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Nutrient Concentrations of Bush Bean (*Phaseolus vulgaris* L.) and Potato (*Solanum tuberosum* L.) Cultivated in Subarctic Soils Managed with Intercropping and Willow (*Salix* spp.) Agroforestry

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Abstract: To ease food insecurities in northern Canada, some remote communities started gardening initiatives to gain more access to locally grown foods. Bush beans (*Phaseolus vulgaris* L.) and potatoes (*Solanum tuberosum* L.) were assessed for N, P, K, Mg, and Ca concentrations of foliage as indicators of plant nutrition in a calcareous silty loam soil of northern Ontario James Bay lowlands. Crops were grown in sole cropping and intercropping configurations, with comparisons made between an open field and an agroforestry site enclosed with willow (*Salix* spp.) trees. Foliage chemical analysis of the sites revealed an abundance of Ca, adequacies for Mg and N, and deficiencies in P and K. Intercropping bean and potato did not show significant crop–crop facilitation for nutrients. The agroforestry site showed to be a superior management practice for the James Bay lowland region, specifically for P. The agroforestry site had significantly greater P for bean plant ($p = 0.024$) and potato foliage ($p = 0.002$) compared to the open site. It is suspected that the presence of willows improve plant available P to bean and potatoes by tree root—crop root interactions and microclimate enhancements.

Keywords: plant nutrients; subarctic agriculture; agroforestry; intercropping; bush bean; potato; ternary plots; northern agriculture management

1. Introduction

Food insecurity in northern Canada's isolated regions has been a recent subject of interest [1–4]. One strategy to improve food security in isolated regions is to cultivate local foods under ambient conditions to reduce dependencies on expensive foods flown into communities [4–6]. However, this food production strategy has challenges in the Canadian subarctic—and other subarctic regions of the world—as the subarctic climate has historically been deemed a limitation for agriculture [4,7–9]. As warming global climate trends continue, and various technologies and techniques advance, these cooler regions have the potential to provide fresh produce for local communities [6,9,10].

Baseline information regarding soil characteristics, agrometerology, and natural vegetation are required to determine management practices that will improve agriculture production under ambient conditions in a given subarctic community [8]. Although there is detailed information on the nutrient availability from naturalized North American subarctic soils [11], knowledge is scarce regarding nutrient availability from cultivated subarctic soils with the few studies available originating from Alaska (i.e., Grünzweig et al. [9], Lukac and Goldbold [11], Koenig and Rader [12], and Stevenson et al. [13])—a subarctic region that is 64° N with an intense summer photoperiod and is situated on acidic soils. Our field study, located in the James Bay lowland, subarctic region of Ontario that is situated at 52° N on alkaline soils, focused on bush bean (*Phaseolus vulgaris* L.) and potatoes (*Solanum tuberosum* L.) macronutrient uptake on historically cultivated soils. Our study objectives were to: (i) obtain baseline macronutrients: nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) concentrations from tissue samples of bush bean and potato cultivated in subarctic, Ontario; (ii) determine the macronutrient status in these plants for future nutrient management strategies by utilizing critical levels and ternary diagrams for bean and for potato; and (iii) examine whether utilizing subarctic agroforestry (i.e., tree-lined plots) and intercropping management enhanced macronutrient concentrations of bean and potato tissue samples in comparison to growing in an open field and practicing sole cropping.

Agroforestry and intercropping are most commonly practiced in the tropics and subtropics, with trees commonly used as windbreaks in temperate climates [14–17]. Only recently has agroforestry been utilized and shown to be viable under ambient conditions in the subarctic [6]. Agroforestry systems (including windbreaks) combine woody perennials (e.g., trees, shrubs) with crops in spatial and temporal arrangements, and intercropping is the cultivation of two or more crops simultaneously on the same field [15,18–20]. The general consensus to apply agroforestry and/or intercropping techniques are to improve agroecosystem services and resource efficiencies (natural and anthropogenic) for enhanced crop production [15–21]. Both agroforestry and intercropping can be low-input management practices and require minimal non-local resources (i.e., a more sustainable practice) [16,22]. Effective local low-cost technologies are imperative for high-latitude agriculture management practices considering food security issues for many communities is dependent on imported consumables [1,5,6], which would include agriculture inputs. Moreover, to avoid negative consequences of intensive cropping practices in high-latitude communities, more sustainable agricultural practices are preferred. Integrating agroecological practices such as intercropping and agroforestry are of interest to best utilize regional ecological services to regulate soil fertility, productivity and crop protection by identifying facilitative and complementary interactions [16,17,22].

Potato and beans were chosen to be cultivated in the agroecosystems for practical and nutritional purposes. Potatoes are considered a global food staple that can tolerate cool wet conditions [23], and the crop was grown in the region historically using conventional agricultural practices [24]. Bush beans have rapid growth rates, tolerate cooler temperatures, and are legumes that host rhizobacteria capable of fixing nitrogen from the atmosphere [12,16,18]. Bush beans and potatoes were grown as sole crops and combined as a bean–potato row-intercropping system, in the present study. In intercropping systems, legumes are commonly combined with other crops (often cereals) to reduce fertilizer requirements, specifically nitrogen [16,18,20]. Fewer studies examine tuber crops in an intercropping system [18,25–32]. The studies using potato intercropping were set in warmer climates and incorporated taller cereals or legumes for the purpose of shading [16,25–32]—a cropping strategy that would be counterproductive for subarctic agriculture. Studies in semi-arid [31] and subtropical [32] climates both found intercropping potatoes and beans provided economic advantages compared to respective sole cropping; however, both studies revealed that management and design are important components as beans were more competitive for nutrient and light resources and potatoes were the suppressed crop.

At the same subarctic site as our study, Barbeau and colleagues [33] examined bush bean–potato cropping systems and found a significant increase in bean and potato yield and above-ground biomass when crops were in an agroforestry system. Potato yield and above-ground biomass was significantly lower when managed as an intercrop, but below-ground biomass was unaffected by intercropping and sole cropping management or by open field and agroforestry systems. Bean below-ground biomass was similar when sole cropped and intercropped with potato in the agroforestry system; however, in an open field, bean below-ground biomass was significantly lower when intercropped with potato opposed to being a sole crop. Based on these results, we extended our investigation towards nutrient status of bean and potatoes to reveal nutrient response to agroforestry and intercropping management practices applied to subarctic soils. Determining nutrient availability for crops grown with different management strategies in the subarctic provides information to create soil and plant fertility and productivity plans specifically for James Bay lowland communities. This can guide other high-latitude communities interested in cultivating local produce, under ambient conditions, particularly during the recent trend of disproportionate warming in subarctic and arctic regions of the world [34].

2. Materials and Methods

2.1. Location

The research location was in Fort Albany First Nations (FAFN) Muskeguwuk Cree territory on the west coast of James Bay, Ontario (Figure 1). The James Bay ecoregion is characterized as flat, near sea level, and dominated by poorly drained muskeg or peat moss situated on limestone bedrock [35]. The ecoclimate of the region is considered to be perhumid high boreal with a mean annual temperature of −2 °C, and a mean annual precipitation of 700–800 mm [36]. In 2014, the frost free growing period was 94 days from 21 June (Julian day of year—DOY 172) to 22 September (DOY 265).

Figure 1. General location of study, Fort Albany First Nations, Ontario, Canada.

Historically, the area of study was boreal forest that was cleared, drained, and plowed for agriculture production by Christian missionaries from the 1930s to 1970s. Fields became disused and naturally progressed with panicled aster (*Symphyotrichum lanceolatum*), cow vetch (*Vicia cracca*), creeping bentgrass (*Agrostis stolinifer*), and hemp nettle (*Galeopsis tetrahit*) [6]. In one field, natural succession of willow trees (*Salix* spp.) as old as 35 years grew in a mantle formation along two manmade drainage ditches creating thicket rows that had the mean height of 4.9 m (±0.67 standard deviation), 6.5 ± 2.59 m in thicket width, with a 15.2 ± 2.82% thicket porosity. Willow coverage had a mean of 0.6 ± 0.20 tree m^{-1} and their structure comprised of numerous mature basal shoots with the mean of 11.0 ± 5.69 shoots per tree and the mean diameter at the base of shoots was 13.0 ± 6.46 cm (n = 88 trees). The thickets ran parallel from southwest to northeast meeting forested areas at each end, creating partially enclosed fields. Two sites were established in year 2012 and were in their third year of bean and potato cultivation in year 2014. An agroforestry site (A) was constructed in the enclosed treed area and an open site (O) was 58 m distance from the nearest tree and was located 200 m distance southwest from the agroforestry site in an open field (Figure 2). The sites had soils with a silty loam texture consisting of 18% sand, 66% silt, and 16% clay; additional physical soil characteristics of each cultivated sites are described in Table 1 and in Spiegelaar et al. [6]. Data from the nearby forest was added to display soil property modifications due to historic land use change (Table 1). The open site had a mean soil temperature that was 2.1 °C cooler and mean soil moisture content was 13.3% higher compared to the agroforestry site. Historic land-use change from forest to cultivation altered bulk density, carbon-nitrogen ratios, and cation exchange capacity (CEC).

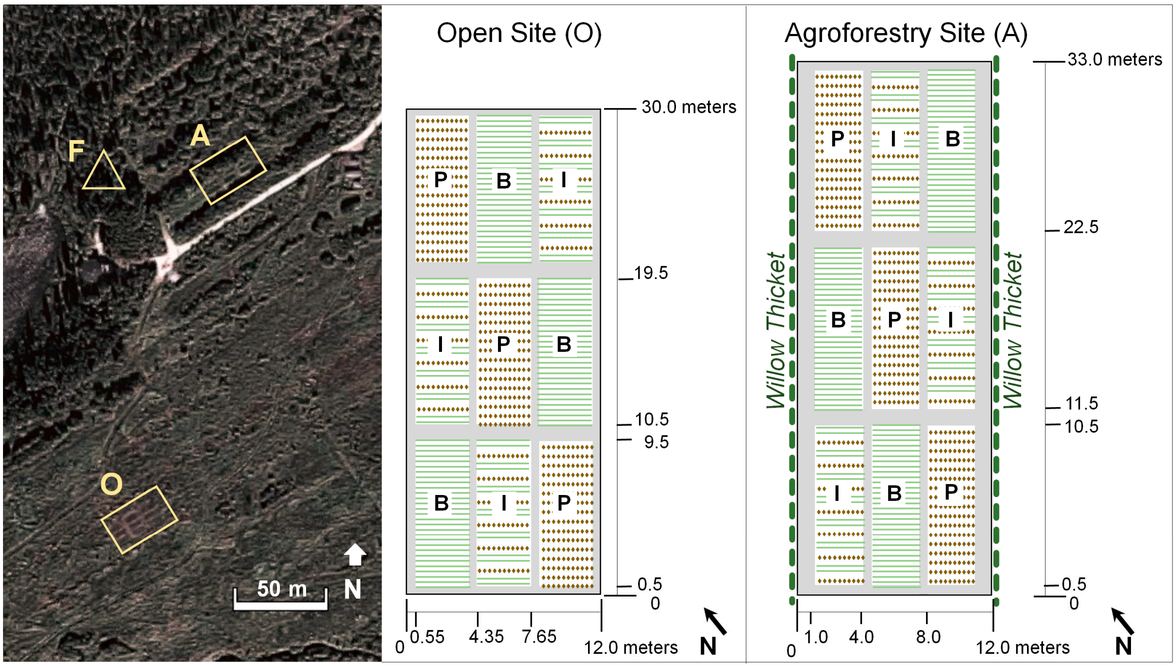


Figure 2. Location of open (O) and agroforestry (A) sites and where Forest (F) soil samples were collected in Fort Albany First Nations, Ontario (left, map modified from Google Earth, 2017, Digital Globe, Westminster, CO, USA) and plot schematics of each site (center and right). Management of sole cropping bush bean is represented with the letter B, the letter P is sole cropping potato, and the letter I is bean–potato intercropping management practices. Light green lines represent bush beans and brown dots represent potatoes.

Table 1. Physical soil characteristics of two subarctic cultivated sites investigated for plant available nutrients, and uncultivated forest soil located in Fort Albany, Ontario, Canada. Bulk density samples were collected at 5 cm depth. Soil moisture and temperature averages and standard deviations were obtained using dataloggers fitted with thermocouples and moisture sensors (HOBO micro stations, Onset Computer Corp., Pacasset, MA., USA) every 30 min at 10 cm depth from 26 June 2014 (day of year (DOY) 177) to 8 August 2014 (DOY 220).

Site	Agroforestry	Open	Boreal Forest
Management	**Cultivated for 3 Years Enclosed with Willow Trees**	**Cultivated for 3 Years in an Open Field**	**Uncultivated Forest Soil**
Soil Characteristics	$n = 9$	$n = 9$	$n = 3$
pH *	7.7 ± 0.08	7.6 ± 0.03	7.5 ± 0.11
Bulk density (g cm^{-3})	0.66 ± 0.07	0.66 ± 0.06	0.30 ± 0.12
C/N *	14.9 ± 0.48	15.7 ± 0.93	22.3 ± 3.29
CEC ($cmol^+$ kg^{-1}) *†	40.6 ± 4.21	41.0 ± 1.74	30.8 ± 12.77
Soil Temperature (°C)			
Mean ± SD §	17.5 ± 2.80	15.4 ± 2.77	n/a
Minimum	12.4	7.4	
Maximum	26.7	21.7	
Soil Moisture (WFPS%) ‡			
Mean ± SD	38.6 ± 0.017	51.9 ± 0.011	n/a
Minimum	35.9	50.6	
Maximum	45.5	55.9	

* Soil characteristics for 0–20 cm depth. † CEC: cation exchange capacity using barium chloride method. ‡ WFPS: Water filled pore space percentage calculated by volumetric water content and bulk density. § SD: standard deviation.

2.2. Site Preparations

The open site dimensions were 30 m × 12 m, and the agroforestry site was 33 m × 12 m with an additional 1 m wide border from the willow treeline. A Latin square was used for the experimental design to control variation due to tree effects (i.e., edge and shading effects). Each site had 3 rows and 3 columns (totaling 9 plots per site); open plot dimensions were 9 m × 3.3 m and the agroforestry plots were 10 m × 3 m (Figure 2).

Sites were rototilled (Troy-Bilt Rear Tine Tiller 208 CC, Cleveland, OH, USA) at 15 cm depth on 16 June to 19 June 2014 (DOY 167–170). There were three crop management treatments, and they were assigned at random—once per row and once per column. The crop management treatments applied were: sole cropped beans (Provider Var. Dam Seeds, Dundas, ON, Canada), sole cropped potatoes (AC Chaleur Var. Holm Potato Farm, Walkerton, ON, Canada), and row-intercropped bean and potatoes. Plots were assigned for each treatment at each site during establishment in year 2012; sole beans and sole potatoes alternated plots by annual rotation and bean–potato intercropping stayed in the same plots. Potatoes were planted in rows on 24 June 2014 (DOY 175) at 10 cm depth. Sole cropped potatoes had a row seeding density of 3.3 tubers m^{-1} spaced 30.5 cm apart (1 ft) with 61 cm (2 ft) inter-row spacing. Bush beans were sown in rows at a planting depth of 3 cm on 26 June 2014 (DOY 177). In the sole cropped bean treatment, the seeding density was 15 seeds m^{-1} spaced 6.5 cm apart with 30.5 cm inter-row spacing. For the bean and potato intercropping treatment, the row ratio was one potato row to two rows of beans. Both potatoes and beans in the intercropping plots maintained seeding row densities; bean–bean inter-row was 30.5 cm and the bean–potato inter-row was 61 cm.

2.3. Crop Tissue Analysis

Plant samples were collected at each site on 10 August 2014 (DOY 222) for nutrient analysis. The newest fully emerged leaf with petiole was collected from potato plants in the sole potato and intercropping potato plots [37]; the sampling period for potato was during inflorescence emergence. More specifically, potato plants in the open site were collected at 51–501 and 59–509 in the agroforestry site according to the Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH) scale that uses decimal code system for phenological development and growth stages for a range of crop species [38]. In each plot, ten plant samples were collected at >0.5 m from the border of each designated plot.

Bush beans had the entire above-ground portion of the plant collected including stems and leaves. Fifteen bean samples were collected by selecting every 10th bean plant that was >0.5 m from the border of each designated plot. This choice of sampling procedure was decided for three reasons. Firstly, the entire bean plant was collected because spacing and bean plant population allowed for some beans to be sacrificed; the larger spacing requirements for potatoes did not permit whole potato plant collection. Secondly, we wanted to eliminate plant development bias as growth stages were dissimilar between the open and agroforestry sites for beans. At the time of collection, the agroforestry site had bean plants that were 35 cm tall, had six trifoliolates, and flowering (BBCH 64); by contrast, the open site had bean plants at inflorescence emergence, that were 21 cm tall, with three trifoliolates (BBCH 51)) [39]. Lastly, we needed to establish plant sampling procedures repeatable by individuals without a background in research methods, as it is hoped that garden data will be continually collected by interested community members.

Plant samples were rinsed immediately with reverse osmosis treated water to remove soil particles. Once water evaporated from the potato and bean samples, they were placed in designated paper bags and hung to air dry in a well ventilated shed. Due to the slower drying process used, samples were monitored to ensure materials dried without mold or rot. Samples were transported to the Agriculture and Food Laboratory services, Guelph, Ontario, Canada to be ground and analyzed for N, P, K, Ca, and Mg.

2.4. NPK Ternary Diagrams

Bean plant and potato foliage nutrient concentrations were evaluated using a critical limit value for each crop. The critical limit in this study is defined as a concentration value that separates nutrient deficiency from nutrient adequacy for a specified plant [37]. Furthermore, concentration ranges of low, adequate, maximum normal, and high were set as non-overlapping parameters to construct boundaries for nitrogen, phosphorus, and potassium (NPK) ternary diagrams for both bean and potato [33] (Table 2). Nutrient concentration ranges and critical limits for bush bean and potato were determined using references from Reuter and Robinson [37], Hochmuth et al. [40], and Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) [41] for most recently matured (MRM) leaf during in bud and early flower growth stages.

Table 2. Nutrient parameters used to interpret nutrient status for bush bean and potato (%) and to develop boundaries on ternary diagrams. Calcium (Ca) and magnesium (Mg) were not implemented in the ternary diagram; therefore, nutrient range parameters for low, adequate, normal max or high were not required.

Nutrient	Low	Critical	Adequate	Normal Max	High
*Bush Bean (Phaseolus vulgaris L.) MRM * trifoliate, In bud to early flower*					
N	2.0	3.0	3.5	4.0	5.5
P	0.25	0.30	0.4	0.5	0.6
K	1.5	2.0	2.5	3.0	4.0
Mg	-	0.26	-	-	-
Ca	-	0.8	-	-	-
Potato (Solanum tuberosum L.)—MRM leaf + petiole—In bud to early flower					
N	2.0	3.0	4.0	5.0	6.0
P	0.15	0.20	0.40	0.50	0.60
K	2.0	3.0	4.0	5.0	6.0
Mg	-	0.25	0.5	-	-
Ca	-	0.6	1.0	-	-

* MRM—Most recently matured.

Boundary lines for the NPK ternary diagrams were drawn using Olde Venterink et al. [42] as a guide (Figure 4, Supplementary Table S1 and Supplementary Figure S1). Nutrient parameters were used in sixty N-P-K combinations for each crop (i.e., low N, critical P, low K). The combinations were plotted on a ternary diagram designated for bean or potato using Equations (1)–(4):

$$[N] + [P \times 10] + [K] = [T], \tag{1}$$

$$C_{[N]} = \frac{[N]}{[T]} \times 100, \tag{2}$$

$$C_{[P]} = \frac{[P \times 10]}{[T]} \times 100, \tag{3}$$

$$C_{[K]} = \frac{[K]}{[T]} \times 100, \tag{4}$$

where [N], [P], and [K] represent total nitrogen, phosphorus, and potassium concentrations (%), respectively, and T is the sum of N, P and K concentration values. NPK coordinates (C) to be plotted on the ternary diagram were determined using Equation (2) for N, Equation (3) for P, and Equation (4) for K.

Boundary lines were fitted to have neutral scenarios (i.e., low N, low P, low K; or critical N, critical P, critical K) in the middle domain of the ternary diagram. The middle domain indicates nutrient ratios that cannot be used to evaluate a nutrient limitation. Furthermore, the boundary lines represent N:P, N:K, and K:P ratios, and they create three other domains: K or K + N limitation that is bounded by N:K and K:P lines; P or P + N limitation that is bounded by N:P and K:P lines; and N limitation that is bounded by N:P and N:K lines. Nutrient values obtained for bean plant and foliar potato at the open and agroforestry site were plotted on designated ternary diagrams using Equations (1)–(4) to assess macronutrient deficiencies.

2.5. Statistical Analysis

Statistical analysis was conducted using SPSS 23 (SPSS Inc., Chicago, IL, USA). Each nutrient from each method type (bean plant concentration, and potato foliage concentration) was assessed separately. A two-way ANOVA for the main effects of Site (agroforestry versus open) and Treatment (sole cropping versus intercropping), and of Site × Treatment interactions, were examined to determine significances at $\alpha = 0.05$. Levene's test for homogeneity of variances revealed that the variances for all nutrients for potato were homogeneous ($p > 0.05$). For beans, most variances were homogeneous with two exceptions (P, N:P) where variances were moderately heterogeneous ($p > 0.02$). However, significant differences between sites were found for both of these metrics and, therefore, the heterogeneity of variances did not impede our ability to detect significant differences. Significant differences from critical levels were made by assessing if the 95% confidence interval for the mean included the critical or adequate levels for plant growth.

3. Results

3.1. Comparison for Site and Management

Significant differences between sites were found for bean plants for P, K and the K:P ratio (Table 3). Whilst bean plants in the agroforestry site had greater P concentrations than in the open site, the opposite trend was observed for K. Subsequently, the K:P ratio in bean plants was significantly greater in the open site than in the agroforestry site. Significant differences in bean plants were not found for management (sole versus intercropped) or the site × management interaction.

Similar to bean plants, potato foliage from the agroforestry site had significantly greater P concentration compared to the open site (Table 3). This, in turn, appears to have led to a greater N:P ratio in potato foliage in the open site. Significant differences in potato foliage were not found for management (sole versus intercropped) or the site × management interaction with one exception: the N:P ratio was significantly greater in potato foliage from the intercropped plots than in the plots containing only potato.

Table 3. Results of *p*-values from two-way ANOVA for leaf tissue (+stems for beans) in cultivated sites in Fort Albany First Nation (James Bay, Ontario, Canada) for 2014. Sites were cultivated from 2012–2014 in either an open field or an agroforestry field enclosed by a willow thicket. The management (Mgmt) treatment was either sole planting or a bean–potato intercrop.

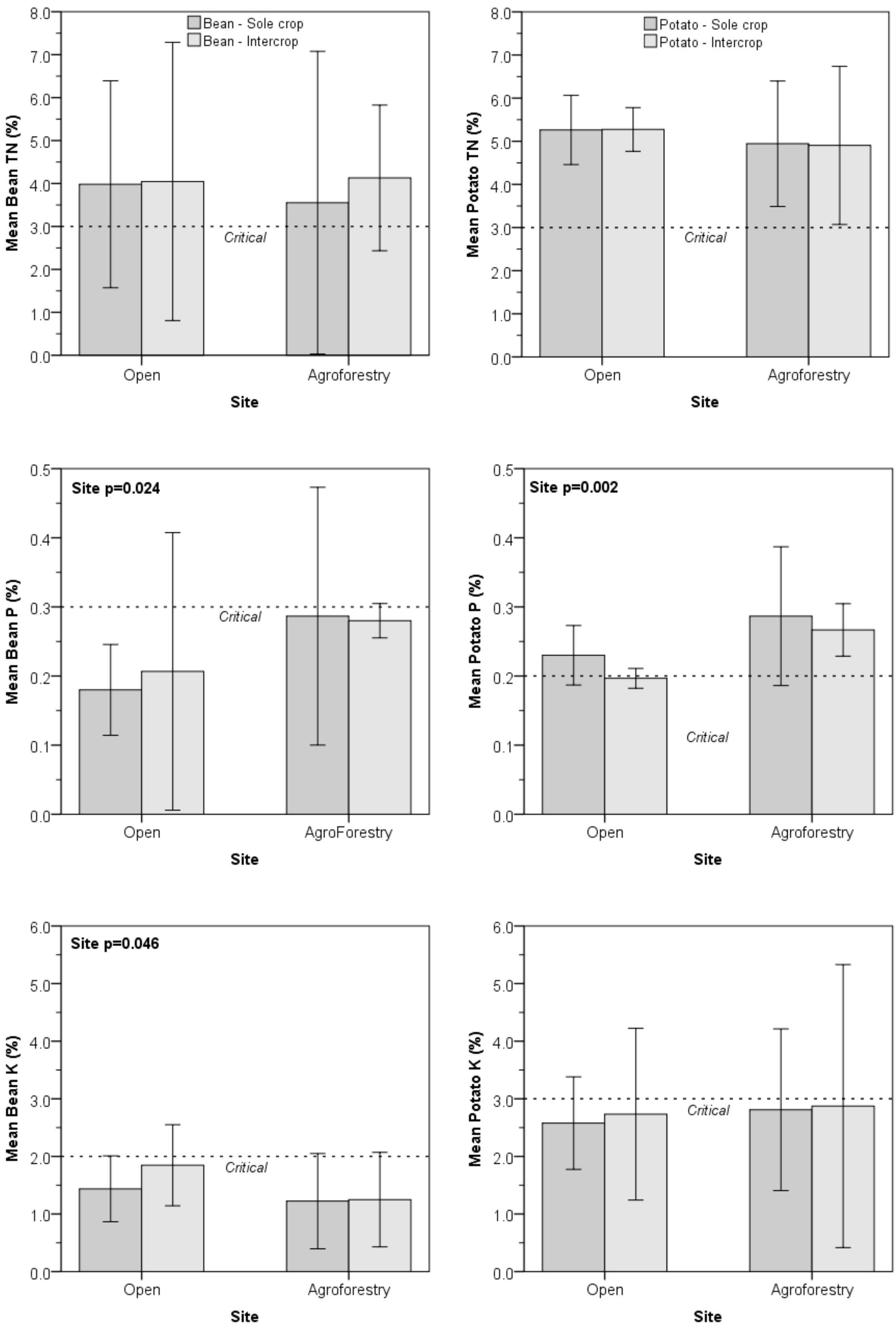
Nutrient	Bush Bean (*Phaseolus vulgaris* L.)			Potato (*Solanum tuberosum* L.)		
	Site	Mgmt	Site × Mgmt	Site	Mgmt	Site × Mgmt
N	0.797	0.637	0.705	0.273	0.960	0.934
P	**0.024** *	0.694	0.605	**0.002**	0.083	0.792
K	**0.046**	0.240	0.294	0.639	0.781	0.906
N:P	0.054	0.782	0.739	**<0.001**	**0.016**	0.184
N:K	0.339	0.887	0.595	0.700	0.938	0.828
K:P	**0.010**	0.689	0.502	0.315	0.394	0.676
Mg	0.264	0.963	0.628	0.504	0.558	0.824
Ca	0.736	0.978	0.457	0.070	0.391	0.606

* Bold font indicates significant differences at $\alpha = 0.05$.

3.2. Comparision to Critical Levels

Nutrient concentrations in bean plants exceeded the critical threshold for adequate growth for N (3.0%), Mg (0.26%) and Ca (0.8%; Figure 3). By contrast, mean P and K concentrations in bean plants were below the critical level across both sites and management treatments. Although only sole beans in the open site had a 95% confidence interval that did not meet the critical concentration of 0.30% P, bean plants in these plots also had a 95% confidence interval that only marginally included the critical level of K = 2.0% (Figure 3).

Nutrient concentrations in potato foliage exceeded the critical level of N (3.0%), Mg (0.25%) and Ca (0.6%; Figure 3). Whilst P concentrations in potato foliage were mostly at or above critical level of 0.2% P, they did not reach the maximum normal level (0.5% P), resulting in an N:P ratio that was above the recommended optimal N:P ratio of 10 and, in some instances, the N:P was >20, indicating severe P limitations [43]. Lower concentrations of P from potato foliage in the open site resulted in N:P ratios (21.6–27.3) that were significantly higher (using the 95% confidence interval) than the agroforestry site (15.8–20.1). Intercropping management resulted in significantly greater N:P ratios for potatoes (0.016) compared to sole cropping; however, this observation is more noticeable in the open site. The mean K concentration for potato foliage in the open site (2.6 ± 1.08% K) and agroforestry site (2.8 ± 0.72% K) were below the critical threshold (3.0% K); the open site's maximum K concentration for potato foliage was 3.1% and, for the agroforestry site, it was 3.7% (Figure 3).



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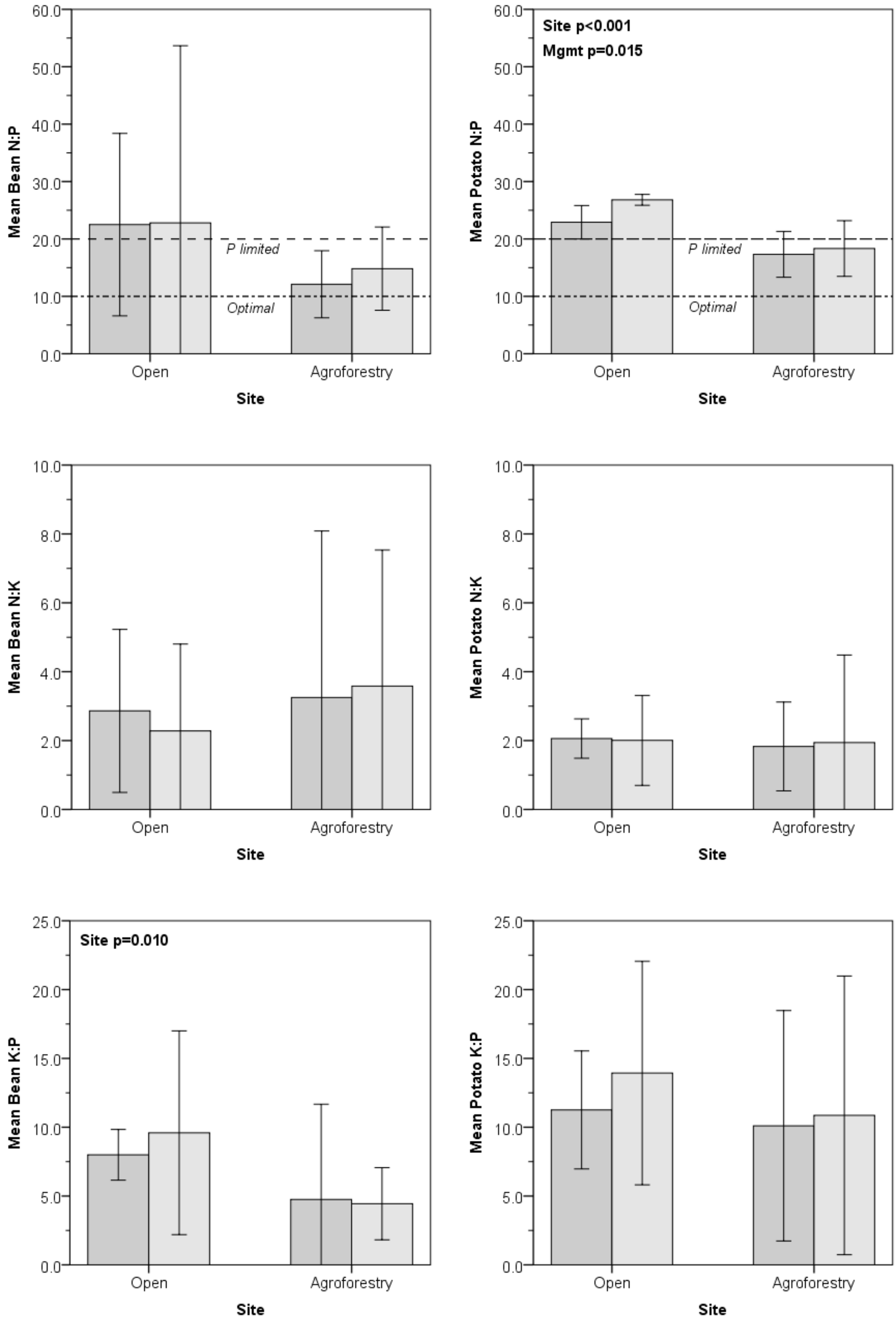

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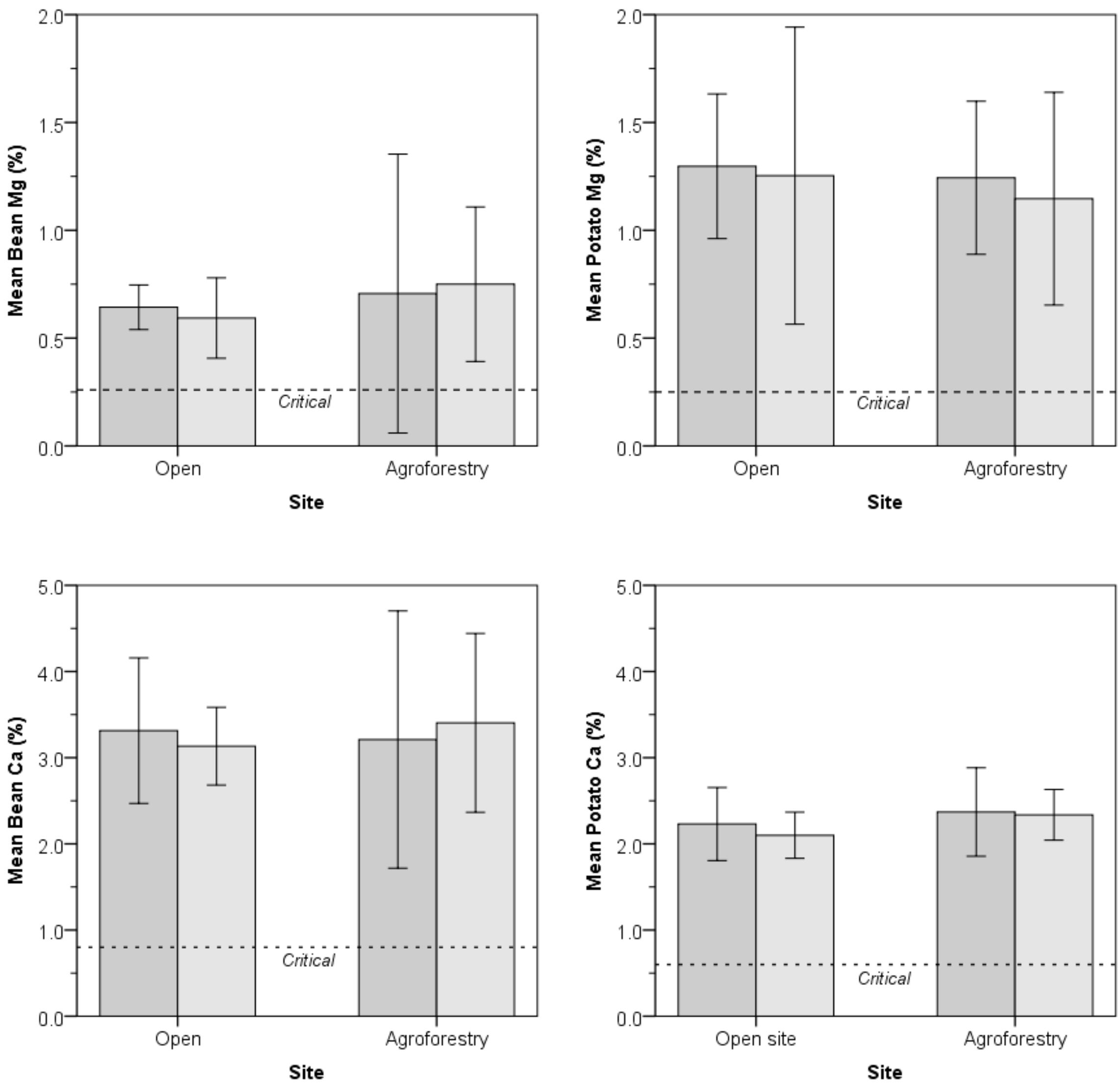
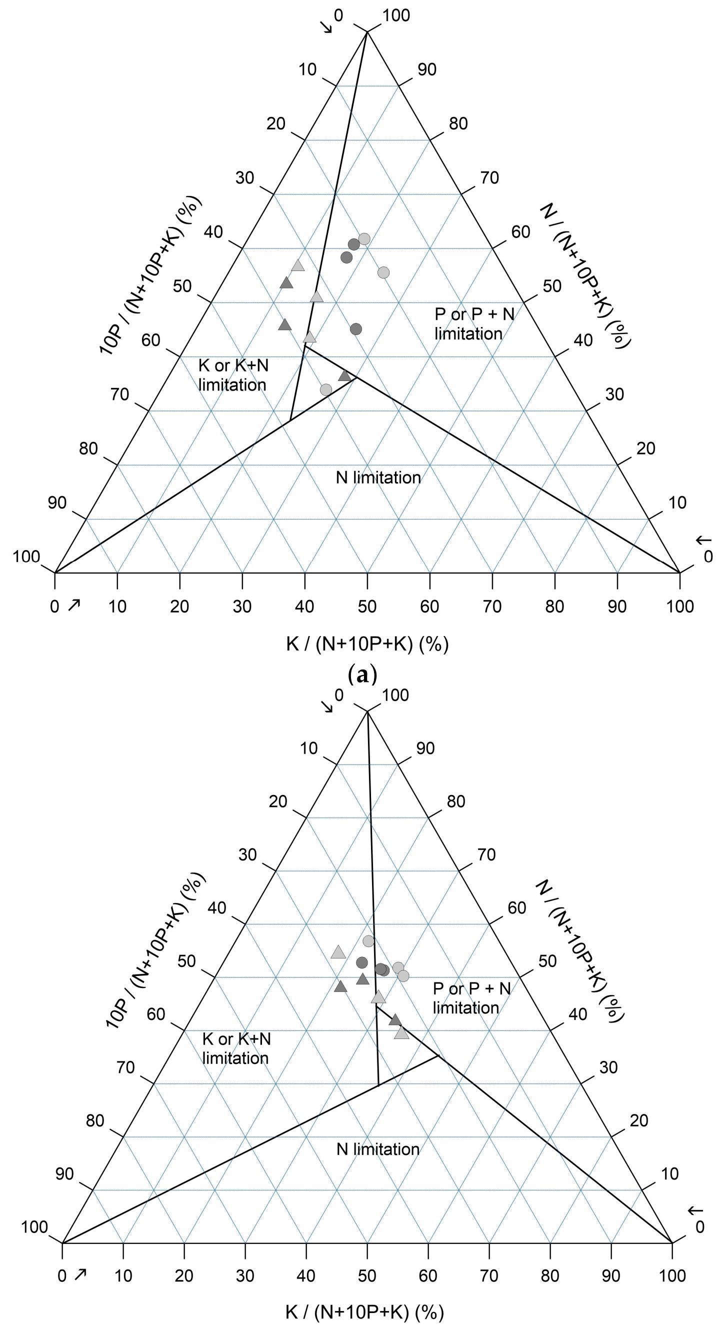


Figure 3. Mean (±95% confidence intervals; n = 3) nutrient concentrations (%) collected for bush bean plants (foliage + stems; *Phaseolus vulgaris* L.) and for potato foliage (*Solanum tuberosum* L.) harvested in 2014 in the subarctic community of Fort Albany, Ontario, Canada. Sites were cultivated during 2012–2014 as either open sites (>58 m from trees) or agroforestry sites (enclosed by willow) and managed (Mgmt) as a sole crop or in a bean–potato intercropping system. Dashed line represents nutrient critical level-below which nutrient deficiencies occur, or indicates optimal or limitation of nutrient ratios (where available from the literature). The p-values are shown from a two-way ANOVA only for significant (<0.05) differences from Table 3.

3.3. Determination of N, P, and K Limitations with Ternary Plots

Ternary plot domains for bean plant were separated by the resulting critical ratios of N:P = 10.8, N:K = 1.2, and K:P = 4.9. Bean plant samples applied to the NPK ternary plots suggest K and/or P limitations. Potassium displayed to be a greater limitation in the agroforestry plots, and phosphorus as a greater limitation in the open plots (although both P and K were critical to low in open plots). Two of the twelve bean foliage samples were in the central part of the ternary diagram where nutrient ratios cannot be used to determine nutrient limitations [42]; these two cases had critical to low levels of N, P, and K (Figure 4).



(**a**)

(**b**)

Figure 4. Nitrogen, phosphorus, potassium (NPK) ternary plots for: (**a**) bush bean plants (foliage + stems; *Phaseolus vulgaris* L.) and (**b**) potato foliage (*Solanum tuberosum* L.) collected from agroforestry site enclosed by willow (triangles) or an open field (circle). Crops were managed as sole crops (darker shading) or in a bean–potato intercrop (lighter shading). Solid lines separate the four domains of the ternary plots; three domains are for samples limited in N, P or P + N, and K or K + N for a targeted crop (bean or potato) and the fourth middle domain is where nutrient ratios cannot be used to determine nutrient limitations.

The NPK ternary plots for potato foliage resulted in critical ratios of N:P = 17, N:K = 0.8, and K:P = 11.1. Potato foliage data applied to the ternary plot revealed that both sites and both management treatments were K and/or P limited (Figure 4). Two potato foliage samples from different managements in the agroforestry site were situated in the middle domain of the ternary plot; these two cases had nutrients ranges of 4.1–4.3% N, 0.25% P, and 3.4–3.7% K, all above critical thresholds.

4. Discussion

Bean and potato nutrition in cultivated soils in Fort Albany were adequate for N, Mg and Ca, but deficient in P and K. Different management techniques (sole versus intercropped) did not appear to affect crop nutrition. This study trial examined one cultivar for each crop within a single design of intercropping. Cultivar traits, crop density, configuration, and spacing all contributes to how two or more intercrops interact below and aboveground which impacts nutrient availability and overall field performance [16,22,28]; further investigation on bean–potato intercropping management is required to maximize positive (facilitative) interactions.

Crops grown under agroforestry conditions had significantly greater P compared to open sites. Conversely, the K content of bean plants in the open site were significantly greater, leading to a concomitant significantly greater K:P ratio for bean plants in the open site. These results provide direction for nutrient management plans and future studies for subarctic cultivated soils, specifically to improve crop acquisition of P, and to address the need for K supplementation.

4.1. Nitrogen Mineralization Occuring in Subarctic Cultivated Soils

Organic soils are known to be acidic, minimalizing microbial decomposition and having high organic matter content with >30 C:N ratio immobilizing N; these are two characteristics that hinder N plant availability [44]. In our study, the organic soil was atypical with a pH of 7.7 and a C:N ratio of ~15 that is ideal for N mineralization. Bean plant and potato foliage [N] were above the critical value of N deficiency.

Bean plant samples had greater variation in [N] and had some samples under the critical value. The varying and lower [N] values found in bean plants compared to potato foliage may relate to sampling biases comparing whole bean plant to critical values specified for foliage samples [37]. Bean roots examined in the agroforestry site had nodulation while the open site bean roots did not have nodule presence. Notwithstanding this difference, there were no significant differences in bean plant N concentrations between sites or management practice. However, this observation may provide some indication of different microbial community structures and networks between the two sites, with communities in the agroforestry site expressing more facilitative interactions. From a physio-chemical perspective, nodule establishment is hindered in soils with low phosphorus and high calcium and nitrate concentrations [45]; similar soil nutrient conditions may be an influential factor to nodule presence or lack thereof in our current study.

4.2. Agroforestry Sites Had More Available Phosphorus

Phosphorus limitations are common in subarctic wetland regions [46] where the availability of P is inhibited by (i) the cool soil temperatures that slows microbial activity [13,46,47]; (ii) an alkaline pH that is ideal for Ca fixation to P preventing the availability of HPO_4^{2-} compounds [16,44,46]; and (iii) high CEC and pH properties of soil that encourage binding P to clay fractions and organic complexes [46].

Although there were many environmental factors that negatively impact phosphorus availability, potato foliage samples were near or above the critical limit for P at both the open and agroforestry sites. For both bean plant and potato foliage, the P was significantly greater in the agroforestry site than in the open site. These findings suggest that the willow thicket provides ecological services that improved the availability of P for bean and potato through tree root mechanisms, improved microclimate, and limited P runoff.

Willow species (Family Salicaceae) are characterized as calcicole species that have adapted to nutrient limitations where calcium is abundant [48]. One adaption mechanism of willows is secreting oxalic and citric acids from their extensive fibrous root system, solubilizing precipitated forms of P that were fixed to Ca [49–52]. In addition, willows have mutual symbioses with ectomycorrhiza and vesicular-arbuscular endomycorrhizae, allowing roots to increase the surface area for nutrient uptake, specifically N and P [19,53–55]. It may be that the greater [P] in agroforestry beans and potatoes partially relate to willows facilitating P through tree root–crop root interactions and enhancing mycorrhizal fungal networks [16,18,20,56]. Additionally, willow roots may provide available P to soil by obtaining nutrients deeper in the soil profile [16,19,56]. Within the willow tree, nutrients translocate and some are released and available for nearby crops when tree roots slough-off tissue during growth or when the roots die or decay [19,21].

Indirectly, the willow thickets may have improved P availability through nutrient cycling and enhanced microclimate [16]. The enclosed design used at the agroforestry site in Fort Albany was to shelter crops from cool winds and reduce nutrient runoff [19,21]. In the James Bay lowlands, spring flooding and high precipitation events increased risk of nutrient runoff and leaching. Unlike the open site, agroforestry sites had the mechanisms to reduce nutrient loss and close nutrient cycles by returning nutrients back to the soil via leaf litter [6,16,19,21]. Theoretically, the organic matter derived from the willows provided nutrients to the microbial community and the trees provided a favorable climate for increased microbial activity [57]. Windbreaks and agroforestry in temperate regions have been found to increase soil and air temperatures [15,57–59]. In general, microbial activity increases with soil temperature with a concomitant increase in N and P mineralization rates and availability for plant uptake [45–47]. The Fort Albany agroforestry site had warmer soil temperatures at 10 cm depth than the open site (Table 1), where the minimum (12.4 °C) was warmer by 1.5 °C, average (17.5 °C) was warmer by 2 °C, and maximum (26.7 °C) was warmer by 5 °C for the period between sowing and plant sampling. Taking into account that subarctic and arctic regions of the world have been and continue to be disproportionately impacted by global warming, the microclimates created by the windbreaks further enhance the once limiting temperature factor. Indeed these findings are similar to Foereid et al. [59] research in Denmark where soil temperatures were warmer up to 20 m from willow windbreaks compared to 100 m away in a field; however, close distances (5–10 m) from the wind break resulted in cooler temperature in the evening due to shading. In our study, lower P values obtained in the agroforestry site from both bean plant and potato foliage were found in plots situated near the southerly tree line, where the area was shaded during morning hours, which likely resulted in cooler temperatures, and less time for photosynthesis [59,60], reducing both the availability P and plants' ability to acquire P.

Few studies focus on the effect of agroforestry microclimate on P availability [60]; however, these studies are based in tropical climates [61,62]. Although our study does not identify causal factors improving P in the agroforestry sites, it is likely a combination of microclimate and biological factors contributed to the results and require further investigations.

4.3. Potassium Deficient Alkaline Soils Promote Nutrient Competition in Bean–Potato Intercropping Systems

The underlying limestone bedrock in James Bay lowlands is the predominant source of Ca and Mg in the soil. Soils that are sufficient in these two elements generally indicate high plant productivity potential; however, large pools of Ca and Mg often signify P and K growth limitations [46,63]. Results from Fort Albany for exchangeable soil nutrients [6,33] confirmed that both sites were low in P and K for agricultural purposes. Although agroforestry management may have mitigated P growth limitations, our study shows that K availability did not improve with the presence of willows. Historic drainage of peatland and intermittent flood events increases potential losses of exchangeable K through leaching [46].

Potatoes highly demand K for tuber development [64] and may have unintentionally obtained Ca; considering Ca was abundant in the soil, both crops [Ca] exceeded critical limits, and cation competition between K, Ca, and Mg for plant uptake is well known [46,65]. Intercropping bean and potatoes at both sites where K is fixed to clay particles and organic complexes may have resulted in competition between the two crops for the nutrient and potato roots likely obtained Ca and Mg when attempting to meet its demand for K.

4.4. Future Research on Local Phosphorus and Potassium Fertilizer in Northern Calcareous Soil

Enhancing microclimates and biological interactions may have improved P availability in the calcareous soil, but further P and K fertilization is required for continued gardening maintenance and improving yields. Considering the remote location of the community, the production of local fertilizer was necessary. In 2015, a 1.6 m^3 turning batch composter (Actium Resources Ltd., Seaforth, ON, Canada) was introduced in the community to provide mostly locally sourced organic materials [66]. Composted local materials sourced specifically for P were ground bones from Canadian geese (*Branta canadensis interior*) and snow geese (*Chen caerulescens caerulescens*)—two species that are traditional diet staples of the James Bay region. Additional K for composting was sourced from wood ash [67,68]—a by-product of traditional cooking. Both wood ash and bone meal are accessible in the region; however, these sources also include calcium, which is already in the soil at high levels, and these sources will need to be added in moderation to prevent further increase in pH [68]. Compost additions to the top soil in late spring is ideal to limit nutrient leaching during thaw events, and to limit time for nutrients to bind to Ca and clay. Adding nutrients in the form of organic matter has been found to increase P availability to plants [69] and delay P fixation to Ca [70]. Our research team is currently investigating the effectiveness of composting in Fort Albany to ameliorate P and K plant deficiencies in order to improve nutrient management for subarctic agricultural initiatives.

5. Conclusions

The use of willow windbreaks at our agroforestry site not only provided food in the form of beans and potatoes to combat food insecurity, but also provided ecosystem services. These ecosystem services included the improved availability of P, the potential of N fixation through the presence of nodules on bean roots, and microclimate temperature effects. The microclimate temperature effects are especially important, because temperature has always been a limiting factor with respect to agricultural activities in subarctic regions. With global warming disproportionately impacting subarctic and arctic regions of the world, and the projections that this trend will continue [71], agroforestry initiatives as described presently can be scaled up and scaled out. In the future, there is the potential that agroforestry practices can one day be used in the arctic dependent on treeline migration [72].

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/12/2294/s1, Table S1 displays ternary plot coordinates for nutrition limits for potato and bean, and Figure S1 consists of nutrient ternary plots for plant analysis of (a) bush bean, and (b) potato.

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Author Contributions: Leonard Tsuji, Meaghan Wilton, and Jim Karagatzides designed the study, interpreted the results, and wrote the manuscript. In addition, Meaghan Wilton conducted the in-field experiments, and Jim Karagatzides conducted the statistical analysis.

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