.0001	NS	NS	0.0215	NS
I × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.0291	NS
Yr × I × N	0.023	0.0058	NS	NS	NS	NS	0.0172	NS	NS	0.0005	NS
M × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Yr × M × N	NS	NS	NS	0.0094	0.0049	NS	0.0001	NS	NS	0.0045	NS
I × M × N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zMeans followed by the same letter are not significantly different within treatment as determined by analysis of variance using Tukey's honestly significant different test ($P > 0.05$).

^yNA indicates data were not available for this year.

^xNitrogen fertilization rates were increased incrementally as plants aged for "Low" (22 to 56 kg·ha⁻¹), "Medium" (67 to 168 kg·ha⁻¹), and "High" (112 to 269 kg·ha⁻¹) treatments.

^w P values shown when $P < 0.05$. NS indicates nonsignificance.

than with sawdust mulch in 4 of 7 years tested, and with the high N rate in 5 of 7 years compared with the low N rate (data not shown). This is similar to what has been found with weed mat over bare soil compared with sawdust (Strik et al., 2019), likely due to the lower soil temperature under sawdust (Strik et al., 2020a) reducing N uptake (Davis and Strik, 2021). Our results of higher leaf N with fertilization rate confirms findings in past studies in blueberry (Bryla et al., 2012; Ehret et al., 2014; Strik et al., 2019).

Leaf P. There was a main effect of year and interactions of year × mulch and year × incorporation × N rate for leaf P (Table 2). Leaf P ranged from 0.09% to 0.14%, with the highest level in 2005. Although plants grown without mulch had higher leaf P in 2004 and 2005 than those with sawdust mulch, the opposite was found in 2010 (data not shown). Plants fertilized with the high rate of N had higher leaf P in 2004, but only in incorporated plots. There was no main effect of incorporation, mulch, or N rate on leaf P (Table 2).

Within each year of the study, leaf P was not generally affected by sawdust incorporation and was only affected by fertilizer rate in 2004 and 2005, when the low N rate had

lower leaf P than the medium (2004 only) and high rates. Mulch affected leaf P in 2005 and 2010, but whereas leaf P was higher with bare soil in 2005 (0.14%) compared with sawdust mulch (0.13%), in 2010 the opposite was found (0.13% for bare soil and 0.14% for sawdust mulch). There were no treatment effects on leaf P from 2011 to the end of the study. Increased leaf P has been attributed to improved root growth, which was found in sawdust mulch compared with weed mat over bare soil and with weed mat over sawdust mulch (Strik et al., 2019, 2020a, 2020b). In this planting, Nemeth et al. (2017) found more fine roots in bare soil than with sawdust mulch in 2011 and 2012, whereas total root growth was greatest in incorporated soil with no mulch and lowest in nonincorporated soil with no mulch, but only in 2011. White (2006) reported no effect of N rate on root dry weight, whereas Nemeth et al. (2017) found the higher N rate increased carbon stock in fine roots, but only in 2011. In young blueberry plants, root dry weight was larger in plants fertilized with a lower rate of N (Bryla et al., 2012; Larco et al., 2013), and corresponded with increased leaf P.

Leaf cations. There was a main effect of year and interactions of year × incorporation, year × mulch, and year × N fertilizer rate for leaf K (Table 2). Leaf K was highest in young plants, as has been reported by Strik et al. (2019), and was higher overall with bare soil and the high rate of N, compared with the low rate. However, most treatment effects diminished after 2005. Sawdust incorporation resulted in higher leaf K in 2004 (0.64%) compared with no incorporation (0.56%), but leaf K was lower with sawdust mulch (0.51%, averaged over 2004 and 2005) than with bare soil (averaged 0.61%). Leaf K was higher with the high N rate in the first 2 years (0.54% in 2005) than the low or medium N rates (averaged 0.51%), but fertilization did not affect leaf K thereafter. In organic blueberry, soil and leaf K were positively correlated in several years of a 10-year study (Strik et al., 2019), whereas in the present study, the higher levels of soil K found when the low N rate was applied did not have the same effect, perhaps because soil K levels in some treatments were considerably higher in their study.

Leaf Ca was highest in the first growing season (Table 2) and did not increase with

planting age, as was noted by Strik et al. (2019). There was a year $\times$ incorporation $\times$ mulch interaction because leaf Ca was lower in nonincorporated plots without mulch (which also had lower soil Ca levels) than sawdust-amended and mulched plots from 2004 to 2010, but not in the later years (data not shown). The effect of pre-plant sawdust amendment may have declined over time and there were also fewer sawdust mulch applications as the planting aged, which would have contributed less Ca to the system. In addition, because soil Ca increased on average for all treatments, any limitations on plant uptake may have dissipated, resulting in fewer treatment differences. Plants fertilized with the low rate of N had higher leaf Ca in 2005 and from 2009 to 2011, particularly in plots without sawdust mulch. On average over the study period, soil amendment, mulching with sawdust, and fertilizing with the low rate of N increased leaf Ca (Table 2).

Leaf Mg was highest in 2004, although there was no pattern of changes in leaf Mg with planting age (Table 2). In 2004, plants grown with a pre-plant amendment of sawdust had higher leaf Mg than those without, particularly for those grown without mulch, whereas there were fewer differences between these treatments in subsequent years (data not shown). With bare soil, there was little effect of N rate on leaf Mg. However, when mulching with sawdust, fertilization with the low rate of N led to higher leaf Mg in 2004, whereas the opposite was found in 2009. On average over the study period, soil amendment increased leaf Mg (Table 2).

Leaf S. Leaf S was not measured before 2009, and concentration was lowest in 2009 and 2018 (Table 2). Mulching with sawdust decreased leaf S in 2011 compared with bare soil, whereas the opposite was found in 2018 (data not shown). Incorporation had little effect except in 2018 when an interaction with fertilizer rate showed that leaf S was higher with the high N rate in nonincorporated plots but there was no effect of N rate with pre-plant incorporation of sawdust (data not shown). Past research has shown that treatment effects on leaf S often have a similar response and pattern of seasonal change as leaf N (Strik et al., 2019; Strik and Vance, 2015). Mulch effects on leaf S were inconsistent among the few years it was significant, and differences were quite small and likely not of major biological importance.

Micronutrients. There was an effect of year and several treatment interactions with year $\times$ incorporation $\times$ mulch, year $\times$ incorporation $\times$ N rate, and year $\times$ mulch $\times$ N rate effects on leaf B (Table 2). Leaf B was below sufficiency levels (Hart et al., 2006) in all years except for 2009 and 2018. Boron deficiency is common for blueberry in western Oregon (Davis and Strik, 2021; Strik et al., 2019; Strik and Davis, 2022). Plants grown without mulch in amended soil had higher leaf B than those with mulch or in nonincorporated soil, but only in 2004 (data not shown). Fertilization with the low rate of N led to higher leaf B in amended soil compared

with the medium and high rates for 2009 through 2018, but only in 2009 and 2018 in nonamended soil. The high rate of N applied without incorporation of sawdust reduced leaf B from 2009 through 2012 compared with the low and medium rates in 2009 and 2011–12 (data not shown). Although the effect of N rate resulted in similar patterns in leaf B between mulched and nonmulched plants over time (low N rate had the highest levels in most years), for plants grown with sawdust mulch there was a larger difference between the high rate of N (lowest leaf B) and the medium rate from 2011 to 2018 (data not shown). On average, over the study period, plants grown in amended soil had higher leaf B than without amendment and fertilization with the low rate of N led to higher leaf B than the other rates (Table 2).

Leaf Mn was higher in 2004 than the other years and was particularly high in soil amended with sawdust but left unmulched (Table 2). On average, leaf Mn was lowest when plants were fertilized with the low rate of N. This effect of N rate on leaf Mn was more prevalent in nonincorporated soil in some years (89 ppm vs. 126 ppm in 2018 for low and high N rates, respectively). In addition, there were more pronounced differences between leaf Mn with the low and high N rates when plants were grown with bare soil compared with sawdust mulch (data not shown). Soil pH was higher in the early years when sawdust was applied as a mulch or incorporated pre-plant and for the duration of the study when the low N rate was used, which likely explains these differences in leaf Mn, as this nutrient is taken up more readily in lower pH soil.

Leaf Fe was affected by year and was higher, on average, when no mulch was present (115 ppm compared with 108 ppm with sawdust mulch; Table 2) but was within recommended standards (45–300 ppm; Strik and Davis, 2022) for all years except 2005 (43 ppm). Leaf Fe results may be variable because of dust deposition on leaves, as speculated by others (Strik et al., 2019); this was particularly notable in 2004 when mulched plants had 150 ppm Fe compared with 176 ppm for unmulched plants.

There was an effect of year, year $\times$ incorporation $\times$ N rate, and year $\times$ mulch $\times$ N rate on leaf Cu (Table 2). Fertilization with the low rate of N increased leaf Cu for incorporated plots from 2010 to 2012, but only in 2004 for nonincorporated plots (Table 2). The low rate of N also increased leaf Cu when plants were grown without mulch in 2010 and 2011, but only did so in 2004 for those grown with sawdust mulch (data not shown). In addition, plants fertilized with the high rate of N had the lowest leaf Cu in 2004 for bare soil, whereas this was not the case with sawdust mulch. Overall, leaf Zn was only affected by year with the highest level in 2004 (Table 2).

Fruit nutrients

Fruit nutrient concentration was measured in 2011 and 2012. Although most nutrients

were similar in ripe fruit between years, Ca, S, and Al were lower in 2011 (0.025%, 0.020%, and 14 ppm, respectively) than in 2012 (0.030%, 0.023%, and 84 ppm). Some treatment effects were found for fruit P, Mg, and S, but differences were only 0.001% and likely of little biological significance. Incorporation of sawdust resulted in lower concentrations of K, Ca, B, and Mn (0.25%, 0.026%, 2.6 ppm, 7.0 ppm, respectively) in fruit compared with those grown in nonincorporated soil (0.27%, 0.029%, 2.8 ppm, and 8.5 ppm), even though soil Ca and Mn were higher in incorporated treatments and there was no incorporation effect on soil K and B. Adding sawdust mulch increased fruit Ca (0.029% compared with 0.026% for bare soil). Fruit from the low N rate treatment had higher Ca and B (0.030% and 2.8 ppm) than the high N rate (0.025% and 2.5 ppm, respectively). Nutrients that did not differ by year or treatment averaged 0.46% N, 0.03% P, 0.014% Mg, 15 ppm Fe, 1.3 ppm Cu, and 2.3 ppm Zn. These levels of fruit nutrient concentration are lower than what we have found in prior research in both organic and conventional systems for other cultivars (Davis and Strik, 2021; Strik and Vance, 2015).

Yield and fruit quality

There were significant effects of year ($P < 0.0001$), year $\times$ incorporation ($P = 0.0071$), and incorporation $\times$ mulch ($P = 0.0020$) on yield. In general, yield increased as plants matured from 2.5 kg/plant in year 3 to 6.6 kg/plant in year 10, although yield fluctuated likely due to pruning and weather conditions (Fig. 1). Incorporating sawdust before planting increased yield over the 8-year period (as well as in 2018: 3.8 kg/plant compared with 3.2 kg/plant for nonincorporated), which was likely related to the higher aboveground biomass produced by plants grown in soil with a pre-plant amendment of sawdust (Nemeth et al., 2017). However, the year $\times$ incorporation interaction showed that in several individual years, there was no significant difference between treatments, and in 2013, plants grown in soil without sawdust incorporation had higher yield (Fig. 1, 2018 not shown). Plants grown with sawdust incorporated and no mulch had higher yield per plant (4.2 kg averaged over 2006–2013) compared with incorporated with mulch or nonincorporated with or without mulch (averaged 3.9 kg), which directly followed the treatment effects on total dry weight of dormant plants (below- and aboveground biomass) reported in 2011 and 2012 (Nemeth, 2013). Throughout the study, the irrigation lines were placed on top of the sawdust, and although soil moisture was always within an acceptable range (White, 2006; D. Nemeth, unpublished data), this may have negatively affected the movement of water and nutrients to the plant roots. Root infection rates of beneficial mycorrhizae were higher with bare soil compared with when sawdust mulch was used, as well as when the low N rate was applied as compared with the high rate (Nemeth, 2013),

Fig. 1. Yield per plant from the third growing season (2006) through year 10 (2013), as affected by incorporation of douglas fir sawdust (incorporated) compared with no sawdust amendment (nonincorporated) before planting in 2003. Error bars represent ± 1 SE.

which may help explain why these treatments performed well.

Nitrogen fertilization rate did not affect yield in any year except 2008, when plants fertilized with the high rate had more yield (2.2 kg/plant) than those with the low rate (1.9 kg/plant). However, in the full analysis of treatments and years, N rate had no effect on yield (data not shown) even though the low N rate was below recommended levels, especially when sawdust mulch is used and an additional 28 kg·ha⁻¹ N is suggested to compensate for N immobilization (Hart et al., 2006). Higher rates of N fertilization have either not improved yield or have reduced yield in blueberry (Bañados et al., 2012; Goulart et al., 1997; Lareau, 1989; Strik et al., 2017a). In this planting, N fertilization also had no impact on plant biomass in 2011 or 2012 (Nemeth et al., 2017). Yield data were collected in 2018 as well, and although yield per plant was lower than normal for mature plants, there was still no effect of N fertilization rate (averaged 3.5 kg/plant).

Berry weight and firmness were very high in all treatments in 2006, as this was the first fruiting season and young plants are commonly pruned more severely to encourage more root growth, resulting in larger berries than in subsequent years (Strik, 2020). Berries were smaller in both diameter and weight with the high N rate (16.9 mm; 2.12 g) compared with either the low or medium rates (averaged 17.0 mm, 2.15 g); however, these differences are quite small and likely of little biological significance. When plants were fertilized with the high N rate, berry weight was similar (2.16 g) to the lower rates when sawdust had been incorporated but lower (2.08 g) with no incorporation. Mulching with sawdust increased berry weight in 2006 (3.31 g) and 2007 (1.88 g) compared with bare soil (3.20 and 1.82 g, respectively), but had little effect from 2008 to 2013 (averaged 2.04 g), except in 2010 when unmulched

plants had higher berry weight (1.86 g) than mulched plants (1.76 g). Plants grown in sawdust-incorporated soil had lower fruit firmness (174 g·mm⁻¹ deflection) in 2006 than nonincorporated (182 g·mm⁻¹ deflection), but over the remaining years firmness decreased and there was either no difference or plants in incorporated soil produced slightly firmer fruit than those in nonincorporated soil (data not shown). Strik and Davis (2021) also found few effects of mulch on berry weight or firmness in 'Duke' blueberry. Fertilizing with the high N rate resulted in slightly firmer berries when analyzed across all years (144 g·mm⁻¹ deflection) compared with the medium (142 g·mm⁻¹ deflection) or low (140 g·mm⁻¹ deflection) rates, perhaps because of the smaller berry size in that treatment. However, when this effect was analyzed by year it was found in only 2 of 7 years measured, and just as with berry weight, these small differences are likely of little biological significance. Berry TSS was higher overall (14.7%) with incorporation compared with no incorporation (14.4%), but using sawdust mulch in combination with incorporation lowered TSS in 2 of 5 years measured compared with bare soil. Mulching had no consistent effect on TSS when there was no pre-plant incorporation (data not shown). In contrast, when sawdust mulch was compared with a combination of black or green polypropylene weed mat layered over a sawdust mulch, berry TSS was higher with sawdust alone (Strik and Davis, 2021).

Treatment cost comparison

Amending soil with sawdust before planting cost \$3150/ha, including materials and custom application. However, average yields (2006–13) were higher when sawdust was incorporated and would have resulted in \$7680 greater net profit from machine-harvested fruit sales over this time, more than enough to compensate for the added cost at

establishment. If some fruit were sold for fresh market, this differential would have been greater because of the associated higher price paid to the grower. Incorporating sawdust before planting remains the recommendation to growers because of the long-lasting increases in SOM compared with no incorporation, from a one-time application and cost, which other studies have shown to be beneficial for yield (Davis and Strik, 2021). Mulching with sawdust is expensive because it needs to be replenished frequently (total cost of \$11,618/ha for four applications between 2003 and 2010). However, weed control costs are considered lower with sawdust as compared with bare soil, as fewer contact herbicide applications or hand removal passes are required in the row area (Strik and Vance, 2017; Tertuliano et al., 2012). Recent research has shown that weed mat mulch (woven, black polypropylene groundcover), and the combination of sawdust with weed mat on top, were even more economical than sawdust mulch alone due to increased fruit yield and lower management costs (Strik and Vance, 2017; Strik and Davis, 2021). From 2004 to 2018, the total cost of nitrogen fertilization at the low rate was \$1342/ha compared with \$4022/ha for medium and \$6494/ha for the high rate. Because fertilization rate did not affect yield, using the low N fertilizer rate would provide a maximum total cost savings of \$5152/ha over this period with no disadvantage to production, and reduced potential for N leaching.

Summary

Incorporating sawdust into the soil before planting increased yield and berry TSS overall even though there were few effects of N fertilization rate on leaf N, Ca, S, and Mn in this treatment compared with no incorporation. Mulching with sawdust in combination with incorporation reduced yield and TSS in some years compared with bare soil, but this effect was not apparently related to SOM or pH. Although soil P and Ca and leaf Ca were higher with sawdust mulch, fertilization rate had a greater influence on soil and plant nutrients than mulching. Fertilizing with the low N rate resulted in higher soil pH and lower leaf N in some cases, depending on amendment, mulch, or year, but higher leaf Ca; the impact of N rate was reduced when sawdust was incorporated. Yield was unaffected by N fertilization rate and berries weighed more and were larger in diameter with low or medium rates, particularly when sawdust was not incorporated, although these differences were small. In addition, berry firmness and TSS were similar among incorporation, mulch, and fertilizer treatments for most years and always within commercially acceptable standards. This long-term study shows that plants can successfully be grown with a relatively low level of N fertilization compared with previous recommendations, although soil pH should be monitored closely to maintain it within the recommended range, thus saving the grower significant fertilizer

costs over the life of a planting. Mulching with sawdust was not a clear improvement over bare soil in this study when soil moisture was well maintained and weeds well controlled, but can be a useful tool for insulating the soil, conserving soil moisture, and reducing weed pressure. Incorporating sawdust before planting is helpful for increasing and maintaining SOM, increasing some soil and leaf nutrients, and in this study, increased yield enough to compensate for the additional cost at planting.

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