Detection of management practices and cropping phases in wild lowbush blueberry fields using multispectral UAV data

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Abstract

NDVI and NDRE are vegetation indices commonly used in agriculture to provide information on crop's growth and health. Here, we investigated the sensitivity of both indices to management practices in lowbush blueberry fields. Images of the experimental plots were collected with a multispectral camera installed on an Unmanned Aerial Vehicle (UAV). Both NDVI and NDRE values were significantly higher in fertilized plots than in controls (0.88 ± 0.03 vs. 0.79 ± 0.03 for NDVI, and 0.37 ± 0.01 vs. 0.33 ± 0.01 for NDRE) due to fertilization effect on vegetative growth. The increase was higher under mineral than organic fertilization during the two first phases of the cropping system (by ~0.3 and ~0.2 for NDVI and NDRE, respectively). NDRE was not affected by thermal pruning and fungicide application but was negatively correlated with Septoria infection level. NDVI was more strongly correlated with stem length than NDRE, but unlike NDRE, NDVI was not impacted by the development of reproductive shoots during the harvest phases. Overall, the results indicate that although both index values are correlated, their sensitivity to changes in canopy characteristics differs depending on the cropping phase. Further research must be conducted to relate these indices to blueberry's nutrient status.

Keywords: NDVI; NDRE; UAV; lowbush blueberry; multispectral images; fertilization; Septoria.

Résumé

Les indices de végétation NDVI et NDRE sont couramment utilisés en agriculture pour fournir des informations sur la croissance et la santé des cultures. Le but de cette étude était d'étudier la sensibilité de ces deux indices aux pratiques culturales dans les champs de bleuets nains. Des images des parcelles expérimentales ont été collectées à l’aide d’une caméra multispectrale installée sur un véhicule aérien sans pilote (UAV). L'application d'engrais a amélioré le NDVI et le NDRE par rapport aux témoins (0.88 ± 0.03 contre 0.79 ± 0.03 pour le NDVI, et 0.37 ± 0.01 contre 0.33 ± 0.01 pour le NDRE) en raison de l’impact du fertilisant sur la croissance végétative du bleuet. Les valeurs de NDRE n’ont pas été affectées par la taille thermique et l'application de fongicides, mais étaient corrélées négativement au niveau de contamination par Septoria. Le NDVI était plus fortement corrélé à la longueur des tiges que le NDRE, mais contrairement à ce dernier, le NDVI n’a pas été affecté par le développement de pousses reproductrices pendant les phases de récolte. Dans l'ensemble, les résultats indiquent que malgré une bonne corrélation entre les deux indices, leur sensibilité aux changements des caractéristiques de la canopée diffère selon la phase de culture. D’autres études doivent être conduites pour tenter de relier ces deux indices au statut nutritif du bleuet nain.

Introduction

Wild lowbush blueberry (*Vaccinium angustifolium* Aiton) is a perennial ericaceous shrub species native to eastern North America and grown for its fruits, especially in Quebec, Maine, and the Canadian Atlantic provinces (Hall et al., 1979). Quebec's commercial production expands over more than 35,000 ha and represents about the third of the Canadian production (MAPAQ, 2016). Fruits are produced generally through a 2-year crop cycle, including a near ground level pruning in the first year (sprout phase) to stimulate new shoot production, followed by a fruit production and harvest the second year and sometimes the third year (harvest or crop phase) (Gagnon et al., 2020; Yarborough, 2012).

Lowbush blueberry is mostly grown on acidic soils with typical low N and P availability. Consequently lowbush blueberry growth and fruit yield are significantly improved by fertilization (Lafond and Ziadi, 2013, 2011; Percival and Sanderson, 2004; Yarborough, 2004). However, the benefits of fertilization markedly depends on the fertilizer type (Marty et al., 2019a; Percival and Sanderson, 2004; Warman, 1987), the time of its application (Sanderson et al., 2008) as well as weed density (Marty et al., 2019b). Although both mineral and organic fertilizers have generally a beneficial effect on soil fertility, growth, stem density and foliar nutrient content, the effect on fruit yield is not always significant (Warman, 1987; Warman et al., 2009) in part due to the presence of weeds which actively compete for mineral fertilizer acquisition and thus impede growth and fruit production (Marty et al., 2019a, 2019b; Penney and McRae, 2000). The application of herbicides can therefore improve yields and the efficacy of the fertilization treatment (Eaton, 1994; Lapointe and Rochefort, 2001).

Lowbush blueberry yield is also affected by several diseases, among which Septoria leaf spots and stems canker (Hildebrand et al., 2016). This disease is caused by the ascomycete fungi *Septoria sp.* and affects several blueberry species (Alfieri, 1991; Hildebrand et al., 2010; Kinsman, 1993; Ojiambo and Scherm, 2005). This disease causes chlorosis which reduces photosynthetic rate (Roloff et al., 2004), increases defoliation and impacts bud set (Ojiambo et al., 2006; Ojiambo and Scherm, 2004). These pathogens can cause serious defoliation during the sprout and harvesting phases and impact fruit yields (Ali et al., 2021). The disease develops during both the sprout and the harvesting phases of the cropping cycle. Fungicide application or pruning by burning reduces disease pressure in the year following the sprout phase (Kinsman, 1993).

Remote sensing is increasingly used in agriculture to assess crop yields and health (Pallottino et al., 2019; Xue and Su, 2017). Recent advances in unmanned aerial vehicles (UAVs) have opened new perspectives in remote sensing research. With spatial resolution as low as a few centimetres, there has been a rapid increase of drone-related applications in precision agriculture, where farmers and scientists have established a unifying goal of improving crop status and productivity (Salami et al., 2014). The UAVs equipped with multi-spectral sensors with higher spatial resolution information compared to satellites images are used to assess the impact of management practices on crop health and yield at fine scale (Jorge et al., 2019). UAV cameras with visible and near-infrared (NIR) bands have been proven to be beneficial for crop monitoring, such as identifying crop diseases and infestations using various vegetation indices (Maslekar et al., 2020). Recent studies were conducted using UAV-derived vegetation indices to study the impact of structural parameters of agricultural crops, crop yield monitoring and detection of irrigation inhomogeneities (Jorge et al., 2019; Milas et al., 2018; Raeva et al., 2019). Overall, these studies showed that normalized difference red edge index (NDRE) (Gitelson and Merzlyak, 1994) performed better compared to widely used Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) and other soil indices by showing higher correlation with canopy chlorophyl of crop leaf. However, both indices have been used in crops such as soybean, fodder (Boiarskii and Hasegawa, 2019), wheat (Bonfil, 2017) or in olive groves and vineyards (Jorge et al., 2019). Some of these researches have highlighted the complementarity and the potential of these indices for inhomogeneities detection in the field and for helping farmers to optimize fertilization (Boiarskii and Hasegawa, 2019; Jorge et al., 2019). Other studies also showed that NDRE was better correlated with the physiological state of plants, yields better sensitivity to Leaf Area Index (LAI) and chlorophyll content, and is less sensitive to the spectral noise caused by soil background and atmospheric components (Baret et al., 1992; Boiarskii and Hasegawa, 2019; Pallottino et al., 2019). Plants increase the reflection coefficient between the red and NIR regions, resulting in a sharp rise in the red-edge band reflection coefficient. This red-edge zone delineates the boundary between red-band chlorophyll absorption and NIR-band scattering owing to leaf interior structure (Filella and Penuelas, 1994; Pinar and Curran, 1996). The red-edge position is extremely susceptible to changes in vegetation qualities since it is a transition region. This red-edge reflectance leads to the creation of a new vegetation index, the NDRE, which has been shown in numerous studies to be superior to the NDVI in terms of understanding photosynthetic activity transitions. In fact, NDRE shows higher sensitivity to plant nitrogen status and change in vegetation properties (Maccioni et al., 2001) whereas NDVI can reach saturation in dense vegetation canopies (Gu et al., 2013).

However, there is limited reporting of the practical use of UAV-based NDRE and NDVI in selection and yield prediction for blueberry in North America. Blueberry fields generally spread over large surface areas and the survey of inhomogeneities in plant growth and health can be cumbersome for the producers. Localization of spots requiring additional fertilization or fungicide treatment could be facilitated by the use of vegetation indices such as NDVI and NDRE. Only a few studies have used NDVI to survey growth and health status (Barai et al., 2021; Ribera-Fonseca et al., 2019) or changes of phenological stages (Forsström et al., 2019) and growth stages of fruits (Zhao and Li, 2021) in blueberry fields. Although Forsström et al. (2019) recently used the red-edge inflection point (REIP2) to detect changes in blueberry phenological changes, the efficacy of the red-edge band-based index NDRE to assess the growth, the nutritional status and the phenological stages has never been assessed for this crop.

In this study, we computed NDVI and NDRE from images collected with a multispectral camera installed on a UAV in an experimental lowbush blueberry field in central Quebec, Canada. Our goal was to assess whether these indices can provide specific information on the growth, health and canopy physiognomy of the crop at different stages of the cropping cycle. More specifically, we investigated the impact of various management practices (pruning, fungicide application and fertilization) on NDVI and NDRE values. We also assessed whether changes in crop characteristics (e.g., stem length, stem density) as well as Septoria contamination level among plots can be detected by NDVI and NDRE values obtained from multispectral images. This aimed to identify which of NDVI and NDRE shows higher sensitivity and is more suitable in the context of blueberry production.

Materials and Methods

Experimental site and set up

The study was conducted at the Bleuetière d'Enseignement et de Recherche in Normandin (QC), Canada (48°49′35″ N; 72°39′35″ W; Fig 1a). The region is the northernmost district in the Province characterized by crop production. The experimental design was established in 2016. The site included three distinct parts corresponding to the three phases of lowbush blueberry's production cycle: the sprout phase (i.e., 2019 cohort), the first harvest year (i.e., 2018 cohort; H1) and the second harvest year (i.e., 2017 cohort; H2) (Fig 1b). The experimental set up included four blocks (replicates) combining the three cropping phases with the experimental treatments. Each block was split into 48 experimental units of 15 x 22 m (330 m^2) separated by a border of three to five meters (total of 4 × 48 = 192 experimental units over a surface area of about nine hectares). In each block, experimental units received one of 12 different treatments according to a split-plot design (Fig 2). Treatments included two pruning types, two fungicide application levels and three fertilization types (see below).

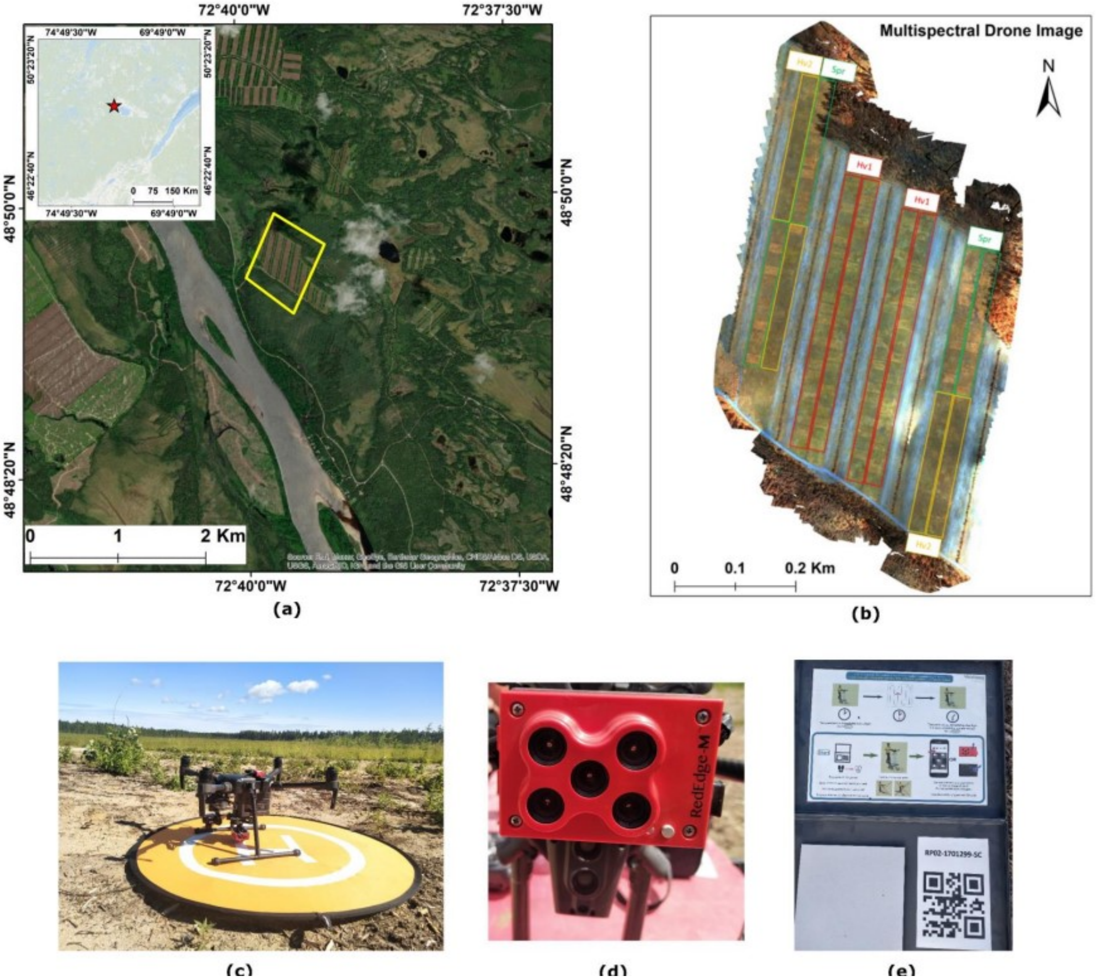

Figure 1. (a) Location of the experimental blueberry fields, (b) multispectral UAV imagery overlaid with cropping phases (Spr: sprout phase; Hv1: first harvest year; Hv2: second harvest year), (c) Image acquisition by an UAV-Camera system: M 210, DJI quadcopter, (d) RedEdge camera (middle-right), and (e) calibration reflectance panel.

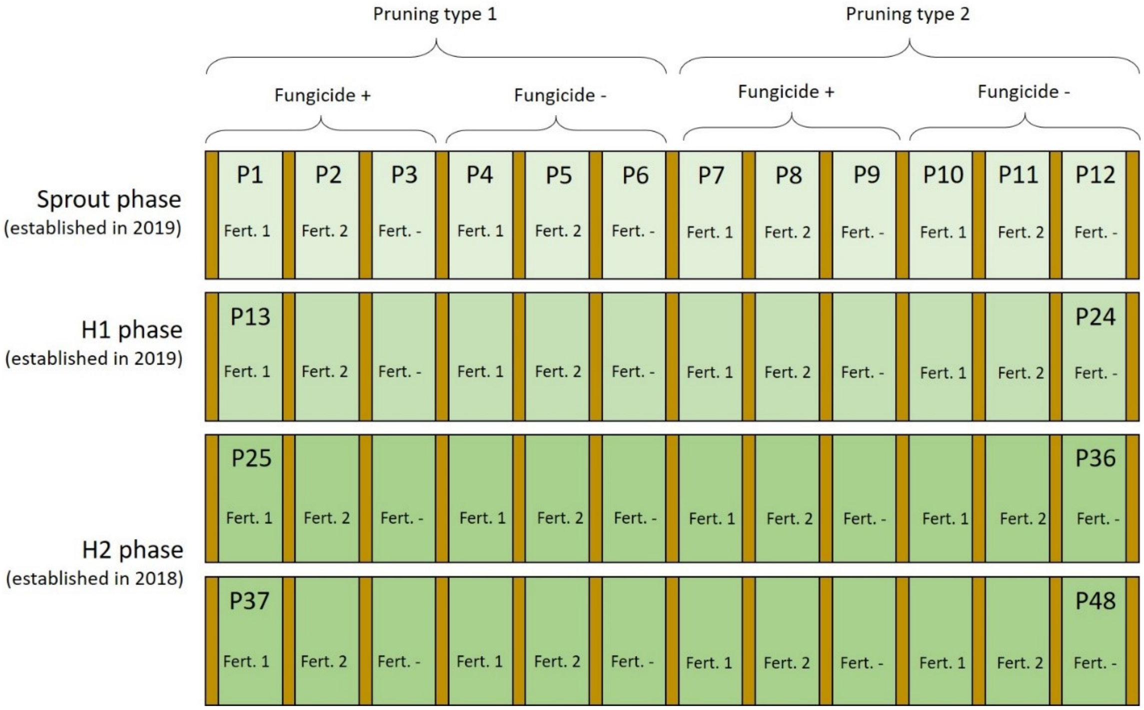

Figure 2. Schematic representation of one experimental block. Each block includes 48 experimental units combining each of the three cropping phases (Sprout phase [12 units], H1 [12 units] and H2 phases [24 units]) with the three treatments (1- Fungicide application [- or +]; 2- Pruning type [1 or 2]; and 3- Fertilization type [1, 2 or -]). Experimental units are separated from each other by an uncultivated band (brown band on the figure).

Pruning types

Mechanical pruning was applied to all plots using a blueberry mower (model TB-1072, JR Tardif, Rivière-du-Loup, Canada). This mechanical pruning was combined with thermal pruning on half of the plots. Thermal pruning was applied with a high-pressure home-made propane burner towed by a tractor to assess the impact on growth and Septoria infection rate. The home-made burner includes four propane burners placed 10 cm above the soil. Burners consumed together about 140 kg of propane ha^{-1} (pressure of 15 psi and tractor speed of 1.5 km hr^{-1}). Pruning was carried out during the plant dormancy, either late in the fall (after the first frosts) or in the early spring.

Fungicide treatment

The application of a broad-range fungicide (Proline©) took place once per year in mid-summer of the sprout year. 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.

Fertilization treatments

Two fertilization treatments were applied (mineral and organic fertilization), and compared to a control (no fertilization). Mineral fertilizer included nitrogen (N) (50 kg of N ha^{-1} as ammonium sulfate), phosphorus (P) (30 kg of P_2O_5 ha^{-1} as super triple phosphate), 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 included identical amounts of N-P-K (50 kg of N ha^{-1}) in 1 000 kg ha^{-1} of granulated chicken manure (Pure Hen Manure, Acti-Sol Inc., Notre-Dame-du-Bon-Conseil, Canada), P (30 kg of P_2O_5 ha^{-1}), K (20 kg of K_2O ha^{-1}), calcium (Ca) (70 kg ha^{-1}), B (0.7 kg of B ha^{-1} as borate) and organic matter (710 kg ha^{-1}). Fertilizers were spread at soil surface before plant emergence in early June.

UAV data collection and spectral indices computation

Three UAV flight missions were executed on the third week of July 2019, between 09:30 and 13:30, after blueberry flowering period and a few weeks before harvesting. We used a quadcopter (M210, DJI) as an unmanned aerial vehicle (UAV) platform (Fig 1c), equipped with the high spatial resolution Micasense RedEdge-M (MicaSense, Seattle, WA, USA) multispectral camera (Fig 1d) and a data logger (Fig 1e) carrying a payload of 150 g. This multispectral camera captures images in six spectral ranges simultaneously, including spectral bands in blue (530-570 nm wavelength), green (530-570 nm), red (640-680 nm), red-edge (730-740 nm wavelength) and near-infrared (NIR : 770-810 nm) (Mamaghani and Salvaggio, 2019) (Table 1). The multispectral camera has a ground sampling distance (GSD) of 8.2 cm per pixel with a lens focal length of 5.5 mm and a horizontal field of view (HFOV) 47.2°. Images were collected at an altitude of 120 m above the ground level with 90% forward and side overlap at one capture per second speed.

Table 1. Specification of sensors used in the present study.

Parameters	**Values**
Flight altitude	120 m
Spectral Bands	Blue (530-570 nm), Green (530-570 nm), Red (640-680 nm), Red-edge (730-740 nm) and NIR (770-810 nm)
HFOV	47.2°
Focal length	5.5 m
GSD	8.2 cm/pixel (per band)
Area covered	32.11 ha
Image resolution of each band	1280×960 pixels

Radiometric resolution	16-bit
Number of Calibrated Images	12633

To obtain calibrated and georeferenced reflectance data, several image pre-processing procedures were conducted in Pix4Dmapper software (Version 4.3.33) (Pix4D SA, Lausanne, Switzerland) for each spectral band (Su et al., 2018). Initial processing steps included image matching key point computation, ortho-mosaic construction, and reflectance calibration for each band using calibration panel images. The first step was the initial processing, which includes image key point extraction. That is, UAV images were matched based on identical ground control points, and then automatic aerial triangulation and bundle block adjustments were computed. The second processing stage involved the creation of a point cloud densification and the generation of Digital Surface Model (DSM). Making a DSM is essential for creating orthophoto mosaics as well as reflectance maps. The ortho-mosaicked images that result have high resolutions and are consistent across consecutive images. As a result, they ensure that the subsequent analysis performs optimally. The final steps involved generation of reflectance map to show the real reflectance of each object on the ground. This was implemented by computing the reflectance map using the DSM and calibrated reflectance panel provided by Pix4D (2017). After that, the final image was exported (five different images, one for each spectral band) to a TIFF format. In total, 12633 images were calibrated and geolocated using 7882 two dimensional matches per calibrated image. NDVI and NDRE were extracted from multispectral images for each research plots (15×22 m; n=192). NDVI is defined as the ratio of $(R_{NIR} - R_{RED})/(R_{NIR} + R_{RED})$ whereas NDRE is the ratio of

$(R_{NIR} – R_{RE})/(R_{NIR} + R_{RE})$, with R_{NIR}, R_{RED} and R_{RE} represents the reflectance in the NIR, red and red-edge spectral bands, respectively.

Field measurements

Stem density (number of stems. m^{-2}) and length (cm) as well as Septoria contamination severity (proportion of contaminated leaves per stem) were measured in three 0.25 m^2-quadrats (50 × 50 cm) in each of the 192 experimental units (sprout, H1 and H2 plots). Measurements were taken between the last week of July and the first week of August during blueberry lignification.

Statistical analyses

A mixed model ANOVA (Harrison et al., 2018) was applied to NDVI, NDRE, stem length, stem density and Septoria contamination severity level with cropping phase, pruning type, fertilization and fungicide treatments as fixed effects and block as random effect. We used the lmerTest package in R, which uses the REML method and the Satterthwaite's degrees of freedom method (Kuznetsova et al., 2017). The level of significance for the analysis was $\alpha = 0.05$. A full description of the method is shown in the supplementary materials.

An ANCOVA was performed to assess the effect of the cropping phase on the relationship between NDVI and NDRE. Pearson correlation analyses were performed to test the individual relationships between NDVI or NDRE on the one hand and canopy characteristics measured in the field (stem length, stem density and Septoria contamination severity) on the other hand. This aimed at identifying which index better reflects these canopy characteristics.

One-way ANOVAs were also performed to compare stem length, stem density and Septoria contamination severity between factor levels for the different treatments and cropping phases. Normality and homogeneity of the variances were verified with a Shapiro-Wilk test and a Bartlett test, respectively. All statistics were performed using R (R core Team, 2019) and SPSS, version 26 (IBM Corp., 2012).

Results

Vegetation indices and cropping phases

Both NDVI and NDRE varied significantly between the cropping phases (Table 2). On average, NDVI was higher during the sprout phase (0.84 ± 0.05) than during the harvest phases (0.82 ± 0.04 and 0.81 ± 0.03 for H1 and H2, respectively) but the difference was statistically significant only in fertilized plots (Figs 3a). NDVI was not significantly different ($P > 0.05$) among cropping phases in unfertilized plots, but was higher during the first than during the second harvest year under mineral fertilization whereas the difference between the two harvest phases was not significant under organic fertilization (Fig 3a). In contrast, NDRE significantly varied among all cropping phases in the three fertilization treatments (Fig 3b). NDRE was significantly lower during the harvest phases (especially the first year) than during the sprout phase (0.28 ± 0.02 and 0.32 ± 0.01 vs. 0.35 ± 0.02).

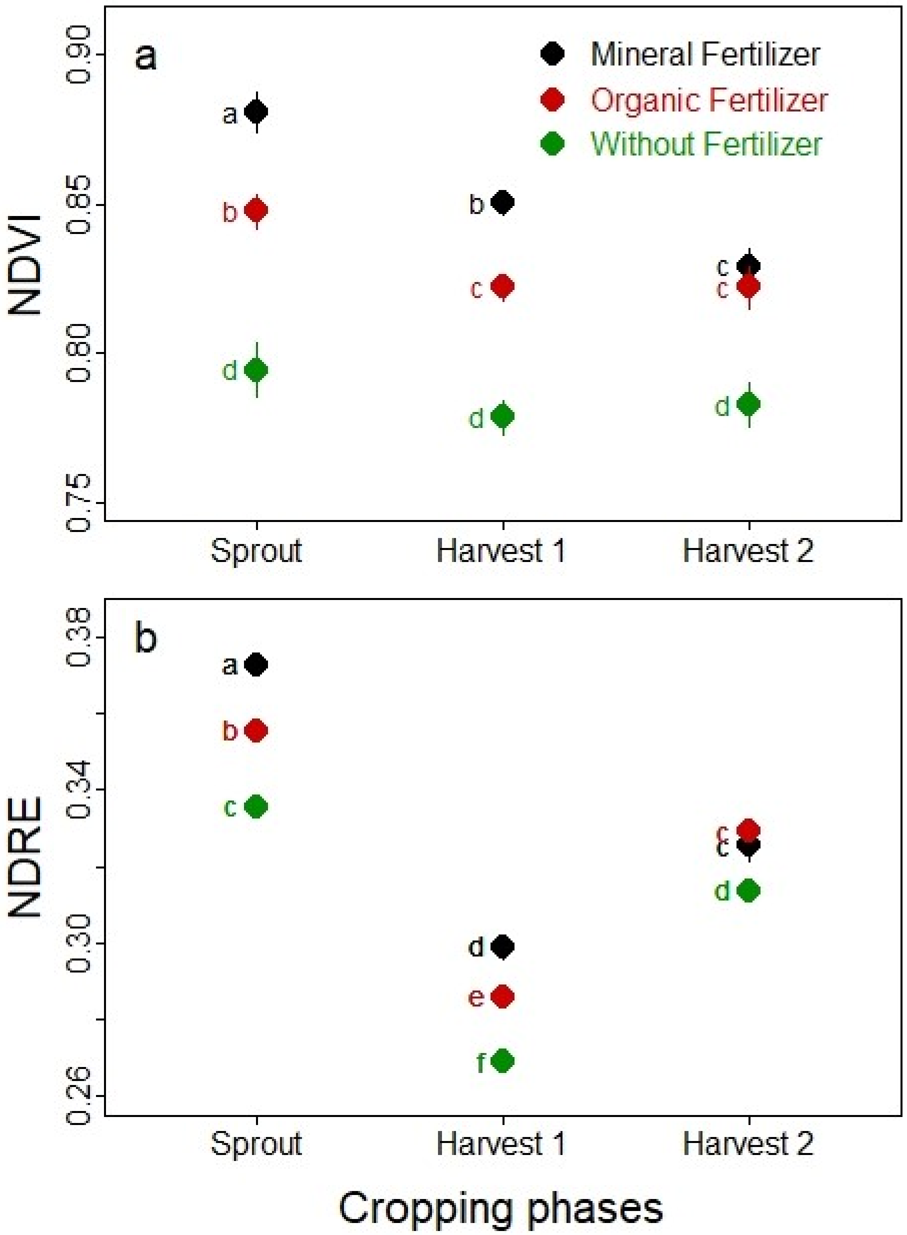

Figure 3 Mean (± SE) a) NDVI and b) NDRE in the different fertilization treatments during the three cropping phases of lowbush blueberry. Values not sharing the same letters are significantly different ($P < 0.05$)

Table 2. Results of the mixed model type III ANOVA using the REML method and the Satterthwaite’s degrees of freedom approximation method. Values in bold indicate a significant effect at α= 0.05.

Source of variation	Degrees of freedom	NDVI	NDRE
		F-value (P-value)	
Cropping phase	2	**18.7 (<0.001)**	**369.9 (<0.001)**
Pruning	1	0.4 (0.51)	0.0 (0.868)
Fungicide	1	2.2 (0.141)	0.0 (0.908)
Fertilizer	2	**117.2 (<0.001)**	**82.6 (<0.001)**
Cropping phase × Pruning	2	**7.2 (0.001)**	2.4 (0.095)
Cropping phase × Fungicide	2	**5.5 (0.005)**	1.4 (0.244)
Cropping phase × Fertilizer	4	**3.0 (0.021)**	**6.6 (<0.001)**
Pruning × Fungicide	1	0.9 (0.352)	0.3 (0.592)
Pruning × Fertilizer	2	0.8 (0.455)	0.1 (0.945)
Fungicide × Fertilizer	2	1.6 (0.208)	0.5 (0.635)
Cropping phase × Pruning × Fungicide	2	0.7 (0.498)	1.8 (0.171)
Cropping phase × Pruning × Fertilizer	4	2.2 (0.068)	0.6 (0.660)
Pruning × Fungicide × Fertilizer	2	0.3 (0.743)	0.1 (0.914)
Cropping phase × Fungicide × Fertilizer	4	0.3 (0.857)	0.7 (0.578)
Cropping phase × Pruning × Fungicide × Fertilizer	4	1.2 (0.323)	1.1 (0.348)

Vegetation indices and treatments

NDVI and NDRE values differed among fertilized and control plots (Table 2). Both indices were up to 12% higher in fertilized than in control plots throughout all cropping phases (Figs 3). There was nevertheless a difference between the two fertilization types, NDVI and NDRE being respectively ~0.3 and ~0.2 higher under mineral than organic fertilization during the sprout and the first harvest year, respectively. Indeed, the spectral reflectance curves show a clear delineation between mineral and organic fertilization treatments' spectral properties as we are moving from red band to red-edge followed by NIR wavelengths (Fig S1). The difference between the two fertilization types was no longer significant during the second harvest year.

The combination of thermal and mechanical pruning reduced NDVI during the sprout phase, and increased NDVI during the second year of harvest, compared to the mechanical pruning (Fig 4a). No difference was found between pruning treatments for NDRE (Table 2). The fungicide treatment significantly decreased NDVI during H1, whereas no differences were observed for NDRE (Table 2, Fig 4b).

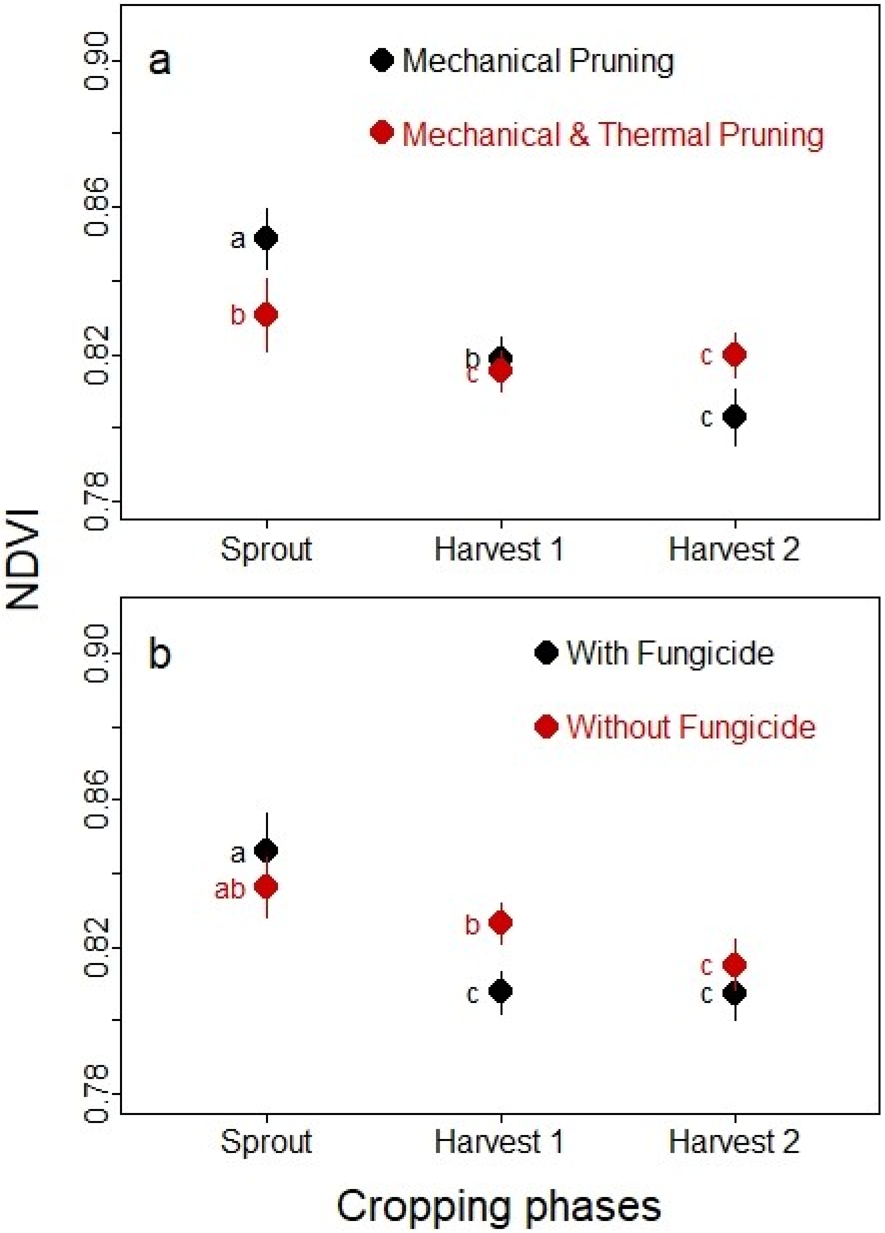

Figure 4 Mean (± SE) NDVI in the different a) pruning and b) fungicide treatments during the three cropping phases of lowbush blueberry. Values not sharing the same letters are significantly different ($P < 0.05$).

Vegetation indices and field measurements

Both NDVI and NDRE were more strongly correlated with stem length than with stem density during all cropping phases, except NDRE during H2 (Table 3). NDVI was more strongly correlated to stem length than NDRE regardless of the cropping phase. NDRE was not correlated to stem length during H2. Unlike NDVI, NDRE was sensitive to Septoria contamination, as indicated by the significant negative correlation between these variables across all cropping phases.

There was a significant correlation between NDVI and NDRE ($r = 0.54$; $P<0.001$), but the relationship varied among cropping phases (Fig 5). The strength of the relationship decreased from the sprout to the first and second years of harvest. The slope of the regression was significantly lower during H2 than during H1 and the sprout phase (ANCOVA; $P=0.001$). NDRE was ~0.07 lower during H1 than during the sprout phase regardless of NDVI values.

Table 3. Pearson's correlation coefficient (r) between NDVI, NDRE and lowbush blueberry plants characteristics during the different cropping phases. P-values are shown in parentheses.

	NDVI				NDRE			
	Sprout	Harvest 1	Harvest 2	All phases	Sprout	Harvest 1	Harvest 2	All phases
Stem density	**0.32 (0.03)**	**0.29 (<0.01)**	0.16 (0.27)	**0.30 (<0.01)**	**0.32 (0.03)**	**0.29 (<0.01)**	**0.48 (<0.01)**	**0.19 (<0.01)**
Stem length (cm)	**0.58 (<0.01)**	**0.55 (<0.01)**	**0.31 (0.03)**	**0.54 (<0.01)**	**0.42 (<0.01)**	**0.37 (<0.01)**	0.09 (0.53)	**0.48 (< 0.01)**
Septoria infection (%)	0.15 (0.30)	0.18 (0.08)	0.01 (0.94)	0.03 (0.67)	0.15 (0.29)	0.007 (0.95)	0.16 (0.28)	**-0.46 (< 0.01)**

Table 4. Mean ± SD stem density, stem length and Septoria infection according to fertilization treatments, cropping phases, pruning types and fungicide application. Values not sharing the same letters within each factor (i.e., Fertilization, Cropping phase, Pruning type and Fungicide application) are significantly different (one-way ANOVA; P < 0.05).

	Fertilization			Cropping phase			Pruning type		Fungicide	
	Mineral	Organic	Control	Sprout	H1	H2	Mechanical	+ Thermal	Fungicide	Control
Stem density	520±124 a	478±111 a	491±120 a	527±134 a	504±108 ab	450±115 b	492±126 a	501±112 a	488±119 a	504±120 a
Stem length (cm)	20.7±3.0 a	19.3±2.3 b	16.7±2.4 c	20.6±3.6 a	17.9±2.6 b	19.2±2.5 c	19.0±3.1 a	18.8±3.0 a	18.8±3.2 a	19.0±2.9 a
Septoria infection (%)	4.2±3.7 a	4.3±3.8 a	4.8±4.9 a	1.8±1.3 a	6.9±4.4 b	2.1±2.0 a	5.3±4.8 a	3.6±3.1 b	3.9±3.4 a	5.0±4.8 b

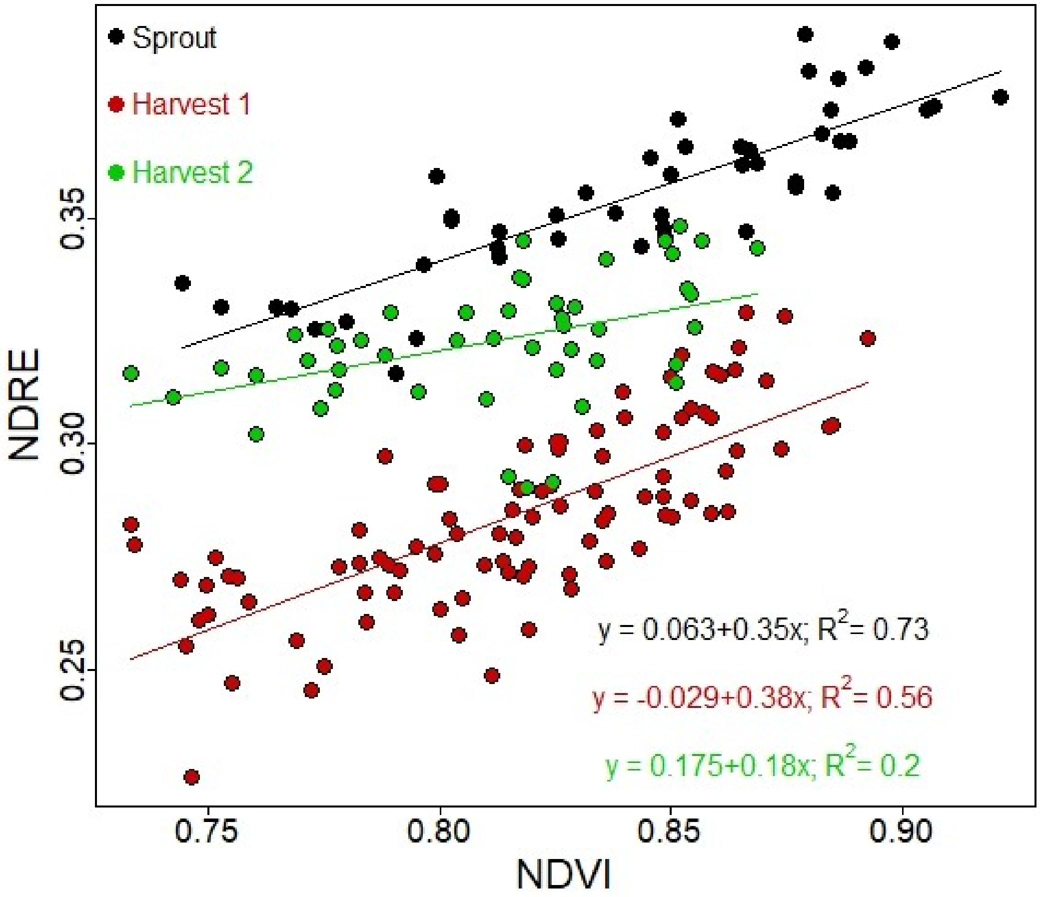

Figure 5 Correlation between NDVI and NDRE during the three phases of lowbush blueberry's cropping cycle.

Discussion

Response of vegetation indices to management practices

As expected, NDVI and NDRE were significantly correlated with growth variables such as stem density and length. Consequently, both indices were able to detect the impact of fertilization on blueberry. Higher NDVI and NDRE in fertilized plots reflected the higher stem length (+24% and +15%) under mineral and organic fertilization compared to the controls (Table 4). The fertilizers were applied only once at the beginning of the sprout phase only, i.e. in 2017, 2018 and 2019 for H2, H1 and sprout phase plots, respectively. This fertilization likely increased LAI as well as foliar chlorophyll and nitrogen contents, which most probably explained the higher NDVI and NDRE during this cropping phase. The lower NDVI in the harvest phase plots likely reflected a decrease in vegetative growth and foliar chlorophyll content the following years, especially under mineral fertilization. Mineral fertilization had a stronger effect on NDVI than organic fertilization during the two first years of the cycle but not 26 months after fertilization (during H2 phase), which corroborates a previous study reporting a stronger effect of mineral fertilization in the short-term but a potentially more prolonged effect of organic fertilizers (Marty et al., 2019a). Although significant, the correlation between both NDVI and NDRE with stem density was low (Table 3). Correlations were stronger for stem length, which explained about 30 and 23 % of the variation in NDVI and NDRE, respectively (Table 3). This suggests that stem length may be more strongly associated to LAI than stem density in blueberry, or that other factors such as foliar chlorophyll content is more strongly correlated to stem length.

Results from the Nova Scotia Wild Blueberry Institute showed a reduction in ericoid mycorrhizal (EM) plant infection by 50% after fungicide application (Percival and Burnham, 2006). As EM are known to facilitate soil nutrient assimilation such as nitrogen (Read et al., 2004), EM infection reduction may explain the slight but significant decrease in NDVI during H1 (Fig 4b), twelve months after fungicide application. However, decreased EM association does not necessarily reduce blueberry nutrient uptake and yields in situations where nutrient availability is not as limited, such as in fertilized plots, because blueberry may be more limited by carbohydrate losses (Percival and Burnham, 2006). The absence of a significant effect the second harvest year may also suggest that this fungicide side-effect is no longer effective 24 months after its application.

Sensitivity of vegetation indices to blueberry canopy characteristics

Given that vegetation indices provide sometimes distinct information regarding crops' canopies, the use of several indices generally allows to best capture crop characteristics (Broge and Leblanc, 2001; Hatfield and Prueger, 2010; Jorge et al., 2019). Our data reveal interesting features regarding the complementarity of NDVI and NDRE and their respective sensitivity in blueberry fields. Both indices were strongly correlated during the sprout phase, while the relationship tended to weaken through the cropping cycle. This might be due to the increased variability in leaf and canopy characteristics over time, as well as the contrasting sensitivity of these indices to certain blueberry's canopy characteristics. The lower correlation between NDVI and NDRE during H2 indicates a partial decoupling between the two indices, an increase in NDVI resulting in only a small increase in NDRE (Fig 5). Similarly low correlation between NDVI and NDRE has been observed in olive groves and vineyards and was interpreted as the result of a larger dispersion of reflectance values in the red-edge than in the red band when water and nitrogen contents vary (Jorge et al., 2019). Unlike NDRE, which was significantly lower during the harvest phases than during the sprout phase, NDVI did not significantly vary throughout the cropping cycle in unfertilized plots, indicating the development of reproductive shoots during the harvest phases had no significant impact on NDVI values. In contrast, the decline in NDRE between the sprout and the harvest phases in all fertilization treatments suggests that this index may be able to detect changes in the physiognomy and architecture of blueberry's canopy. The first harvest year is indeed characterized by the production of reproductive shoots bearing the inflorescences at the top of the canopy (Fig 6). The presence of these non-photosynthetic structures likely caused the strong decline in NDRE between the sprout and the H1 phase. The red-edge band penetrates deeper in the canopy than NDVI's visual band (the red band at ~680 nm) making NDRE generally more sensitive in plants with multi-layered canopies (Boiarskii and Hasegawa, 2019). Nevertheless, lower NDRE during H1 may also simply reflect lower growth for the blueberry plants cohort that started its cropping cycle in 2018 (i.e., in their first harvest phase in 2019) as suggested by their lower stem length (Table 4). A survey of a single cohort of plants over the whole cropping cycle would help clarify this point.

Figure 6 Wild blueberry's canopy architecture at the beginning of bud development during the 1st harvest year (left) and the 2nd harvest year (right). Blue circles show flower/fruit buds.

The lower NDRE during H1 may also partly be the result of higher Septoria contamination (Table 4), which causes chlorotic spots and a dark discolouration of stems with red diffuse margins (Ali et al., 2021). The contamination level was indeed almost three times higher during the harvest phases than during the sprout phase (5.3 ± 4.4 vs. 1.8 ± 1.3). This increased infection level may therefore partly explain the observed lower NDRE values during the harvest phase.

Conclusions

Fertilization increased both NDVI and NDRE compared to the control plots for the three cropping phases, reflecting the enhancement of aboveground biomass production by the fertilizers. This effect was stronger in plots that received the mineral than the organic fertilizer and during the sprout phase and the first harvest year, likely due to higher mineral fertilizer efficacy in the short-term. Pruning and fungicide treatments had comparatively low impacts on blueberry stem length. Our data suggest that NDVI may be a better proxy than NDRE for vegetative growth but not as sensitive as NDRE to changes in canopy features, such as the presence of reproductive shoots. However a survey of each plot over the entire cropping cycle (i.e., three years) should be conducted to assess with more precision the changes in NDVI and NDRE with time. Further research must be conducted to relate these indices to other canopy characteristics such as nutrient status and chlorophyll content. The development of such remote sensing tools may in the future allow the survey of lowbush blueberry's nutritional status and thus contribute to the improvement of yield and the optimization of fertilizer application.

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Figures

Figure 1. (a) Location of the experimental blueberry fields, (b) multispectral UAV imagery overlaid with cropping phases (Spr: sprout phase; Hv1: first harvest year; Hv2: second harvest year), (c) Image acquisition by an UAV-Camera system: M 210, DJI quadcopter, (d) RedEdge camera (middle-right), and (e) calibration reflectance panel.

Figure 2. Schematic representation of one experimental block. Each block includes 48 experimental units combining each of the three cropping phases (Sprout phase [12 units], H1 [12 units] and H2 phases [24 units]) with the three treatments (1- Fungicide application [- or +]; 2- Pruning type [1 or 2]; and 3- Fertilization type [1, 2 or -]). Experimental units are separated from each other by an uncultivated band (brown band on the figure).

Figure 3 Mean (± SE) a) NDVI and b) NDRE in the different fertilization treatments during the three cropping phases of lowbush blueberry. Values not sharing the same letters are significantly different ($P < 0.05$).

Figure 4 Mean (± SE) NDVI in the different a) pruning and b) fungicide treatments during the three cropping phases of lowbush blueberry. Values not sharing the same letters are significantly different ($P < 0.05$).

Figure 5 Correlation between NDVI and NDRE during the three phases of lowbush blueberry's cropping cycle.

Figure 6 Wild blueberry's canopy architecture at the beginning of bud development during the 1st harvest year (left) and the 2nd harvest year (right). Blue circles show flower/fruit buds.