

Article

Soil Nutrient Supply in Cultivated Bush Bean–Potato Intercropping Grown in Subarctic Soil Managed with Agroforestry

Jim D. Karagatzides ^{1,*}, Meaghan J. Wilton ² and Leonard J. S. Tsuji ²¹ Engineering and Environmental Technologies, Georgian College, Barrie, ON L4M 3X9, Canada² Department of Physical and Environmental Sciences, University of Toronto, Toronto, ON M1C 1A4, Canada; m.wilton@utoronto.ca (M.J.W.); leonard.tsuji@utoronto.ca (L.J.S.T.)

* Correspondence: jim.karagatzides@georgiancollege.ca

Abstract: To address food insecurity in northern Canada, some isolated communities started gardening initiatives to reduce dependencies on expensive foods flown in to communities. From 2012–2014, soils in northern Ontario James Bay lowlands were cultivated with bush beans and potatoes, grown in sole and intercropping configurations, in an open field and an agroforestry system enclosed by willow trees. The objective of this study was to compare the supply rates of 15 plant-available nutrients in these soils using in situ ion exchange membranes. After three years of cultivation, the agroforestry site had significantly greater supply of PO₄, Ca, and Zn and these nutrients had positive correlations with yield. By contrast, the open site had significantly greater supply of Mg, SO₄, and B; these nutrients, and Al, had negative correlations with yield. Whilst there were no differences between sole and intercropping configurations, significantly greater supply of NO₃, Ca, Cu, Fe, and Zn occurred early in the growing season, compared to significantly greater supply of K, SO₄, B, and Al later in the season. Significantly greater yields have been harvested in the agroforestry site and it is suspected that the presence of a willow shelterbelt improves the microclimate and plant-available PO₄, Ca, and Zn.

Keywords: nutrient supply rate; subarctic agriculture; agroforestry; bush bean; potato; northern agriculture management; ion exchange resins; PRS probes



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1. Introduction

Agriculture is expanding northwards as global warming increases air temperatures and lengthens growing seasons in the higher latitudes [1,2]. The forms of northern agriculture occurring include intensification within existing areas, and extension to new or historically cultivated areas [1,3,4]. In some subarctic communities of Canada, agriculture is being introduced as a climate change adaptation strategy to improve food sufficiency and mitigate current food insecurities [3–5]. There is also an increasing international interest in northern food production to abate anticipated global food insecurities [1,2]. Both assessment and development of adaptive northern agricultural practices are currently lacking yet are imperative for high-latitude food production initiatives to become sustainable strategies [1,2]. There are concerns that northern agriculture growth, without adapted practices, would negatively impact environmental health, including the deterioration of biodiversity, increased carbon losses, and adverse effects on water and nutrient cycles [1,2]. These concerns are compelling as agriculture expands into the boreal ecoregion—which consists of vast forests and wetlands.

A survey on climate change and northern expansion of agriculture found that investigating nutrient cycles was voted as highly relevant by participating researchers [1]. Having a greater understanding of nutrient cycles and dynamics for agriculture in the boreal deciphers the impacts of land conversion and supports the creation of policy and

best management strategies [1,2,5]. Recently, Kedir et al. [5] assessed nutrient conditions within sandy, acidic boreal soils under agricultural management across Newfoundland and Labrador, Canada, and determined N and P inefficiencies. This nutrient assessment gives guidance for creating a regional nutrient management plan for other regions with similar soil characteristics but is not transferable to all soil types within the boreal, such as the contrasting soil pH and texture of our study in the James Bay Lowlands region of the Canadian Boreal.

The present study assesses the bioavailability of macro- and micronutrients across a growing season in calcareous silty loam soil, cultivated with bush bean (*Phaseolus vulgaris* L.) and potato (*Solanum tuberosum* L.) under open and agroforestry (tree-based) management practices. Agroforestry is the practice of combining woody perennials (e.g., trees, shrubs) with herbaceous crops (plants or pastures) or livestock, in spatial and temporal arrangements [6,7]. There are many forms and designs of agroforestry to meet specific ecological, environmental, economic, or cultural needs [6,7]. Agroforestry research that addresses food security and environmental issues has been more pronounced in (sub)tropical systems than temperate systems [6,7]. In comparison, agroforestry research in boreal settings is minimal. Peer-reviewed studies on boreal agroforestry have examined silviculture—an agroforestry practice that controls forest growth and structure to produce value-added products—such as for timber, biofuel [8,9], and non-timber forest products [10]. In our study site, agroforestry was initially utilized in the form of a shelterbelt to protect bean and potato crops from cold wind [11]. Shelterbelts comprise row arrangements where the distance between rows varies depending on the agrosystem and its purpose. In temperate climate systems, shelterbelts protect crops, pasture, and livestock by minimizing wind, erosion, nutrient run-off, and snowdrifts, and regulating temperature and moisture [6,7]. To our knowledge, utilizing shelterbelts to support the production of fruits and vegetables in the subarctic climate has been undertaken only in the Fort Albany First Nation.

Potato and bush bean were chosen for our study as the far-north remote community wanted to grow fruits and vegetables locally under ambient conditions and be less reliant on imported produce [12,13]. Moreover, potato and bush bean have practical and nutritional purposes. Historical records indicate that potato was briefly cultivated in the region. Additionally, potato is considered a world crop staple, and it grows well in cool and wet climates [14,15]. Bush bean was selected because it is fast-growing, can withstand cooler temperatures, and is a legume that permits nitrogen fixation [13,16]. Both potato and bean are crops used within intercropping systems—the practice of cultivating two or more crops simultaneously on the same field [17]. In some regions, potato is intercropped to mitigate the high risks associated with this high-valued crop [17]. Intercropping with bean is frequently applied to reduce nitrogen fertilization requirements when used in conjunction with non-N-fixing companion crops [16]. The combination of potato–bean as an intercrop is not frequently used [17]. Nevertheless, Sharaiha and Battikh [17] and Gitari et al. [18] found that the bean–potato combination improved the equivalent yield in semi-arid and subtropical climates. At our subarctic study location, Barbeau et al. [13] found bean–potato intercrops increased yields significantly when implemented with agroforestry (as opposed to an open field).

Both intercropping and agroforestry practices have features that enhance agroecosystem services (i.e., enhancing biodiversity, microclimates, and soil formation) and resource efficiencies (i.e., supporting natural pest management and nutrient cycling) [7,16,19]. The services provided from intercropping and agroforestry that improved yields at the Fort Albany First Nation site are not known. Previous studies used soil-extractable nutrients to assess soil fertility [3,11] and foliar macronutrient concentrations of bush bean and potatoes [20]. However, Spiegelaar et al. [11] expressed that there may be a discrepancy between the amount of nutrients extracted from the soil and the actual nutrient uptake by crops due to the uncommon subarctic environment conditions for cultivating soils.

In this study, we examine if agroforestry and intercropping management practices provide soil nutrient advantages compared to cultivating in an open field and sole crop-

ping. Secondly, we test for correlations between soil nutrient supply rate and yield and plant nutrition. This study provides information that contributes to developing knowledge on northern agroecosystems and insights into different management practices in a subarctic climate.

2. Materials and Methods

2.1. Location

The research location was in the boreal community of Fort Albany First Nation (FAFN), which resides in Mushkeguwuk Cree territory on the west coast of James Bay, Ontario (52°30'64" N; 81°72'77" W). The region's terrain is described as flat, 14 m above sea level, and dominated by muskeg or peat moss situated on limestone bedrock. The region is in a subarctic climate (Köppen climate classification Dfc) with mean annual daily temperatures of $-0.5\text{ }^{\circ}\text{C}$, and mean total annual rainfall of 503 mm and snowfall of 227 cm (1981–2010) for Moosonee, ON [21], the nearest weather station 125 km southeast. The frost-free growing period during this study in 2014 was 94 days from 21 June to 22 Sept (Julian day of year (DOY) 172–265).

Two sites were constructed for agriculture in 2012—an agroforestry site (A), and an open field site (O; Figure 1). Historically, the sites were boreal forest that were cleared in the 1930s and drained for agriculture production until the 1970s. The fields became disused and progressed naturally as grasslands [11]. In the Agroforestry section, willows (*Salix* spp.) had naturally grown for 40 years in thicket rows along manually made drainage ditches. The two willow thicket rows utilized for the Agroforestry site ran parallel from southwest to northeast and were approximately 5 m in height and 6 m wide with a $15 \pm 3\%$ optical porosity [22]. The cultivated study area was within the 14 m space that separated the two thickets. The Open site was located 200 m southwest of the Agroforestry site, 58 m from the nearest tree, and surrounded by grassland. Additional details on the location history and site description are in Wilton et al. [20].

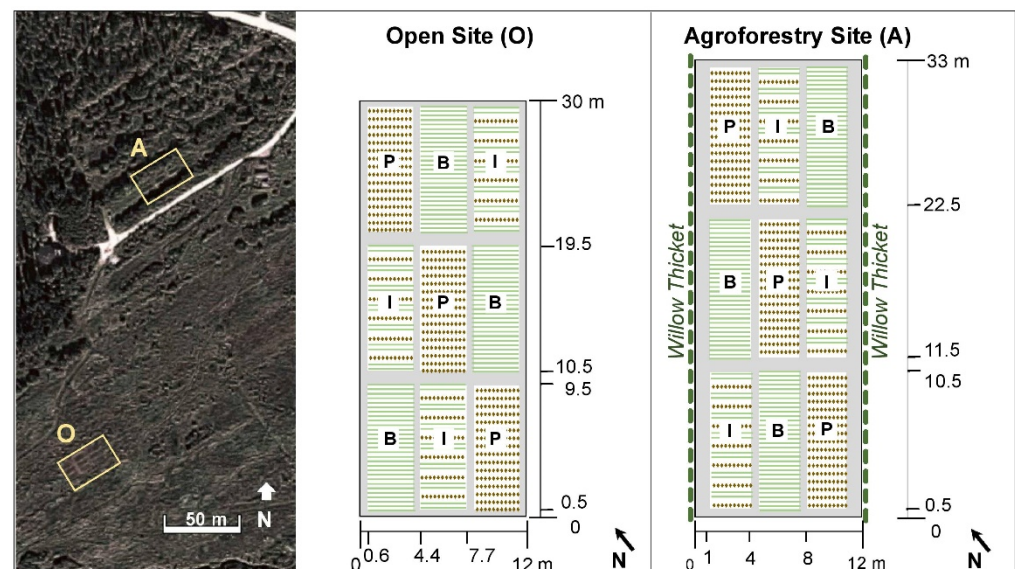


Figure 1. Location of Open (O) and Agroforestry (A) sites where PRS probes were used in Fort Albany First Nation, Ontario (left, map modified from Google Earth, 2017, DigitalGlobe, Westminster, CO, USA). Plot schematics are management practices for sole cropping of bush bean (B, green lines) or potato (P, brown dots) and bean–potato intercropping (I). Figure modified from Wilton et al. [20].

The soils at both the Agroforestry and Open site had a silty loam texture consisting of 18% sand, 66% silt, and 16% clay [20]. The physical characteristics of soil (0–20 cm depth) at each site were similar for pH (A = 7.7, O = 7.6), bulk density (A and O = 0.66 g cm^{-3}), C/N ratios (A = 15, O = 16), and cation exchange capacities (A and B = $41\text{ cmol} + \text{kg}^{-1}$) [20].

The seasonal mean soil temperature and moisture content at 10 cm depth were 17.5 °C with a standard deviation of 2.8 °C and $0.34 \pm 0.052 \text{ m}^3 \text{ m}^{-3}$ in the Agroforestry site, and $15.4 \pm 2.8 \text{ °C}$ and $0.37 \pm 0.023 \text{ m}^3 \text{ m}^{-3}$ in the Open site. No fertilizer amendments had been added to the sites since being established. Though supplementing the soil with nutrients is essential for agriculture production, there is value in studying subarctic soils and management practices before the inclusion of agricultural inputs [6].

2.2. Site Preparations

A Latin square was used for the experimental design to account for variation due to tree effects (i.e., edge and shading effects). The Open site dimensions were 30 m × 12 m compared to 33 m × 12 m for the Agroforestry site, which also had an additional 1 m wide border from the willow treeline (Figure 1). Each site had 3 rows and 3 columns (totaling 9 sub plots per site), and therefore the subplot dimensions were 9 m × 3.3 m in the Open site, and 10 m × 3 m in the Agroforestry site.

Sites were rototilled (Troy-Bilt Rear Tine Tiller 208 CC, OH, USA) at 15 cm depth from 16 June to 19 June of 2014 (DOY 167–170). Within each plot, there were three crop management treatments: sole cropped bean (Provider Var.), sole cropped potato (AC Chaleur Var.), and row-intercropped bean and potato. Each treatment was assigned a subplot randomly in each of the three plots in each site. Potatoes were planted in rows on June 24 (DOY 175) at 10 cm depth. Sole cropped potato had a row seeding density of 3.5 tubers m^{-1} with an inter-row spacing of 60 cm. Bush bean was sown in rows at a planting depth of 3 cm on 26 June (DOY 177). The seeding density was 30 seeds m^{-1} with a 20 cm inter-row spacing in the sole cropped bean treatment. The row ratio was 1 row potato to 2 rows of beans for the intercropping treatment. Both potatoes and beans in the intercropping subplots maintained seeding row densities: bean–bean inter-row was 20 cm, and the bean–potato inter-row was 60 cm. Wilton et al. [20] describe the leaf content of N, P, K, Ca, and Mg for these crops.

2.3. Ion Exchange Resin Probes

Plant root simulator (PRS) probes (Western Ag Technologies, Saskatoon, SK, Canada) were used to quantify the plant-available nutrient supply rate for soil ions in each plot for each site [23]. The advantage of using PRS probes is that they act as an analog for root uptake of bioavailable nutrients. They can also be used on a broad range of soils within different environments [24], and they are practical tools to utilize at remote research sites. The PRS probes consist of a two-sided anion or cation exchange membrane with a surface area of 176 cm^2 . Positively charged anion probes adsorbed NO_3^- -N, phosphorus in the form of H_2PO_4^- , and SO_4^{2-} , while negatively charged cation probes adsorbed NH_4^+ -N, K, Ca, Mg, B, Al, Cd, Cu, Fe, Mn, Pb, and Zn. Within a one-meter border of each plot, three pairs of cationic and anionic PRS probes were vertically inserted randomly into the soil to 10 cm depth on 16 June to 24 June (DOY 167–175), 31 July to 8 August (DOY 212–220), 31 August to 7 September (DOY 243–250), and 26 September to 3 October (DOY 269–276). Probes were left in the soil for 7 or 8 days as determined by consultants at Western Ag using soil-extractable nutrient results found for the same study plots [3].

After removal, the probes were rinsed with reverse osmosis-treated water to remove soil particles, refrigerated at 4 °C, and shipped to Western Ag Technology, Saskatoon, Canada for analysis. Nitrogen compounds were determined colorimetrically using an automated flow injection system, and all other nutrients measured using inductively coupled plasma spectrometry. Results are expressed as the weight of nutrient adsorbed to the surface area of the ion exchange membrane (adjusted to 10 cm^2) over the burial duration (8-day burials adjusted to 7 days) as dividing the time into smaller units is invalid since the adsorption was unlikely to be linear over time.

2.4. Statistical Analysis

Statistical analyses were completed using SPSS 26 [25]. Each nutrient extracted from the PRS probes was assessed in a 3-way analysis of variance (ANOVA) for the main effects of site (Open, Agroforestry), crop (bush bean sole cropping, potato sole cropping, intercropping), month (June, August, September, October), and all possible 2-way and 3-way interactions. The Student–Newman–Keuls (SNK) post hoc test was used to distinguish significant differences among treatments and months. Levene’s test on the variances using the median revealed that variances were homogeneous for all nutrients ($p > 0.2$). Linear correlations were obtained for leaf tissue chemistry for each crop on 10 August 2014 [20] against the nutrient supply rate for June and August. Linear correlations were also obtained for total annual crop yield and total nutrient supply rate across the growing season (the sum of PRS data for the four time periods).

3. Results

3.1. Spatiotemporal Soil Nutrient Supply Rate in Agroforestry and Open Sites

Although there was substantial variation for the nutrient supply rate (e.g., Open site: NO_3 in Sept and B in Oct; Agroforestry site: Mn and Cu in June, Fe in August)—likely because of the small sample size ($n = 3$) of PRS probes sampling a heterogeneous soil environment across a growing season—many significant differences were observed. There were significant differences between Agroforestry and Open sites for six of 13 nutrients and significant seasonal differences for nine of 13 nutrients, as well as three significant interaction effects between site and month main effects (Table 1). However, there were no significant differences among the three crop treatments nor for any interaction effect with crop. Additionally, the supply rate of $\text{NH}_4\text{-N}$, Pb, and Cd was excluded from this analysis because >70% of samples collected for each nutrient were below detection limits (DL). For $\text{NH}_4\text{-N}$ (DL = 2 ppm) and Pb (DL = 0.2 ppm), only samples collected in June were above the detection limit. For Cd, only two of 72 samples collected across the four sampling periods had detectable levels of Cd (DL = 0.2 ppm).

Nitrate supply rates were similar between sites, but a significant seasonal difference was found for June, with rates 75% greater than at other times of the growing season (Figure 2). In contrast to N, the supply rate of soil $\text{PO}_4\text{-P}$ did not reveal seasonal differences, but the Agroforestry site had a significantly greater (nearly double) supply rate of $\text{PO}_4\text{-P}$ compared to the Open site.

Soil K was one of only two nutrients (B being the other) where the supply rate was significantly greater later in the season, with a 50% increase in K measured in October compared to June (Figure 2). There was also a significant site \times month interaction effect: compared to the Agroforestry site, the Open site had a greater supply rate of soil K in June but a significantly smaller supply rate of K in August and October. Similar to K, B had a significantly greater supply rate at the end of the growing season—nearly double the supply rate in October compared to earlier sampling periods. The significantly greater supply rate of B in soil during October was influenced by the Open site and led to the significant site \times month interaction effect for soil B ($p = 0.001$). Regardless of crop type, the Open site had, on average, a 52% greater supply rate of B than that measured in the Agroforestry site.

Table 1. Results from three-way ANOVA (*F*- and *p*-values) for soil nutrient supply rates ($n = 3$ cationic and anionic PRS probes per site \times crop \times month) in cultivated sites in the subarctic community of 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 crop treatment was either sole planting (bush bean or potato) or a bean–potato intercrop. Bold font indicates significant difference $\alpha = 0.05$.

	Site	<i>p</i>	Crop	<i>p</i>	Month	<i>p</i>	Site \times Crop	<i>p</i>	Site \times Month	<i>p</i>	Crop \times Month	<i>p</i>	Site \times Crop \times Month	<i>p</i>
NO ₃	2.19	0.146	0.93	0.402	5.25	0.003	0.26	0.774	2.656	0.059	0.295	0.937	0.19	0.978
PO ₄	31.23	1.1 \times 10⁻⁶	0.11	0.898	1.01	0.395	0.02	0.980	1.41	0.251	1.74	0.133	1.13	0.359
K	0.85	0.361	0.74	0.485	3.57	0.021	0.87	0.426	3.82	0.016	1.24	0.301	0.82	0.557
Ca	9.59	0.003	0.32	0.730	4.58	0.007	0.60	0.556	0.60	0.615	0.70	0.648	2.08	0.073
Mg	61.22	4.1 \times 10⁻¹⁰	1.18	0.316	0.88	0.456	1.854	0.168	0.91	0.445	0.69	0.659	1.37	0.247
SO ₄	301.76	2.4 \times 10⁻²²	0.38	0.683	4.89	0.005	0.36	0.699	6.29	0.001	0.47	0.829	0.099	0.996
B	4.90	0.032	0.59	0.561	3.32	0.027	1.06	0.354	6.02	0.001	0.19	0.979	0.46	0.837
Al	3.44	0.070	1.61	0.211	4.34	0.009	0.45	0.639	0.57	0.637	1.39	0.240	0.69	0.659
Cu	1.22	0.274	0.28	0.756	5.32	0.003	0.53	0.593	2.08	0.116	0.25	0.956	0.59	0.737
Fe	1.68	0.201	0.38	0.685	4.28	0.009	0.81	0.450	0.89	0.454	0.53	0.780	0.43	0.855
Mn	2.81	0.100	0.94	0.398	1.79	0.162	1.29	0.285	0.78	0.511	0.66	0.678	0.88	0.517
Zn	28.08	2.9 \times 10⁻⁶	1.74	0.187	43.50	9.9 \times 10⁻¹⁴	0.26	0.773	2.75	0.053	0.78	0.594	0.98	0.449

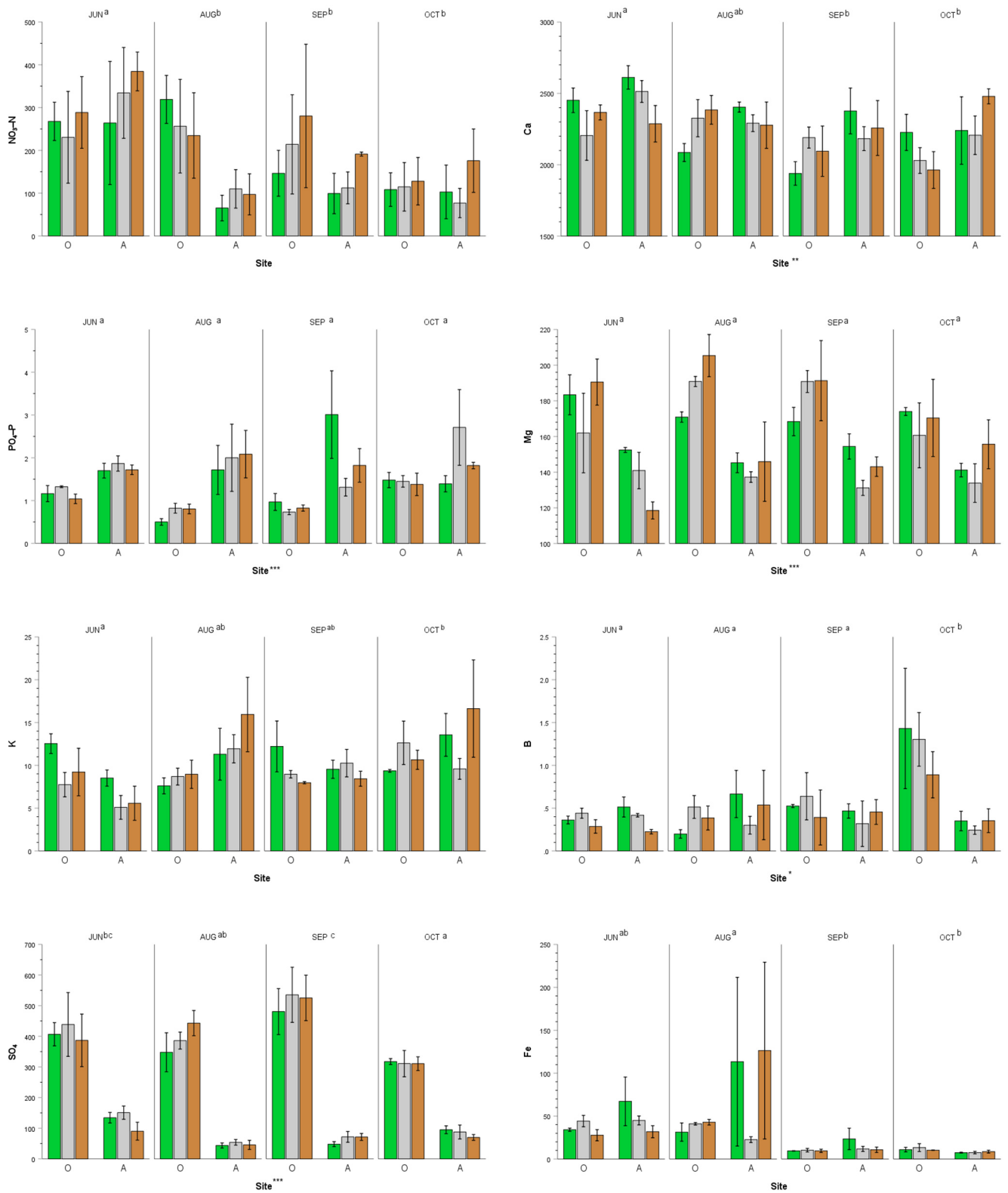


Figure 2. Cont.

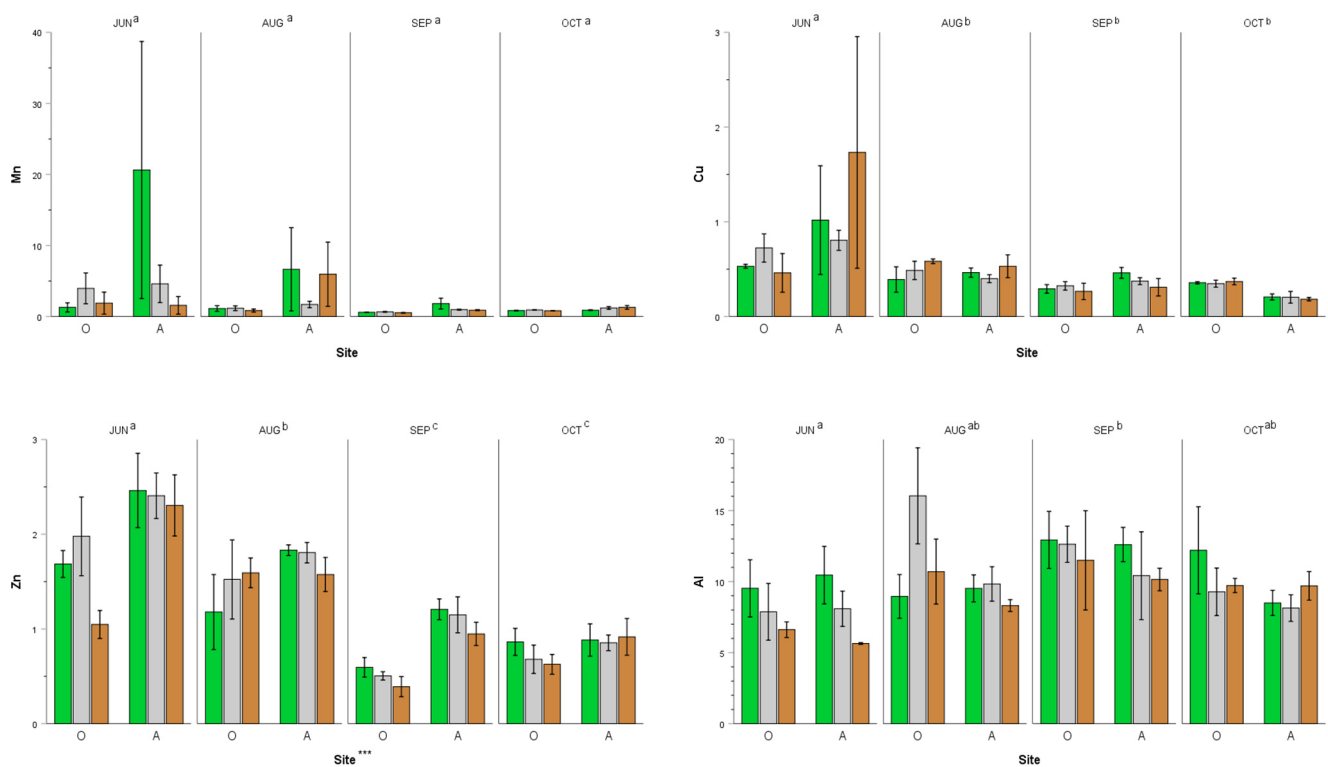


Figure 2. Comparisons of mean (± 1 SE, $n = 3$) soil nutrient supply rate ($\mu\text{g } 10 \text{ cm}^{-3} \text{ week}^{-1}$) in Open and Agroforestry sites in Fort Albany (James Bay, Ontario). Supply rate was measured in soil planted with bush bean (green), potato (brown), and intercropped (gray), during the 2014 growing season. Within each figure panel, significant differences between sites are shown with asterisks (* $p = 0.05$, ** $p = 0.01$, *** $p = 0.001$), and lowercase letters for temporal differences whereby months with different letters are significantly different ($p < 0.05$, SNK post hoc test). There were no significant differences among the three types of crop plantings.

Contrasting patterns in the spatial and temporal supply rate were found between soil Mg and Ca (Figure 2). A small but significant difference in soil Ca supply rate between sites (Agroforestry had $\sim 7\%$ greater Ca supply rate than soil in the Open site) but the opposite trend was found for soil Mg with $\sim 25\%$ greater supply rate in soil in the Open site. In addition, whilst there were no significant seasonal differences for soil Mg, there was a 10% greater supply rate of soil Ca in June compared to September and October.

The supply rate of SO_4 represents one of the largest differences between sites as soil in the Open site had five times greater supply rate of SO_4 compared to the Agroforestry site (Figure 2). Sulfate was also the only soil nutrient with significantly greater supply rate measured in September, which on average was 33% greater than in August and 50% greater than the SO_4 supply rate measured in October. There was also a significant site \times month interaction effect for SO_4 , likely the result of the lower supply rate in October in the Open site, compared to the other sampling periods, which produced the smallest difference between sites in October.

For the five metals (Fe, Mn, Zn, Cu, Al), there were no significant differences between sites, apart from Zn where the supply rate in the Agroforestry soil was $\sim 44\%$ greater than in the Open site when averaged across the growing season (Figure 2). There were, however, significant seasonal differences for four of the five metals, the exception being Mn (Table 1). The supply rate of Fe was nearly five times greater in August than in September and October, driven largely by the greater supply rate of Fe in Agroforestry site soil than in the Open site. Similar to Fe, the supply rate of Zn was two times greater in August compared to later in the growing season, and June had an even greater supply rate of Zn in soil (25% greater in June than in August). The supply rate of Cu in soil also was significantly greater in June—2- to 3-fold greater in June than in other sampling periods—and, like Fe, driven

by the substantially greater increase in the Agroforestry site. In contrast to the other metals, the supply rate of Al was significantly lower in June compared to September, with an average increase of ~45% from June to September.

3.2. The Relationship between Soil Nutrient Supply Rate and Leaf Tissue Chemistry

There were only two significant correlations for each of bush bean and potato between soil nutrient supply rate in June or August and leaf tissue chemistry (Table 2). Significant positive correlations with leaf nutrient concentration in bush bean were found for soil supply rate of PO₄ in June ($r = 0.60$, $p = 0.04$) and for Zn in August ($r = 0.76$, $p = 0.004$). Likewise for potato, a significant positive correlation was found for the supply rate of PO₄ and potato leaf P concentration, though in this case the relationship was significant with the supply rate of both June ($r = 0.71$, $p = 0.01$) and August ($r = 0.69$, $p = 0.01$; Table 2). In addition, there was a significant negative correlation between the supply rate of Ca in soil and potato leaf ($r = -0.58$, $p = 0.05$).

Table 2. Correlations (two-tailed, $n = 12$) of soil nutrient supply rate with leaf chemistry and yield in Fort Albany (James Bay, Ontario) during the 2014 growing season. Correlation with yield is for the sum of the soil supply rate measurements in June, August, September, and October. Bold font indicates significant differences at $\alpha = 0.05$.

Bush Bean		June PRS + Leaves		August PRS + Leaves		Yield	
Soil	<i>r</i>	<i>P</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	
NO ₃ -N	0.57	0.06	0.28	0.38	0.05	0.88	
PO ₄ -P	0.60	0.04	0.25	0.42	0.56	0.06	
K	0.45	0.14	0.14	0.66	-0.16	0.61	
Ca	-0.27	0.40	0.41	0.19	0.72	0.01	
Mg	-0.20	0.53	-0.37	0.23	-0.28	0.38	
B	-0.05	0.44	0.16	0.31	-0.20	0.54	
Fe	-0.22	0.50	-0.01	0.99	-0.22	0.50	
Mn	-0.21	0.52	-0.24	0.46	-0.15	0.64	
Zn	0.52	0.08	0.76	0.004	0.70	0.01	
Cu	-0.15	0.65	-0.34	0.28	-0.30	0.35	
Al	-	-	-	-	0.16	0.63	
SO ₄	-	-	-	-	-0.54	0.07	
Potato		June PRS + Leaves		August PRS + Leaves		Yield	
Soil	<i>r</i>	<i>p</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>p</i>	
NO ₃ -N	0.50	0.10	0.43	0.16	-0.05	0.88	
PO ₄ -P	0.71	0.01	0.69	0.01	0.72	0.01	
K	0.06	0.84	0.13	0.69	0.26	0.42	
Ca	-0.03	0.92	-0.58	0.05	0.36	0.25	
Mg	0.46	0.14	0.34	0.28	-0.61	0.04	
B	-0.10	0.75	0.06	0.87	-0.54	0.07	
Fe	-0.08	0.80	-0.24	0.44	0.46	0.13	
Mn	-0.30	0.34	-0.19	0.55	0.42	0.18	
Zn	-0.12	0.72	0.25	0.44	0.51	0.09	
Cu	-0.06	0.85	0.26	0.42	0.60	0.04	
Al	-	-	-	-	-0.81	0.002	
SO ₄	-	-	-	-	-0.79	0.002	

3.3. The Relationship between Soil Nutrient Supply Rate and Yield

Significant positive correlations between the June + August rate of soil nutrient supply with bush bean yield were found for Ca ($r = 0.72$, $p = 0.01$) and Zn ($r = 0.70$, $p = 0.01$; Table 2). More correlations between soil nutrient supply rates and yield were found for potato than for bean (Table 2). Significant positive correlations were found with PO₄ ($r = 0.72$, $p = 0.01$) and Cu ($r = 0.60$, $p = 0.04$), as well as significant negative correlations with the supply rate of Mg ($r = -0.61$, $p = 0.04$), SO₄ ($r = -0.79$, $p = 0.002$), and Al ($r = -0.81$, $p = 0.002$).

4. Discussion

The objective of this study was to measure spatiotemporal supply rates for 15 nutrients in open and agroforestry (treed shelterbelt) sites in a northern Ontario community, as a potential factor leading to the greater yield of bush bean and potato previously found in this agroforestry garden [3,15]. The Agroforestry site had significantly greater nutrient supply rates for $\text{PO}_4\text{-P}$, Ca, and Zn, and these nutrients had positive correlations with crop yield. By contrast, the Open site had a significantly greater supply of Mg, SO_4 , B, and Al, and these nutrients had negative correlations with crop yield. Whilst there were no differences among crop treatments, temporal differences in nutrient supply rates were revealed: a significantly greater supply of $\text{NO}_3\text{-N}$, Ca, Cu, Fe, and Zn occurred early in the growing season, compared to a significantly greater supply of K, SO_4 , B, and Al later in the growing season. In addition, four significant correlations were found between nutrient supply rate and tissue nutrition. Positive correlations were found between P and Zn for bean. While a positive correlation was also found for soil and tissue P in potato, there was a negative correlation between soil and leaf tissue Ca for potato. Below, we describe the implications of these spatiotemporal differences in soil nutrition supply rates for the differences observed in crop yield.

4.1. Agroforestry Sites Had Greater Supply Rates of Phosphorus, but It Is Still Inadequate for Maximum Crop Yield

There was a greater supply rate of $\text{PO}_4\text{-P}$ in soils in the Agroforestry site and significant positive correlations ($p \leq 0.05$) of $\text{PO}_4\text{-P}$ supply with potato yield and for tissue concentrations of P in both crops. Wilton et al. [20] also determined that leaf P in the Agroforestry site was significantly greater than in the Open site, but leaf N:P ratios indicated deficient amounts of P in the foliage of bean and potato, suggesting that the greater supply of P in the agroforestry plots may still be inadequate for maximum yield. Indeed, the amount of $\text{PO}_4\text{-P}$ adsorbed on the PRS probes was considerably lower than the median value of $6 \mu\text{g P}/10 \text{ cm}^2/\text{week}$ found in the Western Ag agriculture soil database [23].

Small P adsorption is not unexpected in subarctic wetland regions, such as the James Bay lowlands, where cool soil temperatures slow microbial activity, reducing P mineralization and availability [26–28]. At our research location, soil temperature at 10 cm depth indicated that the Agroforestry site was $+2.1 \text{ }^\circ\text{C}$ warmer than the Open site for the period between sowing and harvest [20]. Other agroforestry studies set in temperate climates also observed increased soil temperatures and other microclimate-enhancing effects [6,29–32]. Under subarctic climates, the increase in soil temperature may have a greater impact on nutrient cycling than that observed in temperate climates. The effect of increased soil temperatures on microbial processes in northern Sweden determined that adding leaf litter to the subarctic soil and increasing the soil temperature by $1 \text{ }^\circ\text{C}$ increased soil bacterial growth rate and net mineralization of P [33]. Similarly, increasing soil temperatures by $0.9\text{--}2 \text{ }^\circ\text{C}$ doubled nematode populations, and increased microbial and fungal biomass, enhancing N and P mineralization and the nutrient availability to plants [34]. Utilizing agroforestry practices to improve soil fertility by enhancing soil microbial communities is promising [6]; however, research on the subject is limited [35], focused on tropical climates [36,37], and often contradictory or inconclusive [31,38–40].

Phosphorus limitations are common in calcareous soil [41] where the alkaline pH encourages P to be fixed to Ca, preventing the availability of HPO_4^{2-} compounds [27,41–43]. Additionally, large soil organic matter content and CEC, as seen at our study location, promote binding of P to clay fractions and organic complexes [44,45]. Though the soil had a high potential for fixing P, the root characteristics of willows may have facilitated improved P soil availability in the Agroforestry site. Willows adapt to a wide range of environmental conditions. For example, when grown in soils with high concentrations of Ca, willows secrete organic acids from extensive fibrous root systems [46] and thereby solubilize P precipitates fixed to Ca [42,43].

Another feature of willow (and many other tree species) to acquire P is the ability to explore large volumes of soil. Phosphorus and other immobile nutrients are located through the tree's expansive root networks and symbiotic relationships with ectomycorrhiza and vesicular-arbuscular endomycorrhizae [42,43,47]. Phosphorus acquired by willow can become available to nearby crops through leaf litter decomposition, tree root-crop root interactions, or from sloughed off tissue during the growth and decay of tree roots [6,43,48]. Rytter [49] calculated that the fine root biomass of willow grown in Sweden had annual growth of 900–7200 kg ha⁻¹ and decay of 500–6800 kg ha⁻¹ in a 0–50 cm deep soil profile, while Phillips et al. [50] monitored the root performance of willow poles (3 m unrooted stem cuttings) in a temperate climate and found that roots extended to 9 m within a 9-month period. Considering the willow trees were mature at our Agroforestry site, and the two thickets were 14 m apart, the tree root coverage likely extended into all cultivated plots within the treed site.

The correlations between P supply rates revealed a significant positive association ($p = 0.008$) for potato yield, suggesting that even a small additional supply of PO₄-P improves crop yield. We addressed this issue at Fort Albany by testing the effect of local compost on bush bean growth in a pot experiment. Wilton et al. [51] found that increasing amounts of this local compost significantly increased bean yield—both with the production of more beans per plant and larger individual bean mass.

Although our study does not reveal causal factors directly improving P in the agroforestry sites, it is likely that the willow thicket provides ecological services that improved the availability of P for bean and potato through tree root mechanisms and an enhanced microclimate. Theoretically, the organic matter derived from the willows provides internal recycling of nutrients to the microbial community [6,43].

4.2. Spatiotemporal Dynamics of Macronutrient Supply Rates in Subarctic Cultivated Soil

Nearly all the N collected on the PRS probes was in the form of NO₃-N as most of our samples had NH₄-N levels below the detection limit of 2 ppm. Nitrate levels were in the typical range of 10–600 µg/10 cm²/week for agricultural soils using the Western Ag PRS probes [23], particularly in June when the NO₃-N supply rate in the agroforestry site was >3 times the rate later in the growing season. The availability of soil N was reflected in the N concentrations in bean and potato leaf tissue that were generally above the critical level of 3% N [20].

The trend of smaller soil NO₃-N supply with time has been observed in other PRS probes studies [41,52]. They note that the seasonal decline in NO₃-N was influenced by increased root biomass, crop uptake, and loss through soil-emitted N. However, warmer temperatures can influence N loss through nitrate leaching [53,54]. Therefore, northern agriculture practices should consider mitigating NO₃⁻ entering waterways even when fertilizing is minimal. Applying agroforestry practices have been shown to reduce NO₃⁻ leaching [6,54–57]. Specifically, willows encompass a high filtering capacity for N and their root zone promotes denitrification [55]. It appears that utilizing willow thickets in the James Bay lowlands has great potential for managing potentially excess NO₃⁻ from agriculture initiatives, as these trees are fast-growing, adapt to the climate shifts, and can be a source of bioenergy [47,58–60].

In sharp contrast to NO₃-N, the supply rate of K was significantly greater later in the growing season. However, all soil K supply rates estimated in this study from different sites, times of year, and crop management methods were substantially less than the 40–370 µg/10 cm²/week rates found for agricultural soils using the Western Ag PRS probes [23]. Wilton et al. [20] also found K deficiency in leaf tissue for bean and potato. The small supply of K in June may indicate that environmental conditions earlier in the summer either do not produce sufficient K for plant growth or that the supply of K is below optimal crop requirements throughout the growing season.

Throughout the growing season, both sites had supply rates for Ca and Mg that were within the range reported for agricultural soils of 250–2700 µg Ca/10 cm²/week and

126–262 $\mu\text{g Mg}/10\text{ cm}^2/\text{week}$, occasionally approaching the maximum levels observed of 2700 $\mu\text{g Ca}/10\text{ cm}^2/\text{week}$ in agricultural soils [23]. However, there were spatial differences between these nutrients. The supply rate of Ca was significantly greater in the Agroforestry site (similar to $\text{PO}_4\text{-P}$ and Zn). In comparison, the Mg supply rate was significantly greater in the Open site (along with SO_4^-).

The predominant source of Ca and Mg at Fort Albany is from the underlying limestone bedrock [61]; having these two elements in excess can cause crop deficiencies in P and K [27,43,62]. Our findings from the adsorbed soil nutrients and results from exchangeable nutrients [3,11] confirmed that the soils have P and K deficiencies for agricultural purposes. Agroforestry management with willows may have mitigated P growth limitations, but it did not improve K availability. Both sites had historic drainage of peatland and are prone to annual spring flooding, which influences the loss of exchangeable K through leaching [27]. It is suspected that crops had to rely on K fixed to clay and organic complexes since the sites were never supplemented for nutrient losses [27,63,64]. Limited soil K may explain why foliar tissues for both crops had Ca and Mg concentrations exceeding critical thresholds for adequate growth [20]. In general, cation competition between K, Ca, and Mg can occur during plant uptake [27,44,65]. Hence, it is possible that potatoes unintentionally obtained Ca and Mg while acquiring K for tuber development [66].

Sulfur is important for crop production with many functions in the plant, including synthesizing proteins, enzymes, vitamins, and chlorophyll, and is a crucial component for nodule development in legumes [67]. Though sulfur deficiency is a common issue in agriculture production [67,68], the supply rates of SO_4^- indicate that this nutrient was abundantly available in the soils at our research location. The median SO_4^- soil supply rates adsorbed on PRS probes for agricultural soils is 40 $10\text{ cm}^{-1}\text{ week}^{-1}$ [23]. The Agroforestry site had adsorption rates that ranged from 30–221 $10\text{ cm}^{-1}\text{ week}^{-1}$, while the PRS probes in the Open site had adsorbed a significantly greater amount of SO_4^- , ranging from 249–737 $10\text{ cm}^{-1}\text{ week}^{-1}$. The source of the surplus SO_4^- is not confirmed; gypsum may exist deeper within the bedrock formation [69], or SO_4^- could be derived from the mineralization of organic matter in the cultivated soils or sourced from the surrounding peatland and wetlands [68]. The surplus of S can be beneficial in calcareous soils to improve the solubility and availability of Zn, Cu, Mn, P, and N and lower soil pH [67,70–72]. Conversely, S toxicity is not common but can occur [73]. In our study, the supply rate of S had a significant negative correlation with potato yield. The contrast in SO_4^- supply rates between the two sites suggests that agroforestry may aid in regulating S in the soil—this warrants further study when developing agriculture practices for the James Bay lowlands and other northern regions.

4.3. Spatiotemporal Dynamics of Micronutrient Supply Rates in Subarctic Cultivated Soil

There were also significant spatiotemporal differences among micronutrients at the James Bay study site. For example, we found a decreasing supply rate of Zn from June through October. Zn is least available in alkaline soil, and cold soils inhibit the uptake of Zn [74] (pp. 300–301) and both conditions occur in Fort Albany soil. However, we also found greater supply rates of Zn in the Agroforestry site where the average soil temperature was warmer than in the Open site [20]. Compared to other agricultural soils, the supply rate of Zn is adequate [23]. Zinc also had a significant positive correlation with the yield of bush bean ($p = 0.01$), a pattern consistent with $\text{PO}_4\text{-P}$ and Ca, the other nutrients with greater supply rates in the Agroforestry site. This suggests that the greater supply rate of Zn in the Agroforestry site may contribute to the increased yield.

Boron is an essential nutrient required in small amounts and can be toxic at slightly larger amounts [74] (p. 219). Though the supply rate of B is adequate compared to other agricultural soils [23], we found significantly greater B supply later in the growing season and a greater supply rate of B in the Open site—where previous work measured lower crop productivity [3,13]. Collectively, these results suggest that B levels in the Open site may be approaching toxic concentrations. As found for B, the greatest supply of Al occurred later

in the growing season and in the Open site. Compared to agricultural soils, the supply rate for Al was small [23], but Al still had a negative correlation with potato yield.

Similar to Zn, the supply rate of Fe and Cu were significantly greater in June and August compared to later in the growing season. Compared to agricultural soils, the supply of Fe was high [23], which may create P shortages through P fixation in acidic soils but not in soil with $\text{pH} > 7$ [45], the pH measured in both sites of this study. Lastly, compared to agricultural soils, the supply of Cu was adequate, as was the case for Mn [23]. Manganese was the sole nutrient without significant differences between sites, crop treatments, or across the months sampled, nor any significant interaction effects.

5. Conclusions

Agriculture is expanding to boreal communities adapting to a warming climate as a promising approach to replace food importation and to meet food security needs. Baseline information on subarctic land cultivation is essential to determine northern agriculture practices that are suitable for effective crop production and to mitigate potential environment and health risks. This study examined plant available nutrients with two types of low-input management technologies—willow agroforestry and bean–potato intercropping. Previous research found greater crop yield in agroforestry sites than in open sites [3,13] and our present study suggests that it is associated with greater soil supply of $\text{PO}_4\text{-P}$, Ca, and Zn, and a concomitant smaller supply rate of Mg, SO_4 , B, and Al. Intercropping bean with potato did not improve the availability of soil nutrients. Moreover, $\text{PO}_4\text{-P}$ and Zn had significant positive correlations with bean and potato yield, with the additional positive correlation between soil Ca and bean yield. Conversely, soils in the open site had significant negative correlations between the supply of Mg, SO_4 , B, and Al with potato yield (though not for bean). However, despite the greater supply of P in the agroforestry site, P (and K) deficiencies persist in cultivated soil in the James Bay lowlands of northern Ontario. In order to maintain crop production, additional nutrient supplementation appears to be crucial which can involve local composting initiatives [51]. Agroforestry in the form of a willow shelterbelt is a promising practice to utilize in the boreal region for many potential purposes, including protecting crops from wind, enhancing the microclimate, promoting biodiversity, and supporting wildlife habitats. Additionally, as observed in this study on calcareous silty loam soils, willow shelterbelts increased P bioavailability and potentially regulated and reduced N and S run-off.

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