Supplementary Material:

Maximizing biochar climate change mitigation impact through optimized logistic

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1 LCA Process Description

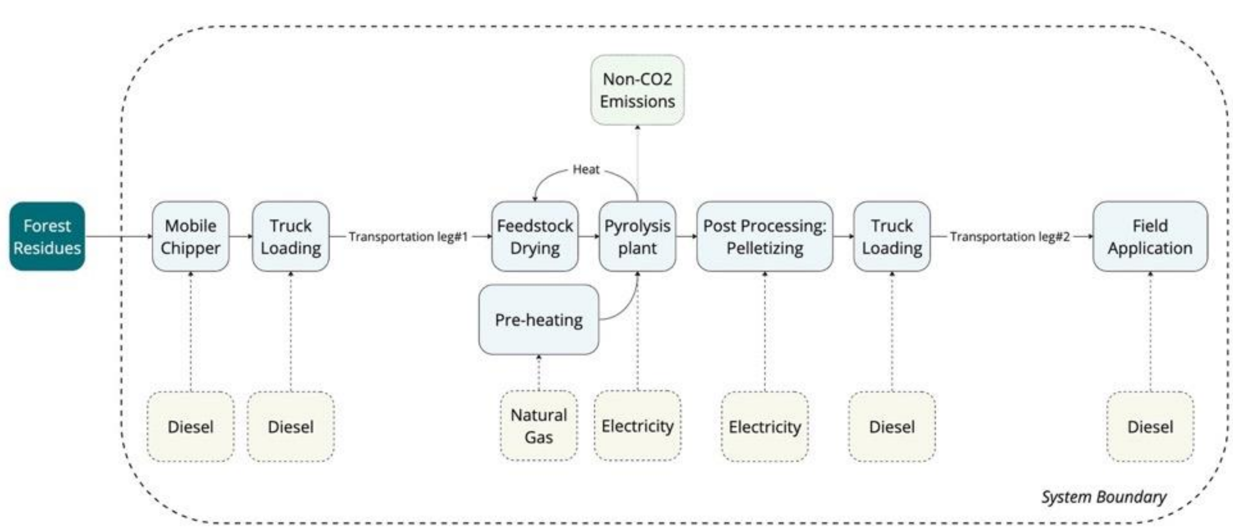

Figure S1: Life cycle assessment system boundary. Blue represents the different processes with their associated main energy source in yellow. Light green specifies that the boundary account for the non-CO2 emissions associated with the pyrolysis process.

1.1.1 Mobile Chipper

Per metric tonne of forest residues, Brassard et al. (2020) account for 0.017 productive hours of wood chipping which is in line with the average of 0.2 hours per tonne of biochar produced assumed in this study. This was calculated using chipping rate from Gustavsson et al. (2011) and Kilpeläinen et al. (2011) and using the wood density from BC Hydro & Industrial Forestry Service Ltd. (2018) and Blackburn (2017).

The process used include the transport of the machinery to the logging site, the input of machinery infrastructure, the input of diesel fuel, lubricants/greases as well as their disposal, and the emissions into air from diesel consumption (Wernet et al., 2016).

1.1.2 Loading Operation

Truck loading operation takes place to load the forest harvest residues from the roadside and to load the biochar after pyrolysis. We have assumed the unloading to be gravity led.

We assumed 0.1875 litres of diesel (uncertainty range: 0.156 – 0.162 l) required to load one metric tonne of goods into a truck (Rosado et al., 2017). Considering the residue to biochar yield to be 22% (Veksha et al. 2014) and the moisture content of residues to be 40% (Jacobson et al., 2021), each tonne of biochar applied to the field correspond to 7.57 tonnes of moist residues transported to the biochar plants. Including the final tonne of dry biochar to be applied to the field, and the energy content of diesel being 36.368 MJ per litre (Canada Energy Regulator, 2016), the total loading operations require 33.94 MJ of diesel.

The process used in EcoInvent include the machine used for loading, its infrastructure, and its oil consumption (Wernet et al., 2016).

1.1.3 Transportation leg #1

Transportation of the forestry harvest residues to the biochar plant is assumed to be made by a vehicle operating with diesel, with emission standard classified as EURO5, and falling under the lorry size class of 16-32 metric tons.

The Monte Carlos was run using 204.844 to 270.941 g CO_2e / tkm as emission factor and considering the residue to biochar yield (Veksha et al. 2014) and the moisture content of residues (Jacobson et al., 2021) in the calculation.

The freight lorry 16-32 metric tonne process from EcoInvent for transport of chipped wood residues to pyrolysis unit in Canada is also assumed by (Ayer & Dias, 2018)

1.1.4 Feedstock drying

Feedstock drying is assumed to be entirely driven by the excess heat generated by the pyrolizer. We have assumed no other uses of the excess heat produced during the process (e.g. electricity generation). Matuštík et al. (2021) reported that drying wood chips arriving at 40% moisture (same moisture content of the forestry harvest residues assumed in this study) only consumes 43% of the produced heat by the pyrolysis process.

1.1.5 Pyrolysis plant construction

Our assessment includes the emissions associated with the pyrolysis plant workshop, equipment, and office buildings (Yang et al., 2016) and include the concrete, steel, and aluminum required to build the pyrolizer (Roberts et al., 2010). We have assumed a plant lifetime of 20 years. The uncertainty associated with these parameters represent the range between the assumed 200 days per year at 7 hours per day running time of the machine to the potential 365 days per year at 24h per day. A conservative assumption compared to the values presented in (Ayer & Dias, 2018).

1.1.6 Pyrolysis plant operation

Pre-heating was assumed similar to Roberts et al. (2010) who stated that 58 MJ of natural gas per tonne of feedstock were needed for a machine with a throughput of 10 dry metric tonne of feedstock per hour.

1.1.7 Emissions from pyrolysis

Air non-CO_2 emissions from pyrolysis were taken from Oneil et al. (2017), used in Sahoo et al. (2021a), who reported emissions of slow pyrolysis of chipped wood residues using a mobile pyrolysis system called the Biochar Solution Incorporated (BSI). The BSI system, being still a mobile system is not as high tech as the system modelled in our study. Hence, the emissions during pyrolysis are likely to be higher than what would actually be emitted from a high-tech pyrolysis system. These values are therefore conservative.

1.1.8 Pelletizing

Bergman et al. (2022) estimated that pelletizing biochar typically requires about 61.47 kWh of electricity per oven-dry tonne of biochar. Our study relies on an EcoInvent process reporting a total of 97.81 kWh per oven dry tonne of biochar and include pelletizing equipment and side energy requirements (Wernet et al., 2016).

1.1.9 Transportation leg #2

Transportation of the biochar to the field is assumed to be made by a vehicle operating with diesel, with emission standard classified as EURO5, and falling under the lorry size class of >32 metric tons.

The Monte Carlos was run using 109.517 to 158.478g CO_2e / tkm as emission factor.

1.1.10 Field Application

For the spreading, the process “Solid manure loading and spreading, by hydraulic loader and spreader” from EcoInvent is used. The same approach was used in Brassard et al. (2020).

Process Name	Value per tonne biochar produced	Unit	Uncertainty	Distribution shape	Uncertainty source	Value source	Note	EcoInvent Process Name or Emission Factor
Woodchipper at forest road	0.2	productive machine hour	0.07 - 0.20 - 1.72 (min - most likely - max)	triangular	(MacDonald et al., 2012) (Blackburn, 2017b) (Gustavsson et al., 2011b) (Kilpeläinen et al., 2011b)	Average of uncertainty range	A forestry chipper can chip between 30 and 150 m^3 per hour (including 15min break) (Gustavsson et al., 2011; Kilpeläinen et al., 2011) Wood Density of forest side residue range from 0.088 ODT/m^3 (Blackburn, 2017) and 0.41 ODT/m^3 (MacDonald et al., 2012)	wood chipping, mobile chipper, at forest road | wood chipping, chipper, mobile, diesel, at forest road | Cutoff, U – RoW Include transport of the chipper Unit: 1 productive machine hour
Truck Loading Operations (all)	58.94	MJ of diesel	0.10	Normal	10% uncertainty	(Rosado et al., 2017)	Include oil, diesel upstream and combustion, and fictive construction machine made of steel Considering 36.68 MJ per litre of diesel (Canada Energy Regulator, 2016)	diesel, burned in building machine | Cutoff, U – GLO Unit: per MJ of diesel burned
Feedstock Drying	0	/	/	/	/	/	Residual heat from pyrolysis process	/
Pyrolysis plant – Pre-heating Natural Gas - Upstream Emissions	6.60	m^3	/	/	/	(Roberts et al., 2010)	Upstream emissions and transport to site only - Canadian market - Considering gross calorific value of 40 MJ per m^3 (Wernet et al., 2016)	market for natural gas, low pressure | natural gas, low pressure | Cutoff, U – CA
Pyrolysis plant – Pre-heating Natural Gas - Combustion Emissions	6.60	m^3	/	/	/	(Roberts et al., 2010)	Combustion only - no upstream - Considering gross calorific value of 40 MJ per m^3 (Wernet et al., 2016)	2.0024 kg CO_2e / m^3 NG based on (Environment and Climate Change Canada, 2023) Clean Fuel regulation database (Government of Canada, 2020)
Pyrolysis plant - Non CO_2 Emissions (CH_4)	0.000821275	t	6.8705E-4 - 9.555E-4	uniform	(Sahoo et al., 2021b)	(Sahoo et al., 2021b)		

Pyrolysis plant - Electricity Requirement (production)	250	kWh	150 - 250 - 350 (min - most likely - max)	triangular	(Yang et al., 2016)	(Yang et al., 2016)	Considering electricity needed for Separation and purification of the pyrolysis products and the electricity needed for auxiliary systems and domestic electricity consumption	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – CA – BC
Pelletizing Biochar	1000	kg	/	/	/	/	Include pre-treatment and considers 20% production bagged and 80% bulked	wood pellet production | wood pellet, measured as dry mass | Cutoff, U RoW Unit: per kg of dry pellet produced
Pyrolysis Plant Construction - Aluminium	0.232	kg	0.0639 - 0.4	uniform	Productions hour per year	(Roberts et al., 2010)	Range from considering 20 years lifetime with min (365 days/year @ 24H/day production) to max (200 days/year @ 7H/day)	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
Pyrolysis Plant Construction - Steel	35.95	kg	9.91 - 62	uniform	Productions hour per year	(Roberts et al., 2010)	Range from considering 20 years lifetime with min (365 days/year @ 24H/day production) to max (200 days/year @ 7H/day)	market for steel, unalloyed | steel, unalloyed | Cutoff, U - GLO
Pyrolysis Plant Construction - Concrete	112.5	kg	31 - 194	uniform	Productions hour per year	(Roberts et al., 2010)	Range from considering 20 years lifetime with min (365 days/year @ 24H/day production) to max (200 days/year @ 7H/day)	market for concrete block | concrete block | Cutoff, U - RoW
Pyrolysis Plant workshop and office building	53	kg CO_2e	/	/	/	(Yang et al., 2016)		
Pyrolysis Plant equipment	25	kg CO_2e	/	/	/	(Yang et al., 2016)		
Field Application of the biochar	1.00	t	/	/	/	/	/	solid manure loading and spreading, by hydraulic loader and spreader | solid manure loading and spreading, by hydraulic loader and spreader | Cutoff, U - CA-QC

2 Transport Optimization Algorithm

Figure 2 (main manuscript) is only a simplified graph of how the network was modelled. We now describe our graph models in detail. Note that in our study: the capacity attributes are known at the nodes (fields and forests) instead of the edges (routes); we need to integrate the field capture potential into the optimization; and we should not prescribe the supply at each forest (as it should be optimized based on their proximity to pyrolysis plants), nor the demand at each field (as it should be optimized based on their capture potential).

We accounted for those factors by introducing two artificial nodes: a common forest node connected to all forests and a common field node connected to all fields. These two nodes hold the total supply and demand, which lets the algorithm decide which forests and fields to use. Additionally, these two nodes introduce an artificial edge for each forest and field, that can hold its capacity attribute, as well as a cost attribute to represent a field's capture capacity (as a negative CO_2e cost).

In Figure S2, we show small-scale networks for each of the four scenarios. Note that we were constrained by the solver to use only integer values for all model attributes. This led to some rounding errors in some cases, for example, the total demand in the Even scenario being slightly different from the other scenarios.

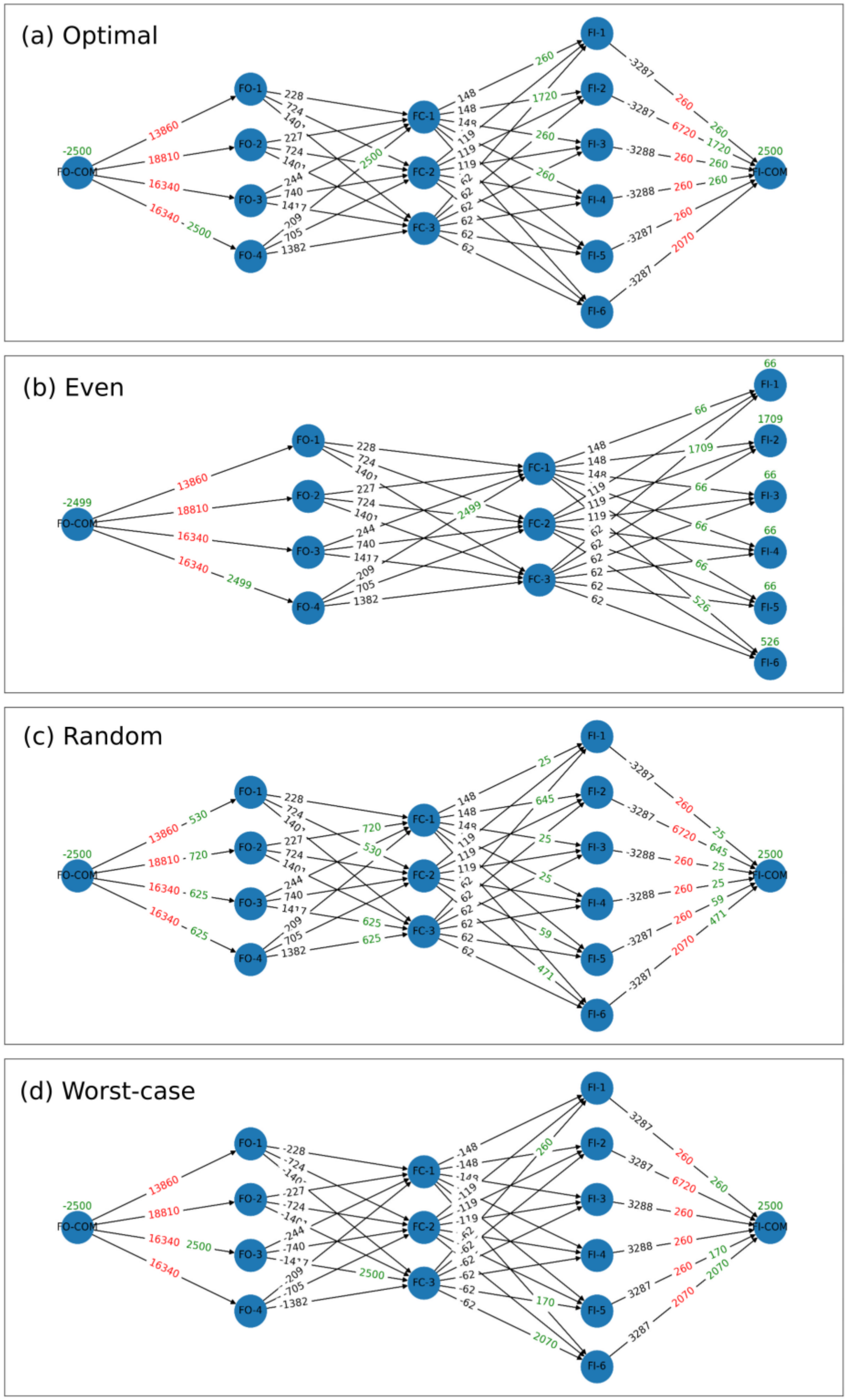

Figure S2: We show the graphs used for each scenario, in a simplified case with 4 forests (FO-), 3 pyrolysis plants (FC-*), and 6 fields (FI-*). Numbers in black indicate the cost of each edge (in gCO_2e / kgBC). We introduced artificial forest and field nodes (FO-COM, FI-COM) and artificial edges to each forest/field, which let us specify: the forest production capacities and field application capacities (in red, in kgBC), the field capture potentials (in black, in gCO_2e / kgBC) that are specified as negative costs, and finally the total supply and demand at the artificial nodes (in green,* in kgBC). The edge attributes in green (in kgBC) indicate the solution found for that specific scenario, i.e. how much feedstock must travel through each edge to satisfy the constraints and objective of the scenario. In this example, an arbitrary amount of 2500kgBC is transported through the network. (a) Optimal scenario: the biochar is transported along the route with the minimum cost, while respecting field capacities. (b) Even scenario: here, we didn't need an artificial field node, as we had to specify demand (in green) on individual field nodes to ensure an even distribution proportional to field areas. (c) Random scenario: no optimization is performed. (d) Worst-Case scenario: here the goal is to maximize cost, therefore, we simply specified the negative of the actual costs, so that the minimization turns into a maximization.

3 Additional Figures

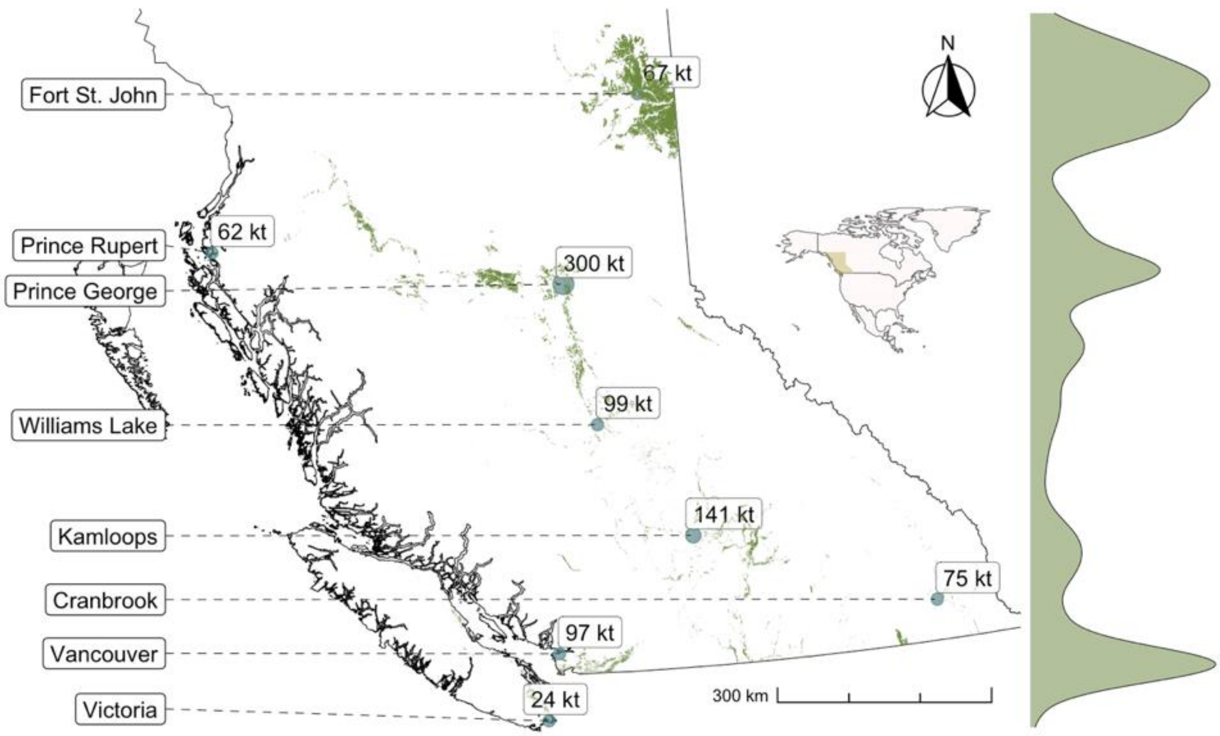

Figure S3: Equal scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock.

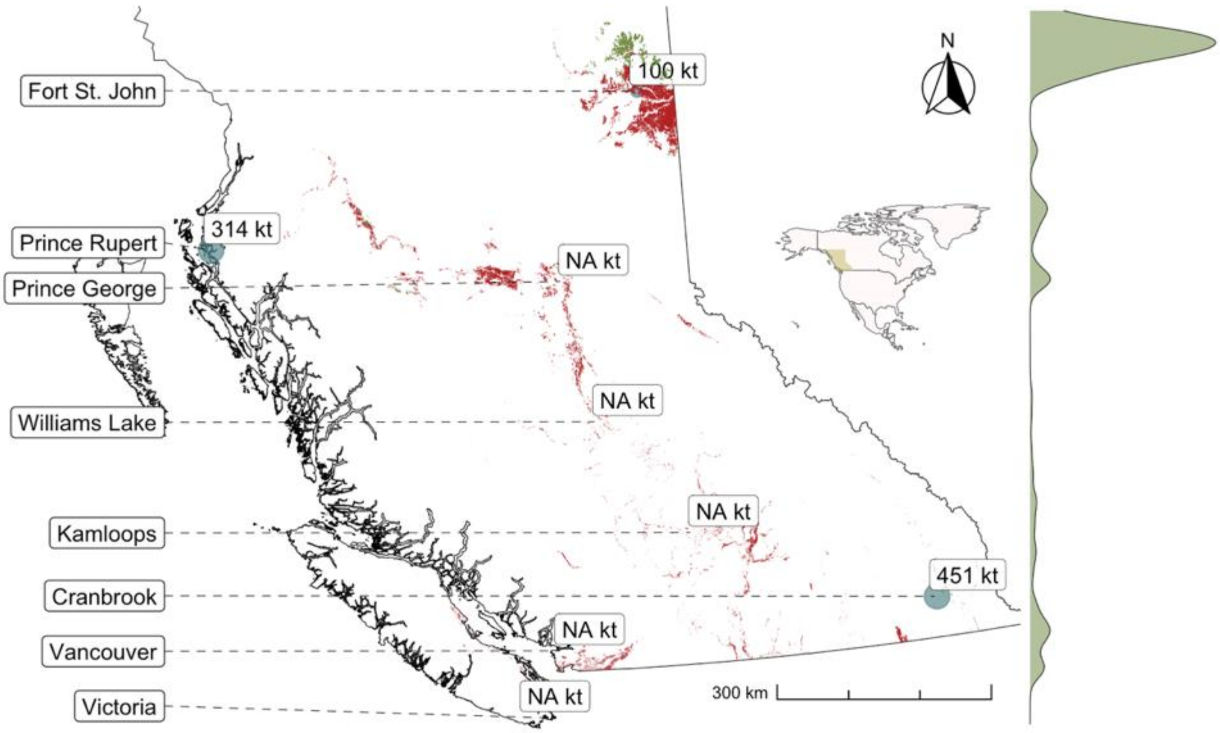

Figure S4: Worst-Case scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock.

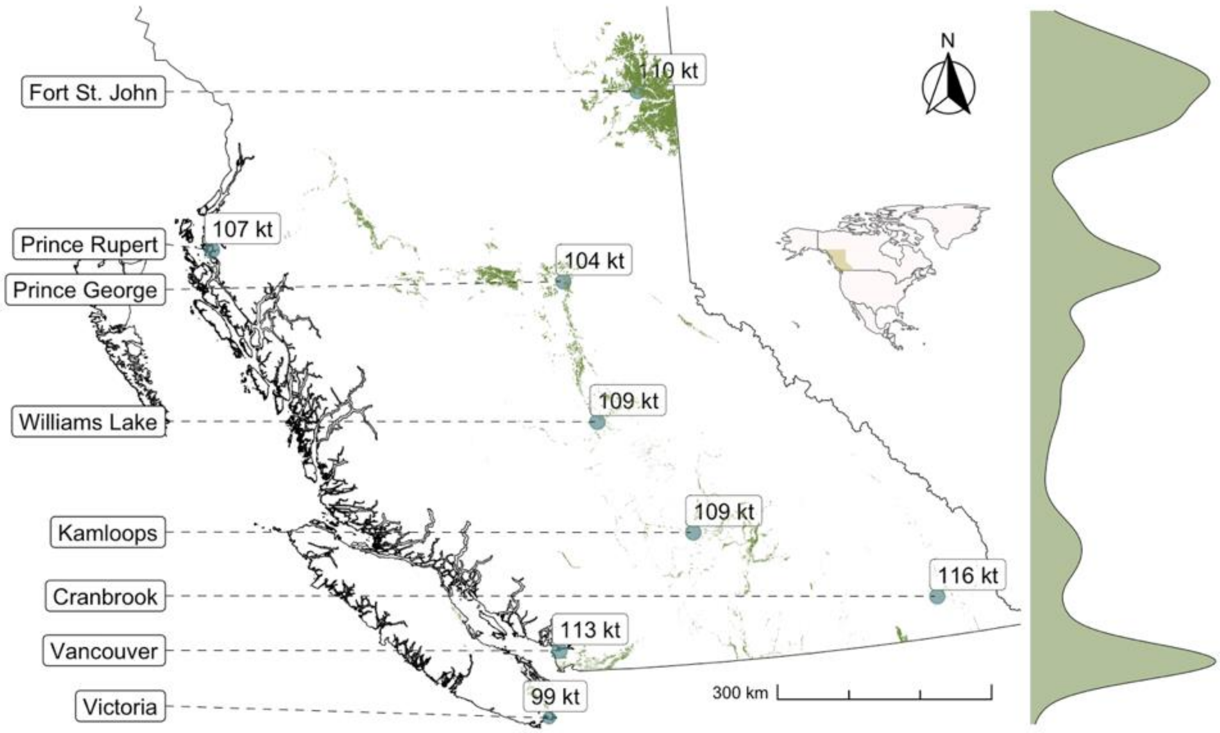

Figure S5: Random scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock.

4 References

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