

Hydroponic fodder and greenhouse gas emissions: a potential avenue for climate mitigation strategy and policy development

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Abstract

This research explores the potential hydroponic systems have for contributing to climate mitigation in fodder agriculture. Using British Columbia (BC) and Alberta as case studies, the study compares greenhouse gas (GHG) emissions and carbon sequestration potential of hydroponically grown sprouted barley fodder to conventional barley grain fodder. GHG emissions were examined through scenarios that assumed Alberta to be the main barley producer, while exploring different situations of BC and Alberta as consumers, distributed/centralized hydroponic systems, and renewable/nonrenewable energy. Carbon sequestration opportunities were examined through scenarios that explored the land sparing potential of transitioning from conventional to hydroponic barley and shifts from tillage to no-tillage practices. Sensitivity analyses were done to examine how changes in hydroponic seed-to-fodder output and energy consumption affect the systems' climate mitigation potential. The results indicated that incorporating hydroponic systems into barley production has the potential to reduce GHG emissions, given seed-to-fodder output and energy consumption are maintained at certain levels and the systems are powered by renewable energy. Results also showed that hydroponic farming can provide greater carbon sequestration opportunities than simply shifting to no-tillage farming. The research indicates that hydroponic fodder farming could contribute to climate mitigation objectives if complemented with effective energy and land use policies.

OPEN ACCESS

Citation: Newell R, Newman L, Dickson M, Vanderkooi B, Fernback T, and White C. 2021. Hydroponic fodder and greenhouse gas emissions: a potential avenue for climate mitigation strategy and policy development. FACETS 6: 334–357. doi:[10.1139/facets-2020-0066](https://doi.org/10.1139/facets-2020-0066)

Handling Editor: Clément Bataille

Received: August 24, 2020

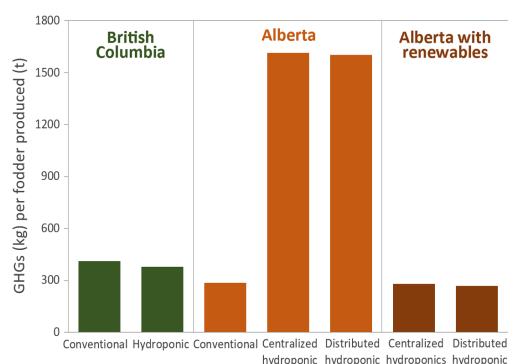
Accepted: January 11, 2021

Published: March 11, 2021

Corrected: June 1, 2021

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Published by: Canadian Science Publishing



Key words: climate mitigation, energy policy, land use, agricultural technology, hydroponic agriculture, animal agriculture

1. Introduction

Great potential exists for reducing greenhouse gas (GHG) emissions in the animal agriculture industry. The imminent pressures on our food systems through demand for consumption of animal products are becoming more apparent as our global population increases, with estimates suggesting a global population of almost 10 billion by 2050 (Sun et al. 2020). As pressures on our global food system grow to meet the demand for animal products (McGregor and Houston 2018), so do the apparent effects of livestock production on climate change. Approximately 70% of all agricultural land is used for some aspect of livestock production (Bonny et al. 2015), and it represents 14.5% of human-induced GHG emissions, with feed production and enteric fermentation from ruminants representing the two main sources, 45% and 39% of sector GHG emissions (Opio et al. 2013). Accordingly, targeting the feed chain of animal agriculture can potentially reap near-term gains toward climate change objectives.

There are promising advances in the structure and technologies of our food systems. For example, cellular agriculture has been shown to emit fewer GHG emissions than conventionally produced meat, requiring only a fraction of land and water (Tuomisto and de Mattos 2011). In addition, consumers are increasingly transitioning to plant-based or vegan diets, minimizing or abstaining from the use of animal products with environmental issues and animal welfare associated with the cost of industrial meat production being the primary concerns (Angus and Westbrook 2019). However, in the near-term, both technology and dietary trends do not comprise viable climate strategies for animal agriculture. Meat products cultured and manufactured through cellular agriculture are not yet widely commercially available; thus, these products discuss more in terms of their “promise”, without a complete understanding of their actual potential to contribute to environmental sustainability (Mouat and Prince 2018). In terms of dietary trends, although plant-based eating is rising, demand for meat is also rising (Lee 2019), particularly with the rise of a middle class with dietary transitions trending towards higher consumptions of meat, dairy products, and other more resource-intensive foods (FAO 2017). It is impractical to regard a complete transition away from animal agriculture as a viable strategy for meeting the critical and immediate challenge of climate change. How, then, can near-term climate goals be achieved?

Meeting the demands for animal products with conventional meat production practices is reaching its limits (Bonny et al. 2015), and innovative approaches with new technology applications are becoming imperative for reducing the current and future carbon footprint of livestock production. One such approach is to focus on addressing a major source of emissions in livestock agriculture, that is, feed production (Opio et al. 2013). Conventionally grown crops are associated with heavy external inputs of nutrients, fossil fuels, water, and land consumption, and as more people consume animal products on a global scale, the environmental impacts of feed crop farming become substantial (McAlpine et al. 2009). Fortunately, the development of agricultural technologies for the advancement of feed production is currently in use. These technologies have the potential to address climate change and other environmental issues by focusing on indoor production facilities, where the environment can be manipulated and adapted to be crop specific (Gnauer et al. 2019). Space can be used much more efficiently resulting in higher yields with much smaller footprints and lower water and nutrient consumption (Marchant and Tosunoglu 2017).

Advancements in agricultural technologies can potentially lead to the production of nutritious foods without requiring extensive land clearing for pasture and feed; thus, these technologies may be able

to serve as strategies for achieving both agricultural and land efficiency objectives. Applying this perspective to hydroponic farming positions the technology within the “land sparing” versus “land sharing” framework, in which land sparing practices increase agricultural intensity and yield in smaller areas to reserve space for habitat, and land sharing consists of ecologically sound practices that reduce impacts and incorporate biodiversity in farmland (Green et al. 2005; Fischer et al. 2014). Hydroponic technologies, in this sense, would be considered land sparing due to their potential to reduce or limit expansion of forage and fodder agricultural lands. The land sparing versus sharing framework generally refers to the benefits of sparing strategies as biodiversity enhancement, as more space is (theoretically) available for ecological reserves (Von Wehrden 2014; Jiren et al. 2017), but this could also be considered a contribution to climate action objectives due to the carbon sequestration and storage benefits associated with habitat conservation (Sollmann et al. 2017; Spencer et al. 2017).

Although promising, hydroponic technologies are emerging and evolving, and their potential contribution to climate objectives are still uncertain. Many indoor farms require inputs that are produced through conventional farming methods; for example, seeds for hydroponic systems may be obtained through outdoor farms. In addition, indoor hydroponic farming involves highly automated systems that control aspects of crop growing, such as temperature, lighting, humidity, etc. (Marchant and Tosunoglu 2017; Gnauer et al. 2019), and although this makes for an efficient farming system, it requires energy and thus has associated GHG emissions. Therefore, to truly assess their potential for climate mitigation, it is important to examine the contributions that value-added hydroponic operations provide to agricultural systems and to ensure that the GHG production from incorporating these technologies into agriculture does not exceed mitigation benefits. In addition, development and use of technology alone are insufficient to drive change toward sustainable development (Huesemann 2003); these are highly dependent on the conditions in which said technology operates, such as the carbon intensity of electrical grids and willingness of farmers to allocate “land spared” for habitat and carbon sequestration purposes. It is important to both understand the potential of agricultural technologies and identify the best complementary policy options to optimize climate mitigation benefits.

This paper examines the use of a fully automated vertical indoor hydroponic system for sprouting fodder and will look at its potential for reducing GHGs in livestock agriculture. Using the western provinces of Canada and the HydroGreen system as a case study, the paper estimates GHG emissions associated with hydroponic and conventional barley fodder production with specific attention to energy consumption, transportation, land use, and farming practices. The paper reports on the results and discusses how the implementation of hydroponic fodder farming practices could be complemented with different policies to enhance climate mitigation (and broader environmental) benefits.

2. Methods

2.1. Case study

2.1.1. Hydroponic farming system

Case studies are a valuable tool for understanding emerging technologies, as early players leave lasting founder effects in the future development of the industrial landscape. The aim of this research is to examine the climate mitigation potential of employing hydroponic farming technology to produce feed crops. To this end, it uses the HydroGreen system as a case study, and it compares fodder produced through this system to conventional feed crops. HydroGreen is an indoor vertical farming system that produces sprouted grains for livestock feed. The system consists of “section” units, which are six stacked trays, and the system automates harvesting, cleaning, seeding, watering, and lighting (HydroGreen Global Technologies 2020). A HydroGreen farm can be developed with growing tables that consist of one to six sections, and larger systems benefit cost-wise from economies

of scale ([HydroGreen Canwest n.d.](#)). This study uses data from a HydroGreen demonstration farm in Abbotsford, Canada, and this farm consists of two six-section tables in one room and two four-section tables in another room.

Fodder is grown over a 6-d period using the HydroGreen system. Seeds are deposited on a mesh for supporting the root system, and lighting and irrigation systems are positioned above each tray. The system does not use nutrient substrates or fertilizer inputs, with the process relying on hydrolytic enzyme activity to release stored seed nutrients during the germination process ([HydroGreen Global Technologies 2020](#)). Every 6 d, a tray level is harvested and reseeded to maintain continual production of sprouted fodder (J. Curtis, personal communication, 22 July 2020), and the harvesting/reseeding is facilitated by a conveyor belt system.

The purpose of the system is to create a larger volume of nutritious feed in a relatively small space and with significantly higher reductions in farming inputs (e.g., pesticides, water, and fertilizer) than is possible when simply harvesting and using livestock grain or hay fodder as feed. The current study examines the GHG reduction potential of hydroponic fodder by comparing sprouted barley feed produced through the HydroGreen system to conventional barley grain feed. Due to a lack of fertilizer inputs and farm machinery powered by fossil fuels, the primary source of GHG emissions is the energy required to operate the system (e.g., lighting, water pumping, temperature regulation, etc.).

The HydroGreen system produces sprouted barley and wheat, and [HydroGreen Global Technologies \(2020\)](#) has released data for both fodder products, including dry matter (DM), total digestible nutrients (TDN), and seed-to-fodder output. The data can be retrieved through a document available from their website by clicking the download button at the bottom of the page: hydrogreenglobal.com/resource-center/. Barley and wheat are common livestock feed products, and examining both would be useful for understanding the mitigation potential of hydroponic fodder farming. However, this research focuses on barley and uses it as an illustrative case study, as GHG emissions associated with wheat farming vary depending on type ([Kulshreshtha et al. 2011](#)); thus, barley provides a more straightforward and reliable analysis for a study that integrates data from multiple sources (i.e., such as this one). In addition, a number of studies have examined hydroponic barley fodder ([Sneath and McIntosh 2003](#); [Dung et al. 2010](#); [Saidi and Omar 2015](#)), which allows for a comparison of previous research to figures obtained from [HydroGreen Global Technologies \(2020\)](#) for data used in this study (e.g., TDN, DM, and seed-to-fodder output).

2.1.2. Study location

The research focuses on the western provinces of Canada, namely British Columbia (BC) and Alberta. BC has a population of approximately 5.1 million people, with over half the population located in the southwest Metro Vancouver Regional District ([BC Stats 2020](#)). Agricultural land is protected in BC through the 1973 *Agricultural Land Commission Act* that established the Agricultural Land Reserve, comprising approximately 5% of the province's land area and with most productive lands concentrated in particular regions, such as the Lower Mainland ([Newman et al. 2017](#)). The dairy industry is the largest primary agriculture sector in BC, and the province has the third largest dairy sector in Canada ([BC Agriculture and Food 2019](#)). Accordingly, forage and fodder crops are in demand in BC as the province has a substantial area for forage; however, high-quality fodder crops, such as grains, are produced in much higher volumes in Alberta ([Alberta Agriculture and Forestry 2020](#)). Producing sufficient feed in BC's Lower Mainland is extremely difficult as land is limited and property prices are high.

Alberta has a population of approximately 4.1 million people, with most of the population concentrated in the Edmonton (1.4 million) and Calgary (1.5 million) metropolitan areas ([Government of](#)

Alberta 2019). Agriculture is a major industry in the province, and it is a major producer of beef, grains, oilseed, and livestock feed crops (Alberta Agriculture and Forestry 2020). Barley crops grow particularly well in Alberta (Kosinski 2012), and it is a major export for the province (Alberta Agriculture and Forestry 2020) both internationally and interprovincially.

BC and Alberta provide an interesting case study for this research for multiple reasons. First, Alberta produces much more barley than BC; thus, hydroponic fodder farms in BC are more likely to source barley seeds from the neighbouring province. This allows for an investigation on the climate mitigation potential of hydroponic fodder that incorporates emissions associated with interprovincial transportation of products, allowing for an analysis that can examine and compare GHG emissions associated with regional (i.e., hydroponic farms in BC) and local (i.e., hydroponic farms in Alberta) systems. Second, BC and Alberta rely on different energy sources to power their electrical grids, with the former primarily using hydropower and the latter primarily using coal and natural gas (Environment and Climate Change 2019; Canada Energy Regulator 2020). This results in significantly different GHG emissions for energy consumption in the provinces, thereby allowing for an analysis that can elucidate whether a more carbon-intensive electrical grid could potentially offset the GHG reduction benefits received from hydroponic farming.

2.2. Data and analysis

The research examines the climate mitigation potential of hydroponic feed farming systems in two areas: (i) transportation and energy consumption and (ii) land use and agricultural practices. The former examines relative “costs” of different feed production, meaning it looks at the GHG emissions produced through energy usage of on-farm activities (both outdoor and hydroponic) and transportation of products. The latter captures “opportunities” associated with the use of different farming systems and approaches, namely land spared through more efficient farming systems and the potential of increasing/optimizing carbon sequestration and storage on this land. Examining hydroponic farming through these two perspectives provides a holistic impression of its potential, both in terms of reduction and removal of GHG pollution.

The research integrates a mix of data sources, with most being secondary data obtained from public databases (e.g., Statistics Canada, BC Data Catalogue, the Government of Alberta Open Data Portal) and studies on agriculture in Canada. The latter involved collecting data through a literature review, and sources targeted were studies that specifically focus on the case study provinces in this research, that is, BC and Alberta. When unavailable, the study sources data from research conducted elsewhere in North America.

Some data were collected from a demonstration farm operated by the Nutriva Group in Abbotsford (BC, Canada), which uses the HydroGreen hydroponic system, and these data were provided by farmers via an e-mail request. The demonstration farm primarily grows wheat; however, the farm experimented with barley production in September 2017. Data obtained from the demonstration farm include the energy consumption associated with operating the system to produce, and it was collected from the farm because it was not available from HydroGreen reports or academic literature. In addition, seed-to-fodder output data were obtained from the farm, and these data were used to inform a sensitivity analysis, which examines losses in GHG mitigation potential with reduced fodder yield. Table 1 provides a list of data (and sources) used in the study, and a spreadsheet containing the complete data table and calculations is included in the Supplementary Material 1. Researchers and practitioners are welcome to modify the spreadsheet to other crop/fodder types and use it for their own research purposes.

Table 1. Data descriptions and sources used for livestock feed GHG emissions analysis.

Analysis	Data	Description	Units	Source
Conventional fodder	Farm-based emissions	GHG emissions for a given mass of fodder as modelled for farming barley grain, including sources such as farm machinery, on-site transportation, farm inputs and fertilizers, and off-site transportation to storage bins	kg/t	Kulshreshtha et al. 2011
	Yield	Yield of feed crops for a given area	t/ha	Alberta Agriculture and Forestry 2020
	Tillage practices	Tillage practices performed in Alberta	ha, %	Statistics Canada 2016a, 2016b
Energy and transportation	No till carbon sequestration	Carbon sequestration benefits from using no-tillage over tillage practices	kg/ha/y	Alberta Environment and Water 2012
	Livestock and fodder farms	Number and distribution of farms within different Census Divisions	Number	Statistics Canada 2016c, 2016d
	Road network and Census boundaries	GIS line and polygon data for BC and Alberta road network and boundaries for Census Divisions	GIS	BC Data Catalogue, Alberta open data portal
	Transportation truck capacity	Load capacity of transportation trucks for barley grain	t	Schroeder 2012
	Fuel economy	Fuel required to transport fodder	L/km	Smajla et al. 2019
	Transportation emissions	GHG emissions produced through transportation of fodder	kg/L	BC Ministry of Environment and Climate Change Strategy 2017
	Hydroponic farm energy	Energy consumption associated with operating hydroponic farms	kWh/d	HydroGreen farm
	GHG emissions from energy consumption	GHG emissions produced through electrical energy consumption associated with hydroponic operations	kg/kWh	Environment and Climate Change Canada 2019
	Barley seed to sprouted fodder	Amount of sprouted barley fodder produced per amount of barley seed	kg/kg	HydroGreen Global Technologies 2020
	Fodder DM	Percentage of fodder mass that comprises the DM of the feed	%	Preston 2016; HydroGreen Global Technologies 2020
	Total digestible nutrients	Percentage of fodder DM that consists of food materials that provide nutrient and energy for livestock	%	Preston 2016; HydroGreen Global Technologies 2020
	Land use	Land conversion CO ₂ sequestration potential	kg/ha/yr	Kosinski 2012

Note: GHG, greenhouse gas; GIS, geographic information system; BC, British Columbia; DM, dry matter.

2.2.1. Conventional fodder

This analysis builds on previous work, which comprehensively modelled emissions related to farming activities for fodder. Such work has been done through multiple studies conducted in North America ([Kulshreshtha and Sobool 2006](#); [Gan et al. 2012](#); [Wiens et al. 2014](#)); however, this study specifically uses estimates modelled by [Kulshreshtha et al. \(2011\)](#) as their study best fits the data selection criteria, meaning it examines barley grain fodder production in Alberta. [Kulshreshtha et al.'s \(2011\)](#) estimates incorporate multiple factors related to GHG emissions, and they report carbon dioxide equivalent values (CO₂e) derived from a combination of carbon dioxide, methane, and nitrous oxide emissions. Their GHG emissions modelling includes farm machinery fuel consumption, on-farm transportation,

fertilizers, crop residue return, farm inputs (production, transportation, and storage), and off-farm transportation to storage bins. For barley grain fodder grown in Alberta, estimates are 229.6 kg/t, with the units referring to CO₂e produced per mass of fodder.

Kulshreshtha et al.'s (2011) estimates capture CO₂e produced through intensive tillage practices; however, according to Statistics Canada (2016a), no-tillage agriculture is prevalent in Alberta, comprising an estimated 69.3% of farming. Carbon sequestration in farmland increases with shifts from tillage to no-tillage practices, and in terms of annual CO₂e uptake and storage, Alberta Environment and Water (2012) estimates that this amounts to 58.9 kg/ha/y in dry prairie areas and 109.1 kg/ha/y in "parkland" (i.e., forested and vegetated) areas.

To gain an accurate estimate of GHG emissions produced through fodder agriculture, Kulshreshtha et al.'s (2011) figures were adjusted to incorporate carbon sequestration from no-tillage farming. Carbon sequestration figures for both dry prairie and parkland areas were multiplied by the provincial proportion of no-tillage farming to capture (on average) how much sequestration is occurring per hectare due to these practices. The relative levels of farming for barley fodder type in the different dry prairie and parkland regions were calculated using figures from Statistics Canada (2016b) and Alberta Environment and Water (2012), which were 38.8% in dry prairie and 61.2% in parkland. These figures were subsequently used to create weighted averages based on the different sequestration potentials of dry prairie and parkland. Then, the yield for barley grain (3.63 t/ha) was calculated based on 10-year (2009–2018) averages obtained from Alberta Agriculture and Forestry (2020), and this figure was used to convert sequestration figures from CO₂e per area to CO₂e per mass of fodder produced. Finally, the weighted averages of carbon sequestration per mass of fodder were subtracted from the intensive tillage figure given by Kulshreshtha et al. (2011).

The GHG emissions adjusted for no-tillage practices was 212.5 kg/t for barley grain. Equation (1) provides the calculation methods for these adjustments. Included in the equation are the adjusted fodder GHG emissions (F_b), fodder emissions from intensive tillage (T_b), carbon sequestration for both dry prairie (C_d) and parkland (C_p), farming activity in dry prairie ($A_{b,d}$) and parkland ($A_{b,p}$), provincial proportion of no-tillage practices (N), and yield (Y_b).

$$F_b = T_b - (N \times C_d \times A_{b,d} + N \times C_p \times A_{b,p}) / Y_b \quad (1)$$

2.2.2. Transportation and energy

GHG emission calculations for transportation and energy consumption considered multiple sources in the fodder-to-livestock supply chain, specifically emissions related to farming, transportation, and hydroponic treatment of fodder products. As noted above, an objective of this research is to examine how hydroponic technologies can be complemented with different policies to effectively support climate mitigation. To this end, multiple scenarios were examined that focused on fodder production and consumption in both Alberta and BC. All scenarios assumed that barley grain is grown in Alberta, but they differed in terms of transportation needs and energy sources. Descriptions for the scenarios can be found in Table 2.

The transportation-related GHG emissions examined here include those produced by the vehicles that move fodder from Albertan feed crop farms to BC cattle farms. The analysis involved estimating average trip length from fodder to livestock based on locations and concentrations of barley farms in Alberta and cattle farms in BC. Data on numbers of farms within sub-provincial Census Divisions were retrieved from Statistics Canada (2016c, 2016d). In ArcMap (v.10.6), the data were added as attributes to GIS polygons of Census Divisions, and then road network data were added to the ArcMap project (the spatial data sets obtained were from the BC Open Data Catalogue and the

Table 2. Scenarios examined in analysis of fodder transportation and energy GHG emissions.

Target consumer	Scenario	Description
BC farms	Barley grain	Barley grain is grown in Alberta and is transported to BC livestock farms
	Hydroponic feed	Barley grain is grown in Alberta and is transported to BC hydroponic farms, where it is used to produce sprouted barley fodder
Alberta farms	Barley grain	Barley grain is grown in Alberta and is transported to Alberta livestock farms
	Centralized hydroponic facilities	Barley grain is grown in Alberta and is transported to Albertan hydroponic farms located in the centres of Census Divisions
	Distributed hydroponic facilities	Barley grain is grown in Alberta and is transported to Albertan hydroponic farms located near grain storage facilities
	Centralized hydroponic facilities, with renewable energy	Barley grain is grown in Alberta and is transported to Albertan hydroponic farms located in the centres of Census Divisions, and hydroponic operations are powered with renewable energy sources
	Distributed hydroponic facilities, with renewable energy	Barley grain is grown in Alberta and is transported to Albertan hydroponic farms located near grain storage facilities, and hydroponic operations are powered with renewable energy sources

Note: GHG, greenhouse gas; BC, British Columbia.

Government of Alberta Open Data Portal). Geometric centroids were created for each of the Census Divisions, and using Network Analyst, distances between fodder and cattle farms were calculated. The output of the network analysis was then used to calculate average distances between Alberta and BC farms, which were weighted by both numbers of feed crop farms in Alberta and cattle farms in BC as it is likely that more trips will occur to and from areas where farm activity is greater. One-way trip averages were estimated to be 995.2 km.

Transportation-related GHG emissions were also calculated for the scenario where hydroponic feed is produced in Alberta through centralized operations. The assumption for this scenario is that each Census Division with significant fodder and cattle farming industries (i.e., enough farms that data are available for the Division) will have its own hydroponic farming centre. It is difficult to calculate exact distances with the available data (i.e., exact farm locations were not available); instead, rough estimates were obtained by using Network Analyst to calculate distances between Census Division centroids and halfway to Division boundaries. These estimates provided a general sense of distances between fodder storage facilities located throughout a Census Division and the Division’s central hydroponic facility; doubling this number provided the full-length trip that includes the remaining trips from the hydroponic facility to livestock farms located within the Division. Average distances for fodder transportation within all Albertan Census Divisions were obtained, and then a weighted provincial average was calculated using the numbers of barley farms and cattle farms as weights. The trip average was estimated to be 106.7 km. For scenarios that involve distributed facilities, the assumption is that these would be near grain storage facilities, and as [Kulshreshtha et al.’s \(2011\)](#) estimates capture emissions related to farm-to-storage transportation, no additional transportation-related emissions were added in these scenarios.

Table 3. Seed-to-fodder output produced through the HydroGreen system (taken from [HydroGreen CanWest n.d.](#)).

Sections (<i>n</i>)	Planting depth (in)	Seed (kg)	Fodder (kg)	Seed-to-fodder (ratio)
4	0.5	117.5	700.8	5.96
4	0.625	145.9	876.3	6.01
4	0.75	174.2	1051.4	6.03
6	0.5	178.5	1068.7	5.99
6	0.625	222.1	1335.8	6.02
6	0.75	267.8	1603.0	5.99

GHG emissions for barley grain were estimated as the sum of farm- and transportation-related emissions. The former was obtained through methods used in Section 2.2.1 (i.e., F_b). The latter was calculated by estimating GHG emissions produced through transportation from fodder to livestock farms (doubling this value to account for the return trip) and then calculating CO₂e emissions per mass of fodder transported for a particular distance (i.e., because F_b are also in units of kilograms of CO₂e per tonnes of fodder). To achieve this, coefficients were obtained for calculating fuel economy of an average diesel semi-tractor-trailer truck (0.39 L/km, as per [Smajla et al. 2019](#)), emissions intensity (2.63 kg/L, as per [BC Ministry of Environment and Climate Change Strategy 2017](#)), and fodder load capacity for the trucks (21.8 t for barley grain, as per [Schroeder 2012](#)). Calculation methods are displayed in eq. (2), and variables include distance traveled (D_b), fuel economy (G), transportation emissions intensity (I), and truckload capacity for barley grain (L_b).

$$E_b = F_b + (2 \times D_b \times I \times G) / L_b \tag{2}$$

The HydroGreen system examined in this research can produce sprouted barley fodder, and similar to conventional feeds, the seed for a HydroGreen farm operating in BC would likely be obtained from Albertan farms. Thus, the barley grain value from [Kulshreshtha et al. \(2011\)](#) provides a useful starting point for calculating GHG estimates. According to [HydroGreen Global Technologies \(2020\)](#), seed-to-fodder output can vary depending on the number of sections in growing tables and the depths in which seeds are planted. For example, the demonstration farm in Abbotsford consists of two six-section tables and two four-section tables, and with this system, seed-to-fodder output can range from 5.96 to 6.04 ([Table 3](#)), meaning that the hydroponic system on average increases fodder output by a factor of 5.99 in terms of fresh weight, which is comparable to hydroponically sprouted barley yields reported in other research ([Al-Karaki 2011](#); [Saidi and Omar 2015](#)). Accordingly, transportation and on-farm GHG emissions per tonne of fodder are 16.7% of that of barley grain, strictly speaking in terms of fresh weight production (see below for DM conversions).

The ability hydroponic farms have for augmenting fodder output has the potential to lead to GHG emissions reductions, due to added increases in fodder production done in relatively small spaces (i.e., indoor farms); however, it is important to recognize that emissions are also associated with the hydroponic systems' energy requirements. To calculate these emissions, energy consumption data were obtained from the HydroGreen demonstration farm in Abbotsford, which amounted to 203.6 kWh/d for the room with four-section tables during the month of September 2017 (data were provided to the researchers by the demonstration farm staff). This estimate captures aggregate energy of the hydroponic farm, and it represents consumption associated with hydroponic equipment and the rooms in which equipment exists, including lighting, irrigation, seeding, temperature regulation, etc. Then, energy was converted to GHG emissions values using five-year averages (i.e., 2013–2017) of CO₂e per unit of electricity consumption obtained from [Environment and Climate Change Canada \(2019\)](#),

for both BC (0.011 kg/kWh) and Alberta (0.878 kg/kWh). Demonstration farm data were also obtained for average daily production associated with the reported energy consumption. Fodder production data were collected for six different harvest days for one four-section table by the demonstration farm staff during the data collection month, with average daily production being 468.5 kg (these data were provided by the farm staff). The total average daily production for the room was estimated by doubling this value (i.e., 937.0 kg), and this estimate allowed for calculations of GHG emissions per mass of fodder. Accordingly, as displayed in eq. (3), GHG estimates for hydroponic farm energy consumption (H) are based on electricity consumption (W), energy-to-GHG conversions (K), and fodder production (P).

$$H = (W \times K) / P \quad (3)$$

As per eq. (4), the sum of 16.7% of barley-related emissions and the hydroponic farm gives the complete GHG emissions per mass of fodder value for hydroponically produced feed.

$$E_h = 0.167E_b + H \quad (4)$$

Fodder types vary in terms of substance and nutritional value, and although certain feed crops are produced at a higher volume, they may not provide the same level of nourishment as a crop produced at a lower volume. To account for such differences, CO₂e kg per fodder kilogram values were converted, using DM and TDN values. As shown in eqs. (5) and (6), GHG emissions were thusly standardized (S) as CO₂e kilogram per mass of TDN, using both DM (M) and TDN (U) percentage values. Values obtained from [Preston \(2016\)](#) were used for barley grain (DM = 89.0%; TDN = 84.0%).

$$S_b = E_b / (M_b \times U_b) \quad (5)$$

$$S_h = E_h / (M_h \times U_h) \quad (6)$$

Values collected from [HydroGreen Global Technologies \(2020\)](#) were used for hydroponically grown sprouted barley's DM (17.96%) and TDN (78.61%); these values are comparable to other research that reports on DM (e.g., [Dung et al. 2010](#); [Fazaeli et al. 2012](#); [Farghaly et al. 2019](#)) and TDN ([Sneath and McIntosh 2003](#)) of hydroponically sprouted barley.

2.2.3. Land use and agricultural practices

Carbon sequestration opportunities offered by hydroponic fodder farming were assessed by examining the land sparing potential of using the HydroGreen system. The analysis explored scenarios that were based on the notion that opportunities exist for converting cropland to permanent vegetation cover when using hydroponic systems, while still achieving the same nutrient output. The converted cropland increases annual carbon sequestration, and accordingly, a scenario explored in this research involves fully harnessing these opportunities when enhancing barley fodder production by sprouting it using hydroponic systems. In addition, as noted in Section 2.2.1, carbon sequestration opportunities also exist when shifting farming practices from tillage to no-tillage, and for comparison, this was explored as a scenario for barley fodder farming. [Table 4](#) provides a summary of the land use and agricultural practices scenarios explored in this study.

Scenario analyses of land use and carbon sequestration opportunities first involved determining the land requirements for producing a given amount of fodder nutrients based on yield values for different fodder types. As noted above, the yield for barley grain (3.63 t/ha) was derived through data obtained from [Alberta Agriculture and Forestry \(2020\)](#). The yield for hydroponically grown fodder was derived using the barley yield, and as per the HydroGreen fodder-seed ratio, it was multiplied by a factor of 5.99 (i.e., 21.8 t/ha). As done for the GHG emission production analysis, yield values were standardized based on nutritional value. This provided an impression of how much land is

Table 4. Scenarios examined in analysis of fodder farming carbon sequestration opportunities.

Strategy type	Scenario	Description
Land sparing	Land sparing through hydroponic barley production	Barley fodder farming is enhanced by incorporating hydroponic systems and land spared is converted to permanent vegetation cover
Shift in practices	Transition from tillage to no-tillage barley farming	Barley grain farmed through intensive tillage practices shifts to no-tillage practices

needed to produce a given value of TDN. As displayed in eqs. (7) and (8), TDN yields (R) were calculated as the product of land yield, DM, and TDN values (Preston 2016; Alberta Agriculture and Forestry 2020; HydroGreen Global Technologies 2020).

$$R_b = Y_b \times M_b \times U_b \quad (7)$$

$$R_h = 5.99 Y_b \times M_h \times U_h \quad (8)$$

It is worth noting that hydroponic operations require space in addition to the space needed for growing seed inputs; however, it is negligible (i.e., in the case of the demonstration farm, the building footprint is below one-sixth of a hectare to produce an estimated 342 t of fodder annually, based on the daily production value reported above). In addition, as per the scenarios described in Section 2.2.2, the hydroponic operations would not consume farmland, rather they would be near storage facilities or centralized within Census Divisions.

Once TDN yields were estimated, the land-sparing potentials associated with implementing hydroponic systems were calculated. The analysis first calculated the conventional barley land productivity equivalence, which is a value that conveys for every hectare used to produce barley fodder through conventional agriculture, farmers could produce the same amount of nutrients and energy using a portion of these hectares when implementing hydroponic systems. Potential land spared was then calculated as the difference between a full hectare and the equivalence value. Land spared figures were multiplied by values derived from Kosinski (2012), which estimated the potential annual carbon sequestration and storage that could be achieved by converting Albertan field cropland to permanent vegetation cover (such as perennial grasses and legumes). Kosinski's (2012) work provides conversion values for different soil types (e.g., brown, black, grey); however, for this analysis, an aggregate value was used (1.75 t/ha/y) that was calculated based on the proportions of different soil types for Albertan farmland, as reported in the work.

As displayed in eq. (9), a scenario explored in this analysis examine the carbon sequestration potential (Q) of increasing carbon uptake and storage capacity by covering cropland that is spared when shifting to hydroponic sprouted barley farming with permanent vegetation (i.e., conversion factor, V).

$$Q_h = (1 - R_b/R_h) \times V \quad (9)$$

The scenario involves an enhancement of barley fodder production through the incorporation of hydroponic systems (Q_h). The other land use and practice scenario focuses on shifting from tillage to no-tillage practices in barley fodder (Q_t) farming. As depicted in eq. (10), the scenario is calculated by determining the no-tillage sequestration potential for dry prairie (C_d) and parkland (C_p) regions and by weighting these by the relative amounts of barley farming occurring in these regions ($A_{b,d}$, $A_{b,p}$).

$$Q_t = (C_d \times A_{b,d}) + (C_p \times A_{b,p}) \quad (10)$$

2.3. Sensitivity analysis

As aforementioned, the climate mitigation potential of hydroponic farming is associated with its ability for augmenting fodder output. The fodder–seed ratio used in this analysis is comparable with that of other studies; however, it is important to recognize that these values can range (Dung et al. 2010; Al-Karaki 2011; Saidi and Omar 2015). The demonstration farm in Abbotsford only collected six data points for conventional barley fodder production during the month of September, 2017, which is not enough to calculate a reliable long-term average; however, it provided a range of seed-to-fodder output values that could occur with a hydroponic fodder system. In turn, this range was used for analyzing GHG emissions from hydroponic farming at different production levels and determining how sensitive the mitigation potential is to changes in seed-to-fodder output. The upper range of the data set is comparable with the HydroGreen Global Technologies (2020) value used in the analysis, and the lower value is approximately 3.7. Roughly based on these values, a sensitivity analysis was conducted to determine the GHG reductions from hydroponic barley systems that range from 6 to 3.5 in terms of seed-to-fodder output. The calculations were rerun using seed-to-fodder values from 6 to 3.5, incrementing by 0.25. A linear regression was done to obtain the best-fit linear relationship between seed-to-fodder and GHG per mass of fodder, and this allowed for the identification of a threshold, where hydroponic barley no longer provides climate mitigation benefits due to a lower fodder-seed ratio.

In addition to seed-to-fodder output, energy consumption for running the system can vary. The energy consumption data collected for this analysis captures energy requirements for every aspect of the hydroponic operations and the room housing these operations, and this consumption can range depending on factors, such as the efficiency of room lighting, heating requirements, etc. In recognition of such variation, another sensitivity analysis was conducted to examine changes in the climate mitigation potential of hydroponic barley fodder farm due to increases in energy requirements and consumption. This analysis used a range that consisted of the energy consumption value reported here for the lower bound to a doubling of consumption for the upper bound, with values incrementing by a scaling factor of 0.1 (i.e., 1.1 times the report energy consumption value, 1.2 times the reported consumption, etc.).

3. Results

3.1. Transportation and energy

Figure 1 displays the results of the GHG emissions production analyses for the different transportation and energy consumption scenarios. For the scenarios that involved the transportation of fodder from Alberta to BC, GHG emissions per fodder TDN for conventional barley fodder was 409.7 kg/t. When including the HydroGreen hydroponic system in the supply chain, it was observed that barley-based fodder was advantageous in terms of climate mitigation, as it added a benefit of a 7.4% reduction in emissions per TDN produced (i.e., 379.3 kg/t). What this suggests is, in the BC context, the GHG emissions produced through energy required to power hydroponic operations did not exceed the GHG reduction benefits from augmenting the volume of fodder by sprouting barley indoors. In this case, the hydroponic system demonstrated to be the better feed-production option for supporting climate change goals.

The results differed when examining fodder options in the scenarios where Albertan cattle farms were the recipients of locally grown feed. GHG emissions were greatest in the scenarios with hydroponic barley, with the centralized and distributed production scenarios, respectively, being 1614.4 kg/t and 1602.6 kg/t, as compared to 284.2 kg/t for conventional barley fodder. As seen in this analysis, implementing hydroponic systems such as the HydroGreen system within the Albertan fossil-fuel based grid results in significantly higher emissions than systems implemented within the BC grid,

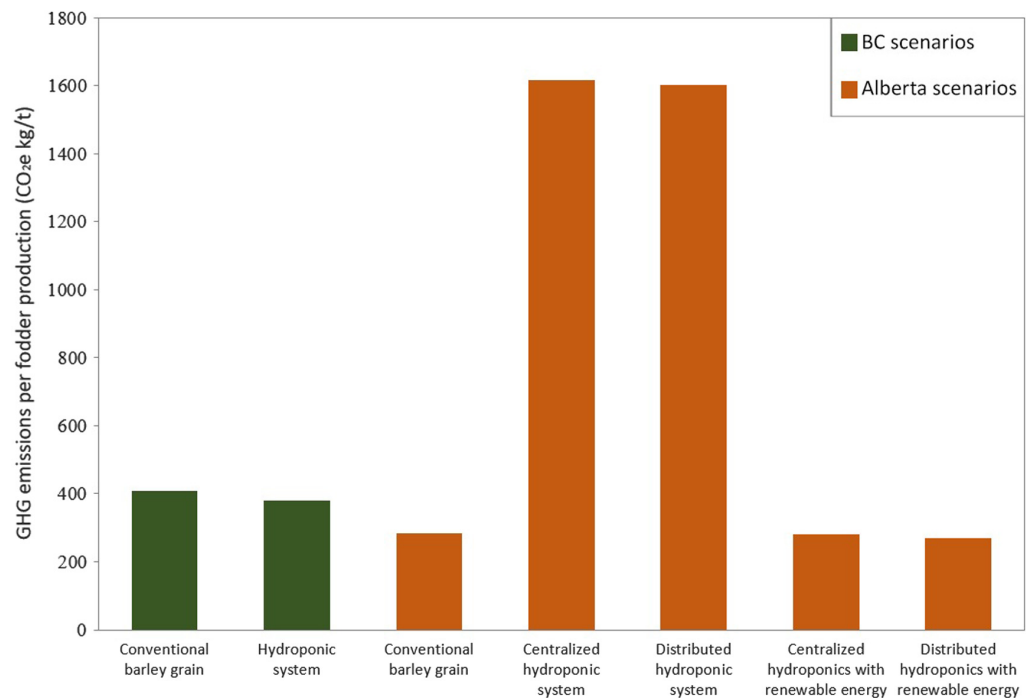


Fig. 1. Greenhouse gas emissions produced for different fodder production scenarios.

being approximately 5.7 (i.e., centralized) and 5.6 (i.e., distributed) times greater in terms of CO₂e per TDN produced. In the Alberta scenarios that involved hydroponic farms being powered by renewable energy (i.e., using the same GHG emissions per kWh value as in BC), GHG emissions were significantly fewer than the hydroponic scenarios involving the current Albertan energy grid, exhibiting reductions of 5.8- and 6.0-fold for centralized (280.3 kg/t) and distributed (268.4 kg/t) hydroponic systems, respectively.

Distributing hydroponic systems resulted in lower levels of GHGs in the Albertan scenarios. The estimated reductions from moving from a centralized system to a distributed system amount to approximately 11.9 kg/t. In terms of percentage, this is a relatively small reduction for scenarios where the hydroponic operations are powered by the current Albertan electrical grid (0.7%), but a more significant percentage reduction in scenarios where hydroponic operations are powered by renewable energy (4.2%). Ultimately, the distributed and renewable energy-powered hydroponic barley scenario in Alberta outperformed all other scenarios in terms of climate mitigation potential.

3.2. Carbon sequestration potential

Analysis of carbon sequestration opportunities confirmed that hydroponic systems have land sparing potential. The analysis indicates that hydroponically sprouted barley can produce a greater nutrient mass per area of land (3.07 t/ha) than conventional barley fodder (2.71 t/ha). The hydroponic system requires less land needed to produce 1 t of TDN, requiring 88.4% of the space used in conventional barley farming to produce the same amount of nutrients. In turn, this provides land sparing opportunities, and for every hectare farmed that includes the hydroponic system in its fodder production instead of conventional barley farming, 0.116 ha could be spared while producing the same amount of nutrients.

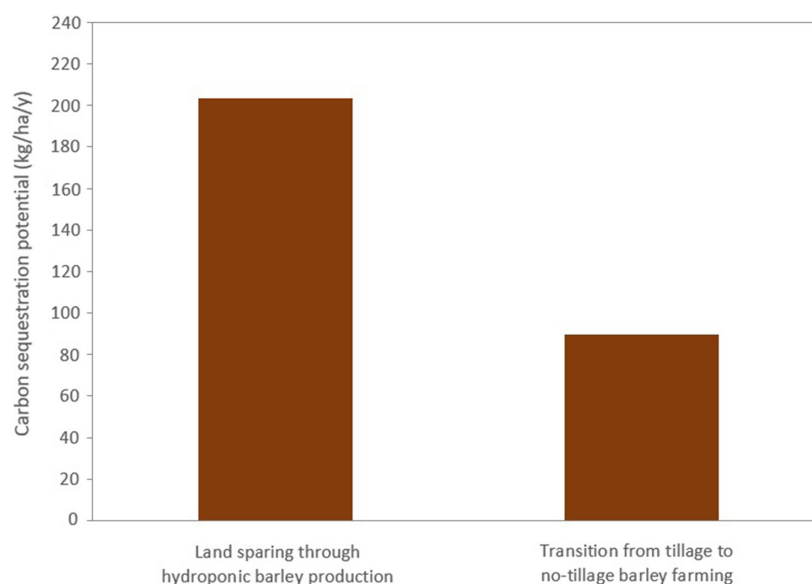


Fig. 2. Carbon sequestration potential for land sparing and agricultural practices scenarios.

Carbon sequestration opportunities were apparent for the scenario involving transitions from conventional barley grain production to hydroponic farming. When covering land spared from conventional to hydroponic barley transitions with permanent vegetation, the carbon sequestration benefits would amount to 203.6 kg of CO₂e per hectare annually. The land-sparing (and vegetation covering) scenario outperformed the scenario involving shifts from intensive tillage to no-tillage practices in barley farming, which was 89.6 kg/ha/y. The results of land use and farming practices scenarios are displayed in [Fig. 2](#).

3.3. Sensitivity analysis

[Figure 3](#) displays the results of the sensitivity analyses for both changes in seed-to-fodder output. The linear regression for the BC hydroponic fodder scenario ($R^2 = 0.98$, $\beta_0 = 967.7$, $\beta_1 = -101.2$) produced a best-fit line that intercepts with the conventional fodder value at a seed-to-fodder output of 5.51 ([Fig. 3A](#)), meaning that below this threshold, the hydroponic system no longer outperforms conventional barley fodder in terms of GHG reductions. In terms of the Alberta scenarios powered by renewable energy, thresholds for the distributed hydroponic systems scenario ($R^2 = 0.98$, $\beta_0 = 707.9$, $\beta_1 = -73.5$) and the centralized system scenario ($R^2 = 0.98$, $\beta_0 = 676.7$, $\beta_1 = -70.2$) were, respectively, 5.76 and 5.59 ([Fig. 3B](#)).

When examining energy consumption, a threshold was not observed for the BC scenario ([Fig. 4A](#)), indicating that hydroponic barley fodder systems could consume energy at levels that are double that of the demonstration farm in Abbotsford and still have climate mitigation benefits ($R^2 > 0.99$, $\beta_0 = 361.7$, $\beta_1 = 0.09$). However, thresholds were observed for the Alberta scenarios ([Fig. 4B](#)); the scenarios that involved distributed ($R^2 > 0.99$, $\beta_0 = 250.9$, $\beta_1 = 0.08$) and centralized ($R^2 > 0.99$, $\beta_0 = 262.8$, $\beta_1 = 0.09$) hydroponic farming systems powered by renewable energy exhibited thresholds associated with energy consumption increases by factors of 1.92 (391.7 kWh/d) and 1.24 (252.0 kWh/d), respectively. Sensitivity analyses were not conducted for the scenarios that involved hydroponic systems powered by Alberta's current fossil fuel-based grid, as hydroponic fodder in these scenarios was already observed to be more GHG intensive than conventional fodder (i.e., without increases in energy consumption).

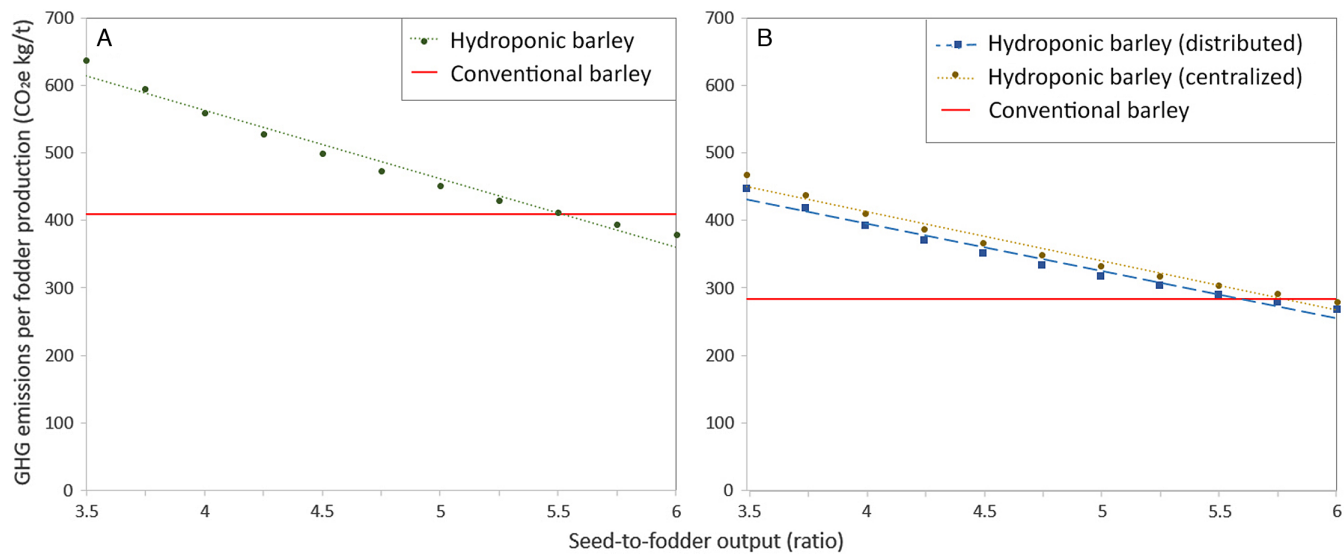


Fig. 3. Sensitivity analysis involving changes in hydroponic seed-to-fodder output for (A) British Columbia and (B) Alberta scenarios powered by renewable energy.

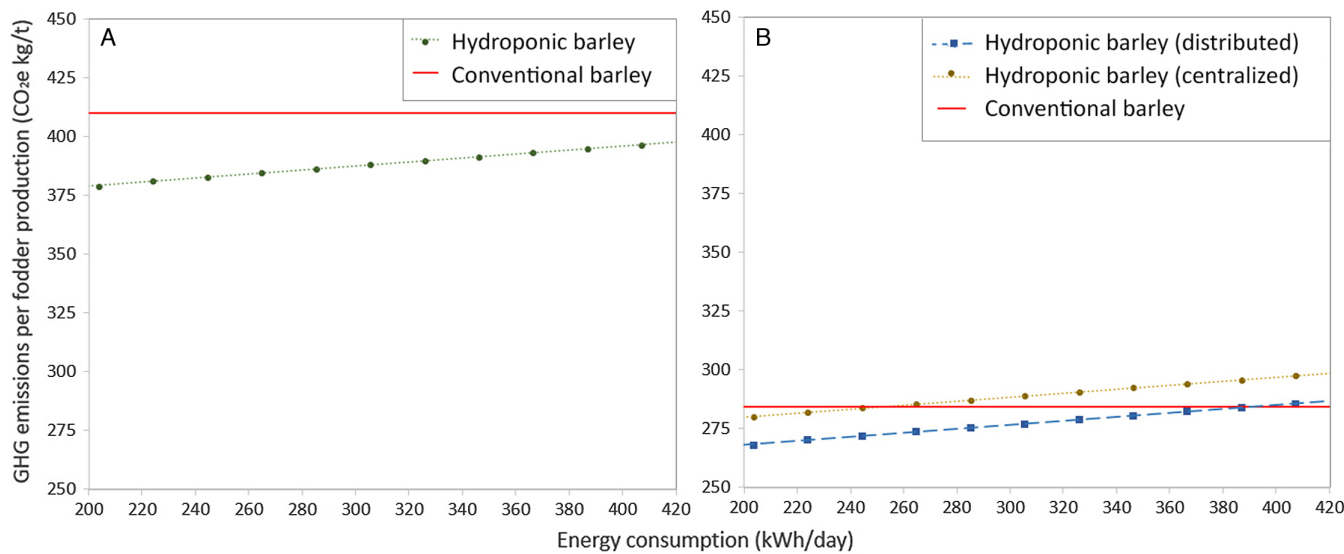


Fig. 4. Sensitivity analysis involving changes in hydroponic energy consumption for (A) British Columbia and (B) Alberta scenarios powered by renewable energy.

4. Discussion

This study demonstrated that the incorporation of hydroponic systems into fodder production can provide added value in terms of climate mitigation benefits. In the case of feeding BC livestock, hydroponic systems could be a particularly valuable strategy, as they have the potential to offset

GHG emissions produced through the transportation of fodder products. A major challenge for climate mitigation in agriculture is that localization of production does not necessarily lead to emissions reductions because, in many cases, certain crops can be produced more efficiently elsewhere (Avetisyan et al. 2014). Ultimately, this can lead to difficult decisions around how to balance trade-offs between production- and transportation-related emissions. However, when using technologies that augment crop output such as the HydroGreen hydroponic system, transportation requirements for crops decrease as only a fraction of the total product mass (i.e., seeds) is being moved inter-regionally, thereby harnessing the benefits of both superior growing conditions in distant regions and (some) local production.

It is important to note that indoor, hydroponic farming is an evolving technology (Marchant and Tosunoglu 2017; Gnauer et al. 2019), and its ability to augment and semi-localize production will improve with technological advancements. The results of this study represent mitigation benefits of implementing agricultural technologies currently, and it is expected that these will increase as the technologies improve over time. Similarly, it is also important to recognize that these systems can range in their performance, as evidenced by studies that report on differing seed-to-fodder output for barley (Dung et al. 2010; Al-Karaki 2011; Saidi and Omar 2015) and as found in the data provided by the HydroGreen demonstration farm. The sensitivity analyses done in this study demonstrated how hydroponic farming systems can no longer provide GHG reduction benefits when they cross certain seed-to-fodder and energy consumption thresholds. Such findings highlight the importance of implementing these systems with monitoring and continual optimization programs for them to effectively serve as climate mitigation strategies.

Interestingly, the sensitivity analysis also revealed that more significant changes in seed-to-fodder and energy consumption levels need to occur before crossing thresholds in situations that involve longer supply chains and product transportation distances. For example, seed-to-fodder output could be lower in BC scenarios than in Alberta scenarios before a hydroponic system's climate mitigation potential is lost. Furthermore, the energy consumption threshold was not reached in the BC scenario, but these thresholds were crossed in both Alberta scenarios. Such findings reinforce the idea that hydroponic systems can be particularly valuable for the semi-localization of fodder agriculture (i.e., sprouting fodder locally, while obtaining seeds from places where these are better produced), in terms of supporting climate mitigation objectives.

This research considers the policy implications for strategically implementing hydroponic fodder systems, and a particularly salient observation in this study was the energy implications around employing these systems. GHG emissions for hydroponic fodder in Alberta were significantly higher than those of conventional barley and the BC scenarios. The differences between the BC and Alberta context reflect the energy sources used to power the electrical grids of each province. Hydropower is the primary source of electricity in BC, whereas coal and natural gas are dominant in the Albertan electrical grid (Environment and Climate Change Canada 2019; Canada Energy Regulator n.d.). The study found that the GHG emissions produced by a hydroponic fodder farming system within a fossil fuel-based grid exceed those of a system that has longer supply chains (i.e., interprovincial transportation of seeds) but a low-carbon grid. When examining scenarios involving the implementation of renewable energy in Alberta, the lowest carbon option for fodder production was realized. Such observations elucidate the importance of strategically implementing low-carbon energy policies along with agricultural technologies. Ideally, this would occur on a provincial scale; however, a complete “greening” of a provincial grid is a significant and lengthy undertaking. Energy policies and strategies could instead target agriculture on local and farm levels in the near-term. For example, governments can develop policies such as those that provide incentives for farmers to implement low-carbon and renewable energy systems to power their operations (Bangalore et al. 2016), which can be coupled

with further incentives for developing and using hydroponic systems. Such a suite of policies and strategies carry the potential for maximizing GHG reductions in fodder production systems.

Another important policy area illuminated through this study involves harnessing the land sparing and (related) carbon sequestration potential associated with implementing hydroponic agriculture systems. The study found that covering the land spared from transitioning to hydroponic farming systems with permanent vegetation produced greater climate mitigation benefits than were found with shifting from intensive tillage to no-tillage farming practices. In addition, this research examined carbon sequestration potential based on calculations for vegetation such as perennial grasses (Kosinski 2012), and it is possible that further (and enhanced) potential for sequestration exists when exploring agroforestry strategies (Bustamante et al. 2014). However, it is important to recognize that the results of this research simply communicate “potential”, and although agricultural technologies provided valuable opportunities for land sparing (Ausubel et al. 2013), increased efficiencies can also result in disproportionately higher production, consumption, and (consequently) resource consumption (Jiren et al. 2017). In addition, the land-sparing potential could be counteracted if the widespread implementation of hydroponic farming systems extends beyond adding to (and ideally improving) current annual crop supply chains and instead results in economic pressures that lead farmers to shift from perennial (i.e., permanent vegetation cover) to annual crops that fit within new (and profitable) hydroponic supply chains. It is critical to complement the implementation of land sparing technologies with policies that incentivize the conversion of cropland to permanent vegetation and (or) easements. Furthermore, these policies must be supported with structures or strategies that ensure certain farmers do not bear the full economic burden of setting aside land for sequestration purposes, such as cooperative systems that allow barley seed and hydroponic farmers to share in the financial benefits of increased efficiencies in and volumes of fodder production.

This research holds implications for agricultural planning, as it demonstrated that hydroponic technologies result in greater benefits depending on how they are integrated into regional and local agricultural systems. In particular, differences were observed between the distributed and centralized hydroponic system scenarios in Alberta, and the analysis indicates that distributing the hydroponic systems so that these operations are nearby grain storage facilities would result in GHG reductions. The distributed system, coupled with renewable energy sources, exhibited the greatest reductions in GHG emissions among all scenarios. Such observations indicate that localization of hydroponic operations (i.e., positioned next to local grain storage facilities) can enhance the technology’s ability to contribute to climate mitigation objectives. The reductions in GHGs resulting from distributing these systems observed in this study may appear minor (e.g., 4.2% for the renewable energy in Alberta scenarios); however, it is important to recognize that the study focuses on units of GHG emissions per TDN of fodder produced rather than total emissions produced. The gross amount of GHG reductions could be relatively large when accounting for the total volume of fodder produced in a year. In addition, localization in food and farm systems reduces supply chain distances and thusly can potentially increase local resilience (Rotz and Fraser 2015); in this case, distributed hydroponic systems may decrease potential problems associated with poor access to and (or) systems failures in fewer, centralized operations. However, it is also important to recognize that this research does not include GHG emissions produced through the construction of hydroponic facilities, and building numerous, smaller operations may be more impactful than building fewer, larger operations that are centralized in (for example) the industrial zones of the Census Districts. A more comprehensive analysis may elucidate such trade-offs between distributed and centralized systems.

This study considered a number of variables related to GHG emissions, incorporating considerations around energy consumption, fertilizer use (Kulshreshtha et al. 2011), transportation, land use, and agricultural practices. However, albeit inclusive of multiple factors, the research did not examine every

aspect of feed crop and livestock agriculture's contributions to GHG emissions. Because of this, the study does not perform a complete lifecycle analysis for the product of livestock products, thereby obscuring the full picture of hydroponic fodder's potential to contribute to climate mitigation objectives. For example, enteric fermentation is a major contributor to emissions (Nguyen et al. 2013; McGregor and Houston 2018), but it was out the scope of this study. This being said, evidence exists for positing that hydroponically grown sprouted fodder has potential mitigation benefits related to enteric fermentation. In an in vitro study that used ruminal fluid, Hafla et al. (2014) observed that treatments of sprouted barley resulted in lower methane production than that of barley grain. Therefore, for this aspect of livestock farming, the value that hydroponic systems add in terms of climate mitigation objectives could potentially extend beyond energy and land considerations and perhaps may also relate to its ability to produce more digestible feed. In addition, it is important to recognize that livestock feed consists of a variety of different fodder types, and it is not the intention of this research to propose a complete shift to a purely hydroponically sprouted diet. The study focuses entirely on barley to provide a clear comparison between hydroponic and conventional barley, but future work that builds on this research could include mixed feeds (Hafla et al. 2014) and perform a similar investigation that examines climate mitigation potential related to on-farm activities, product transportation, and carbon sequestration opportunities.

While examining other factors that contribute to GHGs in the production of fodder, it is important to consider inputs used within a hydroponic system. Inputs for the HydroGreen are water and light, and it does not use fertilizers, instead relying on hydrolytic enzyme activity to release stored seed nutrients in the germination process (HydroGreen Global Technologies 2020). Thus, HydroGreen's GHG production is primarily related to energy consumption. However, other hydroponic systems involve inputs that have associated GHG emissions, such as rockwool substrates used to grow tomatoes and N₂O (Hashida et al. 2014; Yoshihara et al. 2016). Ultimately, such emissions may be significantly lower when using hydroponic systems, rather than conventional, soil-based farming (Hashida et al. 2014); however, as hydroponic farming becomes more widespread, it is important to account for these GHG sources to fully understand the mitigation potential of these systems, similar to how Kulshreshtha et al. (2011) comprehensively modelled the emissions associated with a conventional farming.

The study specifically focuses on GHG emissions and the potential for carbon sequestration to examine the potential of implementing hydroponic fodder systems (and supporting policies) as a strategy for climate mitigation; however, the environmental implications of such systems and strategies are ultimately broader than climate change. Feed crop agriculture is associated with a number of environmental issues, including water consumption, pesticide use, water pollution, fertilizers, and habitat loss (Nguyen et al. 2013; McGregor and Houston 2018). In contrast, indoor farms such as the demonstration farm employing the HydroGreen system do not require pesticides, can reduce or eliminate fertilizer use, can reduce and reuse water, and can be developed in urban and industrial areas without expanding into wildlife habitat (Marchant and Tosunoglu 2017; Gnauer et al. 2019). In addition to contributing to climate objectives, incorporating hydroponic systems into fodder production could produce many co-benefits for addressing other critical environmental issues, such as those related to biodiversity, water conservation, pollution reduction, etc. In some cases, certain farming practices and opportunities may be lost due to changes associated with transitioning from conventional farming to indoor/hydroponic farming; for example, manure from livestock would not serve as a fertilizer inputs for hydroponic systems, which in the case of large-scale transitions to hydroponic farming, could create questions around what to do with manure waste. However, new systems present different opportunities; a livestock farm could integrate systems by establishing on-farm hydroponic and anaerobic digester operations, which would reduce manure-related GHG emissions (Aguirre-Villegas and Larson 2017) while also providing a fuel source that is less GHG-intensive than,

for example, coal (Yu et al. 2008). As hydroponic technologies advance and implementation increases, it is important to consider (and continually improve on) how these agricultural approaches integrate within broader food and farm systems.

5. Conclusions

The long-term future of animal agriculture is uncertain; as new alternatives to meat and dairy products are developed (Mattick 2018), consumer preferences shift toward these alternatives (Aydar et al. 2020), and global trends in vegetarianism rise (Angus and Westbrook 2019). The livestock industry is a major contributor to climate change and other critical environmental issues that challenge global sustainability (McGregor and Houston 2018), and perhaps a complete transition to sustainable food and farm systems involves decoupling these systems from animal-based industries. However, climate change is a critical imperative that requires immediate attention, and although vegetarianism and veganism have experienced dramatic increases in recent years, so has meat consumption (Lee 2019). In addition, animal agriculture is socially, culturally, and economically significant to communities and societies across the globe, and it supports the livelihoods of numerous people. It is impractical and unwise to rely on dietary shifts toward vegetarianism and veganism as the sole strategy for transitioning toward sustainable agriculture, and immediate solutions are needed for reducing the impact of livestock industries.

As evidenced by this study, incorporating hydroponic systems such as the HydroGreen system into fodder agriculture has the potential for reducing the impact of livestock agriculture, as it can contribute to reductions in GHG emissions and climate mitigation objectives. The research estimated that the HydroGreen demonstration farm produced 7.4% fewer GHG emissions (per nutrient mass) than was found with conventional barley grain fodder farming, and greater reductions can be achieved with improved seed-to-fodder output, indicating that transitioning to such systems can result in GHG reductions and (ultimately) climate mitigation benefits. However, to maximize this potential, widespread implementation of agricultural technologies such as the HydroGreen system and (broadly) hydroponic farming must be supported with effective policies in areas such as energy and land use. Technological advancements alone do not comprise effective environmental strategies, and to realize the multiple (potential) benefits offered by hydroponic agriculture, these technologies must be strategically implemented with strong, supporting policies. It is through such strategic implementation of complementary technologies and policies that communities, regions, and countries will make significant progress toward sustainable futures.

Acknowledgements

Funding for this project was provided by the Food and Agriculture Institute (at the University of the Fraser Valley) and Nutriva Group. We gratefully acknowledge the Canada Research Chairs program for the funding that it has provided to the Food and Agriculture Institute.

Author contributions

RN, LN, MD, BV, and TF conceived and designed the study. RN, MD, and CW performed the experiments/collected the data. RN analyzed and interpreted the data. BV and TF contributed resources. RN, LN, MD, BV, TF, and CW drafted or revised the manuscript.

Competing interests

The study focuses on the HydroGreen hydroponic farm system, and HydroGreen is a subsidiary of the CubicFarm Systems Corporation. The fifth author of this paper is affiliated with the CubicFarm Systems Corporation. The analysis was conducted entirely by the researchers at the Food and

Agriculture Institute (University of the Fraser Valley), and we declare that the affiliation did not affect the study. We have provided a comprehensive set of our data, including references and links to data sources (see [Supplementary Material 1](#)) and calculations with our paper to provide complete transparency for the readers of this work, in terms of the analyses and results.

Data availability statement

All relevant data are within the paper and in the Supplementary Material.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:[10.1139/facets-2020-0066](https://doi.org/10.1139/facets-2020-0066).

Supplementary Material 1

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