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How management practices influence vegetative and reproductive plant traits of wild lowbush blueberry species

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Abstract

Optimizing agricultural practices is an effective way to increase fruit productivity in commercial wild lowbush blueberry (*Vaccinium angustifolium* Aiton; *Vaccinium myrtilloides* Michx) fields, but results from northern Quebec (Canada) are scarce. In this study, we assessed the effect of the main crop management practices, namely pruning method (mechanical and thermal), fungicide (with and without), and fertilization (mineral, organic, and without) on key vegetative and reproductive plant traits of both wild blueberry species. The experiment was conducted from fall 2016 to fall 2018, when the combination of pruning, fungicide, and fertilizing was applied. Results show that fertilizer application was the main management practice affecting vegetative and reproductive plant traits followed by fungicide application effects during pruning years only. Mineral fertilizer improved plant traits to a greater extent than organic fertilizer during the pruning phase only, and no significant differences in the second year after application (harvesting phase) suggest a delayed but similar final effect of organic fertilizer. Results also showed that *V. myrtilloides* produces taller stems with more leaves compared to *V. angustifolium*, whereas *V. angustifolium* produces more flower buds, a key reproductive plant trait. Results also highlight the fact that *V. angustifolium* needs both fertilizer and fungicide to keep leaves on the stem during late summer, whereas *V. myrtilloides* needs either fertilizers or fungicides. This study also shows that pruning method has no significant effect on any of the measured plant traits. However, we believe that long-term studies are still needed to assess the impact of pruning method over time.

Key words: *Vaccinium angustifolium*, *Vaccinium myrtilloides*, mechanical pruning, thermal pruning, mineral fertilizer, organic fertilizer, fungicide, propiconazole

Résumé

Optimiser les pratiques agricoles est une bonne façon d'accroître le rendement fruitier des bleuetières commerciales de bleuet à feuilles étroites (*Vaccinium angustifolium* Aiton, *Vaccinium myrtilloides* Michx). Malheureusement, on possède peu de résultats qui l'illustrent dans le nord du Québec (Canada). Les auteurs ont évalué les effets des principales pratiques en usage sur les principaux caractères végétatifs et reproductifs des deux espèces, en l'occurrence l'élagage (mécanique et thermique), l'application (ou pas) d'un fongicide et celle d'un engrais (minéral, organique, aucun). L'expérience s'est déroulée de l'automne 2016 à l'automne 2018, période durant laquelle les auteurs ont combiné l'élagage à l'application du fongicide et de l'engrais. Selon les résultats obtenus, l'usage d'un engrais est la pratique qui affecte le plus les caractères végétatifs et reproductifs de la plante, suivie par l'application d'un fongicide, mais uniquement les années où il y a élagage. L'engrais minéral accentue plus les caractères de la plante que l'engrais organique, mais seulement lors de l'élagage. Si on ajoute à cela le fait qu'on ne relève aucun écart significatif l'année suivant celle de l'amendement (année de la récolte), on présume que l'engrais organique agit de façon identique, mais à retardement. *V. myrtilloides* a des tiges plus hautes portant plus de feuilles que *V. angustifolium*, espèce qui produit plus de bourgeons floraux, un caractère important pour la reproduction. Les résultats obtenus indiquent aussi que *V. angustifolium* a besoin d'un engrais et d'un fongicide pour que les feuilles restent attachées à leur tige à la fin de l'été, alors que *V. myrtilloides* n'a besoin que de l'un ou de l'autre. Par ailleurs, l'étude indique que la technique d'élagage n'a

aucun effet sensible sur les autres caractères de la plante. Quoi qu'il en soit, les auteurs estiment qu'il faudrait entreprendre des recherches de plus longue haleine afin de mieux évaluer l'impact de l'élagage dans le temps. [Traduit par la Rédaction]

Mots-clés : *Vaccinium angustifolium*, *Vaccinium myrtilloides*, élagage mécanique, élagage thermique, engrais minéral, engrais organique, fongicide, propiconazole

Introduction

Wild lowbush blueberry (*Vaccinium angustifolium* Aiton; *Vaccinium myrtilloides* Michx), an endemic shrub of North America, is an important crop in the Canadian agri-food industry. Canada is a major wild blueberry producer with exports exceeding about 200 million dollars per year (MAPAQ 2016). One-third of this is produced in Quebec, and more than 80% of the Quebec wild blueberry fields are located in northern Quebec, in the Saguenay–Lac-Saint-Jean region (MAPAQ 2016). However, Quebec presents lower fruit yields (1.5 t ha^{-1}) compared to other southern areas such as New Brunswick (3.4 t ha^{-1}), Nova Scotia (2.4 t ha^{-1}), and Maine (4.9 t ha^{-1}) (MAPAQ 2016; Yarborough 2017). To increase fruit yields, researchers, agronomists, and farmers are looking for better agricultural practices. In Maine, many practices have been identified to improve fruit yield, such as herbicide and fertilizer applications, pollination, integrated pest control, irrigation, pruning, and harvesting methods (Yarborough 2004; Drummond et al. 2012; Yarborough et al. 2017). Few researches have demonstrated their effectiveness at higher latitudes characterized by a colder climate and lower soil productivity.

Wild blueberries normally have a 2-year crop cycle: after fruit harvesting, farmers prune plants mechanically and (or) thermally in fall or spring (Chiasson and Agrall 1996; Moreau 2014). During the first growing season, named as pruning or sprout year, plant growth occurs from rhizomes (Moreau 2014). At the end of the pruning year, leaf and flower buds are produced for the following year and those buds remain dormant during fall and winter, when no agricultural practices are performed (Eaton and Nams 2006). During the second year, named as harvesting or production year, the fruits are harvested and plants are then pruned (Chiasson and Agrall 1996; Eaton and Nams 2006; Moreau 2014).

Two types of pruning are used by wild blueberry producers: mechanical and (or) thermal. Mechanical pruning is a widely performed technique to encourage stem refreshment and fruit production (Moreau 2014). However, if not performed adequately (i.e., stems longer than 1 cm), it could stimulate rather than reduce branch number and sprouting from the base of the cut stems (Ismail et al. 1981), and ramified plants may produce fewer flower buds and less fruit (Trevett 1966). In addition to mechanical pruning, thermal pruning may also be used as it may increase fruit yield, nitrogen (N) and phosphorus (P) concentrations in leaf tissues, stem height, density, biomass, and mycorrhizal colonizations while reducing weed competition and plant diseases (Black 1963; Smith and Hilton 1971; Ismail et al. 1981; Hanson et al. 1982; Warman 1987; Penney et al. 1997; Kuwar 2012). However, it remains unknown how thermal pruning interacts with other management practices related to fertilization as well as fungicide applications. Moreover, performing thermal pruning over long time periods may also reduce the depth of soil organic hori-

zons, which could limit soil nutrient pools and growing space for rhizomes and roots (Smith and Hilton 1971).

Applications of fungicides during pruning years are becoming common in commercial lowbush blueberry fields, since those products are known to maintain a healthy canopy free of leaf diseases such as septoria leaf spot (*Septoria difformis*), rust (*Naohidemyces vaccinii* (Jørst.) S. Sato, Katsuya & Y. Hirats. ex Vanderweyden & Fraiture), and valdensinia spot (*Valdensia heterodoxa* Peyronel). Indeed, most fungal diseases found in blueberry fields cause chlorosis, which reduces photosynthetic rate (Rolloff et al. 2004), increases defoliation, and reduces bud set (Ojiambo et al. 2006) during both pruning and harvesting years (Ali et al. 2021). However, it is still unclear how fungicide application may interact with other practices such as fertilizer applications (Walker et al. 2010) and (or) thermal pruning, which may reduce, in turn, fungal disease pressure over the years (Drummond et al. 2009).

Fertilizer applications are known to increase fruit yields, but only when weeds are controlled (Ismail et al. 1981; Eaton 1994; Penney and McRae 2000), because wild blueberry is less effective than most weeds in assimilating nutrients from fertilizers (Marty et al. 2019a). Moreover, fertilizer applications—specifically N—increase the plant productivity (Lafond and Ziadi 2011), but excessively tall stems can increase damage from winter frosts (Ismail et al. 1981), since 30 cm depth of snow has recently been identified as a threshold to protect the stems from winter frosts in Saguenay–Lac-Saint-Jean (Girona et al. 2019). Also, adding too much N may substantially favor plant vegetative biomass and significantly reduce fruit yields (Lafond and Ziadi 2011). Since thermal pruning may also increase soil nutrient availabilities (i.e., leaf N and P concentrations) (Black 1963; Smith and Hilton 1971), it remains unclear whether fertilizer practices interact with the pruning method as well as fungicide applications.

The literature contains extensive research on different agricultural practices linked to wild blueberry fruit yields (Black 1963; Ismail et al. 1981; Warman 1987; Eaton 1994; Penney et al. 1997; Eaton and Nams 2006; Lafond 2009; Smagula et al. 2009; Lafond and Ziadi 2011; Marty et al. 2019b), whereas fewer studies focus on key plant traits such as stem height, leaf number, and flower bud number (Trevett 1959; Penney and McRae 2000; Lafond and Ziadi 2011). Furthermore, most studies did not take into consideration potential interactions between pruning, fungicide, and fertilizer management practices. Since bud and leaf phenology is later in *V. myrtilloides* compared to *V. angustifolium* (Fournier et al. 2020), management practices may also differently impact each of those species growing on commercial fields.

In this study, we investigated the simple and combined effects of three major agricultural practices, namely pruning, fungicides, and fertilization applications, on key plant traits of the two main *Vaccinium* species found in northern

Table 1. Experimental design of this study with 12 treatments and 8 blocks (8 plot replicates; 96 plots per phase), each having a specific combination of treatments.

| Treatment | Pruning | Fungicide | Fertilizer | Pruning phase (2017) | | Pruning phase (2018) | | Harvesting phase (2018) | |
|---|---------|-----------|------------|----------------------|---------------|----------------------|---------------|-------------------------|---------------|
| | | | | <i>V. ang</i> | <i>V. myr</i> | <i>V. ang</i> | <i>V. myr</i> | <i>V. ang</i> | <i>V. myr</i> |
| Nb of plot replicate (Nb of stem observation) | | | | | | | | | |
| 1 | M | Without | Mineral | 8 (51) | 7 (13) | 8 (50) | 5 (14) | 8 (49) | 7 (15) |
| 2 | M | Without | Without | 8 (45) | 7 (19) | 8 (43) | 7 (21) | 8 (50) | 6 (14) |
| 3 | M | Without | Organic | 8 (53) | 5 (11) | 8 (43) | 7 (21) | 8 (53) | 5 (11) |
| 4 | M | With | Mineral | 8 (56) | 4 (8) | 8 (49) | 5 (15) | 8 (57) | 4 (7) |
| 5 | M | With | Without | 8 (49) | 7 (15) | 8 (54) | 4 (10) | 8 (52) | 6 (12) |
| 6 | M | With | Organic | 8 (51) | 7 (13) | 8 (41) | 8 (23) | 8 (47) | 7 (17) |
| 7 | MT | With | Without | 8 (47) | 7 (17) | 8 (53) | 6 (11) | 8 (47) | 7 (17) |
| 8 | MT | With | Organic | 8 (56) | 4 (8) | 8 (57) | 6 (7) | 8 (55) | 5 (9) |
| 9 | MT | With | Mineral | 8 (55) | 4 (9) | 8 (48) | 6 (16) | 8 (54) | 5 (10) |
| 10 | MT | Without | Without | 8 (43) | 6 (21) | 8 (45) | 6 (19) | 8 (44) | 6 (20) |
| 11 | MT | Without | Mineral | 8 (51) | 6 (13) | 8 (54) | 7 (10) | 8 (51) | 6 (13) |
| 12 | MT | Without | Organic | 8 (47) | 6 (17) | 8 (48) | 5 (16) | 8 (47) | 6 (17) |

Note: Eight individual *Vaccinium* spp. stems were randomly selected for each of the 96 plots, and classified either as *Vaccinium angustifolium* (*V. ang*) or *Vaccinium myrtilloides* (*V. myr*). M, mechanical pruning method only; MT, mechanical and thermal pruning methods; Nb, number.

Table 2. Crop management calendar for the studied sites.

| Crop management | Site 1 | Site 2 |
|-------------------------|---------------------|-------------------------|
| Pruning year | 2017 | 2018 |
| Harvesting year | 2018 | |
| Mechanical pruning | Week of 15 May 2017 | Week of 17 October 2017 |
| Thermal pruning | 7 November 2016 | 24 October 2017 |
| Fertilizers application | 13 June 2017 | 6 June 2018 |
| Fungicide application | 13 July 2017 | 16 July 2018 |
| Pollinators | 5–28 June 2018 | |

blueberry fields in Quebec. Since more than 10% of wild blueberry lands in Quebec are now under organic management (Gagnon et al. 2020), we also investigated and compared the efficiency of a much-used organic fertilizer (poultry manure) with conventional mineral fertilizers and a control. Taken individually and to a certain extent, all management practices are known to improve wild blueberry growth and fruit yields. Therefore, we expected that fungicide and fertilizer applications (mineral or organic) in combination with thermal pruning will increase stem height and leaf number per stem during pruning years and also increase stem height, flower bud number, and fruit biomass during harvesting year. We also expected more pronounced responses to management practices for *V. angustifolium* compared to *V. myrtilloides*.

Materials and methods

Experimental design

The experiment took place in the field from fall 2016 to fall 2018 at the *Bleuetière d'Enseignement et de Recherche* in Normandin (QC), Canada (48°49'35"N; 72°39'35"W). The first fruit on the field was harvested in 2008. Two sites were sampled, each totalling 96 experimental units (EUs) of 15 × 22 m plots (330 m²), including a 3 m border (buffer zone) between

each EU. All EUs received a combination of 12 different treatments defined as pruning, fungicide, and fertilizer applications organized in an eight-block (replicates) split-split-split plot experimental design (Table 1). A total of 52 beehives (*Apis mellifera* L.) were used (2.5 beehives ha⁻¹) to ensure sufficient flower pollination during harvesting year (Table 2). Pruning years were 2017 and 2018 for sites 1 and 2, respectively, and harvesting year was 2018 for site 1 (Table 2).

Pruning treatments were defined as mechanical or thermal (Table 1). Mechanical pruning was applied to all EUs with a blueberry mower (model TB-1072, JR Tardif, Rivière-du-Loup, Canada), while thermal pruning was only applied to half of the EUs with a high-pressure propane burner towed by a tractor (home-made liquid propane burner). The burner includes four individual propane burners that were placed 10 cm above the soil surface. Burners together consumed about 140 kg of propane ha⁻¹ (pressure of 15 psi and tractor speed of 1.5 km h⁻¹). Considering net heating value of propane of 47 MJ kg⁻¹ (Linstrom and Mallard 2001), this fuel consumption represents about 6580 MJ ha⁻¹. Similar to Vincent et al. (2018), soil temperatures using thermocouples placed at variable soil depths increased by less than 10 °C several minutes after thermal pruning (Figure S1). Pruning dates are reported in Table 2.

The application of a broad-spectrum fungicide (Proline[®], propiconazole as active ingredient) took place once per year (0.315 L ha⁻¹ of proline 480 SC dissolved with 0.250 L ha⁻¹ of AG Surf adjuvant) in mid-July of the pruning phase only (Table 2). This fungicide allows the control of sclerotic rot, rust, septorian spot, and valdensian spot (CropScience 2016). The effect of the fungicide was compared to a control, which was not submitted to fungicide treatment.

Three fertilization treatments were defined as control (no fertilizer applied), mineral fertilizers, and organic fertilizer. Mineral fertilizers consisted of an application of N (50 kg of N ha⁻¹ as ammonium sulfate), P (30 kg of P₂O₅ ha⁻¹ as super triple phosphate), potassium (K) (20 kg of K₂O ha⁻¹ as potassium sulfate), and boron (B) (0.7 kg of B ha⁻¹ as borate). Identical amounts of N, P, K, and B were applied as organic fertilization treatments with 1000 kg ha⁻¹ of granulated chicken manure (Pure Hen Manure, Acti-Sol Inc., Notre-Dame-du-Bon-Conseil, Canada) and borate. Organic fertilization also provided Ca (70 kg ha⁻¹) and organic matter (OM) (710 kg ha⁻¹). All fertilizers were applied on the soil surface using a small broadcast spreader before stem emergence. Dates of treatment applications are reported in Table 2.

Data collection

Eight individual *Vaccinium* spp. stems were randomly selected in each of the EU, and classified either as *V. angustifolium* or *V. myrtilloides* (Table 1). Plant traits of each blueberry stem were monitored during two pruning years and one harvesting year. During pruning years, stem height (mm) and leaf number per stem (nb per stem) were measured in late summer, the second and third weeks of September. During harvesting year, flower bud numbers (nb per stem) were collected at the beginning of bud development (stage 1 of floral budding chart from Fournier et al. (2020), mid-May), stem heights were measured during tip-dieback stage (first week of August), and fruit biomass (g per stem) was estimated in the second week of August by hand-picking fruits of all monitored stems.

Statistical analysis

A linear mixed model (mixed model procedure) was used for variance analysis with SPSS, version 26 for Windows (IBM Corp. 2016). Data normality (Kolmogorov-Smirnov's test) and homoscedasticity (Levene's test) of the variance were verified before any analyses; all variables required log transformation to meet assumptions. Management practices (pruning, fungicide, and fertilizer), year/site (for the pruning phase only), and species were considered as fixed factors, while blocks were considered a random factor. Furthermore, because each plot had unbalanced species numbers (from 0 to 8; see Table 1), nested (EU) was also considered as random factor in the models. For pruning phase, EU was nested into year, pruning, fungicide, and fertilizer, and EU was nested into pruning, fungicide, and fertilizer for harvesting phase. Least significant difference (LSD) post hoc test was used with a significant level of $\alpha = 0.05$ when more than two means needed to be compared.

Results

For pruning years, variance analysis showed significant simple and interaction effects of years, species, fungicide, and fertilizer applications on the measured plant traits, whereas the pruning method has no significant impact (Table 3). Compared to the control, adding mineral fertilizer increased the stem height by about 36.0 mm and the leaf number per stem by about 5.7 (Table 4). Adding organic fertilizer also increased stem height (+18.0 mm) and leaf number (+2.1 leaves per stem), but to a lesser extent than mineral fertilizers. Compared to *V. angustifolium*, *V. myrtilloides* also had higher plant biomass, as reflected by taller stems (+9.5 mm) and more leaves (+2.5 leaves per stem) (Table 4). Adding fungicide increased leaves per stem by 5.7, but for 2018 only, as no significant difference was measured in 2017 (Table 4). Significant interactions between fungicide \times fertilizer \times species showed interesting trends for leaf number per stem. First, not adding fungicide and fertilizer resulted in the fewest leaves per stem for both species. Second, when fertilized with mineral or organic fertilizers, adding fungicide did not improve leaf number for *V. myrtilloides*, but it increased leaf number per stem by 4.5 and 4.9 for *V. angustifolium* when mineral and organic fertilizers were used, respectively (Table 4). Third, *V. angustifolium* needed both fertilizer and fungicide to keep leaves on stems during late summer, whereas *V. myrtilloides* needed either fertilizer or fungicide (Table 4).

For harvesting year, variance analysis showed significant and simple effects only of fertilizer applications and species on stem height and flower bud numbers per stem (Table 3). The pruning method as well as fungicide application had no significant impact on any of the measured variables, whereas fruit biomass (mass of fruit per stem) was not impacted by any of the management practices (Table 3). Compared to the control, adding mineral fertilizer increased stem height by 22.5 mm and flower bud number per stem by 0.7, whereas adding organic fertilizer increased stem height and flower bud number per stem by about 15.9 mm and 0.4, respectively (Table 4). Although not significant, organic fertilizer application tended to produce shorter stems with fewer flower buds per stem compared to mineral fertilizer application (Table 4). Similarly to pruning years, *V. myrtilloides* was about 12.8 mm taller than *V. angustifolium* (Table 4). However, compared to *V. myrtilloides*, our results showed that *V. angustifolium* produced more flower buds per stem (+0.6), suggesting higher fruit yield potential of *V. angustifolium* compared to *V. myrtilloides*.

Discussion

This study sheds new light on the effect of pruning, fungicide, fertilizers, and species on key vegetative and reproductive wild blueberry plant traits. Our results show that fertilizer application was the main management practice affecting vegetative and reproductive plant traits, followed by fungicide application effects during pruning years only. The pruning method (mechanical and thermal) had no significant influence on the measured plant traits. Compared to *V. angustifolium*, *V. myrtilloides* were taller with more leaves (more pronounced vegetative traits), whereas *V. angustifolium* produced

Table 3. Mixed model analysis of variance of plant traits during pruning and harvesting cropping phases.

| Factor | df | Pruning ^a | | Harvesting ^b | | |
|--------------------------|----|--------------------------|---------------------------|-------------------------|---------------------|---------------|
| | | Stem height | Leaf number | Stem height | Flower bud number | Fruit biomass |
| F values (probabilities) | | | | | | |
| Year (Yr) | 1 | 0.49 (0.484) | 204.36 (<0.001) | – | – | – |
| Pruning method (Pr) | 1 | 0.00 (0.989) | 0.40 (0.529) | 1.26 (0.264) | 1.98 (0.161) | 0.36 (0.550) |
| Fungicide (Fu) | 1 | 0.47 (0.494) | 32.98 (<0.001) | 1.33 (0.251) | 0.16 (0.688) | 0.26 (0.610) |
| Fertilizer (Fe) | 2 | 27.92 (<0.001) | 16.43 (<0.001) | 8.60 (<0.001) | 3.16 (0.045) | 0.25 (0.781) |
| Species (Sp) | 1 | 7.36 (0.007) | 14.49 (<0.001) | 11.85 (0.001) | 6.17 (0.013) | 0.42 (0.516) |
| Yr × Pr | 1 | 0.09 (0.766) | 0.82 (0.365) | – | – | – |
| Yr × Fu | 1 | 2.19 (0.140) | 27.92 (<0.001) | – | – | – |
| Yr × Fe | 2 | 0.39 (0.680) | 0.55 (0.579) | – | – | – |
| Yr × Sp | 1 | 0.07 (0.790) | 0.26 (0.613) | – | – | – |
| Pr × Fu | 1 | 0.04 (0.852) | 0.82 (0.366) | 0.00 (0.973) | 0.04 (0.843) | 3.31 (0.072) |
| Pr × Fe | 2 | 0.70 (0.496) | 0.68 (0.510) | 2.05 (0.133) | 1.33 (0.269) | 0.57 (0.569) |
| Pr × Sp | 1 | 0.44 (0.505) | 0.44 (0.506) | 0.00 (0.952) | 0.88 (0.350) | 0.52 (0.470) |
| Fu × Fe | 2 | 0.29 (0.746) | 1.55 (0.214) | 1.06 (0.350) | 0.99 (0.373) | 0.02 (0.976) |
| Fu × Sp | 1 | 0.00 (0.964) | 0.16 (0.690) | 1.77 (0.184) | 0.16 (0.693) | 0.59 (0.444) |
| Fe × Sp | 2 | 0.07 (0.929) | 2.99 (0.051) | 0.08 (0.925) | 1.66 (0.192) | 0.66 (0.517) |
| Yr × Pr × Fu | 1 | 0.04 (0.844) | 0.09 (0.764) | – | – | – |
| Yr × Pr × Fe | 2 | 0.83 (0.435) | 0.04 (0.964) | – | – | – |
| Yr × Pr × Sp | 1 | 0.42 (0.519) | 1.59 (0.207) | – | – | – |
| Yr × Fu × Fe | 2 | 1.67 (0.189) | 0.02 (0.977) | – | – | – |
| Yr × Fu × Sp | 1 | 3.41 (0.065) | 0.32 (0.570) | – | – | – |
| Yr × Fe × Sp | 2 | 0.65 (0.520) | 0.80 (0.452) | – | – | – |
| Pr × Fu × Fe | 2 | 0.41 (0.665) | 0.48 (0.619) | 0.72 (0.487) | 0.81 (0.445) | 1.03 (0.363) |
| Pr × Fu × Sp | 1 | 0.14 (0.705) | 2.30 (0.129) | 0.21 (0.645) | 0.37 (0.543) | 2.11 (0.147) |
| Pr × Fe × Sp | 2 | 2.10 (0.123) | 0.06 (0.944) | 1.34 (0.263) | 2.91 (0.055) | 0.05 (0.947) |
| Fu × Fe × Sp | 2 | 1.41 (0.244) | 6.49 (0.002) | 0.65 (0.523) | 2.35 (0.096) | 0.06 (0.938) |
| Yr × Pr × Fu × Fe | 2 | 3.01 (0.051) | 2.35 (0.097) | – | – | – |
| Yr × Pr × Fu × Sp | 1 | 0.25 (0.619) | 0.02 (0.886) | – | – | – |
| Yr × Pr × Fe × Sp | 2 | 0.54 (0.550) | 0.43 (0.651) | – | – | – |
| Yr × Fu × Fe × Sp | 2 | 0.17 (0.845) | 0.19 (0.830) | – | – | – |
| Pr × Fu × Fe × Sp | 2 | 0.12 (0.886) | 0.11 (0.893) | 0.48 (0.617) | 2.02 (0.133) | 0.12 (0.888) |
| Yr × Pr × Fu × Fe × Sp | 2 | 1.44 (0.175) | 2.31 (0.100) | – | – | – |

Note: df, degree of freedom; significant results are in bold; –, year factor was not present during harvesting cropping phase.

^aBloc and nested experimental unit [EU(Yr(Pr(Fu(Fe))))] as random factors.

^bBloc and nested experimental unit [EU(Pr(Fu(Fe))))] as random factors.

more flower buds per stem, a key reproductive plant trait. Fungicide application improved late summer leaf number per stem in 2018 only, which suggests higher leaf area and higher photosynthesis capacity for treated plants (Fournier et al. 2020). None of the treatments significantly impacted fruit biomass. Because of high variabilities, harvesting fruit at the plot scale (~500 stems per m²) rather than at the stem scale (here eight stems per plot) may explain this lack of significance.

Fertilizer

Blueberry plants need significant amounts of nutrients to support primary growth and reproductive bud development during the pruning year, as well as vegetative growth and fruit development during the harvesting year. As already demonstrated by other studies (Penney and McRae 2000; Eaton and Nams 2006; Lafond and Ziadi 2011), the positive

effects of fertilization on these key plant traits were also observed during both years. Improvements in vegetative traits (stem height and leaf number) by adding fertilizers likely increased photosynthesis (Fournier et al. 2020) and carbon reserve capacities during the pruning years, allowing more energy to produce flower buds and have more resources to achieve growth during the harvesting year (Swain and Darnell 2001; Weiner et al. 2009; Kaur et al. 2012). During the pruning year, vegetative plant traits after organic fertilizer applications did not increase as much as for mineral fertilizer applications, but were still generally higher compared to controls. However, from a 2-year cycle perspective, organic fertilizer applications showed similar (nonsignificant) plant traits during the harvesting year as compared to mineral fertilizer applications, which suggests a delayed effect of organic fertilizer. Indeed, organic fertilizer contains high proportions of organic N materials (e.g., proteins, amino acids,

Table 4. Significant results of plant traits obtained during both pruning and harvesting cropping phases.

| Significant factors and interactions | | | Pruning | | Harvesting | |
|--------------------------------------|--------------------|-------------------------|-----------------|---------------------------|-----------------|---------------------------|
| | | | Stem height | Leaf number ^a | Stem height | Flower bud number |
| | | | – | Number stem ⁻¹ | – | Number stem ⁻¹ |
| Fertilizer | | | | | | |
| Mineral fertilizer | | | 113.67 (3.32) a | 20.41 (0.66) a | 120.67 (4.58) a | 3.29 (0.22) a |
| Organic fertilizer | | | 95.98 (3.25) b | 16.82 (0.64) b | 114.01 (4.34) a | 3.01 (0.21) ab |
| w/o fertilizer | | | 77.96 (3.05) c | 14.70 (0.61) c | 98.15 (4.14) b | 2.64 (0.20) b |
| Species | | | | | | |
| <i>V. angustifolium</i> | | | 91.13 (1.73) b | 16.06 (0.35) b | 104.55 (2.55) b | 3.27 (0.11) a |
| <i>V. myrtilloides</i> | | | 100.60 (3.04) a | 18.56 (0.63) a | 117.34 (4.21) a | 2.69 (0.21) b |
| Year × Fungicide | | | | | | |
| 2017 | w/fungicide | | – | 21.04 (0.77) a | – | – |
| 2017 | w/o fungicide | | – | 21.12 (0.69) a | – | – |
| 2018 | w/fungicide | | – | 16.38 (0.75) b | – | – |
| 2018 | w/o fungicide | | – | 10.70 (0.72) c | – | – |
| Fungicide × Fertilizer × Species | | | | | | |
| w/fungicide | Mineral fertilizer | <i>V. angustifolium</i> | – | 19.06 (0.80) b | – | – |
| w/fungicide | Mineral fertilizer | <i>V. myrtilloides</i> | – | 24.26 (1.62) a | – | – |
| w/fungicide | Organic fertilizer | <i>V. angustifolium</i> | – | 19.45 (0.81) b | – | – |
| w/fungicide | Organic fertilizer | <i>V. myrtilloides</i> | – | 15.85 (1.65) bc | – | – |
| w/fungicide | w/o fertilizer | <i>V. angustifolium</i> | – | 14.53 (0.81) c | – | – |
| w/fungicide | w/o fertilizer | <i>V. myrtilloides</i> | – | 19.11 (1.54) ab | – | – |
| w/o fungicide | Mineral fertilizer | <i>V. angustifolium</i> | – | 16.92 (0.82) c | – | – |
| w/o fungicide | Mineral fertilizer | <i>V. myrtilloides</i> | – | 21.42 (1.56) ab | – | – |
| w/o fungicide | Organic fertilizer | <i>V. angustifolium</i> | – | 14.06 (0.84) d | – | – |
| w/o fungicide | Organic fertilizer | <i>V. myrtilloides</i> | – | 17.90 (1.42) b | – | – |
| w/o fungicide | w/o fertilizer | <i>V. angustifolium</i> | – | 12.32 (0.87) d | – | – |
| w/o fungicide | w/o fertilizer | <i>V. myrtilloides</i> | – | 12.84 (1.28) d | – | – |

Note: Mean (standard error); letters indicate significant differences between averages using a least significant difference (LSD) post hoc test ($P < 0.05$); –, not significant (see Table 3). w/o, without; w/, with.

^aAs determined during the second and third weeks of September.

etc.) and nutrients trapped in organic materials that become available to plants after being mineralized/degraded by soil microorganisms (Näsholm and Persson 2001; Persson et al. 2003; Caspersen et al. 2016). Furthermore, Ericaceae like *Vaccinium* spp. have a symbiotic interaction with ericoid mycorrhizae that improves both the mineralization and assimilation of organic N materials (Marschner and Dell 1994; Schimel and Bennett 2004; Näsholm et al. 2009; Caspersen et al. 2016). Nonetheless, all of these soil processes need time, thus explaining the delayed effect of organic fertilizer as compared to mineral fertilizers. Nevertheless, organic fertilizers have several long-term benefits over mineral fertilizers. First, compared to mineral fertilizers, organic fertilizers generally provide more macronutrients that are required for plant growth such as Ca, Mg, etc. Second, organic fertilizers can increase soil OM content, which may, in turn, increase soil fertility (Tilman and Wedin 1991; Näsholm and Persson 2001; Percival and Sanderson 2004) and soil water retention capacity (Caspersen et al. 2016). However, as application rates of organic fertilizer added tiny amounts of OM (~710 kg of

OM ha⁻¹ every 2 years), we believe that this benefit would be marginal in our context.

Fungicide

Adding a fungicide such as propiconazole has been shown to significantly increase wild blueberry fruit yields in the past (Percival and Dawson 2009; Percival and Beaton 2011). Indeed, fungicides are known to protect wild blueberry leaves against many fungal diseases such as sclerotic rot, rust, and septorian/valdensian leaf spots, which result in preventing premature defoliation of the plant (Percival and Dawson 2009). According to this, our study shows that fungicide application increased leaf number per stem during late summer (mid-September) in 2018, which was about 4 weeks after the tip-dieback stage. Compared with 2017, cooler temperatures measured in early season May to mid-June 2018 (Figure S2) may explain this significant year × fungicide interaction. Furthermore, because propiconazole may also mitigate the adverse effects of drought stress by increasing the plant antioxidants (Manivannan et al. 2007), a much warmer and

drier mid-June to late-August in 2018 compared to 2017 (Figure S2) may explain why fungicide application increased leaf number per stem during late summer of 2018 only. Finally, application of fungicide had no significant impact on either flower bud number or fruit biomass per stem. The fact that we did not measure reproductive traits on site 2 (in 2018) may explain this lack of significance.

Species

Species was an important factor affecting plant traits during both pruning and harvesting phases. Overall, results showed that *V. myrtilloides* produces more vegetative traits (taller stems with more leaves), whereas *V. angustifolium* produces less vegetative traits but with more flower buds, a key reproductive plant trait that is positively related to fruit yields (Maust et al. 1999; Penney and McRae 2000; Drummond and Yarborough 2012). However, as *V. myrtilloides* may also contain more flowers per bud compared to *V. angustifolium* (Fournier et al. 2020), relating flower bud number to fruit yield may be too simplistic, at least in this case. This flower per bud difference may also explain why fruit biomass did not differ between species (Table 3). Another important difference found between species is related to leaf number. As we monitored leaf number in late summer (the second and third weeks of September), higher leaf number here may mean more leaves have been produced and (or) less leaves have fallen (less leaf senescence), explaining why we observed a significant fungicide \times fertilizer interaction between species (Table 3). In other words, we believe that fertilizers produce more leaves and fungicide helps to keep leaves on stems for a longer time. As the production of reserves in stems and rhizomes occurs toward the end of summer and until plant dormancy or leaf senescence (Kaur et al. 2012), producers have a reason to perform management practices that keep more leaves on stems during fall. This is especially true since the date of the first frost is expected to be delayed by about 11 days by 2050 in this region as climate change occurs (Prairie Climate Centre 2019). To keep leaves on stems, our results showed that *V. angustifolium* needs both fertilizer and fungicide, whereas *V. myrtilloides* needs either fertilizer or fungicide (Table 4). As no difference in leaf phenology was measured between species during the pruning phase (Fournier et al. 2020), this suggests that *V. myrtilloides* is more resistant to leaf aging than *V. angustifolium*. Major genetic differences between species (Sakhanokho et al. 2018) may explain this.

Pruning

Compared to mechanical pruning, thermal pruning had no significant effect on all measured vegetative and reproductive plant traits. As compared to fertilizer and fungicide management practices, the effects of pruning method were not important. Although a number of studies showed improvements in fruit yields after thermal treatment as compared to not-burned controls (Black 1963; Ismail et al. 1981; Warman 1987; Penney et al. 1997), thermal treatment has several disadvantages compared to mechanical pruning. Indeed, costs related to thermal treatment (e.g., burning and tractor fuel,

extra times, etc.) are much higher than for mechanical pruning alone. Furthermore, thermal pruning may reduce soil OM content/depth over time (Smith and Hilton 1971). However, since thermal pruning can also be used as an organic control strategy against weeds and diseases (Black 1963; Ismail et al. 1981; Penney et al. 2008), more years of results will be needed to highlight the effects of thermal pruning compared to mechanical pruning—and its interaction effects with other treatments such as fertilizer and fungicide applications—to better advise producers on the best agricultural practices to use in the Quebec context.

Conclusion

In this study, we showed that mainly fertilizers and to a lesser extent fungicide application had significant effects on key vegetative and reproductive wild blueberry species plant traits. Pruning method had no significant effect, although long-term research is still needed to clearly assess the question of whether thermal pruning is profitable compared to mechanical pruning over time. Except for fruit biomass, fertilizer applications significantly improved all of the measured vegetative and reproductive plant traits. During the years of fertilizer applications (pruning phase), mineral fertilizer performed significantly better than organic fertilizer. The year after fertilizer application (harvesting phase), mineral and organic fertilizers performed equally, showing a delayed response of wild blueberry to organic fertilizer. Our study also showed that *V. myrtilloides* produced taller stems with more leaves than *V. angustifolium*. Compared to *V. myrtilloides*, *V. angustifolium* produced significantly more flower buds per stem, a key reproductive plant trait often related to fruit yield. Finally, *V. angustifolium* needs both fungicide and fertilizer to keep their leaves in place during fall, whereas *V. myrtilloides* needs either fertilizer or fungicide to do so. Since *V. angustifolium* dominates most of the wild blueberry commercial fields, application and utilization of fertilizers and fungicide may help producers to take advantage of warmer falls that are expected for the upcoming years.

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Supplementary material

Supplementary data are available with the article at <https://doi.org/10.1139/cjps-2021-0242>.

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