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Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest

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Abstract
This study calculates the economic feasibility of converting biomass from black spruce forests into biochar and using it as soil amendment to grow potatoes (*Solanum tuberosum* L.) and beets (*Beta vulgaris* L.) to improve food availability in one of Canada's most consistently food insecure provinces. The trees were clear cut for the construction of the controversial Muskrat Falls hydroelectric dam and have been left to decay due to a lack of economically feasible processing options. A stochastic analysis conducted on a biochar production budget of a slow pyrolysis mobile biochar unit reveals fixed and variable cost estimates of \$505.14 Mg^{-1} and \$499.13 Mg^{-1}, respectively. Applying the biochar as a soil amendment for local beet or potato production makes the biochar venture profitable. Beet field trial data from the study region using 10 t C biochar application rates increases beet yield from 2.9 Mg/ha to 11.4 Mg/ha with a midline increase of 5.59 Mg/ha. A stochastic analysis with variable prices and yields shows a 0.99 probability of biochar production being profitable when applied to beets at the midline production rate, with an average annualized net return over variable costs of \$4,953 ha^{-1}, and maximum annualized net return of \$11,288 ha^{-1}, over variable costs. Potato production yields average annualized net returns of \$965.48 ha^{-1} over variable costs, but with much more downside risk, considering the minimum annualized net return of −\$318.82 ha^{-1} over variable costs. Biochar application covers average total costs for beets but not potatoes. Using biochar from forest biomass as a soil amendment presents an opportunity to create a local market for biochar in a remote area of Canada, where biochar may be used as an experimental soil amendment to improve food security.

KEYWORDS
agriculture, biochar, food security, Muskrat Falls, Newfoundland and Labrador, techno-economic analysis

1 | INTRODUCTION

Given the low levels of greenhouse gas emissions emitted in the energy production process, hydropower is often categorized as renewable or "clean energy" (Rausch & Mowers, 2014). Upon closer examination with Life Cycle Assessment, the carbon and methane created from the degradation of biogenic carbon in hydropower reservoirs indicate that the potential for climate change mitigation may not be as beneficial as hydropower proponents may lead the general public to believe (Hertwich, 2013). Moreover, remote, marginalized (often Indigenous) communities disproportionately endure the deleterious environmental impacts of hydroelectric dam development, including methylmercury contamination in rivers and streams (Calder et al., 2016; Keske, Mills, Tanguay, & Dicker, 2018). Although these megaprojects are often promoted as bringing regional economic development and employment, once the construction is complete and the transient labor force departs, the permanent residents are left to manage the environmental damages and a dramatically changed landscape.

The present study of a remote region in Labrador, Canada, is an example of a rural community that must manage the environmental impacts of clear-cut forest used for the construction of a hydroelectric dam project.

The study uses a stochastic, techno-economic analysis to calculate the economic feasibility of converting forest biomass from clear-cut black spruce into biochar. The proposed biochar enterprise is economically viable when the biochar is utilized as an agricultural soil amendment for crops that have exhibited preliminary success in agricultural field trials in the region (Abedin, 2015, 2018). Without agricultural coproduction, a biochar commercial venture would otherwise not be a financially sound investment due to lack of clear demand for biochar, which exhibits promising, but limited, efficacy. Likewise, in this case, the production of biomass markedly improves the chance of producing a profitable crop in the local region, resulting in a unique synergy that results in an economically feasible application of biochar.

The genesis for the economic feasibility study arises from the quandary of managing forest biomass cleared for the construction of the controversial Muskrat Falls hydroelectric dam within the province of Newfoundland and Labrador in Atlantic Canada. The dam site is located approximately 25 km west of Happy Valley-Goose Bay, a town with a population of 8,109 in central Labrador, shown in Figure 1. The Muskrat Falls mega-project is the most recent hydroelectric dam installment on Labrador's Churchill River (Canadian Broadcasting Corporation, 2019). More than 2.0×10^6 m^3 of wood, equivalent to approximately 1.25% of Canada's 2016 timber harvest, and more than 160% of the province's annual timber harvest (Natural Resources Canada, 2016), was cleared and left to decay beginning in 2012, to develop the hydroelectric mega-project to supply electricity to more heavily populated northeastern North America, including Montreal, Quebec, and the northeastern United States.

Since 2012, whole timber logs have rested at the main site, as well as in remote piles cleared for transmission line. Photographs of the clear-cut study area and log piles are provided.

Conditions in this cold and remote region are aligned to exploit biochar. There is a ready source of low-cost fuel through felled timber from the Muskrat Falls project. There is demand for responsive agricultural soils in the region, and the local population desperately needs income from economic development, as well as healthy, local food sources. Transportation costs stemming from region's remote location and harsh climate prohibit the cost-effectiveness of converting the timber into higher-value applications like dimensional lumber and engineered wood products (Moody, 1984). The wood has been available for public collection at no additional cost for years, with the provincial government even transporting the wood to more convenient pick-up areas for household use (Pardy, 2013; Province of Newfoundland and Labrador Forestry and Agrifoods Agency, 2015). The log piles that remain are a poignant example of a commodity that has

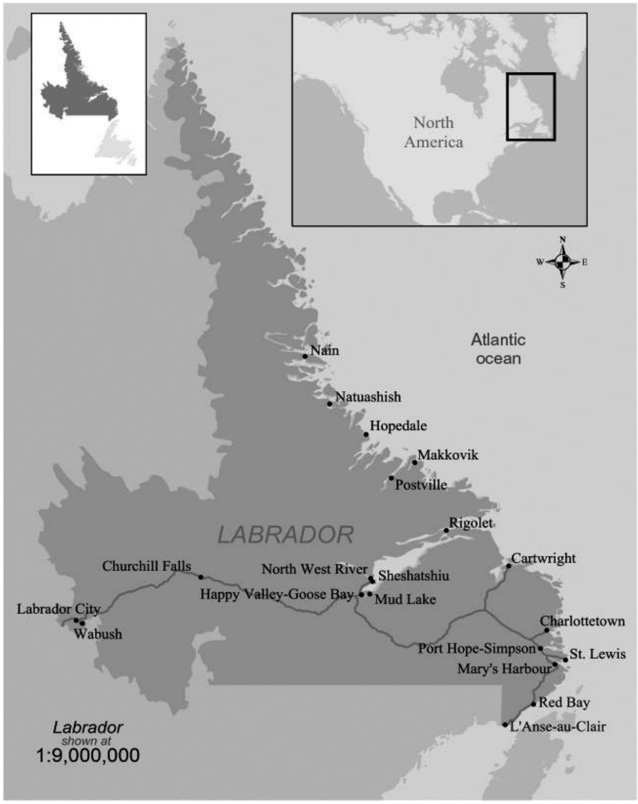

FIGURE 1 Map of Labrador. The proposed biochar facility is located west of Happy Valley-Goose Bay, shown in the center of the collage. The province of Newfoundland and Labrador, Canada's easternmost province, is depicted in the right-hand side of the collage. The upper left-hand diagram illustrates the scale of the two landmasses that comprise the province of Newfoundland and Labrador; Labrador is situated in eastern mainland Canada, just north of the Island of Newfoundland. There are no sawmills in Labrador. Though there is a sawmill in Newfoundland, transportation costs make lumber processing economically infeasible, which contributes to the study motivation to pursue biochar processing from black spruce forest. Cartography credit: Myron King and Morgon Mills

essentially been left for waste, as there are no sawmills in Labrador with capacity to process the wood (FORISK Consulting, 2019). In light of the lack of other economically viable options for using the logs, this study demonstrates the economic feasibility of converting the wood into biochar and using it as soil amendment for agricultural production to boost food production in one of Canada's consistently most food insecure provinces (Loopstra, Dachner, & Tarasuk, 2015). Moreover, more than 50% of the population in the study region is Indigenous, and the prevalence of food insecurity is estimated to affect 62%–83% of these households (Schiff & Bernard, 2018).

2 | METHODS

The breakeven, sensitivity, and stochastic analyses presented in this paper expand upon an Excel-based enterprise budget previously developed for a prospective biochar production project colocated at the Muskrat Falls hydroelectric megaproject site (Keske, Mills, Godfrey, Tanguay, & Dicker, 2018), which is slated to begin energy production in late 2019 or early 2020. In that article, the authors postulated that biochar and agricultural coproduction, incorporating biochar as a soil amendment, show potential as a profitable venture, which motivated the presenting research study. While biochar markets are slowly beginning to form across North America, additional scientific work is still needed to consistently predict the impact of different biomass feedstocks on various soil types. Hence, biochar production is considered a high-risk business venture. Furthermore, there are several site-specific considerations that would increase production costs of establishing a biochar operation in Happy Valley-Goose Bay. Among these is the remote location of the project site relative to other population centers where biochar may be sold as an experimental soil amendment. Quebec City, Montreal, and St. John's, the nearest population centers, are roughly between 1,500 and 1,700 km from the Muskrat Falls mega-project. Moreover, Labrador is subject to extreme cold and heavy snowfall during winter months. This would restrict biochar production operating times and would require char bagging and storage. Snow begins to accumulate in the fall, with an average depth of 1 cm at month end in October and 11 cm in November. For example, snow depth is still substantial in April, with an average of 45 cm, and the snow then melts to an average of 4 cm in May. Due to these conditions, an outdoor biochar operation would likely only be feasible from May 15 to November 15.

In order to recover fixed and variable costs of a biochar plant, the analysis presented in this paper expands the proposed biochar facility to include agricultural production using biochar as a soil amendment for growing beets (*Beta vulgaris* L.) and potatoes (*Solanum tuberosum* L.*)* in Happy Valley-Goose Bay, Labrador. The Newfoundland and Labrador provincial government is opening up Crown lands currently covered by boreal forests in order to boost local food production (Government of Newfoundland & Labrador, 2017), but these lands typically have very poor soils that require soil amendment for crop production (Abedin, 2018). The present study capitalizes on research in the region that examines the agronomic viability of using biochar as a soil amendment (Abedin, 2015, 2018). Beets and potatoes were selected because they can be grown in the region, they are commonly sold at grocery stores, and there is a strong potential for increased demand for freshly grown vegetables within the study area and across Labrador, which is considered extremely food insecure (Schiff & Bernard, 2018).

While the present study is based upon local field trials, many uncertainties remain. Therefore, this techno-economic study utilizes stochastic risk and sensitivity analyses

TABLE 1 Biochar production enterprise budget, Labrador, Canada (2015) baseline

Type of cost	Cost per unit ($)	Unit	Units per year	Cost per year ($)	Cost per tonne ($)
Variable costs					
Fuel, oil, and lubricants					
Diesel					
Truck	1.36	Liter	5,861	7,971	16.27
Horizontal grinder	1.36	Liter	10,244	13,932	28.43
Utility tractor	1.36	Liter	8,536	11,610	23.69
Pyrolysis unit	1.36	Liter	4,165	5,664	11.56
Biochar bagging equipment	1.36	Liter	683	929	1.90
Total diesel cost				40,106	81.85
Gasoline (Chainsaw)	1.38	Liter	3,241	4,473	9.13
Total gasoline cost				4,473	9.13
Engine oil mix					
Chainsaw	26.49	Liter	65	1,717	3.50
Total oil mix cost				1,717	3.50
Lubricants					
Chainsaw	5.28	Liter	670	3,539	7.22
Horizontal grinder				5,127	10.46
Utility tractor				4,272	8.72
Pyrolysis unit				2,084	4.25
Biochar bagging equipment				342	0.70
Total lubricant cost				6,357	12.97
Total fuel cost				52,653	107.45
Labor					
Transportation	25.00	Hour	1,566	39,150	79.90
Preprocessing and operations	25.00	Hour	4,698	117,450	239.69
Total labor cost				156,600	319.59
Miscellaneous					
Biochar bags	110.90	100	270	29,942	61.11
Waste disposal (ash)				5,381	10.98
Total miscellaneous				35,323	72.09
Total variable costs				244,575	499.13
Fixed costs					
Machinery				199,966	408.09
Miscellaneous				23,898	48.77
Overhead charges				23,655	48.28
Total fixed costs				247,519	505.14
Total costs (Canadian Dollars)				492,094	1,004.27

to explore how parameter choices might alter results. The Results section presents a summary of biochar and agricultural production costs. Average net returns over variable and fixed costs are calculated for both beets and potatoes. Breakeven yields per hectare and prices per unit yield are estimated to attain a profitable, joint biochar-agricultural operation. The best, typical, and worst case yield scenarios are evaluated through a stochastic analysis, using @Risk, an Excel Add-In (Palisade, 2019), to predict the range of expected returns from the project. A sensitivity analysis is also presented for the impacts of carbon application and biochar production rates.

3 | RESULTS AND DISCUSSION

3.1 | Fixed and variable production costs

A summary of fixed and variable biochar production costs is presented in Table 1. Total costs equal \$1,004.27 Mg^{-1}, which is comprised of \$499.13 Mg^{-1} variable costs and \$505.14 Mg^{-1} fixed costs. As follows is a description of assumptions used in the cost calculation.

3.1.1 | Biochar production costs

A mobile pyrolysis unit is selected in order to reduce capital costs and take advantage of the log piles (pits) left after forest clearance. The largest of these pits is located next to the Muskrat Falls mega-project site. Biochar production would ensue at the pit nearest Muskrat Falls, while the business headquarters would be located in Happy Valley-Goose Bay near the proposed agricultural production site.

Slow pyrolysis is chosen because it produces more biochar than fast pyrolysis (Ahmed, Zhou, Ngo, & Guo, 2016; Kung, McCarl, & Cao, 2013; Pratt & Moran, 2010; Ronsse, Van Hecke, Dickinson, & Prins, 2013). Slow pyrolysis also has lower pretreatment costs (Ahmed et al., 2016; Wrobel-Tobiszewska, Boersma, Sargison, Adams, & Jarick, 2015), which is favorable for a small-scale operation, like the one proposed.

The biochar enterprise budget includes costs from five stages of the production process—transportation to and from production sites; preprocessing; pyrolysis; biochar bagging; and biochar storage. The process begins with transporting an empty trailer from Happy Valley-Goose Bay to Muskrat Falls and ends with transporting bagged biochar back to Happy Valley–Goose Bay for storage. The loader brings the logs from the pits to the biochar unit. Preprocessing consists of cutting logs with a chainsaw to a maximum of two meters for the pyrolysis unit. A utility tractor with a grapple bucket is used to move logs from the pit for cutting and then into metal cages built specifically for the pyrolysis unit. These cut logs are loaded directly into the pyrolysis unit without any additional drying using a utility tractor with pallet forks to lift the cages. The slow pyrolysis process takes approximately four hours. This includes a “highest temperature” treatment of about 480 degrees Celsius and a residence time of about 180 min (Wrobel-Tobiszewska et al., 2015). After pyrolysis, the biochar is quenched by water inside the unit. Once the charcoal is removed from the pyrolysis unit and has time to sufficiently cool, the charcoal logs from slow pyrolysis must be ground using a horizontal grinder. Charcoal logs must be moved using a utility tractor with a grapple bucket. After the biochar is ground, it is loaded into the bagging machine's hopper using a utility tractor with a regular bucket. It is then bagged with a bagging machine to prevent degradation, loaded onto a trailer, and hauled to a storage unit in Happy Valley-Goose Bay to be stored until sale or use.

Fixed costs, which include machinery, miscellaneous, and overhead, do not directly change with biochar production operations. Machinery costs for a truck, grinder, utility trailer, mobile pyrolysis unit, and bagging machine include repairs, interest (6%), depreciation, insurance (1% of purchase price), and taxes (15% of purchase price); the useful life and salvage value vary. The five-year fixed closed interest rates at the time the budget was developed, for Canadian Imperial Bank of Commerce (CIBC), Scotiabank, and Toronto-Dominion (TD) were 4.99%, 5.14%, and 5.14%, respectively. The ten-year fixed closed interest rates for CIBC, Scotiabank, and TD were 6.29%, 6.39%, and 6.1%, respectively. Miscellaneous expenses include setup and transportation of pyrolysis unit, biochar storage, water tank, and portable toilet. Overhead costs include administration costs (5% of total costs) plus fees, permits, and other payments (2,221 dollars). Annual fixed costs of biochar produced (Canadian dollars in 2015) equal \$505.14 Mg^{-1}.

Unlike fixed costs, variable costs change with production levels. The proposed plant would operate 245 days/year, but employees are paid for 261 days to account for paid holidays. Variable costs also include fuel, lubricants, labor, and miscellaneous (e.g., waste disposal fees of 5,381 dollars, based on Brown, Brady, Mowry, & Borek, 2011). Fuel costs \$1.36 L^{-1} and is required for the truck, grinder, using the utility trailer, and for the pyrolysis unit and bagging equipment. Lubricants are needed for these items and for chainsaws. Labor, at \$25 hr^{-1}, is required for transportation and preprocessing and operations. Variable costs equal \$499.13 ha^{-1}, based on an assumed 2 Mg/day biochar production rate from a slow pyrolysis system.

3.1.2 | Biochar application costs

The proposed project applies biochar to agricultural plots in Happy Valley-Goose Bay as a soil amendment. It takes 0.7 Mg/ha of biochar to generate 1 Mg/ha of carbon (C), which is expressed as 0.7 in field efficiency. Biochar application quantities of 10 and 20 Mg C/ha were attained from Abedin's beet (*Beta vulgaris* L.) field trial data (Abedin, 2015, 2018) in Happy Valley-Goose Bay. An application rate of 10 Mg C/ha is equivalent to 14.29 Mg biochar/ha, and 20 Mg C/ha is equivalent to 28.58 Mg biochar/ha. Abedin (2015) showed no statistically significant increase in yields between 10 and 20 Mg C/ha treatments, although costs would undoubtedly increase with 20 Mg C/ha application. In the breakeven and sensitivity analyses presented in this paper, the impacts of both rates, 10 and 20 Mg C/ha, are evaluated.

TABLE 2 Net returns, with sensitivity analysis, for biochar with average prices and yields

	Total costs ($ ha^{-1})	Variable costs ($ ha^{-1})	Net return (beets) ($ ha^{-1})	Net return (potato) ($ ha^{-1})	Net return over var cost (beets) ($ ha^{-1})	Net return over var. cost (potato) ($ ha^{-1})
Total cost/ha	14,347	7,130	NA	NA	NA	NA
Annual cost/ha (Baseline[a])	3,406	1,693	2,044	−1,290	3,758	423
Sensitivity analysis						
10-year life span	1,949	969	3,501	166	4,481	1,147
20-year life span	1,251	622	4,199	865	4,829	1,494
20 Mg C/ha biochar applied	6,812	NA	−1,361	−4,696	NA	NA
2.5 ton/day pyrolysis rate	2,725	NA	2,726	−609	NA	NA
1.5 Mg/day pyrolysis rate	4,541	NA	909	−2,426	NA	NA
Best case—20 year life, 10 Mg C, 2.5 Mg pyrolysis rate	1,001	NA	4,450	1,115	NA	NA
Worst case—5-year life, 20 Mg C, 1.5 ton pyrolysis	9,082	NA	−3,632	−6,967	NA	NA

[a] Baseline assumes 10 Mg C/ha biochar applied at 0.7 efficiency (10/0.7 = 14.29 Mg biomass/ha applied), and 5-year life span before reapplication.

Abedin (2015) proposed that biochar might need to be reapplied every 5 years, though data are unavailable to test this premise. Without long-term data, researchers speculate that treatment effects could last longer than 5 years (Campbell, Sessions, Smith, & Trippe, 2018; Singh & Cowie, 2014). Hence, 5-, 10-, and 20-year life spans are tested in the sensitivity analysis.

At a biochar production cost of $1,004.27 Mg^{-1} calculated in the first part of the analysis and 0.7 field efficiency, cost per hectare to apply biochar at the 10 Mg C/ha rate equals 10/0.7 × 1,004.27 dollars = 14,347 dollars. If applications last 5, 10, or 20 years, the annualized cost at the 6% interest equals 3,406 dollars, 1,949 dollars, and 1,251 dollars, respectively. It requires $1,693 ha^{-1} year^{-1}, $969 ha^{-1} year^{-1}, and $621 ha^{-1} year^{-1}, respectively, to cover variable costs.

3.1.3 | Beet and potato yields

The Department of Forest Resources and Agrifoods, Government of Newfoundland and Labrador identified short growing seasons (late springs and early fall frosts), low soil organic matter, sandy soil textures, and soil acidity as the primary problems affecting crop production in Happy Valley-Goose Bay (Abedin, 2015). Farmers have no ability to control weather and soil texture, but they can effectively manage soil organic matter and soil acidity. The combination of the cold, sandy soil texture and low organic matter in the study region restricts the mineralization rate of organic matter and the nutrient holding capacity of soil.

Biochar applications have been shown to increase soil organic carbon levels, increase cation exchange capacity, reduce nutrient leaching, supply essential plant nutrients, and increase pH in acidic soils (Abedin, 2018). Abedin conducted his study from 2012 to 2015 to look at the ability of biochar to influence crop yields in the harsh Labrador environment. He used a randomized block design to compare beet yields, with cv. Detroit Dark Red in 2014 and cv. Red Ace in 2015 over 10 total treatments. Treatments included a control condition; a full application of fish meal and a half application chemical fertilizer; biochar-only; and biochar with either a half or full allocation of fish meal or chemical fertilizer.

At the beginning of the study, the soils had a coarse texture (82.5% sand, 15% silt, and 2.5% clay at a 0–15 cm depth), a highly acid pH (4.7–4.8), moderate soil organic matter, and very low cation exchange capacity (CEC) (7.6 cmolc^{-1} kg^{-1}). By the end of the study, soil pH, CEC, and many micronutrient levels had improved where biochar had been applied (Abedin, 2018). Yields could not even be produced on fertilizer-only or biochar-only plots, but economically feasible yields could be realized with a combination of biochar and fertilizer, a result that Abedin (2018) indicates has been observed in other studies, as well. Yields never topped 0.5 Mg/ha on conditions other than biochar with fertilizer (Abedin,

TABLE 3 Breakeven prices and yields to cover biochar costs

	Breakeven yield ha^{-1}	Breakeven price per unit yield in dollars
Beets (Mg)	3.49	609
Potato (km)	6,030	0.91

2015, 2018). Abedin (2018) found that beet yields increased substantially in biochar applications that added either fish meal or chemical fertilizer. Results ranged from 2.9 Mg/ha, when subtracting a confidence interval from Abedin's low estimate, to 11.4 Mg/ha when adding the confidence interval to his high estimate. The present study uses these values as the low and high range of values, respectively, and a more modest expected yield (5.59 Mg/ha) is used for more in-depth analysis.

The present study also examines the economic value potato production, since it, too, is a priority crop of the Newfoundland and Labrador provincial government. Local yield data were unavailable for potato production, so estimates were obtained from a related study that looked at a meta-analysis of vegetable yields from biochar application. Biochar applications increase potato yields approximately 19%, based upon a meta-analysis of 59 pot experiments from 21 countries and 57 field experiments from 21 countries (Liu et al., 2013). In their study, Liu et al. (2013) found a 28.6% average increase in vegetable crop yields. Given that a typical potato rotation requires at least one of three years in fallow, the economic analysis multiplied Liu et al., 2013 study findings by two-thirds in order to obtain a grounded value for the projected potato yields in the present study. Newfoundland and Labrador provincial price and yield data from 2009 to 2012 (Statistics Canada, 2012) and 2013 to 2017 (Statistics Canada, 2018) were used in the economic analysis. After converting from lb $acre^{-1}$ $year^{-1}$ to kg ha^{-1} $year^{-1}$, and increasing the yield by 19%, the average potato yield equals 17.5×10^3 kg/ha, with a low 14.0×10^3 kg/ha and high 33.5×10^3 kg/ha. Price was found in the same location to average about \$0.5647 kg^{-1}. Beet prices for 2013–2017 were found in the "area, production, and farm gate value of vegetables" report from Statistics Canada (2018), and \$975 Mg^{-1} was selected.

3.2 | Average net returns over variable and fixed costs, and sensitivity analysis

Average net returns for beet and potato production after biochar application were calculated using average prices and yields (Statistics Canada, 2012, 2018). Average net returns are presented in Table 2. Baseline yields reflect the most likely yield increases (5.59 Mg/ha for beets and 3.746×10^3 kg/ha for potatoes), based upon Abedin's (2015, 2018) beet field trials, with 10 Mg/ha biochar application rates and 0.7 efficiency (10/0.7 = 14.29 Mg biomass/ha applied), and assuming a 5-year life span before reapplication.

The value of biochar is calculated as the revenue increase from higher beet and potato yields. In this study, beet production covers total costs per hectare with 2,044 dollars additional profit, and it covers variable costs with 3,758 dollars to spare. Under the baseline scenario, potato production cannot cover total costs, losing on average \$1,290 ha^{-1}, but can cover average variable costs, at \$423 ha^{-1}, in the baseline scenario.

Since these data are based on field research trials, there is still considerable uncertainty, and there will likely be a range of production values. Therefore, a sensitivity analysis was conducted to evaluate the impact of three variables on profit, holding all other factors equal. These three variables were pyrolysis/biochar production rates (Mg/day), biochar application quantity (Mg/ha), and biochar application frequency (in years). Yields were also varied through a stochastic process explained in the following section.

A sensitivity analysis included the rate and life span of biochar application and the slow pyrolysis system per day biochar production. The baseline assumes 10 Mg C ha^{-1} $year^{-1}$ application rate, 0.7 field efficiency, and 2 Mg/day biochar production rates from the proposed slow pyrolysis system. Expanding the life of the system to 10 years reduces costs to \$1,949 ha^{-1}. Costs fell to \$1,251 ha^{-1} with 20-year biochar application life span. Costs do not fall proportionately to the ratio of the increased life span due to the cost of borrowing of 6% interest. Costs double, however, if the application rate doubles to 20 ha^{-1}. If the pyrolysis rates could increase to 2.5 Mg/day instead of 2 Mg/day, costs would fall to \$2,725 ha^{-1}. Costs would increase to \$4,541 ha^{-1} if pyrolysis produces biochar at a rate of only 1.5 Mg/day.

The sensitivity analysis demonstrates that applying biochar at either a 10-year life span or a 20-year life span is enough to make biochar application on potatoes profitable; otherwise, potato production does not cover total costs.

Best case and worse case scenarios were also modeled, using variations in production pyrolysis rates, the amount of biochar application, and time between reapplications. A "best case" scenario would reduce overall production costs to \$1,001 ha^{-1} with 10 Mg C/ha biochar application every 20 years, and 2.5 Mg/day biochar production rates from a slow pyrolysis system. A "worst case" scenario with 20 ha^{-1} application every 5 years and only biochar production of 1.5 Mg/day would cost over \$9,000 ha^{-1}. Beet production is profitable under all scenarios except for the 20 Mg C/ha biochar application rate and worst case scenario.

3.3 | Breakeven prices and yields to recover biochar costs

The breakeven yield and price for beets and potatoes are presented in Table 3. The increase in beet yield can fall to as low as 3.49 Mg/ha to keep biochar profitable; the price can fall

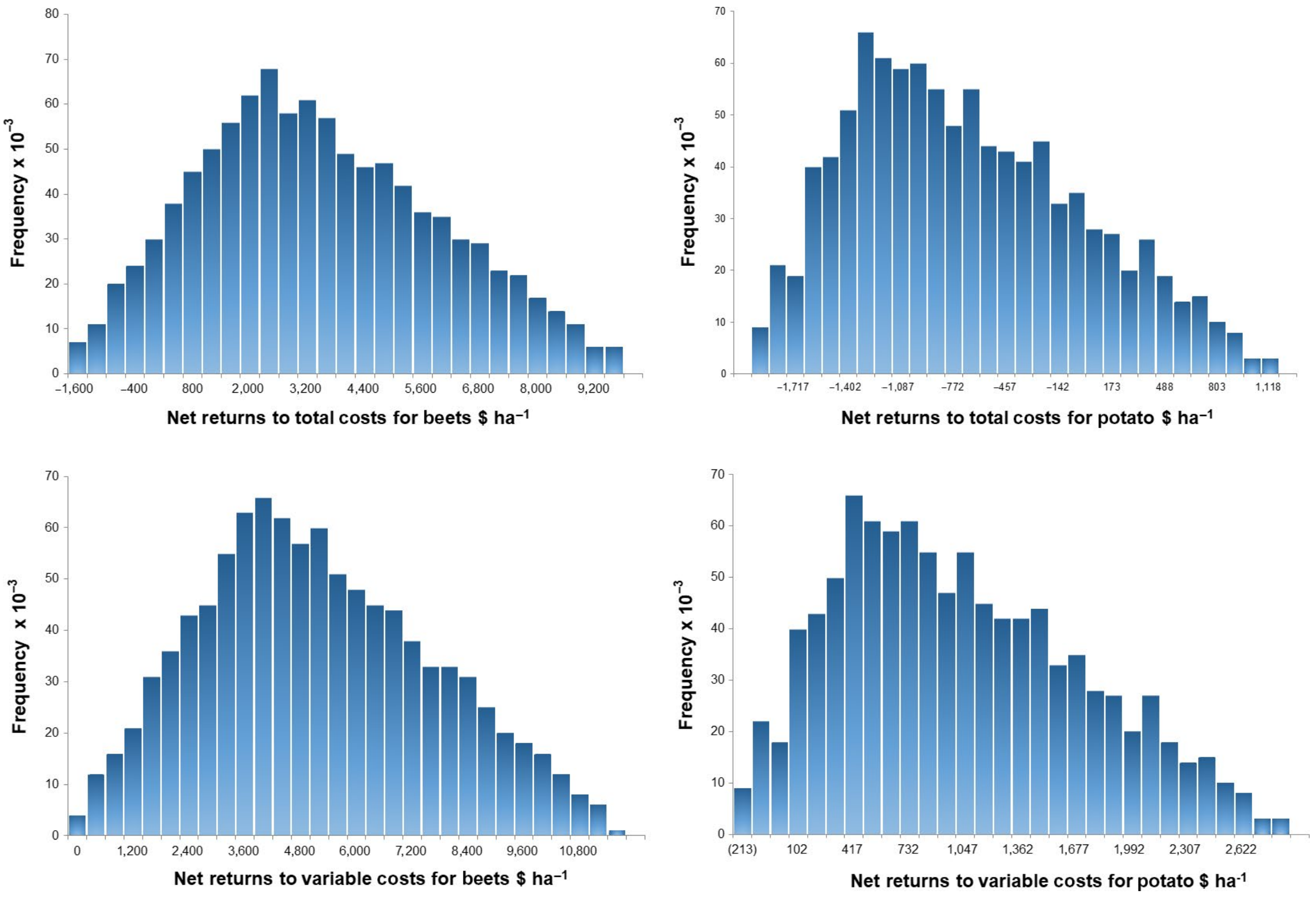

FIGURE 2 Probability density histograms for net returns over total and variable costs for beets and potatoes in the Labrador scenario

from 975 dollars to 609 dollars. For potatoes, yield would have to increase from 3.746×10^3 Mg/ha to 6.030×10^3 Mg/ha. Achieving the breakeven price and yield for potatoes is unlikely, though the stochastic analysis in the next section shows that there is a low probability that the venture may be highly profitable.

3.4 | Stochastic analysis

Given the high degree of uncertainty in pyrolysis rates and crop yield, among other variables, select items in the budget were made stochastic to test the sensitivity of net returns to certain assumptions. Distributions for the price of fuel, beet yield, and potato yield were created in @RISK software (Palisade, 2019); then, net returns were recalculated for 1,000 simulations for net returns over total costs for beets and potatoes and net returns over variable costs for beets and potatoes. The “Tringen” application was used to develop a probability distribution for each stochastic input. This feature creates a distribution based on a low, most likely, and high value. It functions like a Triangular distribution but allows for a specified probability of falling below the low and rising above the high in the Triangular distribution. This case allowed for a 5% probability of falling below and 5% probability of falling above the low and high values specified in each distribution. The low yield (worst case), most likely, and high yield (best case) are 2.9, 5.59, and 11.4 Mg/ha for beets and 2,997, 3,746, and 6,957 Kg/ha for potatoes, respectively. For fuel, the low was 92.5% of the most likely values specified in the budget in Table 1, and the high was 115% of the most likely value, based on 2018 prices in Labrador City, Labrador (Natural Resources Canada, 2018).

The resulting probability distributions of net returns ha^{-1} for beets and potatoes, covering total or variable costs, are presented in Figure 2. Low, mean, and high values for each panel are presented in Figure 3. The cumulative probabilities are also shown in Figure 3. The impact of the expected range of fuel prices and crop yields, weighted by the probability of those ranges, produces uncertainty about the expected value of biochar. For example, the minimum returns for all four cases examined are negative. However, the probability of profitability varies considerably between the two crops. While the minimum net returns for beets and potatoes are very close, the mean return over total costs for beets is over \$3,200 ha^{-1} and the maximum is more than \$9,500 ha^{-1}. There is <10% probability that net returns for beets would be negative. However, the probability of a negative return to potatoes, when considering total costs, is much higher, nearly

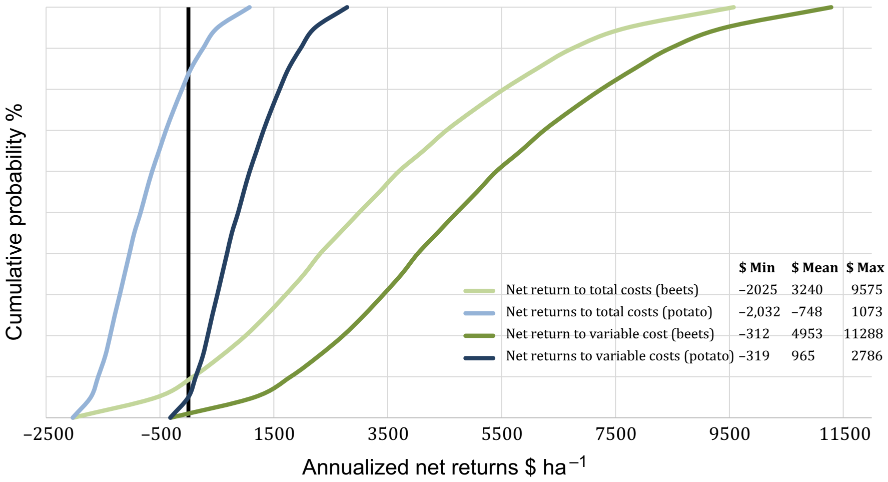

FIGURE 3 Cumulative density functions showing net returns above variable and total costs for beets and potatoes

85%, and mean returns are negative. Both beets and potatoes look like better investments if fixed costs are not considered. This may be a prudent approach due to the high certainty surrounding the high capital investment costs that have been calculated for the fixed costs in this study (Dahl, 2015). For example, average returns over variable costs are approximately 5,000 dollars and 1,000 dollars for beets and potatoes, respectively, and for either crop, there is <10% probability that returns will be negative. Fixed costs are often ignored in the short run because they might be reduced over time by new technologies, experience, cost sharing, or by spreading them across other crops. Moreover, in this particular case, if the province was to proceed with the proposed biochar project, it is likely that competitive bidding for the mobile pyrolysis unit would lower the overall fixed costs, and a more accurate start-up cost estimate could be calculated for the large capital equipment expenses. Hence, one may wish to consider the fixed cost value as a "starting point" that will eventually become refined over time and as more information becomes available.

4 | CONCLUSIONS

The economic analysis presented in this paper illustrates a high likelihood of profitability for biochar and beet coproduction in the study area under most biochar production and agronomic conditions. Beet production may generate maximum yield values as high as \$9,575 ha^{-1} under a best case scenario which is primarily attributable to the high yield potential exhibited in two years of regional beet growing trials where the control condition showed close to zero production capacity. These values may reflect an optimistic scenario, though modeling a more modest midline value of 5.59 Mg/ha demonstrates strong profitability at \$3,240 ha^{-1} net return over total costs. Given certain circumstances, biochar and potato coproduction may also be profitable, based upon data extrapolated from Liu et al. (2013) used to estimate the increases in potato yields. The potential for profitable potato production augmented with biochar supports the supposition that potato-biochar field trials are needed to illustrate higher yields or at least lead to a site-specific range of yield values.

In general, biochar field studies show site-specific sensitivity, which creates general uncertainty throughout the literature about the transferability of results. Local environmental, transportation, and market conditions make every project unique. Combined with a nascent market for biochar demand, any biochar production business venture would be considered highly risky. However, this study employs agronomic field data collected from the study region, creating a realistic, though relatively broad, range for the economic feasibility of biochar, and agronomic production. The analysis shows that beets would be profitable in greater than 90% of the conditions modeled, making it a highly viable operation compared to many agronomic ventures.

In many situations, production in remote areas presents additional costs and risks due to added transportation costs and low market demand. However, in this particular situation, the region's remoteness and harsh climate motivate the pursuit of creative options to improve food security. There is considerable unfilled demand for beet and potato production within the province and across Canada's North. The proposed biochar and agricultural operation may facilitate much needed employment and community income, in addition to increased local food supplies.

Though the stochastic economic models show that potato production is profitable <15% of the time, the province's desire to increase local production, and specifically potatoes, may justify provincial or national financial support for the endeavor. Specifically, the province of Newfoundland and Labrador has identified provincial potato production as a priority to enhance food security (Forestry and Agrifoods, 2013). Potato field trials should reflect varieties suited to the region and document potential differences between potato varieties. Given the potential profitability of beet growing trials, this could diversify costs of potato production, as well, in order to move the province closer to achieving food security.

Ostensibly, from an environmental justice perspective, it could be argued that other Canadian provinces and states within northeastern United States should compensate the province of Newfoundland and Labrador for the environmental impacts that the region has sustained as a result of the construction of the Muskrat Falls hydroelectric dam. However, practically speaking, this would be difficult to administer. Although the Churchill River hydroelectric projects have been viewed as contentious and deliver relatively meager financial benefits to the Newfoundland and Labrador government and residents, the Courts (including Canada's Supreme Court) have declined to allow contracts to be renegotiated (Harris, 2018). There is a case to be made that the Newfoundland and Labrador government should consider compensating central Labradorians for the resource and associated environmental damage; however, given that the province itself does not benefit enough from Muskrat Falls, it may lack the capacity to compensate the region's residents.

Using this environmental justice argument, the Newfoundland and Labrador provincial government could provide the start-up capital required to open the biochar production facility or cover potential downside losses of a critical crop like potatoes, which could feed many households in the region. Extending the environmental and social justice thread a bit further, within Labrador, as well as across the Canadian North, the Canadian federal government does increasingly recognize a mandate for supporting northern food security (and/or food security for Indigenous communities). A subsidy would be consistent with other efforts in that area. Moreover, it would be proper to include Indigenous communities in a joint biochar-agricultural production venture that creates a circular economy in the region. Support from the Canadian government to facilitate this transition into an economically viable enterprise would facilitate economic opportunity and social justice.

In sum, with a nascent market for biochar, two years of field trial data, and preliminary efficacy of biochar field trials, it is difficult to provide a definitive answer to the question of whether to embark on a risky biochar-agricultural coproduction venture. However, we are confident that findings from this analysis should embolden local and national governments to fund additional pilot agronomic studies to examine the efficacy of biochar on local agricultural production in the quest to pursue improved food security.

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CONFLICT OF INTEREST

None declared.

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