UQAC
Université du Québec
à Chicoutimi

Le bleuet sauvage au Saguenay-Lac-Saint-Jean : Comment mieux le produire ?

par Anne Schmitt

Mémoire présenté à l'Université du Québec à Chicoutimi en vue de l'obtention du grade de Maître ès sciences (M. Sc.) en Ressources renouvelables

Québec, Canada

RÉSUMÉ

Le rendement en fruits du bleuet nain (*Vaccinium angustifolium* et *Vaccinium myrtilloides*) est variable puisqu'il dépend de plusieurs facteurs, dont certains peuvent être influencés par les pratiques agricoles effectuées par les producteurs. L'objectif principal de cette recherche est donc d'expérimenter l'impact des principales pratiques sur le rendement en fruits du bleuet et d'autres variables connexes comme le nombre et la hauteur des tiges, l'état nutritionnel de la plante ainsi que la présence des maladies et des plantes indésirables. Les pratiques testées dans le cadre de ce projet sont i) le type de fauche (mécanique ou thermique), ii) l'utilisation de fongicide (avec ou sans) et iii) l'apport d'engrais (minéral, organique ou sans engrais). Cette étude s'est déroulée à la bleuetière d'enseignement et de recherche (BER) localisée à Normandin, Québec, Canada. Deux sites de quatre blocs divisés en douze combinaisons spécifiques de traitements comprenant les trois facteurs étudiés ont été disposés selon un dispositif de recherche en tiroir à 96 parcelles ou unités expérimentales. Aucune des pratiques à l'étude a affecté significativement la présence des plantes indésirables. Le brûlage n'a pas entraîné de gain de rendement, ni d'amélioration cohérentes des autres paramètres évalués. L'application de fongicide a entraîné un gain de rendement en fruits de 212 kg ha^{-1}, une diminution de près de 1% du taux de maladies foliaires et une augmentation du nombre de tiges par unité de surface lorsqu'ils sont combinés avec un engrais minéral. La fertilisation minérale a également réduit la présence des maladies, amélioré l'état nutritionnel de la plante et engendré un gain de rendement de 853 kg ha^{-1}. Enfin, la fertilisation organique a accru les rendements de 691 kg ha^{-1}, tout en améliorant plusieurs traits tels que la hauteur des tiges et la teneur des feuilles et des fruits en nutriments. Les applications de fongicide et d'engrais ont également augmenté la quantité de nutriments exportés par les fruits à la suite des récoltes. De ce fait, il serait pertinent d'axer les prochains suivis sur les nutriments foliaires et du sol pour assurer la durabilité des systèmes de production.

TABLE DES MATIÈRES

LISTE DES TABLEAUX

LISTE DES FIGURES

LISTE DES SIGLES

Ca : Calcium
CAFN : Corporation d'Aménagement Forestier de Normandin
CF : Without fertilizer
CFun : Without fungicide
EU : Experimental unit
Fun : Fungicide
Hectare : ha
K : Potassium
MAPAQ : Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec
M : Mechanical pruning
MF : Mineral fertilizer
Mg : Magnesium
MT : Thermal pruning
N : Nitrogen
OF : Organic fertilizer
P : Phosphorus
SLSJ : Saguenay-Lac-Saint-Jean
SOM : Soil organic matter

REMERCIEMENTS

Je termine ce mémoire en remerciant tout d'abord Maxime Paré, mon directeur de maîtrise. Depuis plus de 5 ans maintenant, du baccalauréat jusqu'ici, il a su me guider. Ses conseils m'ont aidée bien au-delà de mon parcours académique. Je serai éternellement reconnaissante pour toute la patience et surtout la compréhension dont il a fait preuve envers la jeune maman que je suis. Je remercie également mon co-directeur, M. Jean Lafond, qui s'est montré généreux de son temps, de ses conseils et de ses connaissances. Ce projet ne serait pas le même sans lui.

Je tiens à remercier tous les gens qui ont contribué à la réalisation de ce projet, de près ou de loin. Entre autres, toute l'équipe du Club Conseil Bleuet, pour l'aide technique apportée, mais également pour m'avoir accepté dans leur famille malgré tout ce que cela impliquait. Aux employés d'Agriculture et Agroalimentaire Canada (AAC) à Normandin, mais plus particulièrement à M. Denis Bourgault pour son aide sur le terrain, mais également pour les analyses de toutes sortes. Ainsi qu'à toutes les autres personnes qui se sont impliquées dans la réalisation des travaux sur cette bleuetière, je pense entre autres aux membres de la Corporation d'Aménagement Forestier de Normandin (CAFN), à Catherine Tremblay, Stéphanie Cloutier, Geneviève Telmosse, Anthony Pelletier, Anna-Marie Devin, et j'en passe… Ils sont encore nombreux, mais ils se reconnaîtront. Merci pour votre travail qui m'a permis d'accomplir ce projet.

Enfin, je ne peux passer outre tout le soutien apporté par ma famille. Max, merci de m'avoir permis de réaliser ce rêve à travers tous les nombreux autres projets que nous avions déjà entamés. Merci pour ta patience et ta compréhension. Et merci à mes parents pour leur admiration et leur confiance sans faille en mes capacités.

AVANT-PROPOS

Le mémoire qui suit a été réalisé dans le cadre du programme de Maîtrise en ressources renouvelables de l’Université du Québec à Chicoutimi (UQAC). Le projet a été dirigé par M. Maxime Paré de l’UQAC et codirigé par M. Jean Lafond d’Agriculture et Agroalimentaire Canada (AAC). Le dispositif expérimental de cette étude était situé sur la Bleuetière d’Enseignement et de Recherche (BER) de Normandin au Lac-Saint-Jean, site appartenant à la Corporation d’Aménagement Forestier de Normandin (CAFN). Le sujet de cette étude porte sur l’impact de différentes pratiques agricoles sur le bleuet nain sauvage en bleuetière commerciale.

Les résultats de cette étude ont été présentés aux producteurs et intervenants du secteur du bleuet sauvage du Saguenay-Lac-Saint-Jean (SLSJ) via le webinaire bleuet organisé, entre autres, par le ministère de l’Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) en mars 2022. Il aurait été impossible de réaliser ce projet sans les supports financiers du Syndicat des Producteurs de Bleuets du Québec (SPBQ) et du Conseil de Recherches en Sciences Naturelles et en Génie (CRSNG) (Projet RDCPJ-503182-16). De plus, l’accessibilité au site d’étude a été possible grâce à la collaboration de la Corporation d’Aménagement Forestier de Normandin (CAFN). Enfin, il est nécessaire de remercier les employés du Club Conseil Bleuet (CCB) ainsi que d’Agriculture et Agroalimentaire Canada (AAC) à Normandin pour leurs assistances sur le terrain et au laboratoire.

INTRODUCTION GÉNÉRALE

L'industrie du bleuet sauvage

La famille des Éricacées comprend près de 1 500 espèces, dont plusieurs se retrouvent en Amérique du Nord (Frère Marie-Victorin 1935 ; Eaton 1994). Le bleuet sauvage (*Vaccinium angustifolium Ait.* et *Vaccinium myrtilloides Michx*) fait partie de cette famille. C'est un arbuste indigène cultivé pour ses petits fruits fortement prisés par les consommateurs pour leurs propriétés antioxydantes et leur goût (Wilhelmina *et al.* 2001). L'Amérique du Nord produit 85 % du volume total de bleuets à travers le monde (MAPAQ 2016). Les États-Unis cultivent principalement le bleuet en corymbe (*Vaccinium corymbosum*) alors que le Canada est le premier producteur mondial de bleuets sauvages (MAPAQ 2016). Entre 2010 et 2014, 64 000 tonnes métriques de bleuets ont été produits au Canada en comparaison à environ 40 000 tonnes métriques aux États-Unis (MAPAQ 2016). Les superficies cultivées au Canada sont principalement partagées entre le Québec, la Nouvelle-Écosse et le Nouveau-Brunswick, l'Île-du-Prince-Édouard et Terre-Neuve (MAPAQ 2016). Toutefois, la principale province productrice de bleuets sauvages demeure le Québec avec plus de 46 % des superficies récoltées au pays (MAPAQ 2016). En 2018 au Québec, près de 35 000 tonnes ont été produites par un total de 474 exploitants (MAPAQ 2019).

Au Québec, l'industrie du bleuet sauvage est responsable d'importantes retombées économiques pour la province, mais aussi pour la région du Saguenay-Lac-Saint-Jean (SLSJ) qui possède plus de 80 % des superficies québécoises cultivées, soit près de 30 000 hectares (ha) (MAPAQ 2019). La production du bleuet sauvage est ainsi la deuxième production agricole la plus importante de la région, derrière la production laitière (MAPAQ 2016). Entre 2015 et 2019, la moyenne des recettes monétaires annuelles au Québec est passée de 31 à 52 millions de dollars canadien et ce malgré le fait que les rendements varient beaucoup d'une année à l'autre en raison des conditions climatiques (MAPAQ 2022).

La culture du bleuet sauvage

Les bleuetières sont développées et aménagées sur des sols qui démontrent certaines caractéristiques favorables à la production du bleuet sauvage. De façon générale, ce sont des sols sableux (podzoliques), acides, pauvres en éléments nutritifs et bien drainés (Laberge Pelletier 2007). Au SLSJ, les plants de bleuets sauvages se retrouvent généralement sous des peuplements de pinèdes grises (*Pinus banksiana*). Lors de l'aménagement des bleuetières, les plants de bleuets sont présents initialement sous le couvert forestier de pins gris et s'étalent sur le territoire défriché à l'aide de leurs rhizomes (Hall *et al.* 1979; Blatt *et al*. 1989).

Les bleuetiers sont des plantes à rhizomes dont les bourgeons peuvent s'activer pour développer des tiges aériennes ou de nouvelles pousses sous-terraines leur permettant de coloniser de grandes surfaces (Morin 2008). Leurs rhizomes sont situés près de la surface du sol, dans la couche de matière organique qui constitue le principal réservoir en éléments nutritifs (Lafond et Ziadi 2013). En ce sens, la matière organique est la source principale de nutriments pour la culture et il devient donc primordiale de la conserver. De plus, le bleuet possède quelques racines qui sont enfouies à plus d'un mètre dans le sol qui lui permettent de puiser l'eau et d'autres nutriments nécessaires à son développement (Hall 1957).

En bleuetières comme en forêts, les rendements en fruits du bleuet sauvage sont variables d'une année à l'autre puisqu'ils dépendent de plusieurs facteurs. Entre autres, la croissance du bleuet nain dépend des conditions météorologiques, des maladies par lesquelles il est affecté ainsi que par la présence de mauvaises herbes avec lesquelles il se retrouve en compétition pour accéder aux éléments nutritifs (McIsaac 1997; Yarborough 1999). Peu de pratiques agricoles agissent sur les conditions climatiques, mais les producteurs utilisent différentes techniques afin de pallier d'autres mauvaises conditions de culture et conserver un bon rendement. Cette étude s'intéresse à trois d'entre elles, à savoir la fauche des plants, l'utilisation de fongicides et enfin l'application de fertilisants.

Objectifs et hypothèses

Le but de ce projet est d'expérimenter l'incidence de diverses pratiques agricoles sur le rendement en fruits et plusieurs autres variables ou traits connexes soient : le nombre et la hauteur des tiges, le pourcentage de plantes indésirables et de maladies ainsi que l'état nutritionnel des bleuetiers. Les pratiques agricoles évaluées sont : le type de fauche (mécanique ou thermique), l'utilisation de fongicides (avec ou sans) et l'application d'engrais (minéral, organique ou aucun). Les hypothèses associées à chacune de ces pratiques sont décrites ci-dessous.

Type de fauche

Les rendements en fruits, le nombre et la hauteur des tiges ainsi que l'état nutritionnel des plants seront plus élevés lorsque la fauche thermique sera utilisée. Les taux de mauvaises herbes et de maladies seront quant à eux plus faibles avec la fauche thermique.

Utilisation de fongicides

L'application de fongicide permettra un meilleur rendement, une augmentation de la hauteur des tiges et une diminution du taux de maladies. Cependant, elle n'aura pas d'effet sur la présence de plantes indésirables ainsi que les teneurs foliaires en éléments nutritifs des bleuetiers.

Application des engrais

La fertilisation, particulièrement minérale, produira un meilleur rendement, une augmentation du nombre et de la hauteur des tiges. De plus, elle accroîtra les teneurs en nutriments des feuilles et la présence de mauvaises herbes et diminuera le taux de maladies foliaires.

Combinaison de pratiques

Le dispositif permet aussi de s’intéresser aux interactions entre les pratiques. Une fauche mécanique, sans fongicide et sans engrais occasionnera sans doute un rendement plus faible, ainsi qu’une diminution du nombre et de la hauteur des tiges. Les taux de maladies foliaires et en seront augmentés alors que les teneurs en éléments nutritifs des plants seront diminuées.

CHAPITRE 1

EFFECT OF AGRICULTURAL PRACTICES ON AGRONOMIC PARAMETERS AND YIELD OF LOWBUSH BLUEBERRIES

1.1 Abstract

Lowbush blueberry (*Vaccinium angustifolium* Ait. and *Vaccinium myrtilloides* Michx) yields are highly variable since they depend on several factors, some of which can be influenced by producers with different agricultural practices. The main objective of this research is to assess the impact of several management practices on blueberry yield and other related variables such as the number and height of stems, nutrient status of the plant and crop pests. During four years, twelve combinations of three practices were tested and replicated four times on two sites in a split-split-plot experiment: i) type of pruning (mechanical or thermal), ii) use of fungicide (with or without) and iii) application of fertilizer (mineral, organic or without). This study took place at Normandin, Quebec, Canada, and involved two sites that include 48 plots on each. None of the management practices affected weed coverage. Burning did not improve fruit yield nor all other parameters evaluated. Throughout the years, fungicide applications caused a yield gain of about 212 kg ha^{-1} yr^{-1}, a decrease in disease rate and an increase in the number of stems density when combined with mineral fertilizer. Mineral fertilizer also reduced the number of diseases, improved the plant nutrient status, and caused a gain in yield of about 853 kg ha^{-1} yr^{-1}. Finally, organic fertilization improved yield by about 691 kg ha^{-1} yr^{-1}. Results also showed that fungicide and fertilizer in combination and fungicide alone increased the quantity of nutrients exported by the harvested fruits highlighting the importance of monitoring nutrient status in the long term.

1.2 Introduction

Wild lowbush blueberry (WLB) belongs to the Ericaceae family and is naturally found in North America (Frère Marie-Victorin 1935 ; Eaton 1994). Canada is the world's largest producer of WLB (MAPAQ 2016), and Quebec is the main province producing WLB with nearly 35,000 tonnes per year harvested by about 474 farms (MAPAQ 2019).

Sandy, acidic, nutrient-poor, and well-drained soils are the most suitable edaphic properties that favor WLB establishment and development (Laberge Pelletier 2007). WLB are not planted, they grow from initial WLB clones that were present in the forest understory. Commercial fields of WLB are thereafter maintained by pruning mechanically or by burning every 2 or 3 years (Moreau 2014). Pruning allows WLB stem regrowth and improves the number of flowers per stem and fruit yield per hectare (Gagnon and Moreau 2014).

Mechanical and thermal pruning are mainly performed in the fall, after fruit harvest and when the plants have lost their leaves or early in the spring before the buds begin their development (Ismail and Hanson 1982). Mechanical pruning is mainly done using a mower, whereas thermal pruning is usually performed after mechanical pruning with propane or oil burners (Gagnon and Moreau 2014). The latter method may help to better control the presence of unsuitable organisms and pests such as weeds, insects and pathogenic fungi (Warman 1987). In addition, the ash deposit caused by thermal pruning can increase soil fertility through increasing mineral forms of the main soil nutriments. Morvan *et al.* (2022) recently showed an increase of mineral soil phosphorus concentrations one month after burning at high intensity. On the other hand, it is essential to burn at optimal intensity and frequency since excessive burning may reduce the layer of organic matter present at the soil surface, which can cause a drop in production in the longer term (Trevett 1956; Black 1963). In this case, the soil may become sensitive to wind and water erosion and a large fraction of mineral elements can be leached out of the field (Bouchard *et al.* 1982). Thermal pruning may also increase the soil pH due to the presence of alkaline elements in ashes and the destruction of organic acids that make up soil organic matter (Gomendy 1992). Because of this, it is important to assess the effect of thermal pruning in the long term, which has never so far been done in Quebec.

Fungicide applications is a practice gaining popularity among WLB growers since several foliar diseases can affect lowbush blueberries through leaf discoloration, defoliation, and reduction of flower buds (Hildebrand *et al.* 2016). The most important foliar disease is Septoria leaf spot (*Septoria sp.*), a leaf and fruit diseases that have caused significant yield reductions in Quebec and Canada (Cline 2002; Percival and Dawson 2009). Septoria leaf spot increases in severity when conditions are warm and humid in May and June (Barker *et al.* 1964). In addition, hot and dry weather conditions in July and August may favor the premature fall of infected leaves and fruits (Hildebrand *et al.* 2016). The fallen leaves will then incubate the development of pycnidia and spores, which will make the areas more susceptible to disease infection the following year (Hildebrand *et al*. 2016). Consequently, all management practices that delay leaf fall or senescence may also help to reduce Septoria leaf spot over the years. Studies have shown that fungicide applications decrease leaf diseases and increase chlorophyll content, photosynthesis rates, as well as the number of fruit buds per stem and fruit yields (Percival and Dawson 2009). Most fungicides are protectant that must be applied before the disease appears on leaves. However, not all fungicides have so far been effective and how fungicides may interact with other agricultural practices such as pruning and fertilizer applications is still unclear (Walker *et al.* 2010; Drummond *et al.* 2009).

In terms of fertilizers, mineral fertilization generally increases WLB yields (Eaton 1994). However, fertilization should not be done in every context. For example, complete mineral fertilization (N-P-K) increases plant growth and number of buds (Eaton 1994; Morin 2008; Lafond 2009). However, it has also been shown to increase the presence of weeds (Smagula and Ismail 1981; Yarborough *et al.* 1986). Once weeds are established, mineral fertilizer becomes useless or even harmful since WLB are not effective in accessing nutrients in a situation of competition with weeds such as Comptonia peregrina and Danthonia spicata (Marty *et al.* 2019a). Once degraded, nutrients from organic amendments are accessible to plants and, when applied in sufficient quantity, can increase the amount of soil organic matter, improving soil cation exchange capacity, soil water retention and soil microbial activity (Gagnon *et al.* 2003; Warman *et al*. 2004). However, organic fertilization effect on plant characteristics such as growth and bud number could be delayed compared to the application of mineral fertilizers (Fournier 2020). Since costs of mineral fertilizers recently became very high, growers would benefit from obtaining clarifications as to the relative efficacy of organic fertilization on the productivity of WLB.

The main objective of this study is to test the impact of various agricultural practices on WLB yield and several other related variables such as the stem density, stem height, percentage of weeds and diseases, as well as nutritional status of the plants. The agricultural practices evaluated here are pruning method (mechanical or mechanical + thermal), use of fungicide (with or without) and fertilizer application (mineral, organic or without). It is assumed that thermal pruning and the application of fungicide and fertilizer will increase yields as well as the number and height of stems, in addition to improving the nutritional status of plants. It is also expected that the disease incidence will be reduced by both the application of fungicide as well as the burning pruning method. Finally, weed coverage will be affected by fertilization and pruning method.

1.3 Material and methods

1.3.1 Experimental design

The experiment took place in the field from fall 2016 to fall 2020 at the *Bleuetière d'Enseignement et de Recherche* in Normandin (QC), Canada (48°49'35"N; 72°39'35"W). Two sites were established, both of which were divided into 48 experimental units (EU) of 15 x 22 m (330 m^2) separated by a buffer of three to five meters (Pelletier *et al.* 2022). Each bloc was divided into twelve (12) specific combinations of treatments including pruning, fungicide and fertilization. All factors were organized in a split-split-plot experimental design with four replicates, for a total of 96 EU (Table 1).

TABLE 1: Combinations of twelve treatments tested in this study.

Treatment	Pruning	Fungicide	Fertilizer
1	Mechanical	Without	Mineral
2	Mechanical	Without	Without
3	Mechanical	Without	Organic
4	Mechanical	With	Mineral
5	Mechanical	With	Without
6	Mechanical	With	Organic
7	Mechanical and Thermal	With	Without
8	Mechanical and Thermal	With	Organic
9	Mechanical and Thermal	With	Mineral
10	Mechanical and Thermal	Without	Without
11	Mechanical and Thermal	Without	Mineral
12	Mechanical and Thermal	Without	Organic

Mechanical pruning was applied to all EU using a blueberry mower (model TB-1072, JR Tardif, Rivière-du-Loup, Canada). Thereafter, thermal pruning was done on half of the EU. Thermal pruning was performed with a high-pressure propane burner towed by a tractor (home-made liquid propane burner) including four individual propane burners installed 10 cm above the soil surface. Both pruning methods were carried out in fall or in spring during plant dormancy (Table 2).

Fungicide application took place in mid-summer during the pruning years only (Table 2). The effect of two treatments was studied, a treatment with fungicide and another without fungicide. The broad-spectrum fungicide Proline © was used according to manufacturer's recommendation (315 L ha^{-1} Proline + 0,250 L ha^{-1} AG Surf adjuvant). Proline © allows the control of mummy berry (*Monilinia vaccinii-corymbosi*), rust (*Thekopsora minima*), septoria (*Septoria sp*.) and valdensinia leaf spot (*Valdensinia heterodoxa*) (Bayer 2021).

Three fertilization treatments were defined as mineral fertilizers, organic fertilizer, and control (no fertilizer). Mineral fertilizers included nitrogen (N) (50 kg of N ha^{-1} as ammonium sulfate), phosphorus (P) (30 kg of P_2O_5 ha^{-1} as triple superphosphate), potassium (K) (20 kg of K_2O ha^{-1} as potassium sulfate), and boron (B) (0.7 kg of B ha^{-1} as borate). Organic fertilizer was applied at a rate of 1 000 kg ha^{-1} of granulated chicken manure (Pure Hen Manure, Acti-Sol Inc., Notre-Dame-du-Bon-Conseil, Canada), which provided identical amounts of N P and K as for plots fertilized with mineral fertilizers. Moreover, compared with mineral fertilizers, organic fertilizer provided calcium (Ca) (70 kg ha^{-1}) and organic matter (710 kg ha^{-1}). Borax (0.7 kg of B ha^{-1}) was also applied in organic fertilized plots. Fertilizers were spread during pruning years on the soil surface at the beginning of June just before plant emergence (Table 2).

TABLE 2: Crop management calendar for the studied sites.

Sites	**1**					**2**			
Year	2016	2017	2018	2019	2020	2017	2018	2019	2020
Mechanical pruning	-	May 15	October 9	-	October 19	October 17	-	October 18 & 21	-
Thermal pruning	November 7	-	November 7 & 8	-	November 9	October 24	-	October 22 & 24	-
Fungicide application	-	July 13	-	July 16	-	-	July 16	-	July 13
Fertilizer application	-	June 13	-	June 6	-	-	June 6	-	June 13

1.3.2 Data collection

1.3.2.1 Agronomic data

Fruits were harvested using a tractor (F3680, Kubota, Osaka, Japan) equipped with a commercial blueberry harvester (Les équipements D.H. Inc., Albanel, QC, Canada). The yields (kg ha^{-1}) of site 1 were measured in 2018 and 2020 while site 2 was harvested in 2019 only. The stem density (number of stems per m^2) and stem height (cm) were measured all years using a 30-cm ruler and a quadrat. In 2017 and 2018, 4 quadrats of 0.25 m^2 (50 x 50 cm) were spatially distributed on a transect crossing each EU diagonally. This sampling method allows a representative sampling to be obtained of the whole EU and to sample the same locations throughout the years. In 2019 and 2020, 3 quadrats (same size and same locations) were used for technical reasons. Weeds and septoria leaf spot rate were also measured within each of the quadrats. The weeds include several species: *Maianthemum canadense, Cornus Canadensis, Carex, Gaultheria procumbens, Melampyrum lineare, Kalmia angustifolia, Comptonia peregrine* and *Apocynum androsaemifolium*. The diseases observed were septoria and valdensian leaf spot, rust, red, sclerotic rot and phomopsis blight. However, only septoria leaf spot was retained since the others were not present enough. All data using quadrats were taken during tip dieback stage, between the last week of July and second week of August.

1.3.2.2 Foliar and fruit analysis

During pruning years, leaf samples were collected during the last week of July during tip-dieback stage (Lafond 2009). The leaf samples were taken from 25 randomly selected blueberry stems. The leaves were dried (55 °C) and reduced to powder before chemical analyses. More specifically, N, P, K, Ca and Mg in leaves were evaluated after wet digestion (sulfuric acid-peroxide-selenious acid) (Isaac and Johnson 1976). N and P concentrations were determined by colorimetry (Lachat Instruments, Quickchem Method 13-107-06-2-E; 15-501-03). K concentrations were determined by flame emission spectrophotometry, whereas Ca and Mg concentrations were determined by atomic absorption spectrophotometry (Perkin Elmer AAnalyst 300, Überlingen, Allemagne) (Hanlon 1998). During harvesting years, the same laboratory procedures were applied to determine fruit nutrient concentrations from a 500g fresh sub-sample for each of the harvested plots.

1.3.3 Statistical analysis

Since we dealt with an unbalanced data set, the statistical models were separated into two categories, data collected during harvesting years and those collected in the pruning years. Results were analyzed using linear mixed model (package *lmerTest*) in R (R-4.1.2, 2021), which estimates the degrees of freedom using Satterthwaite's method (Kuznetsova *et al.* 2017). Blocs (or replicates) and sites were considered as random factors, while treatments (pruning, fungicide and fertilizer) and years were considered as fixed factors. The effect of each treatment has been analysed separately then by interaction between them. This model was chosen since it was the one that was balanced and demonstrated the lowest AIC criterion (Table S1). Some data were logarithmically transformed to improve the normality of their distribution. Honest significant difference (HSD) post-hoc Tukey tests were performed (package *emmeans*) when significant differences were observed in the models.

1.4 Results

During both pruning and harvesting years and when no fungicide was applied, adding mineral or organic fertilizers did not significantly improve stem density (number of stems m^{-2}) (Figure 1a and 1b). However, when fungicide was applied, adding mineral fertilizer significantly increased stem density by about 75 and 95 stems m^{-2} during pruning and harvesting years, respectively (Figure 1a and 1b). Adding organic fertilizer did not significantly improve stem density in any of the management situations. Throughout the years, adding mineral and organic fertilizers increased stem heights by about 4 and 2 cm during pruning years and by about 4 and 2.5 cm during harvesting years (Figure 1c and 1d). Compared to organic fertilizer, mineral fertilizer significantly increased stem heights by about 2 and 1.5 cm during pruning and harvesting years, respectively (Figure 1c and 1d). The type of pruning, mechanical or thermal, did not influence the stems density or height. During pruning year, the average number of stems is 506 stems m^{-2} when thermal pruning and 514 stems m^{-2} when mechanical pruning. The average height of stems is 15.9 cm and 16 cm when thermal pruning and mechanical pruning, respectively. During harvesting year, the average number of stems is 521 stems m^{-2} when thermal pruning and 519 stems m^{-2} when mechanical pruning. The average height of stems is 18.1 cm and 18.3 cm when thermal pruning and mechanical pruning, respectively.

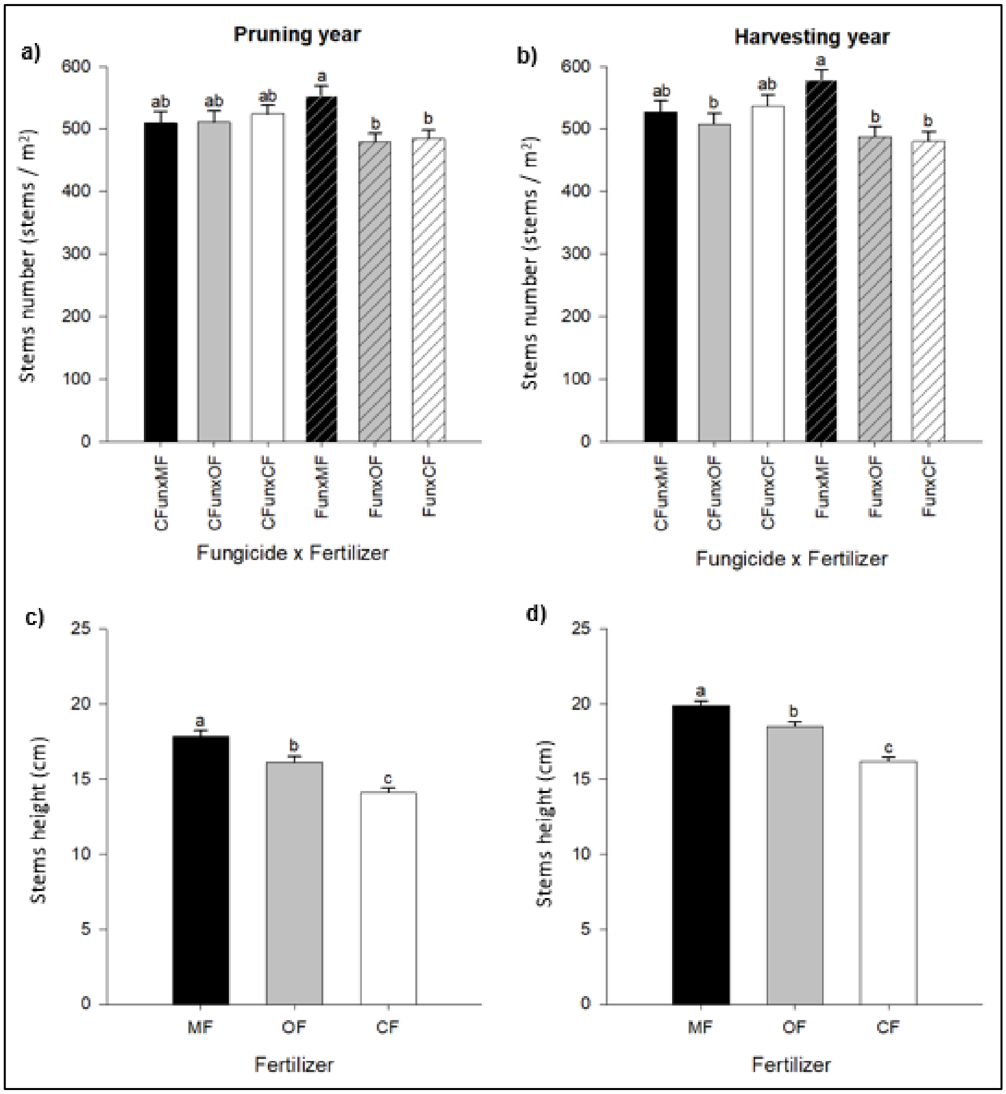

FIGURE 1. **a)** Stems density per m^2 collected in the pruning year by fungicide x fertilizer treatments interaction. **b)** Stem numbers per m^2 collected in the harvesting year by fungicide x fertilizer treatments interaction. **c)** Stem heights collected in the pruning year by fertilizer treatments. **d)** Stem heights collected in the harvesting year by fertilizer treatments. In each figure, error bars represent the standard error from the mean ($n_{pruning}$ = 336 ; $n_{harvesting}$ = 240). Different letters represent significant difference at level α = 0.05. CFun = without fungicide, Fun = with fungicide, MF = mineral fertilizer, OF = organic fertilizer, CF = without fertilizer.

Thermal pruning significantly but minimally decreased the N, P and K foliar concentrations, and slightly improved the Mg fruit concentration (Table 3). Adding fungicide did not significantly influence the leaf or fruit nutrient concentration (Table 3). Compared to the control, adding fertilizers significantly improved N, P and K foliar concentrations (Table 3). More specifically, compared to no fertilizer, organic fertilizer significantly increased N, P and K concentrations by 9.11%, 9.48% and 7.68%, respectively, while mineral fertilizer increased N, P and K concentrations by 18.66%, 21.55% and 19.39% (Table 3). Mineral fertilizer significantly decreased Ca foliar concentrations by 7.35% compared to organic fertilizer and by 10.30% compared to no fertilizer (Table 3). Compared to the control, adding fertilizer (organic or mineral) also significantly decreased Mg foliar concentrations by about 5% (Table 3). In terms of fruits nutrient concentrations, adding mineral fertilizers significantly increased N concentrations by about 3.19% compared to organic fertilizer and by 12.02% compared to no fertilizer (Table 3). Using fertilizer (organic or mineral) also increased fruit P concentrations by about 8% (Table 3). Finally, adding organic fertilizer significantly increased fruit K concentration by 5.80% compared to the control, while mineral fertilizer showed no significant difference (Table 3).

TABLE 3: Foliar and fruit nutrient concentrations (in percentage) between treatments.

Factors		Foliar analysis (Pruning year)					Fruit analysis (Harvesting year)				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
Pruning	M	1.761 (0.021)[a]	0.136 (0.001)[a]	0.580 (0.016)[a]	0.442 (0.009)	0.170 (0.001)	0.524 (0.009)	0.110 (0.001)	0.534 (0.007)	0.141 (0.004)	0.062 (0.001)[b]
	MT	1.720 (0.021)[b]	0.129 (0.002)[b]	0.558 (0.015)[b]	0.439 (0.008)	0.171 (0.002)	0.528 (0.009)	0.108 (0.001)	0.533 (0.006)	0.143 (0.002)	0.063 (0.001)[a]
Fungicide	Fun	1.741 (0.022)	0.128 (0.002)	0.565 (0.019)	0,430 (0.006)	0.169 (0.002)	0.527 (0.011)	0.107 (0.002)	0.529 (0.008)	0.138 (0.004)	0.055 (0.001)
	CFun	1.738 (0.023)	0.132 (0.002)	0.571 (0.019)	0.434 (0.008)	0.170 (0.002)	0.521 (0.012)	0.107 (0.002)	0.533 (0.007)	0.137 (0.003)	0.054 (0.001)
Fertilizer	MF	1.892 (0.018)[a]	0.143 (0.002)[a]	0.624 (0.018)[a]	0.410 (0.000)[b]	0.171 (0.002)[b]	0.548 (0.012)[a]	0.112 (0.001)[a]	0.525 (0.009)[ab]	0.134 (0.004)	0.058 (0.002)
	OF	1.740 (0.016)[b]	0.132 (0.002)[b]	0.557 (0.020)[b]	0.443 (0.000)[a]	0.169 (0.001)[b]	0.530 (0.011)[b]	0.111 (0.003)[a]	0.547 (0.010)[a]	0.141 (0.004)	0.051 (0.001)
	CF	1.591 (0.013)[c]	0.120 (0.001)[c]	0.521 (0.017)[c]	0.448 (0.000)[a]	0.184 (0.002)[a]	0.491 (0.008)[c]	0.103 (0.002)[b]	0.520 (0.007)[b]	0.140 (0.004)	0.052 (0.001)

Numbers in parentheses represent the standard error from the mean (n_{foliar} = 336 ; n_{fruit} = 240). Different letters represent the significant differences obtained according to p-value α = 0.05. M = mechanical pruning, MT = thermal pruning, Fun = with fungicide, CFun = without fungicide, MF = mineral fertilizer, OF = organic fertilizer, CF = without fertilizer. In black, the foliar concentration is within the reference range for nutrient concentrations in wild blueberry leaves while the foliar concentration is above the reference value for maximum nutrient concentrations in green and below the minimum reference value of nutrients in red (Lafond 2009).

When combined with fruit yields, fruit nutrient concentrations allow us to estimate site nutrient exportations. Thermal pruning did not significantly influence the quantity of exported nutrients (Table 4). Compared to the control, adding fungicide significantly increased quantity of exported N, P and K by about 0.120, 0.210 and 0.080 kg ha^{-1}, respectively (Table 4). Compared to the control, adding fertilizer (organic or mineral) significantly increased N, P, K, Ca and Mg exportations by at most 0.663, 0.121, 0.573, 0.138 and 0.059 kg ha^{-1}, respectively (Table 4).

TABLE 4: Quantity of exported nutrients in kg ha^{-1} in the harvested fruit depending on the pruning, fungicide uses and type of fertilizer applied.

Factors		Nutrients exportation (kg ha^{-1})				
		N	P	K	Ca	Mg
Pruning	M	1.220 (0.321)	0.240 (0.066)	1.230 (0.448)	0.332 (0.099)	0.124 (0.032)
	MT	1.240 (0.321)	0.242 (0.066)	1.230 (0.448)	0.327 (0.099)	0.127 (0.032)
Fungicide	Fun	1.290 (0.321)^a	0.252 (0.066)^a	1.270 (0.448)^a	0.338 (0.099)	0.130 (0.032)
	CFun	1.170 (0.320)^b	0.231 (0.066)^b	1.190 (0.448)^b	0.320 (0.099)	0.122 (0.032)
Fertilizer	MF	1.494 (0.323)^a	0.287 (0.066)^a	1.434 (0.445)^a	0.380 (0.100)^a	0.149 (0.032)^a
	OF	1.357 (0.322)^a	0.270 (0.066)^a	1.393 (0.445)^a	0.366 (0.100)^a	0.138 (0.032)^a
	CF	0.831 (0.322)^b	0.166 (0.066)^b	0.861 (0.445)^b	0.242 (0.100)^b	0.090 (0.032)^b

Numbers in parentheses represent the standard error of the mean (n_{fruit} = 240). Different letters represent the significant differences obtained according to p-value α = 0.05. M = mechanical pruning, MT = thermal pruning, Fun = with fungicide, CFun = without fungicide, MF = mineral fertilizer, OF = organic fertilizer, CF = without fertilizer.

Treatments had no significant effect on weed rates, whereas all treatments significantly influenced septoria leaf spot in some ways (Tables S2 and S3). Adding mineral fertilizer significantly decreased septoria leaf spot by about 1% and 2% during pruning and harvesting years, respectively (Figure 2a and 2b). During pruning years, the pruning method did not make any significant difference, except in 2017 when mechanical pruning decreased the septoria leaf spot by 2% compared to thermal pruning (Figure 2c). During harvesting year of 2019 only, thermal pruning reduced septoria leaf spot by about 3% (Figure 2d), whereas pruning method had no significant influence during other harvesting years. For pruning years of 2017 and 2020, adding fungicide decreased septoria leaf spot by 2.5% and 1.5%, respectively. For harvesting years, adding fungicide significantly decreased the overall disease rate by about 1% (Figure 2f). Septoria leaf spot was particularly high in 2017 and low in 2018 (Figure 2e).

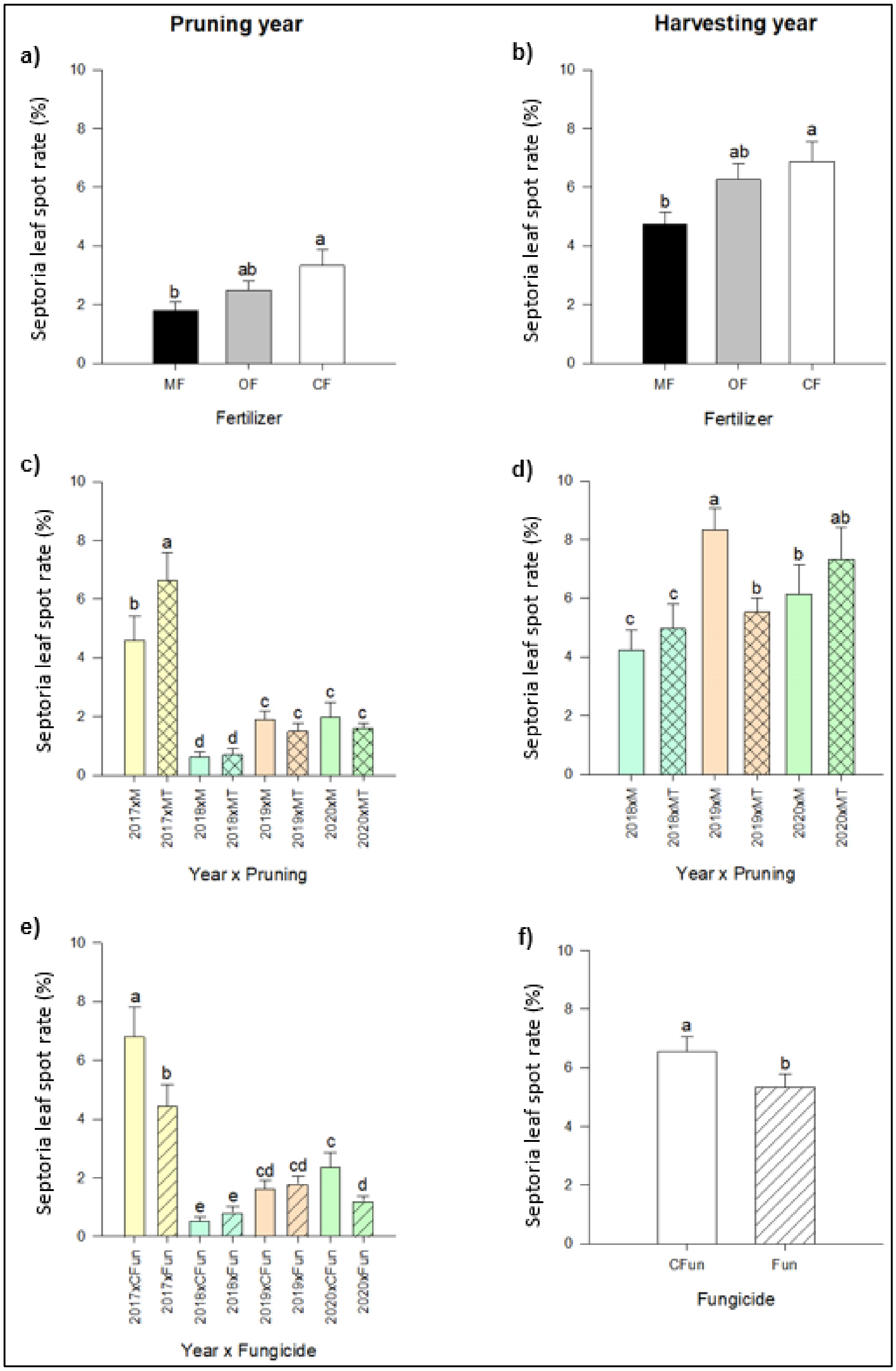

FIGURE 2. a) Septoria leaf spot rate collected in the pruning year by fertilizer treatments. **b)** Septoria leaf spot rate collected in the harvesting year by fertilizer treatments. **c)** Septoria leaf spot rate collected in the pruning year by year x pruning treatments interaction. **d)** Septoria leaf spot rate collected in the harvesting year by year x pruning treatments interaction. **e)** Septoria leaf spot rate collected in the pruning year by year x fungicide treatments interaction. **f)** Septoria leaf spot rate

collected in the harvesting year by fungicide treatments. In each figure, error bars represent the standard error from the mean ($n_{pruning\ year}$ = 336 ; $n_{harversting\ year}$ = 240). Different letters represent significant difference at level α = 0.05. MF = mineral fertilizer, OF = organic fertilizer, CF = without fertilizer, M = mechanical pruning, MT = thermal pruning, CFun = without fungicide, Fun = with fungicide.

Compared to the control, adding fertilizer strongly increased the overall fruit yield by about 852,57 kg ha^{-1} for mineral fertilizers and 690,58 kg ha^{-1} for organic fertilizer (Figure 3a). However, the differences between mineral and organic fertilizer were not significant (Figure 3a). Throughout the years, adding fungicide also increased overall fruit yield by 211,87 kg ha^{-1} (Figure 3b).

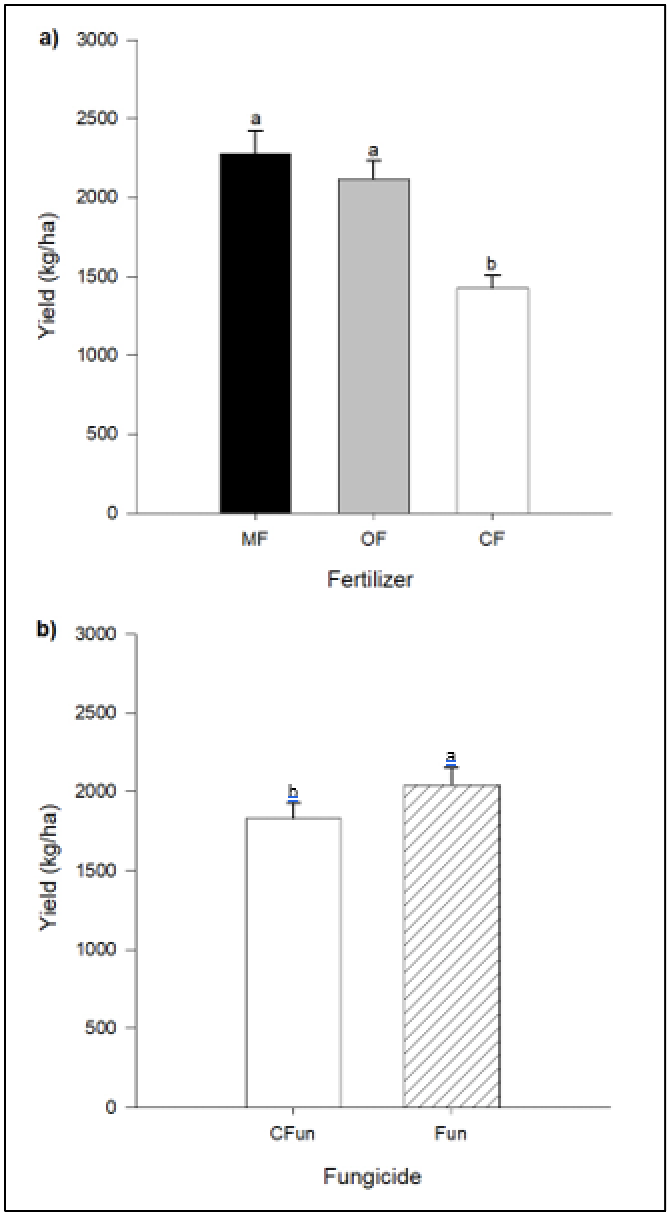

FIGURE 3. Fruit yield according to **a)** fertilizer and **b)** fungicide treatments. Error bars represent the standard error from the mean (n = 240). Different letters represent significant difference at level α = 0.05. MF = mineral fertilizer, OF = organic fertilizer, CF = without fertilizer, CFun = without fungicide, Fun = with fungicide.

1.5 Discussion

1.5.1 Stem density and stem height

During both pruning and harvesting years, adding mineral fertilizer significantly improved stem density, but only when fungicide was also applied (Figures 1a and 1b). The positive effects of fertilization on stem density had already been demonstrated by others (Lafond and Ziadi 2011; Percival and Sanderson 2004), but the role of fungicide remains uncertain. Although there is very little information about how lowbush blueberry rhizomes grow, it seems likely that more photosynthesis (e.g., sugars) produces new stems or underground shoots (Morin 2008). Paré *et al.* (2022) demonstrated that for Vaccinium angustifolium, the most prevalent species in commercial blueberry fields, fungicide applications improved late summer leaf number per stem, which may lead to higher photosynthetic capacity. Indeed, it is possible that an increase of photosynthesis capacity (and in turn carbon reserve) could be responsible for the stem density improvement.

In this experiment, adding organic fertilizer did not significantly improve stem density in any of the tested management situations (Figures 1a and 1b). Lower nitrogen availability of organic fertilizer compared to mineral fertilizer may explain this, since stem density is known to be mainly affected by N fertilization (Percival and Sanderson 2004; Lafond and Ziadi 2011). Nitrogen is also known to positively influence the flower buds number per stem, as well as stem height (Lafond and Ziadi 2011). Several studies conducted in recent years have demonstrated and suggested the ability of Ericaceae species (*Vaccinium spp*.) to assimilate organic forms of nitrogen (Nasholm *et al.* 1998; Lévesque 2019). Indeed, WLB can associate with ericoid mycorrhizae fungi (ERM), which helps to mineralize and assimilate organic forms of nitrogen (e.g., proteins, peptides, amino acids, etc.), such as molecules found in organic fertilizer (Nasholm and Persson 2001; Persson *et al.* 2003; Caspersen *et al.* 2016). Marty et al. (2019b) tested the addition of an organic nitrogen amendment in the form of composted chipped ramial wood and observed no effect on blueberry above ground biomasses. They attributed this absence to the short duration of the experiment. Indeed, the processes allowing plants to assimilate organic nitrogen are slow compared to mineral nitrogen assimilation (Fournier 2020). Therefore, several years are likely necessary to observe significant changes, which is not the case with mineral fertilizer as it has been shown that the nutrients from ammonium sulfate are quickly used by the crop (Lafond and Ziadi 2011; Marty *et al.* 2019b; Eaton *et al.* 2009). It also explains how, in this study, during both pruning and harvesting years, adding fertilizer increased stem height, especially when it comes to mineral fertilizer. As said, fertilizer applications, specifically N, improve the allometric traits of plants, such as their height and overall biomass (Eaton 1994; Lafond and Ziadi 2011).

1.5.2 Foliar analysis

Thermal pruning significantly decreased the N, P and K foliar contents, but to a very small extent (Table 3). Warman (1987) also observed that thermal pruning significantly decreased nitrogen content of WLB leaves and stems. Over time, burning may reduce the soil organic matter (SOM) content (Black 1963), but in this experiment the intensity was not enough to produce ash or to burn SOM (Morvan *et al.* 2022). Since N availability is related to the decomposition of SOM (Dijkstra *et al.* 2009), it remains possible that burning can increase the recalcitrance of SOM (Pellegrini *et al.* 2021) and lower its ability to be decomposed by soil microbial organisms. The same reasons can explain lower leaf P content of burned plots, since the availability of P also depends on the mineralization of SOM (Lafond2014). As burning mainly occurred during fall (Table 2), it is likely that burning increased nutrients mobility and leaching, which depleted soil nutrients during the following cropping years. As soil K is highly mobile and leachable in soils (Neilsen *et al*. 1999), this latter explanation is most likely to explain lower leaf K contents when thermal pruning was used. However, each agricultural system is unique and the effect of burning on the soil remains unclear and variable among studies, so it is difficult to rely on the results obtained in the literature.

Adding fertilizer improved N, P and K foliar concentrations, especially with mineral fertilizer (Table 3). Even though WLB are calcifuge plants with low nutrient requirements, the addition of complete NPK fertilization has been shown to be beneficial for the nutrient content of plant tissues (Korcak 1988; Percival and Sanderson 2004; Lafond 2020). Lafond and Ziadi (2011) even demonstrated that fertilization composed of N alone is sufficient to significantly increase the NPK foliar concentrations, as P and K are dependent and both elements are commonly better absorbed following N additions (Penney and Mc Rae 2000; Percival and Sanderson 2004; Smagula *et al.* 2004). The opposite situation is also true. Generally, adding K alone can significantly increase foliar N contents due to the beneficial impact of K on protein synthesis and photosynthesis (Lafond 2020). Soil-applied N and K also have a synergetic effect on P foliar concentrations throughout WLB-ERM association (Percival and Sanderson 2004). More precisely, soil-applied N and K increase plant carbohydrate and biomass production, which provides more energy (e.g., sugars) to ERM and feeds their P and N soil foraging behaviour (Read and Stribley 1973; Goulart *et al*. 1993; Jeliazkova and Percival 2003). The application of organic fertilizer slightly increased foliar NPK concentrations. However, as mentioned previously, the assimilation of nutriments from organic fertilizer is done partly via the WLB-ERM association, which could possibly make it an indirect and less efficient process, as compared to the assimilation of inorganic nutrients from mineral fertilizers (Fournier 2020).

In the absence of fertilizer, foliar N, P and K concentrations were below the nutrient thresholds as proposed by Lafond (2009) (Table 3), which demonstrates the need to fertilize these sites to ensure adequate crop nutrition. The SOM mineralization potential (Trevett 1972), the climatic conditions for the mineralization of SOM (Hall *et al.* 1979), and the genetical heterogeneity (i.e., clones) throughout blueberry fields (Hepler and Yarborough 1991) are all important factors influencing the nutrient supply and need at a given site, which is the reason why fertilizer requirements are not the same among fields (Lafond and Ziadi 2011).

Adding mineral fertilizer significantly decreased Ca and Mg foliar concentrations, while adding OF significantly decreased Mg foliar concentrations only (Table 3). This could be explained by the soil-applied N since high N fertilization applications could limit Ca and Mg plant assimilations (Lafond and Ziadi 2011; Lafond 2020). Sanderson and Eaton (2004) reported that adding P did not influence

WLB foliar Ca and Mg concentrations. Inversely, according to Santiago and Smagula (2012), high applications of Ca would be beneficial only in the case of N or P deficiencies. However, in this experiment, the Ca foliar concentrations were all above the maximum reference value established for this nutrient, regardless of the treatment that was used (Table 3), which suggests that Ca did not limit plant growth at our sites.

1.5.3 Fruits analysis

Few studies were interested in the concentration of nutrients found in fruits as well as the quantity of nutrients that are exported by harvests. Interestingly, information about fruit nutrient status and nutrient exports can help to assess a crop's minimal fertilization needs to sustain crop yields and soil fertility over the years (Santos *et al.* 2012; Mattar *et al.* 2018). Mineral fertilizer and organic fertilizer significantly increased N and P fruit concentrations, particularly mineral fertilizer (Table 3). For K, only organic fertilizer allowed higher fruit concentration compared to the control and mineral fertilizer. Finally, the Mg fruit concentration was slightly increased by thermal pruning (Table 3).

The significance of fruit nutrient analysis gains importance when combined with fruit yields, which reflects nutrients that are exported from the site. Results clearly show that both fungicide and fertilizer applications significantly increased most nutrient exportations (Table 4). Although the quantity of nutrients exported by harvesting WLB remains low (Eaton and Patriquin 1990), these results demonstrate the importance of applying N, P, K, Ca and Mg, especially when fungicides are used to ensure the replacement of these elements in the soil system.

1.5.4 Septoria leaf spot rate

In this study, adding mineral fertilizer significantly reduced the rate of Septoria leaf spot by approximatively 2 and 3%, since mineral fertilizer helps to keep leaves on the stems until early fall (Pare *et al.* 2022). Percival *et al.* (2003) also suggested that fertilization can reduce water deficit symptoms by increasing, among other things, photosynthesis and water use efficiency, root growth, and foliar nutrient concentrations. These observations have also been made in other crops such as mint and rice (Alsafar and Al-Hassan 2009; Tran *et al.* 2014). Therefore, it is likely that mineral fertilizer decreases the prevalence of Septoria leaf spot simply because it limits the early defoliation of stems, which reduces both the number of leaves on the ground in early fall and disease spore development (Hildebrand *et al.* 2016).

During pruning years, the pruning method did not make any significant difference, except in 2017 when mechanical pruning decreased the disease rate by about 2%. During 2019 harvesting year only, thermal pruning reduced disease by about 3%. Although results from the literature are not consensual, it has been suggested that thermal pruning may significantly control the presence of harmful organisms such as weeds, insects and pathogenic fungi (Black 1963; Warman 1987; Lambert 1990). Burning effectively destroys eggs of the pests and the substrate in which they reproduce and are protected from the winter conditions (Duval 2003). However, Vincent *et al.* (2018) demonstrated that thermal pruning only increases the temperature of the soil very little, from the first cm of depth, which makes the method irrelevant for most organisms. Various studies have also shown that thermal pruning was not able to significantly reduce the presence of certain diseases. Nickerson and MacNeill (1987) found studies that showed no difference in the incidence of red leaf (*Exobasidium vaccinii*) in burned fields. Also, since Septoria spp. spread using spores, it is essential to treat large areas to limit their field expansion (Hildebrand *et al.* 2016). It is possible that burning the entire field would have changed the outcome of this study, but the effects of thermal pruning on the Septoria leaf spot rates are extremely weak, inconsistent and variable. Longer term monitoring is still needed.

Adding fungicide significantly decreased Septoria leaf spot by about 2% during harvesting years and some of the pruning years (2017 and 2020). Low disease reduction is explained by both low disease incidence at this site (<10%) and the fact that fungicide was applied only once during pruning years only. Percival and Dawson (2009) observed that the most effective technique for reducing fungal disease incidence was to apply fungicide during both the pruning and harvesting year. Therefore, another application of fungicide during harvesting years would likely increase treatment efficiency and better reduce the prevalence of the disease. However, since most WLB from Quebec are traded as free-pesticide label during harvesting years, other techniques to better control fungal diseases are still needed.

As mentioned above, the presence of Septoria leaf spot is minimal on this research site, with a disease rate of less than 10%. However, disease rates were highly variable over the years, with higher and lower incidences in 2017 and 2018, respectively (Figure 2e). The moment in which the data were collected plays an important role in these results. Indeed, in 2017, the data were taken from August 14th to 17th. In other years, the data were collected much earlier. In 2018, data were collected from July 19th to 23rd and from August 3rd to 6th in 2019 and in 2020. Since the symptoms of the disease start to become visible in mid-July and progressively increase until the end of the growing season (Ojiambo *et al.* 2006), it is likely that this year-to-year variation was simply and mainly caused by the timing of data collection.

1.5.5 Yield

Adding fertilizer increased yield, especially mineral fertilizer (Figure 3). N-P-K fertilization leads to an improvement of several wild blueberry reproductive plant traits, such as plant density, number of fruit buds and flowers per stem (Fournier 2020). Increasing these traits through fertilization raises fruit yield (Lafond and Ziadi 2011). Also, as said, results from Percival *et al.* (2003) and Alsafar and Al-Hassan (2009) suggested that fertilizer application mitigates the negative effects of water deficit by improving other traits. For other crops such as wheat and rice, it was previously shown that N application increased root dry weight, total root length, root volume and root surface area (Wang and Yamauchi 2006; Fan *et al.* 2010; Gharakand *et al.* 2012). Roots are thinner and root hairs more developed with an increase in N application (Fageria 2010), and these morphological changes in the root system enabled plants to absorb more nutrients and water compared to thicker roots with less fine root hairs. Thus, the nutrient status in the soil, which is improved by fertilizer applications, strongly affects root system development and functions, which allows the plant to produce higher yield and biomass (Tran *et al.* 2014).

Adding fungicide significantly increased wild blueberry fruit yield (Figure 3b), suggesting that fruit yields are negatively impacted by fungal diseases as it has been showed with other *Vaccinium sp.* (Ojiambo *et al.* 2006). Foliar diseases cause reduction in carbohydrate supply; less energy is available for floral buds' formation and development (Percival and Dawson 2009). Floral buds can be linked to fruit yield, but this is not the only factor that can influence yield. Indeed, climatic conditions are also a strong driver of fruit yield, which often explains year to year fruit yield variations (Parent *et al.* 2020). For example, a late spring drought or frost can affect flower buds fruit set, while an early fall frost is directly related to fruit numbers and quality (Deslauriers *et al.* 2021). In a study where disease incidence was very high (around 90%), the use of several fungicides almost doubled yields (Percival and Dawson 2009). In our study, as the presence of leaf diseases was very low, it is likely that the gain in yield cannot be explained solely by a better control of pathogens nor with greater photosynthetic capacity of the treated plants (Percival and Dawson 2009). A study carried out with *Vigna unguiculata* (L.) showed that fungicide increased the antioxidant potential of the plant, thus limiting the negative effects associated with droughts and water deficits (Manivannan *et al.* 2007). And this is not the only study to have made this connection. Numerous reports in the literature pointed out the intimate relationship between antioxidant contents and resistances to environmental stresses (Vranova *et al.* 2002; Bor *et al.* 2003). In addition, Percival and Burnham (2006) demonstrated that the use of fungicide, although it significantly reduced the presence of ERM, prolonged leaf retention as it decreased incidence and severity of leaf blight (Paré *et al.* 2022). They also concluded that prolonged leaf retention combined with foliar pathogen suppression improved flower quality and fruit number, leading to increasing the overall fruit yields (Percival and Burnham 2006).

1.5.6 Best management practices

Thermal pruning did not improve fruit yield, nor any other studied variables. The use of fungicide increased yield by about 200 kg ha^{-1}, decreased the rate of Septoria disease, and increased the number of stems when combined with mineral fertilizer. In addition to this, mineral fertilizer applications increased the stems height and most of the nutrient concentrations in leaves and fruits, reduced the level of Septoria disease and allowed a yield gain of about 800 kg ha^{-1}. Although nutrients from organic fertilizer are more difficult to assimilate, organic fertilizer applications increased the stems height and nutrient concentration in leaves and fruits, which resulted in a fruit yield gain throughout the time by about 700 kg ha^{-1}. Therefore, the best management practices in a conventional system are to apply fungicide in combination with mineral fertilizer after mechanical pruning. Adding fertilizer when fungicide is used is particularly important since more nutrients were exported through fruits after fungicide applications. However, these inputs also generate costs. At the time of writing this paper, the application of Proline and mineral fertilizer at recommended rates costs approximately \$110 ha^{-1} and \$215 ha^{-1}, respectively. However, the price of wild blueberries in Quebec varied between \$0.66 kg^{-1} and \$1.80 kg^{-1} during the last five years, resulting in an average profit of \$815 ha^{-1} (MAPAQ 2020). In an organic management system, the application of organic fertilizer costs about \$900 ha^{-1} and the price of blueberries was \$2.50 kg^{-1} in 2018, resulting in an average profit of \$850 ha^{-1} (MAPAQ 2020). Thermal pruning turned out to be unnecessary and costs more than \$600 ha^{-1} only in fuel (propane). Solutions such as biofungicide for organic production still need to be found and developed. Few studies have been conducted over the last couple of years. It would be interesting to test biofungicide effectiveness, especially in combination with organic fertilizer.

1.6 Conclusion

The main objective of this research was to experiment the impact of these practices on lowbush blueberry yield and other related variables as the yield is unpredictable and can be influenced by agricultural practices chosen by the producer. None of the tested practices significantly influenced weed coverage. Results also demonstrated that thermal pruning is useless, as it did not improve WLB traits and yield. However, this study demonstrated the broad role of fungicide, not only to decrease the disease rate but to improve the growth and the yield of the WLB. This highlights the importance of studying the efficiency of biofungicide to preserve the environment. Finally, results demonstrated the importance of applying NPK fertilizer in combination with fungicide to ensure a sufficient level in the long term. Also, our results demonstrated that thermal pruning seems to bring a short-term change in nutrients uptake by the plant. It would be interesting to take a closer look at this process and assess the role of SOM quality.

CONCLUSION GÉNÉRALE

L'objectif principal de cette recherche était d'expérimenter l'impact de diverses pratiques agricoles sur le rendement du bleuet et d'autres variables connexes telles que le nombre et la hauteur des tiges, la teneur en nutriments des feuilles et des fruits ainsi que le pourcentage de maladies. Le rendement du bleuet nain est imprévisible et peut être influencé par les pratiques agricoles choisies par le producteur. Entre autres, trois principales pratiques ont été étudiées : la fauche (mécanique ou thermique), l'utilisation de fongicides (avec ou sans) et l'utilisation d'engrais (minéral, organique ou aucun). Aucune de ces pratiques n'a influencé l'incidence et la présence des plantes indésirables, raison pour laquelle les résultats n'ont pas été présentés. Toutefois, cette étude a démontré les gains importants associés aux applications de fongicide puisque ceux-ci permettent de diminuer le taux de maladie (*Septoria* sp.), mais également possiblement d'améliorer la capacité photosynthétique des plants. Cela souligne l'importance d'étudier l'efficacité des biofongicides en culture biologique pour préserver l'environnement. Enfin, les résultats ont démontré l'importance d'appliquer l'engrais NPK en combinaison avec un fongicide pour assurer une fertilité adéquate sur le long terme. Finalement, les résultats ont démontré que le brûlage est inutile car cette pratique n'a pas amélioré de façon importante les rendements et les différents traits mesurés. Dans une moindre mesure, nos résultats ont démontré que le brûlage apporte un changement à court terme dans l'absorption des nutriments par la plante. Il serait intéressant d'examiner de plus près ce processus et le rôle que joue la matière organique labile et récalcitrante dans ce phénomène.

BIBLIOGRAPHIE OU LISTE DE RÉFÉRENCES

Alsafar MS and Al-Hassan YM. 2009. Effect of nitrogen and phosphorus fertilizers on growth and oil yield of indigenous mint (*Mentha longifolia* L.). Biotechnology, 8 : 380-384.

Barker WG, Hall IV, Aalders LE and Wood GW. 1964. The lowbush blueberry industry in eastern Canada. Journal of Economic Botany, 357-365.

Bayer CropScience. 2021. Proline 480 SC fungicide. Label, 29 p.

Black WN. 1963. The effect of frequency of rotational burning on blueberry production. Canadian Journal of Plant Science, 43 : 161-165.

Blatt CR, Hall IV, Jensen KIN, Neilson WTA, Hildebrand PD, Nickerson NL, Prange RK, Lister PD, Crozier L et Silbey JD. 1989. La production du bleuet nain. Agriculture et Agroalimentaire Canada, Ottawa, Ontario, Canada, 62 p.

Bor M, Ozdemir F et Turken I. 2003. The effect of salt stress lipid peroxidation and antioxidants in leaves of sugarbeet (*Beta vulgaris* L.) and wild beet (*Beta maritima* L.). Plant Science, 164 : 77-84.

Bouchard AR, Francoeur A et Gagnon R. 1982. Un réseau de station climatique dans les bleuetières. Université du Québec à Chicoutimi, Chicoutimi, 6 p.

Caspersen S, Svensson B, Hakansson T, Winter C, Khalil S et Asp H. 2016. Blueberry - Soil interactions from and organic perspective. Scientia Horticulturae, 208 : 78-91.

Cline WO. 2002. Blueberry bud set and yield following the use of fungicide for leaf spot control in North Carolina. Acta Horticulturae, 574 : 71-74.

Deslauriers A, Garcia L, Charrier G, Buttò V, Pichette A and Pare MC. 2021. Cold acclimation and deacclimation in wild blueberry: direct and indirect influence of environmental factors and non-structural carbohydrates. Agricultural and Forest Meteorology, 301-302.

Dijkstra FA, Bader NE, Johnson DW and Cheng W. 2009. Does accelerated soil organic matter decomposition in the presence of plants increase plant N availability? Soil Biology and Biochemistry, 41(6) : 1080-1087.

Drummond F, Annis S, Smagula JM and Yarborough DE. 2009. Organic production of wild blueberries I. insects and diseases. In IX International Vaccinium Symposium. Int. Soc. Horticultural Science. Edited by K.E. Hummer. Leuven, 1: 275–285.

Duval J. 2003. Production de bleuets biologiques. Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ), 25 p.

Duval J, Grenier S, La France D, Legault C, Rabi L, Ricquart M et Scholtz M. 2003. Guide de transition en agriculture biologique. Fédération d'agriculture biologique du Québec, 26 p.

Eaton LJ. 1994. Long-term effects of herbicide and fertilizers on lowbush blueberry growth and production. Canadian Journal of Plant Science, 74(2) : 341-345.

Eaton LJ et Patriquin DJ. 1990. Fate of labelled fertilizer nitrogen in commercial lowbush blueberry stands. Canadian Journal of Soil Science, 70 : 727-730.

Eaton L, Sanderson K and Fillmore S. 2009. Nova Scotia wild blueberry soil and leaf nutrient ranges. International Journal of Fruit Science, 9 : 46–53.

Fageria NK. 2010. Root growth of upland rice genotypes as influenced by nitrogen fertilization. 19th World Congress of Soil Science, Australia.

Fan JB, Zhang YJ, Turner D, Duan YH, Wang DS et Shen QH. 2010. Root physiological and morphological characteristics of two rice cultivars with different nitrogen-use efficiency. Pedosphere, 20 : 446-455.

Fournier M-P. 2020. Dynamique de la phénologie, de l'allométrie et du rendement des bleuetiers nains sauvages du Québec selon l'espèce et divers traitements agricoles. Mémoire de maîtrise, Université du Québec à Chicoutimi, Chicoutimi, 119 p.

Gagnon S. et Moreau M.E. 2014. La taille de régénération dans les bleuetières. Chapitre 3.7 dans Gagnon S, Robitaille S, Ferland C et Lauzon L. Éditeurs. Guide de production du bleuet sauvage... dans une perspective de développement durable. Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ), 316 p.

Gagnon B, Simard RR, Lalande R et Lafond J. 2003. Improvement of soil properties and fruit yield of native lowbush blueberry by papermill sludge addition. Canadian Journal of Plant Science, 83 : 1-9.

Gharakand JA, Hashemi-maid K, Mosavi SB, Feiziasl V, Jafarzadeh J et Karimi E. 2012. Effects of nitrogen application on dry land wheat roots and shoot. Greener Journal of Agricultural Sciences, 2 : 188-194.

Goulart BL, Schroeder ML, Demchak K, Lynch JP, Clark JR, Darnell RL et Wilcox WF. 1993. Blueberry mycorrhizae: current knowledge and future directions. Acta Horticulturae, 346 : 230-239.

Gomendy V. 1992. Transferts thermiques et modifications physico-chimiques dans les horizons supérieurs du sol lors du passage du feu. Mémoire. Université Nancy, Montpellier, 27 p.

Hall IV. 1957. The tap root in lowbush blueberry. Canadian Journal of Botany, 35 : 933-934.

Hall IV, Aalders LE, Nickerson NL et Vander Kloet SP. 1979. The biological flora of Canada. *Vaccinium angustifolium* Ait., sweet lowbush blueberry. Canadian Field Naturalist, 93 : 415-430.

Hanlon EA. 1998. Elemental determination by atomic absorption spectrophotometry. Dans : Kalra YP éd. Handbook of reference methods for plant analysis. CRC Press LLC, Boca Raton, 157-164.

Hepler PR et Yarborough D. 1991. Natural variability in yield of lowbush blueberry. Horticultural Science, 26 : 245-246.

Hildebrand PD, Renderos WE. Et Delbridge RW. 2016. Diseases of lowbush blueberry and their identification. Agriculture and Agri-Food Canada, Ottawa, 44 p.

Isaac RA et Johnson WC. 1976. Determination of total nitrogen in plan tissue, using a block digestor. Journal of the Association of Official Analytical Chemists, 59 : 98-100.

Ismail A. et Hanson E. 1982. Interaction of method and date of pruning on growth and productivity of the lowbush blueberry. Canadian Journal of Plant Science, 62 : 677-682.

Jeliazkova EA et Percival D. 2003. N and P fertilizers, some growth variable, and mycorrhizae in wild blueberry (*Vaccinium angustifolium*). Acta Horticulturae, 626 : 297-304.

Korcak RF. 1988. Nutrition of blueberries and other calcifuges. Horticultural Reviews, 10 : 183-227.
Kuznetsova A, Brockhoff PB et Christensen RHB. 2017. ImerTest package: Tests in linear mixed effects models. Journal of Statistics Software, 82 : 1-26.

Laberge Pelletier C. 2007. L'environnement des éricacées des forêts de l'Est du Québec. Mémoire de maîtrise, Université Laval, Québec, 99 p.

Lafond J. 2009. Optimum leaf nutrient concentrations of wild lowbush blueberry in Quebec. Canadian Journal of Plant Science, 89 : 341-347.

Lafond J et Ziadi N. 2011. Fertilisation azotée et phosphatée dans la production du bleuet nain sauvage au Québec. Canadian Journal of Plant Science, 91 : 535-544.

Lafond J et Ziadi N. 2013. Biodisponibilité de l'azote et du phosphore dans les sols de bleuetières du Québec. Canadian Journal of Soil Science, 93 : 33-44.

Lafond J. 2014. La fertilisation de la culture du bleuet sauvage. Chapitre 9.2 dans Gagnon S, Robitaille S, Ferland C et Lauzon L. Éditeurs. Guide de production du bleuet sauvage... dans une perspective de développement durable. Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ), 316 p.

Lafond J. 2020. Fertilisation azotée, phosphatée et potassique dans la production du bleuet nain sauvage. Canadian Journal of Soil Science, 100(2) : 99-108.

Lambert DH. 1990. Effects of pruning method on the incidence of mummy berry and other lowbush blueberry diseases. Plant Disease, 74 (3): 199-201.

Lévesque JA. 2019. Compréhension de l'écologie du bleuet nain (*Vaccinium angustifolium* Ait.) cultivé pour améliorer sa production au Saguenay-Lac-Saint-Jean. Mémoire de maîtrise. Université du Québec à Chicoutimi, Chicoutimi, 71 p.

Manivannan P, Abdul Jaleel C, Kishorekmuar A, Sankar B, Somasundaram R, Sridharan R et Panneerselvam R. 2007. Changes in antioxidant metabolism of *Vigna unguiculata* (L.) Walp. by propiconazole under water deficit stress. Colloids and Surfaces B: Biointerfaces, 57 : 69-74.

MAPAQ. 2016. Monographie de l'industrie du bleuet sauvage au Québec. Gouvernement du Québec, Québec, 22 p.

MAPAQ. 2019. Culture du bleuet. Gouvernement du Québec. https://www.mapaq.gouv.qc.ca/fr/Productions/Production/Pages/Culture-du-bleuet.aspx

MAPAQ. 2020. Documents internes. Gouvernement du Québec.

MAPAQ. 2022. Portrait-diagnostic sectoriel de l'industrie du bleuet sauvage au Québec. Gouvernement du Québec, Québec, 28 p.

Marty C, Levesque J-A, Bradley RL, Lafond J et Pare MC. 2019a. Lowbush blueberry fruit yield and growth response to inorganic and organic N-fertilization when competing with two common weed species. Plos one, 14 : e0226619.

Marty C, Levesque J-A, Bradley RL, Lafond J et Pare MC. 2019b. Contrasting impacts of two weed species on lowbush blueberry fertilizer nitrogen uptake in a commercial field. Plos one, 14 : e0215253.

Mattar GS, Cinto de Moraes C, Meletti LMM et Purquerio LFV. 2018. Accumulation and exportation of nutrients by yellow Passion fruit cv. IAC 275. Revista Brasileira de Fruticultura, 40 p.

McIsaac D. 1997. Growing wild lowbush blueberries in Nova Scotia. Consulté le 10 octobre 2018, http://nsac.ca/wildblue/facts/grow.asp

Moreau M.E. 2014. La croissance et le développement du bleuetier. Chapitre 3.1 dans Gagnon S, Robitaille S, Ferland C et Lauzon L. Éditeurs. Guide de production du bleuet sauvage... dans une perspective de développement durable. Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ), 316 p.

Morin C. 2008. Étude morphologique et physiologique du rhizome du bleuet nain : une contribution à l'amélioration de la régie de culture. Mémoire de maîtrise, Université Laval, Québec, 111 p.

Morvan S, Pare MC, Schmitt A, Lafond J and Hijri M. 2022. Limited effect of thermal pruning on wild blueberry crop and its root-associated microbiota. Plant science, 13 : 21 p.

Neilsen GH, Neilsen D and Peryea F. 1999. Response of soil and irrigated fruit trees to fertigation or broadcast application of nitrogen, phosphorus and potassium. HortTechnology, 9(3). 393-402.

Nasholm T et Persson J. 2001. Plant acquisition of organic nitrogen in boreal forests. Physiologia Plantarum, 111 : 419-426.

Nasholm T, Ekblad A, Nordin A, Giesler R, Hogberg M et Hogberg P. 1998. Boreal forest plants take up organic nitrogen. Nature, 392 : 914-916.

Nickerson NL and MacNeill BH. 1987. Studies on the spread of red leaf disease, caused by *Exobasidium vaccinii*, in lowbush blueberries. Canadian Journal of Plant Pathology, 9(4) : 307-310.

Ojiambo PS, Scherm H et Brannen PM. 2006. Septoria leaf spot reduces flower bud set and yield potential of rabbiteye and southern highbush blueberries. Plant Disease, 90 : 51-57.

Paré MC, Fournier MP, Lafond J et Deslauriers A. 2022. How management practices influence vegetative and reproductive plant traits of wild lowbush blueberry species. Canadian Journal of Plant Science, 102 : 1007-1015.

Parent S, Lafond J, Paré MC, Parent LE et Ziadi N. 2020. Conditioning machine learning models to adjust lowbush blueberry crop management to the local agroecosystem. Plants, 9 : 1401.

Pellegrini AFA, Harden J, Georgiou K, Hemes KS, Malhotra A, Connor JN and Jackson RB. 2022. Fire effects on the persistence of soil organic matter and long-term carbon storage. Nature geoscience, 15 : 5-13.

Penney BG et Mc Rae KB. 2000. Herbicidal weed control and crop-year NPK fertilization improves lowbush blueberry (*Vaccinium angustifolium* Ait.) production. Canadian Journal of Plant Science, 80 : 351-361.

Percival D et Sanderson K. 2004. Main and interactive effects of vegetative-year applications of nitrogen, phosphorus, and potassium fertilizers on the wild blueberry. Small Fruits Review, 3 : 105-121.

Percival D et Burnham J. 2006. Impact of the mycorrhizal association and soil-applied nitrogen and phosphorous on the lowbush blueberry. Acta Horticulturae, 715 : 781-788.

Percival D, Janes DE, Stevens DE et Sanderson K. 2003. Impact of multiple fertilizer applications on plant growth, development, and yield of wild lowbush blueberry (*Vaccinium angustifolium* Ait). Acta Horticulturae, 626 : 415-421.

Percival DC et Dawson JK. 2009. Foliar disease impact and possible control strategies in wild blueberry production. Acta Horticulturae, 810 : 345-354.

Persson J, Hogberg P, Ekblad A, Hogberg M, Nordgren A et Nasholm T. 2003. Nitrogen acquisition from inorganic and organic sources by boreal forests plants in the field. Oecologia, 137 : 252-257.

Read DJ et Stribley DP. 1973. Effect of mycorrhizal infection on nitrogen and phosphorus nutrition of ericaceous plants. Nature, 244 : 81-82.

Sanderson K et Eaton LJ. 2004. Gypsum - An alternative to chemical fertilizers in lowbush blueberry production. Small Fruits Review, 3 : 57-71.

Santiago JP et Smagula J. 2012. Gypsum rate evaluation for wild lowbush blueberry (*Vaccinium angustifolium* Ait.) soils. International Journal of Fruit Science, 12 : 23-34.

Santos MR, Sediyama MAN, Moreira MA, Megguer CA et Vidigal SM. 2012. Rendimento, qualidade e absorção de nutrientes pelos frutos de abóbora em função de doses de biofertilizante. Horticultura Brasileira, 30 : 160-167.

Smagula J, Litten W et Loennecker K. 2004. Diammonium phosphate application date affects *Vaccinium angustifolium* Ait. nutrient uptake and yield. Small Fruits Review, 3 : 87-94.

Smagula JM et Ismail AA. 1981. Effects of fertilizer application, preceded by terbacil, on growth, leaf nutrient concentration, and yield of the lowbush blueberry, *Vaccinium angustifolium* Ait. Canadian Journal of Plant Science, 61 : 961-964.

Tran TT, Kano-Nakata M, Takeda M, Menge D, Mitsuya S, Inukai Y et Yamauchi A. 2014. Nitrogen application enhanced the expression of developmental plasticity of root systems triggered by mild drought stress in rice. Plant and Soil, 378 : 139-152.

Trevett MF. 1956. Observation on the decline and rehabilitation of lowbush blueberry fields. Maine agricultural experiment station, Orono, 626 p.

Trevett MF. 1972. The integrated management of lowbush blueberry fields: review and foreast. University of Maine, Orono, 699 p.

Vincent C, Lemoyne P, et Lafond J. 2018. Management of blueberry maggot with high temperatures. Journal of Economic Entomology, 111: 1313-1317.

Vranova E, Inze D et Van Brensegem F. 2002. Signal transduction during oxidative stress. Journal of Experimental Botany, 53 : 1227-1236.

Walker JF, Johnson LC, Simpson NB, Bill M and Jumpponen A. 2010. Application of fungistatics in soil reduces N uptake by an arctic ericoid shrub (*Vaccinium vitis-idaea*). Mycologia, 102: 822–834.

Wang H et Yamauchi A. 2006. Growth and function of roots under abiotic stress soils. Dans : B H éd. Plant-environment interactions. CRC Press, New-York, p. 271-320.

Warman PR. 1987. The effects of pruning, fertilizers, and organic amendments on lowbush blueberry production. Plant and Soil, 101 : 67-72.

Warman PR, Murphy J, Burnham JC et Eaton LJ. 2004. Soil and plant response to MSW compost applications on lowbush blueberry fields in 2000 and 2001. Small Fruit Review, 3 : 19-31.

Wilhelmina K, Ryan DAJ, Duy JC, Prior RL, Ehlenfeldt MK et Vander Kloet SP. 2001. Interspecific variation in anthocyanins, phenolics, and antioxidant capacity among genotypes of highbush and lowbush blueberries (*Vaccinium* Section *cyanococcus* spp.). Agriculture and Agri-Food Canada, 49 : 4761-4767.

Yarborough DE. 1999. Flower primordia development stage with temperature tolerance using irrigation systems for frost protection. University of Maine, Orono, 2 p.

Yarborough DE, Hanchar JJ, Skinner SP et Ismail AA. 1986. Weed response, yield, and economics of hexazinone and nitrogen use in lowbush blueberry production. Weed Science, 34 : 723-729.

ANNEXE 1

TABLE S1: Akaike information criterion for different combinations of models carried out in the first year of harvest with the variable yield.

Years	**Sites**	**Blocs**	**AIC**	**Particularity**
Fix	Fix	Random	13.2	Unbalanced
Fix	Random	Random	15.2	none
Excluded	Fix	Random	93.0	Unbalanced
Excluded	Random	Random	76.1	none

.

ANNEXE 2

TABLE S2: Mixed model with test of effect on plant traits measured at pruning year. The results include F statistic and p-value (F (p-value)). p-value obtained according to α = 0.05: bold font was significant in the main and pairwise model.

		Agronomic data		Foliar analysis					Crop pest	
Factor	**df**	**Stems density**	**Stem height**	**N**	**P**	**K**	**Ca**	**Mg**	**Weed rate**	**Septoria leaf spot rate**
Transformation		none	none	none	none	Log(X)	Log(X)	none	Log(X+1)	Log(X+1)
Year (Yr)	3	**8.03 (<0.01)**	**167.27 (0.01)**	**124.43 (<0.01)**	**88.44 (<0.01)**	**308.22 (<0.01)**	**24.92 (<0.01)**	**22.72 (<0.01)**	**6.63 (<0.01)**	**81.35 (<0.01)**
Pruning (Pr)	1	1.42 (0.24)	1.12 (0.29)	**10.28 (<0.01)**	**5.01 (0.03)**	**4.91 (0.03)**	2.60 (0.11)	2.58 (0.11)	0.48 (0.49)	0.67 (0.41)
Fungicide (Fu)	1	0.36 (0.55)	1.51 (0.22)	0.07 (0.79)	0.65 (0.42)	0.80 (0.37)	0.21 (0.65)	0.03 (0.86)	2.39 (0.12)	**4.87 (0.03)**
Fertilizer (Fe)	2	**4.17 (0.02)**	**71.74 (<0.01)**	**195.90 (<0.01)**	**123.92 (<0.01)**	**70.60 (<0.01)**	**15.41 (<0.01)**	**10.89 (<0.01)**	1.52 (0.22)	**4.51 (0.01)**
Yr x Pr	3	1.19 (0.31)	2.69 (0.05)	2.11 (0.09)	2.21 (0.09)	0.13 (0.94)	2.08 (0.10)	0.36 (0.79)	0.56 (0.64)	**3.02 (0.03)**
Yr x Fu	3	0.36 (0.79)	1.06 (0.37)	1.98 (0.12)	1.80 (0.15)	0.21 (0.89)	1.03 (0.38)	0.09 (0.96)	0.54 (0.65)	**4.52 (<0.01)**
Pr x Fu	1	0.70 (0.40)	0.00 (0.97)	1.35 (0.25)	0.39 (0.53)	0.07 (0.80)	2.18 (0.14)	1.12 (0.29)	0.05 (0.82)	1.49 (0.22)
Yr x Fe	6	1.19 (0.31)	1.53 (0.17)	**2.79 (0.01)**	**5.89 (<0.01)**	1.55 (0.16)	**3.42 (<0.01)**	0.55 (0.77)	0.21 (0.97)	1.19 (0.31)
Pr x Fe	2	0.90 (0.41)	0.09 (0.91)	0.20 (0.82)	1.21 (0.30)	0.17 (0.84)	0.60 (0.55)	1.46 (0.24)	0.93 (0.40)	0.77 (0.47)
Fu x Fe	2	**7.24 (<0.01)**	1.29 (0.28)	1.37 (0.26)	0.46 (0.63)	0.12 (0.89)	0.39 (0.67)	2.02 (0.13)	0.24 (0.79)	0.06 (0.94)
Yr x Pr x Fu	3	1.29 (0.28)	0.09 (0.91)	0.76 (0.52)	2.20 (0.09)	0.44 (0.73)	1.54 (0.21)	0.89 (0.45)	0.37 (0.77)	1.95 (0.12)
Yr x Pr x Fe	6	0.48 (0.82)	0.56 (0.76)	0.45 (0.85)	0.79 (0.58)	0.27 (0.95)	0.90 (0.50)	0.49 (0.81)	0.26 (0.96)	0.60 (0.73)
Yr x Fu x Fe	6	0.92 (0.48)	0.45 (0.84)	1.31 (0.25)	1.03 (0.40)	0.22 (0.97)	0.46 (0.84)	0.65 (0.69)	0.65 (0.69)	0.52 (0.79)
Pr x Fu x Fe	2	0.04 (0.96)	1.10 (0.33)	0.17 (0.84)	0.01 (0.99)	0.14 (0.876)	1.00 (0.37)	0.51 (0.60)	0.39 (0.68)	0.31 (0.73)
Yr x Pr x Fu x Fe	6	0.08 (0.99)	0.46 (0.84)	0.33 (0.92)	0.47 (0.83)	0.70 (0.65)	0.74 (0.62)	0.73 (0.62)	0.20 (0.98)	0.12 (0.99)

df = degree of freedom.

ANNEXE 3

TABLE S3: Mixed model with test of effect on plant traits measured at harvesting year. The results include F statistic and p-value (F (p-value)). p-value obtained according to α = 0.05: bold font was significant in the main and pairwise model.

		Agronomic data			Fruit analysis					Crop pest	
Factor	**df**	**Yield**	**Stems density**	**Stem height**	**N**	**P**	**K**	**Ca**	**Mg**	**Weed rate**	**Septoria leaf spot rate**
Transformation										Log(X+1)	Log(X+1)
Year (Yr)	2	**58.86 (<0.01)**	2.59 (0.28)	**14.92 (<0.01)**	**237.22 (<0.01)**	**29.44 (0.03)**	**33.04 (<0.01)**	**11.58 (<0.01)**	0.53 (0.59)	1.10 (0.48)	**9.05 (<0.01)**
Pruning (Pr)	1	0.20 (0.65)	0.00 (0.95)	0.88 (0.35)	0.24 (0.62)	1.26 (0.26)	0.57 (0.45)	1.67 (0.20)	**6.40 (0.01)**	0.80 (0.37)	0.02 (0.89)
Fungicide (Fu)	1	**17.09 (<0.01)**	0.28 (0.60)	0.94 (0.33)	0.52 (0.47)	0.03 (0.86)	0.26 (0.61)	0.07 (0.79)	1.86 (0.17)	1.45 (0.23)	**5.43 (0.02)**
Fertilizer (Fe)	2	**16.73 (<0.01)**	**8.72 (<0.01)**	**61.01 (<0.01)**	**41.71 (<0.01)**	**13.74 (<0.01)**	**5.20 (0.01)**	1.82 (0.16)	0.53 (0.59)	1.41 (0.25)	**4.36 (0.01)**
Yr x Pr	2	1.39 (0.25)	1.14 (0.32)	0.65 (0.52)	0.90 (0.41)	0.77 (0.46)	1.73 (0.18)	2.62 (0.08)	**3.19 (0.04)**	1.66 (0.19)	**3.39 (0.04)**
Yr x Fu	2	1.01 (0.37)	0.08 (0.93)	1.22 (0.30)	1.38 (0.24)	0.08 (0.78)	0.30 (0.58)	0.00 (0.94)	0.18 (0.67)	0.16 (0.85)	0.59 (0.56)
Pr x Fu	1	1.40 (0.24)	0.02 (0.89)	0.09 (0.76)	0.78 (0.38)	0.17 (0.68)	0.36 (0.55)	0.13 (0.72)	0.06 (0.81)	1.13 (0.29)	1.52 (0.22)
Yr x Fe	4	1.21 (0.31)	1.57 (0.18)	0.38 (0.82)	2.07 (0.13)	0.08 (0.92)	0.11 (0.90)	0.08 (0.92)	0.16 (0.85)	0.51 (0.73)	0.95 (0.44)
Pr x Fe	2	0.29 (0.75)	0.60 (0.18)	1.32 (0.27)	1.68 (0.19)	0.17 (0.84)	0.10 (0.91)	0.05 (0.95)	0.38 (0.69)	3.05 (0.05)	1.11 (0.33)
Fu x Fe	2	1.37 (0.26)	**6.74 (<0.01)**	0.05 (0.95)	0.66 (0.52)	0.07 (0.93)	0.47 (0.63)	0.58 (0.56)	1.18 (0.31)	1.80 (0.17)	0.17 (0.84)
Yr x Pr x Fu	2	0.68 (0.51)	2.61 (0.08)	0.01 (0.99)	1.22 (0.30)	1.80 (0.17)	0.04 (0.96)	0.47 (0.62)	0.22 (0.80)	2.13 (0.12)	0.47 (0.63)
Yr x Pr x Fe	4	0.25 (0.91)	0.63 (0.64)	0.42 (0.79)	0.19 (0.95)	0.33 (0.86)	0.17 (0.95)	0.42 (0.79)	0.48 (0.75)	0.68 (0.60)	0.49 (0.75)
Yr x Fu x Fe	4	0.78 (0.54)	0.70 (0.59)	0.69 (0.60)	0.74 (0.57)	0.67 (0.61)	0.16 (0.96)	0.03 (1.00)	0.29 (0.88)	0.52 (0.72)	0.33 (0.86)
Pr x Fu x Fe	2	1.63 (0.20)	3.01 (0.05)	0.99 (0.37)	1.59 (0.21)	0.32 (0.73)	0.48 (0.62)	0.10 (0.90)	0.93 (0.40)	0.03 (0.97)	0.64 (0.53)
Yr x Pr x Fu x Fe	4	0.36 (0.84)	1.12 (0.35)	2.11 (0.08)	1.29 (0.27)	0.34 (0.85)	0.76 (0.55)	0.64 (0.63)	0.62 (0.65)	0.27 (0.90)	0.40 (0.81)

df = degree of freedom