SCALING LAND-BASED MITIGATION SOLUTIONS IN CANADA

LAND-BASED MITIGATION NARRATIVES

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2. Introduction

Reinforcing its commitment in the Paris Agreement, Canada has recently announced the increase of its emission reduction targets by 2030 and its intention to achieve net-zero emissions by 2050 (Canada Energy Regulator, 2020). From Canada's *mid-century long-term low-greenhouse gas development strategy* report to the United Nations Framework Convention on Climate Change (UNFCCC) in 2016, LMTs are considered of importance to meet Canada's climate targets but are perceived as long-term high uncertainty technology alternatives (Environment and Climate Change Canada, 2016a).

In recent reports, the Canadian Institute for Climate Choices and Navius Research Inc. explored a variety of net-zero pathways for Canada (Dion et al., 2021; Riehl and Peters, 2021). These pathways considered a cap of emissions by 2050 as the only policy in place and contemplated uncertainties around availability and price of low-carbon technologies and negative emissions technologies, policies in other jurisdictions and commodity prices. The reported results indicated that Canada has several pathways to achieve net-zero by 2050 but LMTs are essential to meet this goal. Also, the Canadian Oil and Gas sector is susceptible to changing international oil demand and policies implemented today will have a big impact on the future pathways as argued by Riehl and Peters (2021). This research separated technologies in commercially available technologies today (safe bets) and technologies under development with higher uncertainty for their implementation (wild cards). The modelling projections found that 2/3 of the expected emission reduction by 2030 could be achieved by "safe bets''. However, achieving net-zero by 2050 would require 2/3 of contributions from "wild card" technologies. Special attention was brought in this study to engineered negative emission technologies such as Direct air capture (DAC) and Bioenergy with carbon capture and storage (BECCS) due to its potential and lower uncertainty concerning nature-based solutions. LMTs are considered part of "wild cards since" most of them are immature and require further investment to become available at the required scale (Dion et al., 2021).

This description presents of a general nation-wide transition scenario for the implementation of land-based mitigation technologies and practices (LMTs) for the AFOLU sector (agriculture, forestry, and other land use sectors) in Canada. The report shows a summary of the different narratives and relevant elements built from literature and stakeholder engagement. The information included on this document reflect the outcomes of a series of research steps that have been conducted in this country since the start of the project in June 2020 until the end of 2022.

The first section of this report introduces the different LMTs considered relevant in the Canadian context and presents the rationale for scoping a national LMT portfolio. In the second section, we expand more on relevant elements of the LMT narratives including policy contexts, implementation and consequential risks, and economic implications. The presented narratives were mainly developed from scientific and grey literature. Stakeholder feedback from interviews and bilateral meetings were incorporated to refine the perspectives in the narratives. These narratives are use for scenario assessment both with stakeholder and in models to understand their potential implications at national and regional levels.

3. Scoping of land-based mitigation solutions in Canada

A summary of LMTs and estimated potential for Canada is shown in Table 1. About half of the technical potential can be considered as constrained by biodiversity and food security safeguards (Roe et al., 2019).

Table 1: Estimated LMT potential in Canada.

LMT Category	Sector	LMT	Technical potential [a] Mt CO_2/y	Constrained potential [b] Mt CO_2/y
Nature-based	Forest	**Natural forest management**	127.86	
		Reforestation	54.58	
		Afforestation	12 [c]	
	Agriculture	**Enteric fermentation**	6.4	
		Grazing: legumes in pastures	5.32	
		Synthetic fertilizer	4.95	1.1
		Manure management	4.26	0.25-1.36
		Cropland management	4.23	2.7
		Soil carbon	11.4	3.6-6.1
	Peat-lands	**Peatland restoration**	1	
		Reduced conversion of peatlands	0.2	
Engineered and hybrid		**Biochar**	52-86.5 [b]	7-9
		BECCS (post-combustion CO2-capture)	218	
		Direct Air Capture (DAC)	426	
		Mineralization / Enhanced Weathering	80 [d]	25
		TOTAL	**1008.2**	

sources: (a) (Roe et al., 2019), (b) (Haugen-Kozyra et al., 2010), (c) (Natural Resources Canada, 2020a), (d) (Beerling et al., 2020).

Canada has vast expanses of forested and agricultural landscapes with substantial land-based negative emissions potential in the form of biomass production (afforestation), soil carbon sequestration (climate smart agriculture), and organic carbon fixing (biochar). The federal government acknowledges the negative emissions potential of land-based carbon sequestration approaches (Environment and Climate Change Canada, 2020a) and yet these strategies have been excluded from national GHG emission reduction strategies (Riehl and Peters, 2021). This is likely due to the technical and logistical challenges associated with measuring, validating, and modelling net carbon emissions linked to dynamic carbon cycling processes across that vary broadly across temporal and spatial scales and land use types. However, land-based mitigation strategies should be an essential part of Canadian mitigation strategies considering the vast land extension available in the country, the scale of the agricultural sector, and decreasing of vulnerability of portfolios only focused on engineered solutions alone.

Today, there is no specific roadmap or policy to develop and deploy LMTs or achieving net-zero emissions in Canada. In September 2020, the Canadian government introduced the *Canadian Net-Zero Emissions Accountability Act* - Bill C-12 which requires the government to develop a plan for emission reduction but does not establish a specific action plan (Minister of Environment and Climate Change, n.d.). In February 2021, an independent advisory committee - Net-Zero Advisory Body – has been announced and will be tasked to provide advice on the most likely pathways to achieve net-zero by 2050 (Environment and Climate Change Canada, 2021a).

In this scoping report, we will review the status and potential of different LMTs in Canada. Also, we will discuss the scope of the case study and its position within the context of current efforts to reduce carbon emissions in the country.

3.1 Relevant nature-based solutions for Canada.

3.1.1 Afforestation

Out of all terrestrial ecosystems, forests have the greatest capacity for negative carbon emissions and approximately 9% (over 347 million ha) of the world's forests are located in Canada (Natural Resources Canada, 2020b). Afforestation and reforestation of Canada's landscapes deforested by agriculture, industrial development, resource extraction and urban expansion since the 1800s is an effective climate change mitigation strategy because it increases both soil and vegetative carbon stocks and provides a sustainable feedstock for bioenergy (Amichev et al., 2012; Rowe et al., 2009). Within the boreal forest region alone over 10.9 Mha of land have been converted to agricultural use (Environment Canada, 2013) since early European settlement during the mid-1800s (Boucher et al., 2014; Hobson et al., 2002).

Forest ecosystems can act as both carbon emission sources and sinks depending on their health and how they are managed (Metsaranta, 2019; Seddon et al., 2019; White and Kurz, 2005, p. 200). Globally, forests represent up to 80% of above ground and 70% of below-ground biomass carbon stores (Ameray et al., 2021). Therefore, sustainable forest management and afforestation practices and policies provide valuable opportunities for supporting Canada's climate change mitigation initiatives. Afforestation is defined as the conversion of non-forested land (land that has not been forested within the previous 50 years), to forested land through planting and seeding (IPCC, 2006). While reforestation is defined as direct human-induced conversion of non-forested land to forested land through planting and seeding (IPCC, 2006). Forests provide carbon sink/sequestration ecosystem services by transforming atmospheric carbon dioxide into biomass via photosynthesis. Afforestation and reforestation increase landscape carbon stocks through production of above-ground (i.e., branches and foliage) and belowground (i.e., roots) biomass (IPCC, 2006). Conversely, forests can become carbon emission sources from deforestation and soil disturbance, fire, disease, and decomposition (Kurz and Apps, 2006). Because of the dynamic nature of carbon stocks within forests and the vast expanses of forested land across Canada, forest carbon modelling is becoming an increasingly important land-use planning tool (Laganière et al., 2010).

Fortunately, deforestation rates in Canada have steadily decreased over the last three decades, from approximately 64,000 hectares in 1990 to 34,300 in 2018 hectares per year and is expected to continue decreasing over time (Natural Resources Canada, 2020b). Currently, afforestation rates in Canada are approximately 9,000 hectares of new forests planted per year which is estimated to sequester approximately 1 million tonnes of carbon dioxide capture each year (Natural Resources Canada, 2020b). In 2020, Canada announced it will be planting two billion trees over 10 years to support nature-based solutions and it is expected the initiative to sequester 12 MtCO2 per year by 2050 (Natural Resources Canada, 2020a).

Figure 1 indicates that Canadian forests sequestered approximately 47 million tonnes of carbon per year between 1990 and 2008. This diagram presents they typical annual rates of carbon cycling through the atmosphere, biosphere, and pedosphere in Canada and demonstrates how the rates of atmospheric carbon fixing and emissions are driven by dynamic biological (photosynthesis and heterotrophic respiration) and abiotic (fire and soil chemistry) processes. Negative carbon emissions (carbon capture and sequestration) occurs when the rates of carbon fixing into biomass and soil chemical compounds are faster than the rates of carbon release into the atmosphere from fire and respiration. As long as the soil carbon is maintained, harvesting from managed forests can contribute to net negative emissions when the harvested wood products are put into long term use such as furniture.

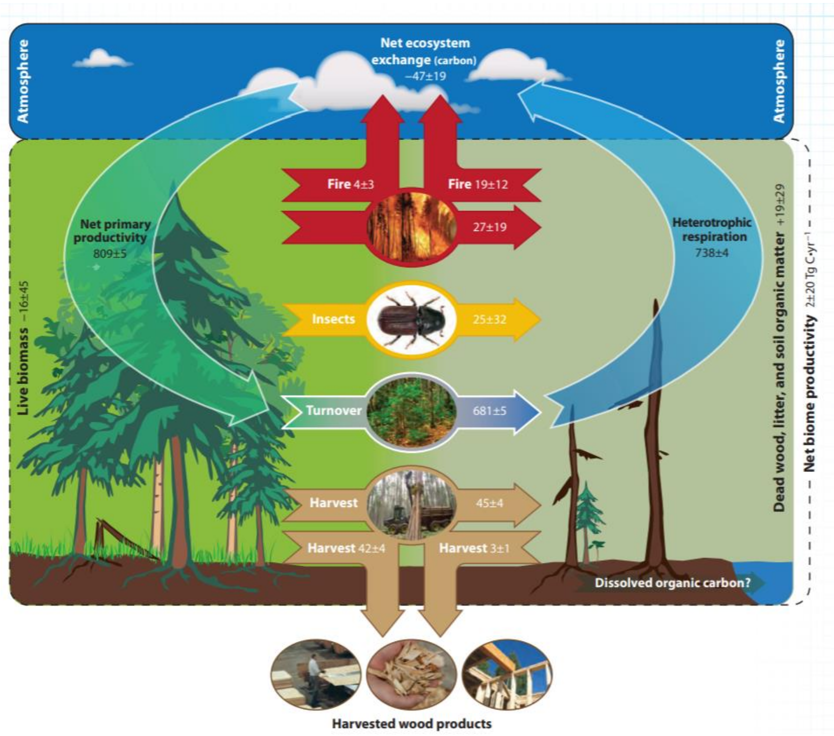

Figure 1. Estimated carbon balance of Canada's managed forest for 1990-2008, Tg (Mt)C/y. The number show the annual mean +/- one std. deviation based on 2019 annual values. Reproduced from "A Blueprint for Forest Carbon Science in Canada: 2012-2020", Canadian Forest Service (Natural Resources Canada, 2012).

The soil carbon sequestration potential and economic opportunities associated with afforesting marginal agricultural lands with short rotation woody crops like willow (*Salix* spp.) has been gaining attention in recent decades. Amichev et al. (Amichev et al., 2012) estimates that afforesting 0.4 Mha of agriculturally marginal land in the Saskatchewan Boreal Plains using short-rotation coppice willow (*Salix* spp.) could sequester as much as 1.1 t CO_2/ha/year of soil carbon and generate enough biomass to offset 16.9 t CO_2/ha/year worth of bioenergy over a 44-year period (LemprièreT.C et al., 2013).

Further research is required to fully understand the total life cycle costs and benefits of implementing afforestation systems designed to maximize climate change mitigation benefits taking into account biophysical conditions and potential carbon leakage (LemprièreT.C et al., 2013).

Both Canada Federal and Alberta Provincial Government has started investing in the investigation of co-benefits of afforestation abandoned areas of coal mines with willows as a means to sequester soil carbon, reclaim disturbed lands, generate biofuel feedstock and create new jobs for rural communities once reliant on the coal industry. In 2019 Alberta Innovates in partnership with several industry and NGO organizations invested over $14 million dollars into the BIOSALIX project : a mine reclamation program using fabricated soils and organic residuals to augment soil quality and underpin a cleantech economy through short rotation willow feedstock production and sequestering carbon into the developing soils (Government of Canada, 2020a) . The BIOSALIX project will be the first of its type and size, providing a path for clean energy growth through the transition of prairie coal mines to biomass production while providing mining communities with economical stability through the development of a cleantech economy. By using municipal organic residuals to overcome mine reclamation challenges BIOSALIX integrates societal challenges to achieve a highest, best end use and outcome – achieving carbon sequestration, closing the nutrient cycle, building long-term soil productivity, and kickstarting a new economic opportunity through a large-scale demonstration. The result: sequestration of thousands of tonnes of carbon in both the soils and biomass, and new opportunities for communities on the threshold of coal mine closure (Government of Canada, 2020a). In 2020, the Federal government announced $2M in funding for Calgary's willow tree plantation farm to pursue reduction of about 200,000 tonnes of greenhouse gas emissions.

3.1.2 Soil carbon

Soils play a major role in the global carbon cycle. With an estimated total of 2000-2500 Gt of soil carbon within the top 1 m, soils hold four times more carbon than the biotic pool (vegetation and organisms) and three times more carbon than the atmospheric pool (Sommer and Bossio, 2014). Therefore, even small changes in global soil carbon pools can measurably influence total atmospheric carbon concentrations (Lal, 2016; Tian et al., 2009; Wijesekara et al., 2017). Kirschbaum (2000), estimated that a 10% increase in the global SOC pool would equate to capturing 30 years' worth of anthropogenic emissions. Figure 2 shows the key drivers for GHG emissions from soils .

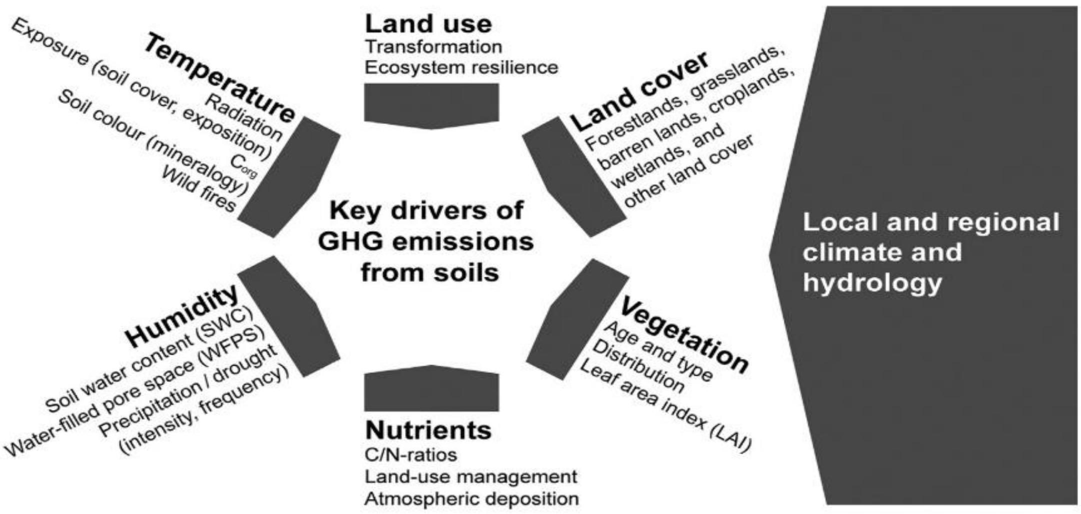

Figure 2. Key drivers of GHG emissions from soils. Reproduced from (Oertel et al., 2016).

Soil carbon sequestration (SCS) increases of the organic carbon content of the soil which results in a net removal of CO_2 from the atmosphere (Fuss et al., 2018). Soil has the capacity to hold four times more carbon than above ground biomass, and its global potential is estimated to 2-5 $GtCO_2e$/yr (Fuss et al., 2018). Increasing soil carbon can be achieved through various strategies. For this report, soil carbon sequestration includes non-till agriculture, grassland management, cover crops, Silvopasture and tree intercropping (Drever et al., 2021; Griscom et al., 2017).

The climate change mitigation potential of SOC sequestration received global attention during the 2015 COP21 United Nations Climate Change Conference when the "4 per Thousand" target was proposed. This target aims to increase the upper 40 cm of the world's topsoil soil organic carbon (SOC) concentrations by 0.4% each year by adopting the conference's recommended climate smart agricultural practices (Wijesekara et al., 2017).

Agriculture's Role in Climate Change and Climate Change Mitigation

The agricultural industry is one of the top contributors to anthropogenic climate change (Environment and Climate Change Canada, 2020b). By converting approximately 40% the earth's ice-free land surface from natural ecosystems to arable lands agriculture has been the second largest generator (25%) of total GHG emissions after fossil fuel combustion (75%) (IPCC, 2014; Lal, 2016). Agriculture generates GHG emissions by intensifying soil carbon losses through soil disturbance and utilizing fossil-fuel based inputs for machinery and fertilizers (West and Marland, 2002). North American prairie soils alone have lost between 25% and 50% (~0.46 Gigatons (Pg)) of their original carbon content due to deforestation and cultivation (Lemus and Lal, 2005; Post and Kwon, 2000). The total soil carbon losses resulting from converting natural ecosystems to agriculture lands worldwide is estimated at ≥350 CO_2e Pg (Oertel et al., 2016). Agricultural practices deplete soil carbon pools in three ways (1) enhancing oxidation and mineralization of SOC compounds (2) leaching and translocating dissolved organic carbon compounds, and (3) accelerating soil erosion (Lal, 2002). Additionally, annual fossil-fuel based agriculture inputs generate approximately 10-12% of total annual anthropogenic greenhouse gas emissions (IPCC, 2014).

By implementing climate smart agricultural practises promoted by COP21 such as no-till cultivation, organic amendments application and agroforestry much of these agricultural-based carbon emissions can be reversed through soil re-carbonization (Lal, 2016; Paustian et al., 2016). Lal (2005, 2016) estimates that through applying SOC sequestration land management practices carbon-depleted agricultural soils have the potential to re-carbonize up to 60-70% (62 Mg C ha-1, 227 Mg CO_2e/ha) of their native ecosystem SOC levels within 50-75 years. While the IPCC (2014) estimates that with the right combination of Agriculture, Forestry, and Other Land Use (AFOLU) practices, SOC sequestration could contribute between 20% and 60% of the total cumulative GHG offsets within 15 years.

As of 2006, the total area of cropland in Canada was almost 36 million hectares equating to roughly 53.1% of all land (Statistics Canada, 2006) . In Alberta government efforts have been made to mitigate the climate change impacts of agriculture by developing agriculture carbon offset quantification protocols such as conservation cropping (no-till agriculture) and biofuel production and usage to incentivise climate smart agricultural practices. Although the carbon offset potential for SOC sequestration is considerable, because soils have a maximum carbon holding capacity and land management or climate pattern changes can release soil carbon, the long term climate change mitigation impact of this strategy is finite and reversible (Goglio et al., 2015; Lal, 2016). Therefore, instead of viewing SOC sequestration as a climate change mitigation solution, it should be considered an effective initial stop-gap measure and used in tandem with other land based (e.g. biochar) and technological negative emissions approaches (e.g. bioenergy production) that do not have upper limits to their negative emissions potential.

3.1.3 Wetlands

Wetland ecosystems have a vital importance in the socio-economic and ecological health of Canada. They account for about 14% of the total land area of Canada, which accounts for about 25% of the world's total wetlands (Kennedy and Mayer, 2002). Wetlands play an important role in the environment as an intermediary between aquatic and terrestrial ecosystems. According to Mitch and Gosselink (2007), they could be called "nature's kidneys" for the natural water quality improvements they provide. They are also crucial for mitigating GHG in a national and international context. Canadian soil store approximately 384±214Pg of organic carbon in the first meter of soil, which is about 25% of the world's total soil carbon storage. Peatlands account for 24% of this carbon stored in the soil of Canada (Sothe et al., 2022). Wetland reclamation, or the creation of wetlands in areas where they do not exist, is thus an important process for regenerative agriculture and carbon sequestration.

A Local Indigenous Perspective of Wetlands in the Athabasca Region

Wetlands are integral to the ecosystems and their significance has been traditionally recognized by the Indigenous peoples of Canada. Boreal peatlands and bogs are called *Muskeg* by the Cree. The Cree are one of the largest Indigenous groups in Canada, living across the provinces from Alberta to Quebec and in parts of the Northwest Territories. Cecilia Fitzpatrick, a Cree Elder in Fort McKay, Alberta, shares stories her father shared with her about the Muskeg: *" My father would tell me that our body is like the Earth…that the Muskeg is your heart and that the mountains are your brain, and the creeks and rivers are blood vessels…Muskeg is very important to rivers and creeks, and everything in them – with that comes our spiritual values and how we are connected to and respect the Earth. When you take from the Earth, you always put something back. The Muskeg is why the Earth breathes…We treat the Earth with respect- it is like treating your own body with respect. We take care of ourselves to live a life of longevity, to maintain a life of health and happiness. We need to treat our Earth the same way. Caring for our future, for our children"*. This narrative of the Muskeg emphasizes the need to protect wetlands, which are not only integral to the health of the wider ecosystem and represent a strong spiritual connection and respect for the land.

3.1.4 Biochar

Biochar is produced through thermal degradation of biomass in the absence of oxygen. This method sequesters carbon by transforming it to its elemental form so it cannot be degraded into carbon emissions through soil bacteria respiration processes. When biochar is added to the soil, this stabilized form of carbon can permanently increase soil carbon content and improve soil quality by increasing soil water retention. The net benefit of using biochar as a negative emissions strategy has been debated because of uncertainties associated with the sustainability of some biomass sources. In some cases, biochar has been produced from biomass of unsustainably harvested forests resulting in carbon emissions from degraded soils and thereby negating some of the net negative carbon emissions effects of this carbon fixing process (Woolf et al 2010). More transparency around best practises for sourcing biomass feedstocks (i.e. using organic waste products such as lumber industry offcuts and woodchips instead of intact forests as feedstock) are required for this negative emissions strategy to build momentum in Canada. In Alberta programs such as Bio-Resource Information Management System (https://www.brims.ca) have emerged to advertise sources of sustainable biomass waste resources for biochar production and other carbon management uses. According to (Woolf et al., 2010), sustainable biochar implementation could offset up to 12% of annual anthropogenic GHG emissions Globally and (Haugen-Kozyra et al., 2010) reports that biochar production from agricultural surplus wastes could generate approximately 3.4 Mt CO2 e y -1 in Alberta, Canada. Figure 3 highlights the potential net carbon sequestration and emissions outcomes associated with the system lifecycle of converting agriculture-base organic waste into biochar. In addition to storing carbon in an inert form, the process of generating biochar can offset additional carbon emissions when paired with coproduction of heat and bioenergy (Homagain et al., 2016).

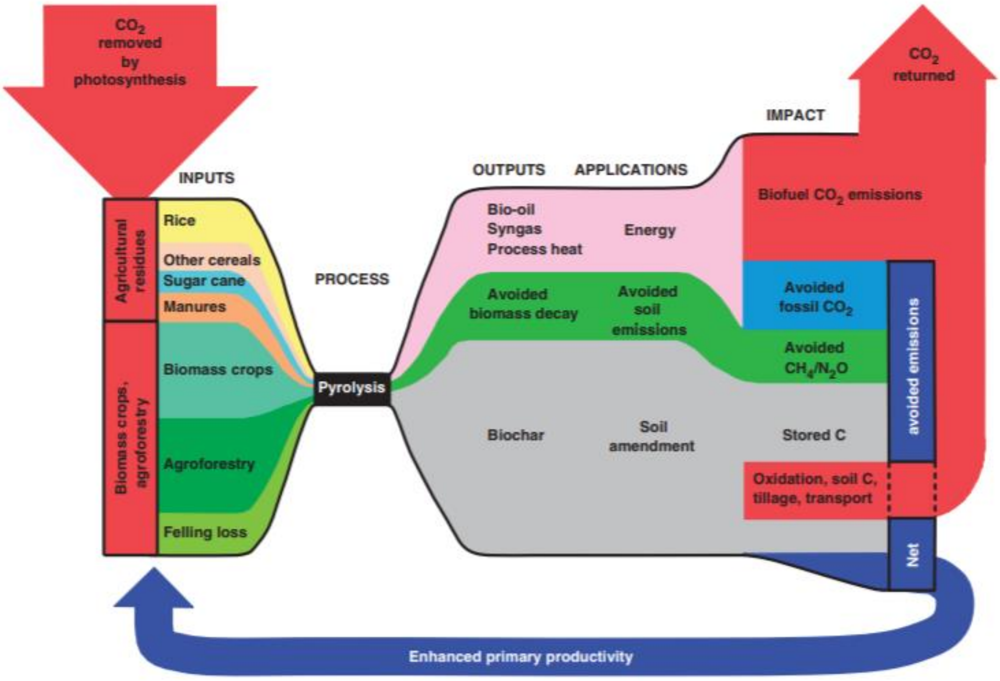

Figure 3. Overview of the sustainable biochar process. Reproduced with permission from (Woolf et al., 2010).

Biochar technology shows promise in mitigating climate change and improving soil quality, as well as reducing waste and producing energy as a by-product (Spears, 2018). Biochar is a charcoal-like substance produced by burning organic material from agricultural and forestry wastes (also called biomass) in a controlled process called pyrolysis. Although it looks a lot like common charcoal, biochar is produced using a specific process to reduce contamination and safely store carbon. During pyrolysis organic materials, such as wood chips, leaf litter or dead plants, are burned in a container with very little oxygen. As the materials burn, they release little to no contaminating fumes. During the pyrolysis process, the organic material is converted into biochar, a stable form of carbon that can't easily escape into the atmosphere. The energy or heat created during pyrolysis can be captured and used as a form of clean energy. Biochar is by far more efficient at converting carbon into a stable form and is cleaner than other forms of charcoal (Spears, 2018).

Biomass pyrolysis is a type of bioenergy production in which biomass is exposed to high temperatures for short periods, with little or no oxygen. Besides biochar, this produces syngas and bio-oil, both of which can be used for heat and power or be further refined into road transport or possibly aviation fuel. Pyrolysis can be done in large plants and small kilns or stoves (Paul et al., 2009).

Although biochar technology is considered a more recent strategy for carbon sequestration, the practice of adding charred biomass to improve soil quality is not new. This process is modelled after a 2,000-year-old practice in the Amazonian basin, where Indigenous people created areas of rich, fertile soils called terra preta (meaning "dark earth") (Spears, 2018). By heating the feedstocks and transforming their carbon content into a stable structure that does not react to oxygen, biochar technology ultimately reduces carbon dioxide in the atmosphere (Spears, 2018).

Biochar also contributes to the mitigation of climate change by enriching the soils and reducing the need for chemical fertilizers, which in turn lowers greenhouse gas emissions. The improved soil fertility also stimulates the growth of plants, which consume carbon dioxide. The many benefits of biochar for both climate and agricultural systems make it a promising tool for regenerative agriculture (Spears, 2018).

3.1.5 BECCS

BECCS, also challenged to change to biomass carbon removal and storage (BiCRS), consists of a series of technologies (a process) where biomass systems remove CO_2 from the atmosphere and oceans, people harvest the energy through conversion, and the carbon is stored under the ground (geosphere)(FRIEDMANN et al., 2020) – Figure 4. BECSS represents a pivotal technology in most pathways for limiting global warming by 1.5 C (Masson-Delmotte et al., 2019). Globally, it is expected for BECSS to have a LMT potential of 0.5-5 $GtCO_2$/yr, 3-8% of total energy consumption (Canadell and Schulze, 2014), with a cost of 100-200 USD/tCO_2 (Fuss et al., 2018). However, significant overestimation of the capacity of BECCS deployment by Integrated Assessment Models (AIMs) has led to broad debate about appropriate scale-up of this technology and large uncertainties remain around technical feasibility and governance (e.g. transform traditional governance structures and policy-making models) issues (Sandalow et al., 2021).

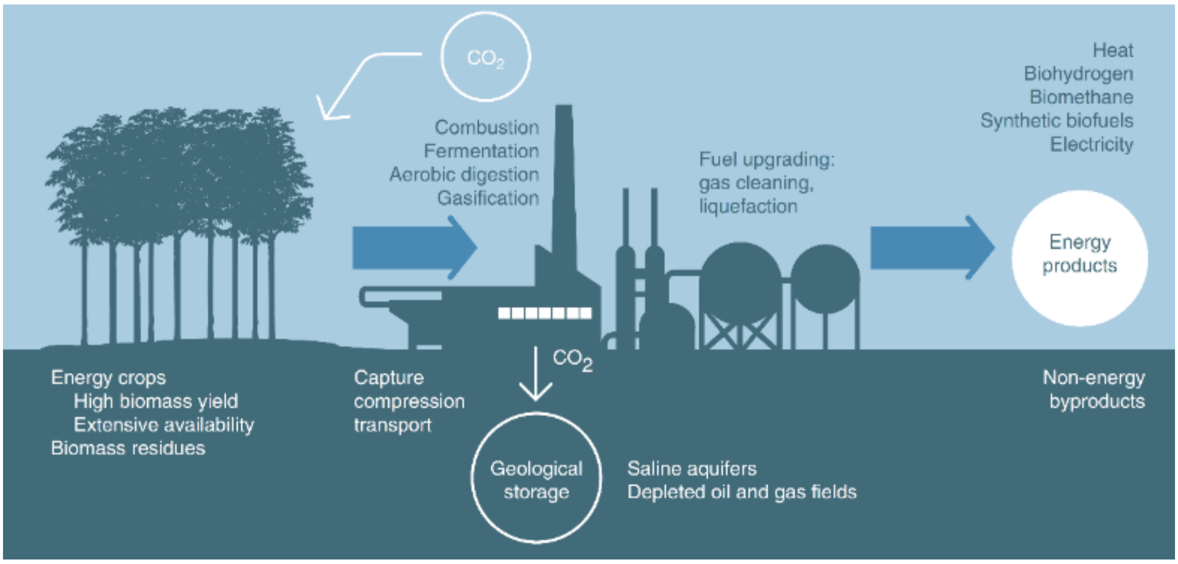

Figure 4. Bioenergy with carbon capture and storage process. Reprinted with permission from Canadell et al. Nature (2014).

Today, only five facilities are actively using BECCS technologies reaching ~1.5 million tonnes per year (Mtpa) of CO_2 removal mostly dedicated to enhanced oil recovery (EOR) (Consoli, 2019). In Canada, there are two BECCS projects deployed: (i) Husky Energy Lashburn and Tangleflags CO_2 Injection in

Heavy Oil with a capacity of 90,000 Mtpa, and (ii) Saint-Felicien Pulp Mill and Greenhouse Carbon Capture Project with a capacity of 90,000 Mtpa. No other projects have been announced to date.

Canada considers BECCS as a key long-term opportunity to achieve net-zero by 2050. However, there are no policies in place to further develop the sector. A recent report by Navius research (Riehl and Peters, 2021) estimated that negative emission CCS could contribute up to a 218 $MtCO_2e$ emission reduction with respect to 2020 levels by 2050. This estimate contemplates emission reduction from combustion emissions from sectors like hydrogen, cement, and coal plants, not only BECCS, and is sensitive to the dynamic with different other scenarios.

Further studies are necessary to more precisely estimate the potential risks and rewards for BECCS in Canada. The full carbon cycle of BECCS is not comprehensively studied and the LMT potential benefits could be overstated. The effectiveness of BECCS heavily relies on the type of biomass, geographic location, total final consumption of energy, ways and efficiency of energy consumption, and other relevant factors. Therefore, the carbon removed from the atmosphere can be off-set by emissions related to land-use and energy-use changes (Harper et al., 2018), and it may only remain as LMTs if residues are used from currently managed forest lands (Withey et al., 2019).

3.1.6 Direct Air Capture with storage (DACS)

Technologies for air purification and carbon removal from the atmosphere have existed since the 1940s for use in submarines, spacecrafts, and fuel production. However, DACS was first introduced for climate change mitigation in 1999 (Lackner, K. et al., 1999). DACS removes CO_2 directly out of the atmosphere and delivers a pure compressed gas stream for storage under the ground or reuse (Riehl and Peters, 2021). Although removing low concentrations of CO_2 in air (~400 ppm) is challenging and costly, DACS in concept is presented as an alternative for distributed emission sources, low water and land footprint, and potential to locate near storage sites eliminating the need for transport. Carbon removal from air can be achieved using liquid or solid sorbents as well as chemical looping with oxides, electrochemistry, photocatalysis, membranes, and biological routes (Sanz-Pérez et al., 2016).

There are currently 15 DACS plants operating capturing more than 9,000 tCO_2/y and 1 $MtCO_2$/y in advanced development in the US (International Energy Agency, 2020). Globally, it is expected for DACS to have a LMT potential of 0.5-5 $GtCO_2$/yr with a cost of 100-300 USD/tCO_2 (Fuss et al., 2018). Canada is home of Carbon Engineering Ltd., one of the few companies trying to commercialize DACS currently at pilot scale with a capacity of 1 t/d (National Academies of Sciences, 2019). Major support is growing for DACS locally with international and national partnerships developing to accelerate the scale up of DACS. For Canada, it is projected that DACS could be adopted at a very large scale with a potential capacity up to 426 $MtCO_2e$ by 2050 (Riehl and Peters, 2021).

3.1.7 Carbon mineralization of CO_2 / Enhanced Weathering

Carbon mineralization is a natural process where CO_2 is sequestered by an exothermic reaction of alkaline silicates and hydroxides forming a stable carbonate mineral (Power et al., 2013). In the1990s It was first proposed as a climate mitigation strategy and promising natural materials, such as ultrabasic/ultramafic rocks, through the engineering of a process to maximize this effect via pulverization and maximizing solid-gas contact (Lackner et al., 1995; Seifritz, 1990). In the past decades, other routes for mineralization using synthetic materials, industrial wastes, and integration with cropland have been developed increasing the potential for this LMT. Challenges in energy use and reaction kinetics remain as barriers for this technology, as well as political and social inertia for policy development (Beerling et al., 2020).

Enhanced Weathering remains a very early technology. However, it is expected for enhanced weathering to have a LMT potential globally of 2-4 $GtCO_2$/yr with an approximate cost of 50-200 USD/tCO_2 (Fuss et al., 2018). In Canada, there has been significant research in the identification of appropriate geological storage areas and the first major field trials looking at site weathering of mining waste are underway. However, no comprehensive study of national potential or specific policies for enhanced weathering has been found.

3.2 Determining the LMT scope for national level simulation modelling

In this section we discuss which set of LMTs we will study in detail for Alberta, Canada. Table 2 summarises the main LMTs and indicates which ones are included in the short-list of the LMT portfolio for Canada. The main rationales for including the various LMTs in the national level scaling simulation assessment are presented below.

Table 2: Long-listing of relevant land based LMTs

LMT Category	LMT	Included in national LANDMARC LMT portfolio
Nature-based	**Afforestation**	Y
	Soil carbon	Y
	Wetlands	Y
Engineered and hybrid	**Biochar**	Y
	BECCS (post-combustion CO2-capture)	Y
	Direct Air Capture (DAC)	N
	Mineralization / Enhanced Weathering	N

Risks and uncertainties around LMTs raise criticisms around the likelihood for deployment, especially about overestimation of IAMs, necessary land extensions to meet the projections, climate vulnerability, and potential social inequities resulting from development in remote/rural communities (Anderson and Peters, 2016). Although the negative emission potential of land-based negative emission approaches is widely understood, including them as part of international emissions reduction commitment strategies is challenging because both it is difficult and costly to accurately measure and predict the complex biogeochemical and climactic systems that control soil carbon sequestration and biomass production and the economic markets that incentivise land-based negative emissions projects (LemprièreT.C et al., 2013; Oertel et al., 2016; Saiz and Albrecht, 2016).

In Canada, significant negative emissions can be gained through re-carbonizing Canadian landscapes that have been depleted by extensive deforestation and till-based agricultural practices since the 1800s. However, the landscape's total biomass production and soil carbon sequestration potential is finite, and rates of negative emissions decrease over time as forest and soil systems approach their carbon holding capacity. Therefore, it could be argued to broaden the scope to other carbon emissions offset strategies like Biochar and BECCS biogenic approaches because their performance and potential are easier to accurately measure, verify, and forecast and they have theoretically limitless carbon negative and carbon neutral offset potential.

However, through consultation with local communities it was highlighted that from a stakeholder perspective, the local ecosystem play a vital role in the livelihoods of those communities. Beyond their climate change mitigation potential, issues associated with land and how to better use it connect more with culture, religion, health, and identity. A shift on perspective with regards to LMTs is needed to better understand the human dimension and incorporate it on policies to better support a just transition.

Considering the critical role of the local context in the feasibility and scalability of LMTs, our case study aims to explore the climate change mitigation potential of restoration of damaged landscapes, particularly of boreal forests. This approach will evaluate the synergies and barriers for various LMTs interacting:

- Afforestation – reclamation and afforestation of damaged land using energy crops
- Soil Carbon – increasing soil carbon content through land reclamation
- Wetlands – restoration and protection of wetlands and peatlands in the Canadian north
- BECCS – use of energy crops and long-term storage of carbon
- Biochar – use of biochar by-products to replenish soil carbon content

Our study will focus on the LMT potential benefits of restoring and protecting boreal ecosystems, how to develop a sustainable enterprise, and its role as a green economic alternative for communities largely affected by extractive industries and traditionally left out of energy transition strategies such as rural and indigenous communities.

4. Co-design of LMT narratives

Nature-based solutions provide Canada with valuable opportunities to support national carbon offsets greenhouse gas emissions reduction target commitments. The following five LMTs have been shortlisted for their value to local communities, technical potential, and supportive federal and provincial policies.

Further details of these LMTs will be presented in this section to highlight current policy frameworks, risks, co-benefits, and trade-offs. Effects of avoided disturbances, though significant on the overall emission reduction, will not be addressed on this section since LMTs are focused on implemented strategies to reduce carbon emissions.

4.1 Wetland protection and restoration

4.1.1 Policy Context

Federal Level

The Pan Canadian Framework (Environment and Climate Change Canada, 2016b) lays out a detailed plan of how Canada wants to achieve GHG reduction targets. The key components of their plan entails ecosystem conservation and restoration. A particular focus is laid on converting Canada to a low-carbon economy (Alcock, 2017). The national Green Infrastructure Fund was introduced in 2017 to provide financial support for investments in green infrastructure, i.e, constructed wetlands and urban forests, as wetlands and trees are effective carbon sinks that also provide ecological benefits.

The Agricultural Policy Framework of 2022 (APF) is a five-year funding program that aims to provide funding for agricultural investments across Canada until 2028. The APF, along with the Canadian Agricultural Partnership, have previously focused solely on environment-beneficial management practices (BMPs), but according to Farmers for Climate Solution (FCS), which is a farmer-led task force of experts who aim to implement the most cost-effective climate change measures, a more system-wide approach is required. FCS recommends standard cost-share programs as well as reverse auctions and collective bonus payments (Farmers for climate solutions, 2022a)

Canada has committed to a number of UN Aichi Biodiversity Targets to improve biodiversity by 2020. One target was described as follows: *"By 2020, at least 17% of terrestrial areas and inland water, and 10% of marine and coastal areas of Canada are conserved through networks of protected areas and other effective area-based measures."* As of August 2019, there was still 492,981 km^2 of land left to achieve the 17% target (Wark, 2019).

Provincial Level

Alberta's unique scientific research capabilities and biomass availability has led to it being a key region for improvements in wetland and forest management (Government of Alberta, 2016). The creation of the Indigenous Protected and Conserved Areas (IPCAs), which are "lands where Indigenous governments have the primary role in protecting and conserving ecosystems through Indigenous laws, governance and knowledge systems." Is also a significant step in this direction since wetlands in the oil sands regions are linked to the traditional way of life of the indigenous Metis communities.

The Alberta Water act (1999) and the Alberta Environmental Protection and Enhancement Act (EPEA) (2022) are the most important legislations for the reclamation of wetlands. The objective of EPEA is to return disturbed landscapes to "equivalent land capability". The Provincial Land Use Framework (LUF) of the Alberta Land Stewardship Act (ALSA) (Government of Alberta, 2022b), is also an important framework whose key objectives are to enable healthy ecosystems and people-friendly communities by restoring wetlands and grasslands. However, in 2013 a specific policy was developed - the "The Alberta Wetland Policy" which came into full effect in 2016 across the province (Government of Alberta, 2013). The policy aims to conserve and restore wetlands while allowing economic growth. In this policy, wetlands are managed by avoiding, minimizing, and replacing lost wetland value by restoration or payment. However, some of the directives were just in place since 2018, and their implementation is undergoing review.

One of the major concerns with this policy is that it has been stated that it does not apply to projects approved before July 4, 2016, which are most of the Oil Sands mining projects in Northern Alberta (Huynh, 2018). Therefore, there is uncertainty about the capacity of this policy to restore the function of the damaged areas in the green areas (mostly public land, forested and less settled).

4.1.2 Current land use

Wetlands in Canada account for 24% of the global wetlands. The Boreal region is the largest biome in Canada, accounting for 58% of the land base (Anielski and Wilson, 2009). Within Canada, 119 million ha consists of wetlands. Alberta's unique geography sets 70% of the land base within the boreal region which largely consists of wetlands (Alcock, 2017). This makes Alberta especially rich in soil carbon storage. Approximately 15,000 ha of wetlands are converted to crop land every year in Canada (Farmers for climate solutions, 2022b). Careful management is required for the proper management and reclamation of these lands to limit the destruction of peatland ecosystems.

4.1.3 Potential climate risk sensitivities

The destruction of wetlands and conversion to cropland results in an estimated GHG emissions of over 1.2 Mt of CO_2e per year but Canada's National Inventory Report does not account for these emissions. The draining of wetlands leads to the release of the carbon stored under as CO_2 over a period of years or decades. Evidence points to an increased rate of conversion of wetlands to croplands in recent years due to the rising prices of commodities. Creating or restoring wetlands is less effective than preventing conversions in the context of mitigation of GHG, but it is still beneficial as it could provide a mitigation of 22,000 tons of CO_2 e per year (Farmers for climate solutions, 2022b).

Other risks to wetlands associated with climate change involve the dry up and disappearance of small wetlands, seasonal water levels of larger wetlands, wetlands over permafrost may shrink or disappear, impaired water retention, burnt due to increase wildfire risks, and greenhouse gas emissions associated with decomposition and brunt of wetlands and peatlands (Aquality Environmental Consulting Ltd., n.d.; Wilkinson et al., 2021).

4.1.4 Economic implications

Wetland management is costly to farmers as they would rather use the land for cropping. Wetland restoration is expensive, with the cost in the Prairies at the rate of $5,200/ha and around $31,000/ha in the rest of Canada. Drever et al. (2021) estimated wetland restoration costs ranging between 3500-400 USD/ha. FCS estimates an annual expenditure of per year for the mitigation of 1.4 Mt CO_2e in the year 2028 at $50 Million per year (Farmers for climate solutions, 2022b). The cost for carbon sequestration and CO_2e reduction is also calculated in detail by in the FCS in their Economic Analysis report of March 2022 (Table 1).

Table 3.6.3: Program spending, emissions reduction, carbon sequestration, and program abatement cost for 2023-2024.

Management Practice	Incentive Cost in 2023 ($)	Emissions Reduction in 2023 (t CO2e)	Carbon Sequestration in 2023 (t CO2e)	Abatement Cost in 2023 ($/t Co2e)
Nitrogen	35,952,942	760,843	0	47.25
Manure	12,373,402	479,589	0	25.80
Livestock	13,031,887	405,121	455,034	15.15
Soil	68,260,290	152,306	700,373	80.05
Trees/Wetlands	55,828,069	200,917	85,600	194.85
Total	**185,446,591**	**1,998,775**	**1,241,007**	**57.24**

Table 1. Emissions reduction, carbon sequestration and program abatement costs for 2023-2024 (Farmers for climate solutions, 2022b).

4.1.5 Co-benefits and trade offs

Wetlands are valuable carbon sinks that also provide numerous ecological benefits. Successful avoidance of the conversion of wetlands into croplands can result in significant reduction in emissions while restoration of wetlands can increase soil C to a large extent. Natural Boreal Wetlands are also natural habitats of a large number of important Canadian wildlife species such as moose, muskrats, beavers and woodland caribou. Wetlands are also deeply connected to the Aboriginal way of life due to the cultural significance of the presence of the flora and fauna of wetlands. Wetlands also provide ecological benefits such as water storage, groundwater regeneration, storm runoff generation and shoreline stabilization (Government of Alberta, 2018a). However, it is uncertain if the soil in a reclaimed wetland that has been previously mined will retain soil permeability, as some evidence suggests an increased permeability that could impact groundwater recharge and water input to wetlands (Devito et al., 2005).

4.1.6 Risk of scaling up

Expansion of wetlands via reclamation may interfere with pre-existing ecosystems and the natural habitats of wildlife species. As the interactions between wildlife may be complex and as of now indeterminable, a specific focus must be laid on studying the neighbouring ecosystem before scaling up. Wetlands also require a water supply to support hydrophytic plants which produce saturated soil, hence it is necessary to study how water moves through reclaimed soil before large scale implementation. Vegetation design and trees on upland hill-slopes must also be considered as forests on upland hill slopes will reduce surface runoff (Government of Alberta, 2018a). Physical, biological and chemical monitoring methods must be incorporated to ensure long term feasibility of reclaimed wetlands and ecosystems.

Local stakeholders have expressed their concern about the success of wetland restoration efforts. Some have indicated that seedlings and trees being brought from outside areas are not successfully growing. As well as reclamation efforts substituting wetlands with high-lands due to lower costs. In addition, local stakeholders indicate that the spiritual value of the wetlands are lost and can't be recovered by restoration efforts that do not take into consideration Traditional Environmental Knowledge. To our knowledge, there are no known examples of successful constructed peatlands which pose a great challenge in Alberta particularly in the peatland zone in the north that overlaps with the oil sands (Locky, 2011; Nwaishi et al., 2015). Therefore, major technical and economic challenges need to be overcome if the ecosystem is to be restored.

4.1.7 Research and Implementation Gaps

The uncertainties with peatland restoration mainly concern the lack of proper understanding of chemical and nutrient interactions in groundwater from reclaimed landscapes along with changes in the long-term permeability of the soil. The interaction of old and new animal species flocking to reclaimed wetland is also unpredictable (Alberta Environment 2008)(Nwaishi et al., 2015).

The wetlands of Alberta were also traditionally maintained effectively by indigenous communities living in the area. However, the current policy aims and regulations create an unfavourable position for the respectful application of traditional ecological knowledge from the communities. This disconnect between policy aims and inclusion of communities must be addressed to enable successful implementation of climate mitigation technologies.

4.2 Forest Management and Afforestation

4.2.1 Policy context

International level

Afforestation was initially introduced during the 2002 United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body on Scientific, Technical and Technological Advice (SBTSA) 19 when discussions were initiated to define and scope afforestation and reforestation project activities under the Clean Development Mechanism (CDM) (UNFCCC, 2021). Since then, afforestation and reforestation have been mentioned several times at Conference of the Parties (COP) and SBSTA meetings. Most recently, the UNFCCC COP has adopted special rules to ensure that accounting for GHG emissions removals from afforestation projects comply with Kyoto Protocol objectives and do not cause negative impacts within the regions they are implemented (UNFCCC, 2021).

Federal level

In 2016, Environment and Climate Change Canada adopted the Pan-Canadian Framework on Clean Growth and Climate Change plan. The objective of this plan is to grow the domestic economy while reducing emissions and building resilience to adapt to a changing climate (Environment and Climate Change Canada, 2016b). As part of the Pan-Canadian Framework on Clean Growth and Climate Change, the federal, provincial, and territorial governments committed to collaborate through Canadian Council of Ministers of the Environment (CCME) on a pan-Canadian greenhouse gas (GHG) offsets framework. Pan-Canadian Greenhouse Gas offset framework was adopted by CCME in 2019, and it supports federal, provincial and territorial governments in developing and implementing their offset systems. The Framework also offers several means of managing carbon emissions including best practices on carbon offset program design and implementation to support future offset fungibility (CCME, 2019).

The Forestry, Agriculture and Waste subsection of the Pan-Canadian GHG offset report highlights the role of forests, wetlands and agricultural lands in carbon emissions reduction (CCME, 2019). Although afforestation is not specifically named in the report, it is noted that advancement of forestry and agricultural management practices that help reduce emissions is one of the federal and provincial objectives (CCME, 2019).

On July 2, 2020, the Government of Canada released a discussion paper on the proposed Federal Greenhouse Gas Offset System (the "Federal GHG Offset System") that clarifies how the protocols for offset credits will be developed for specific project types (Richardson and Williams, 2020). The federal government shortlisted eight project types for the development of offset protocols of which afforestation/restoration, improved forest management, and soil organic carbon are included (Richardson and Williams, 2020).

Provincial level

Afforestation is recognized by the provincial Government of Alberta as one of several effective GHG offset solutions. In September 2007, the Government of Alberta published Quantification Protocol for Afforestation Projects that includes guidance on afforestation projects in Alberta (Alberta Environment, 2007) and in 2020 the Government of Alberta released Specified Gas Reporting Regulation (Alberta Regulation 251/2004), which provides the legal basis for afforestation practices in Alberta (Alberta Queen's Printer, 2020).

The afforestation project protocol notes that carbon offsets are primarily generated by carbon sequestration occurring from planting trees on non-traditionally forested lands i.e. agricultural land, urban land, agro-forestry operations, and reclamation of industrial sites (Alberta Environment, 2007).

Projects and Actors in Canada

Forest management and Afforestation projects Canada involved several actors where the Federal and Provincial Governments have important participation:

- Growing Canada's Forests program (Government of Canada, 2021a)
  This program applies where trees can be planted: "on public and private lands across the country in remote, rural, suburban and urban areas via afforestation, which is the creation of new forest cover on lands that currently do not have trees (e.g abandoned fields), and via reforestation, which is the regeneration of forests that have temporarily lost their tree cover through natural disturbances (e.g. wildland fire) or in areas where commercial disturbances (e.g. forestry roads and landings, mining or seismic lines) have occurred, but for which there is no current legal requirement to plant trees. To restore forest habitat, including under recovery strategies for species at risk, conservation agreements and related planning processes (e.g. range plans)"
- The Prairie Farm Rehabilitation Administration Shelterbelt Centre in Indian Head, Saskatchewan, part of Agriculture and Agri-Food Canada (AAFC), is currently the only federal organization that has a national agro- forestry mandate. A national strategy is being developed with the goal of improving the competitive position of the agricultural sector by incorporating agroforestry systems for the sustainable management of the agricultural land base (Policy Options, 2008)

- In Alberta, all projects listed on the AEOR must meet system requirements as outlined in the Standard for Greenhouse Gas Emission Offset Project Developers (Government of Alberta, 2019).
- Forest resource improvement association of Alberta (Forest Resource Association of Alberta, 2021)

Allowing regulated facilities to use market-based compliance tools such as emission offsets creates incentive for Albertans from all areas of the economy to innovate and invest in activities that will reduce greenhouse gas emissions - from farmers to municipalities to small renewable energy industry developers (CSA Group, 2019).

In Alberta, the conservative ideology mostly favours business-oriented projects (Biggs, 2009). One can expect that afforestation generated carbon offset projects would conform to the conservative values including low permanence, explicit inclusion of carbon offsets as fungible with emissions reductions, standards not compliant with those relevant to the Kyoto Protocol, and operated as profit-generated businesses (Biggs, 2009).

- TreeCanada - Since 1992, we've planted more than 83 million trees and sequestered millions of tons of carbon pollution in the process. Every year we deliver mass plantings in each of Canada's five major regions; Atlantic & North, Québec, Ontario, the Prairies and British Columbia (Tree Canada, n.d.).

- The National Greening Program is mass seedling plantings across Canada, where there is a need for reforestation or afforestation (Tree Canada, n.d.).
- For private Land owners (Government of Ontario, 2021) This program, funded by the Ministry of Natural Resources and Forestry and administered by Forests Ontario and other partners, provides funding and information for landowners willing to plant trees on their property.

Within the 2021 federal budget, the government of Canada has committed to investing over the next two years $54.8 million CAD to foster new forest-based economic opportunities, $28.7 million CAD to map wildfires risks, $67.2 million CAD to deploy Clean Fuel Standards, and $15 million CAD to plant 2 billion trees (Government of Canada, 2021b). Locally, Alberta has dedicated more than $100 million CAD a year to support the forestry sector through infrastructure development and wildfire mitigation. Also, an annual budget of $30 million CAD to mitigate the effects of mountain pine beetle infestation. However, no direct mention to afforestation has been proposed in Alberta.

4.2.2 Current land use and potential land-use competition

Canada has 348 million hectares (ha) of forest and accounts for approximately 7% of global forest cover. Forest land is subdivided into managed (226 million ha) and unmanaged (122 million ha) and it is mostly under provincial or federal jurisdiction. Deforestation rates have been on decline in Canada since 1990. In 2018 Canada had 35,000 ha deforested mostly due to oil and gas, agriculture, and urban development, but the deforestation rate has been ~1% in the period. Hydroelectric developments have shown significant peaks in deforestation during the deployment of specific projects (Natural Resources Canada, 2020b).

To fully evaluate forestry potential as an LMT, Drever et al. (2021) identified a potential area of 139 million ha for improved forest management with an expected mitigation potential of approximately 8 MtCO_2e/y and 4.34 million ha for afforestation with an expected mitigation potential of approximately 0.05 MtCO_2e/y. This potential has not considered areas already considered for food production or urban development, as well as already burnt areas since new forest are growing or will grow on it.

4.2.3 Climate risks & sensitivities

As Canada's territory is expected to warm up more than the world average, the effects of climate change on Canada's forests are already evident in the form of increased frequency and severity of fires, droughts, severe storms, damaging insects and disease attacks. Forest fire season has become more frequent and destructive with an estimate of 74-118% of projected increase of burned areas by the end of the century (Williamson et al., 2009). Extreme weather events will also include floods and droughts that are expected to have major economic impacts in the region, such as the 2013 Flood in Southern Alberta or the Fort McMurray Fire from 2016 (Sauchyn et al., 2020). Out of the 20 most costly weather events in Canada since 1983, 13 happened in the Prairie provinces demonstrating a major vulnerability in the Canadian North and the Central Prairies.

On the other hand, climate change will result in more frequent, extended, intense and longer outbreaks of pests. Insect species with the potential for increased economic impacts under climate change include the mountain pine beetle, the larch sawfly, the spruce bark beetle, the jack pine budworm, the spruce budworm, the gypsy moth, the forest tent caterpillar, and the large aspen tortrix. Also, climate change will likely increase the risks for diseases to become more established in the Canadian forests (Meyer, 2018; Natural Resources Canada, 2013; Prairie Climate Centre, 2021).

With regards to biodiversity, a northward movement of climate envelopes is expected to boost productivity and species diversities. However, not all species will be able to adapt so quickly, tending to disappear. Also, the genotypes will evolve in response to climate making some forest areas disappear. For example, over parts of the boreal forest will convert to aspen parkland and what is today aspen parkland will convert to prairie grassland type ecosystems. Considering these risks adaptation and mitigation measures need to be in place to maintain current levels of harvesting (Boucher et al., 2018).

4.2.4 Economic implications

Forest pathways can provide ~11.9 $MtCO_2e$ per year by 2030 in a cost-effective and readily available manner with more than 40% of it is estimated achievable at less than \$50 CAD/tCO_2e. For improved forest management, almost all the projected capacity 2021-2030 could be covered below \$80 CAD/tCO_2e, while for afforestation costs are estimated below \$1000 CAD/tCO_2e during the first years and below \$200 CAD/tCO_2e 2021-2050. These differences were explain as the afforestation costs take place on the initial years while the benefits of the LMT were observed in the long term (Drever et al., 2021).

4.2.5 Co-benefits and trade-offs

Utilizing forestry practices and increasing forest coverage as an LMT could bring benefits on ozone abatement and air filtration, avoided air quality impacts as a result of slash burning, contribute to the restoration of habitat for other dependent species, create wildlife corridors and buffer areas, reduce soil erosion and nitrogen loss, improve availability of water for irrigation increase employment opportunities and socio-economic benefits for local communities (Drever et al., 2021; Government of Canada, 2020b). Also, the incorporation of trees into predominantly agricultural landscapes has environmental benefits including enhanced soil conservation, nutrient management, and water quality. However, maximizing the short-term emissions reduction can reduce the forest's ability to contribute to longer term objectives such as reduce C stocks and increasing the sustainable rate of harvesting (Smyth et al., 2014).

4.2.6 Risks associated with scaling up

When considering scaling up forestry LMTs, it is important to highlight that these practices require large amounts of land (up to 1.10 Mha) leading to competition with agricultural land (IPCC, 2014). Strong afforestation policies could drive to lock-in in other sectors reducing incentives to invest in other in those that are more expensive to decarbonize, such as the energy sector. In addition, forest LMTs could be susceptible to reversibility due to severe climate conditions, storms, wildfires, and extended diseases (Doelman et al., 2020). Lastly, grow rates in colder climates is slower therefore it takes a long time for benefits to be realized increasing potential back-lash from groups advocating for other climate change mitigation strategies.

- "Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (high confidence). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (high confidence). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (high confidence). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (high confidence). (Masson-Delmotte et al., 2019)

4.2.7 Research gaps

During this review, here are some of the research gaps identified (Crossley, 1980):

- Forest inventory requires more certainty. There are many forest areas that are inaccessible and will impact the real potential for managed forest areas
- Proper monitoring of forest residues and residue handling during harvesting activities
- Lack of unified framework for mitigation assessment (Smyth et al., 2014) and the impact of the specific local context
- The intersectionalities of forestry and other sectors, as well as how this LMT impacts food security in Canada.
- Proper analysis of ecosystem vulnerability due to climate change impacts
- Verification of estimated potential with in-situ measures to confirm the projected capacity (Drever et al., 2021)

4.3 Soil Carbon

4.3.1 Policy context

Federal level

Along with afforestation, soil organic carbon was also included into discussion paper on the proposed Federal Greenhouse Gas Offset System (released in July 2020) (the "Federal GHG Offset System") that clarifies how the protocols for offset credits will be developed for specific project types (Richardson and Williams, 2020).

According to the Government of Canada (Agriculture and Agri-Food Canada, 2021), soil carbon levels performance in eastern and western provinces is very distinct. On the Prairies, farm soil carbon levels have stabilized or increased over the past few decades, largely from adoption of no-till cropping, which avoids disturbing the soil while growing crops (Lynch, 2019). In Eastern Canada, however, most estimates suggest that the intensity of crop production (especially reduced use of forage crops) is causing soil carbon levels to decline. This situation is made more challenging by the fact that in higher moisture regions such as Eastern Canada and British Columbia no-till cropping does not enhance soil carbon (Lynch, 2019). According to the Western Producer, Canadian east versus west politics likely factors into why the federal government isn't talking about the sequestration of carbon in prairie soil (Booker, 2018). If specific farming sectors are rewarded or punished for the amount of greenhouse gases, including carbon, that is emitted into the atmosphere, then it's feasible the farming practices used by western Canadian grain growers would provide dividends (Booker, 2018). However, there is little indication from the federal government that it's interested in considering the actual balance of greenhouse gases emitted or sequestered by specific farming regions, practices or sectors. Due to the East-West divide, the federal government does not want to take risks by paying more dividends to western farmers. "That's a political nuclear bomb. That's why we aren't hearing much about carbon sequestration at a national level." (Booker, 2018).

Provincial level

The Conservation Cropping Protocol provides opportunities for farmers to earn carbon offsets by increasing soil carbon levels through no-till management (Government of Alberta, 2021a). The Conservation Cropping Protocol is nearing the end of its life. Fields in existing projects can continue to generate credits for 2021, but the protocol ends on December 31, 2021 (Government of Alberta, 2021a).

"Since the year 2000, Alberta soils have sequestered more carbon than emitted," the Team Alberta release stated (Tateson et al., 2021). The Conservation Cropping Protocol recognizes those efforts by setting up a price (which is shared with a carbon aggregation company) on carbon captured in the soil by specific practices. For example, in the Parkland area, it says 0.279 Mg/ha can be sequestered using no till. The no-till specs allow one pass of an opener with up to 46 per cent soil contact or two passes with up to 38 per cent soil contact (Cheater, 2021).

Through long-lasting policies, Canadian farms have implemented many soil carbon strategies since 1981. The main actors involved in the implementation of agricultural practices correspond to large farming companies, small farmers, farming associations, as well as large scale investors who have recently increase their involvement in the agricultural sector. For example, Farmers in Canada and the US, so called "Soil Carbon Cowboys" (Carbon Nation, 2021) are changing the way they graze cattle. By moving herds between small temporary pens, they allow other areas to regenerate, mimicking the grazing patterns of wild bison herds (GALLANT, 2018). In addition, local, provincial and federal government have an important role when it comes to regulation and deployment of incentives for these practices.

In the Federal budget, the agricultural sector will receive mainly support on innovation of clean technologies to address sustainability challenges allocating ~$34 million CAD/y. In the provincial budget, Alberta has set to invest $245 million CAD to improve the irrigation infrastructure and support the diversification of the crops produced. Other smaller funding available until 2021 includes conservation agriculture protocol which provides a $23/Mg offset to farmers to be able to reduce carbon emissions (Government of Alberta, 2021a) .

4.3.2 Current land use and potential land-use competition

It is estimated that the total 55.2 million hectares (Mha), currently in agricultural production, should contain about 4,140 Mt of C in the top 30 cm of soil and 5,500 Mt to a depth of 100 cm (Minasny et al., 2017). Agricultural land in Canada, could sequester 22 MtCO_2e/y equivalent to 11% of Canada's total emissions (Smulker, 2019). Much of this potential would materialize in the Prairie provinces which account for 80% of Canada's agricultural land.

In Canada, the soil organic carbon index has shown an increased trend from 1981 to 2011, with carbon sequestration of ~11.9 MtCO_2e/y (Agriculture and Agri-Food Canada, 2021). The main reason for this increase had to do with the incorporation of conservation tillage (no mechanical soil intervention) in the Prairies. However, in eastern Canada, soil carbon content has decreased due to a switch from perennial crops, such as pasture and forage, to annual crops such as cereals and oil seeds as a result of the decreased of Canada's cattle industry.

Since the federation, the number of farms in Canada has decreased while the size of the farms has increased. Today, ~53% of all Canadian territory. Competing land-uses include urban development, recreational uses, aggregate extraction, and transport corridors (Walton, 2013). As the population in Canada grows, more competition of urban development will be put on agricultural land and it may hinder potential expansion. Also, in many provinces the best quality land is located near urban centres which poses more challenges to expand soil carbon sequestration.

4.3.3 Climate risks & sensitivities

Numerous projections expect Canada to warm over the next 60 years. The changing climate is expected to have both positive and negative impacts in agriculture. Warmer temperatures will extend the growing season and allow the incorporation of new crops that are more efficient for warmer climates. However, increases in draughts and severe storms are expected to increase affecting crop yields and increasing climate vulnerability of farmers (Agriculture and Agri-Food Canada, 2020; Chung, 2020).

4.3.4 Economic implications

Drever et al. (2021) evaluated the implementation of soil carbon sequestration in about half of the total arable land in Canada (~20.5 Mha) and identified no negative impact on crop economics. The estimation on this study indicated that 1.4, 4.5 and 8.3 MtCO_2e/y by 2030 could be possible at $10, $50 and $100 CAD/t$CO_2$e, respectively. These estimates align with international estimates reported by Fuss et al. (2018) and Roe et al. (2019).

4.3.5 Co-benefits and trade-offs

Agricultural practices that might promote soil C sequestration, such as the application of fertilizers and manures to improve yields or the reduction of tillage, can also lead to increased nitrous oxide (N_2O) emissions. These emissions can in turn, offset any climate mitigation benefits (Smulker, 2019). Today, Canadian agriculture had net emissions of ~70 $MtCO_2e$/y in 2016 accounting sectors specific emissions as well as the emissions associated with the energy consumed in fertilizer production and farm activities (Environment and Climate Change Canada, 2021b).

Increasing cropland leads to loss of C-stored due to loss of woody biomass through extending croplands as well as negative impacts on biodiversity. Also, it could lead to an increase of use for fertilizers and pesticides which has a negative impact on the environment. When using alternatives to increase crop yields, the use of manure and mineral fertilizers has also increased the losses of phosphorous into the environment. Another impact of using animal manure as fertilizers involves the contamination of ground water with pathogens such as viruses, bacteria, and protozoa. In Canada, specific buffer strips and manure fraction separations have been implemented to allow farmers to utilize nutrients more efficiently. Further impacts of increasing cropland is associated with higher risks for soil erosion, reduced wildlife habitats.

Smulker et al. (2019) evaluated the trade-offs of agri-environment indicators such as GHG, pesticides, Nitrogen, Phosphorus, Coliforms, Cover and Wildlife. The study found that when evaluating these indicators with the increasing intensification of agricultural practices, GHG emissions have not been significantly addressed by current policies resulting on a marginal reduction of carbon emissions in the sector.

4.3.6 Risks associated with scaling up

Similar to forestry, some actors consider that too many resources on climate policies for the agricultural sector could deviate much needed resources necessary to decarbonize more expensive sectors. To maximize sequestration potential of the Canadian agricultural sector, efforts are needed to address emissions associated with livestock production, manure fertilizer use and energy consumption in the agricultural processes. Also, the soil theoretical capacity and local dynamics on each province difficulties the application of a unique strategy while maintaining the response to evolving markets.

4.3.7 Research gaps

For Soil Carbon Sequestration, we have fund gaps in specific ways of accounting for GHG emissions, establish the stability of the carbon sequestered, clear understanding of the interconnections of the agricultural sector with other carbon intensive sectors.

The East-West divide between Western Canada when Western farmers contribute more into carbon offsets is not quite addressed at the federal level. This is a gap in federal legislation. Another gap refers to Carbon Cowboys voluntary project, in which farmers use grazing rotation technologies that help to generate more soil carbon on their lands (The List Show TV, 2020)

4.4 BECCS

4.4.1 Policy context

International level

ISO Technical Committee (TC) 238 was established in 2007 to develop International Standards on solid biofuels. Many of these Standards are based on existing CEN (European Committee for Standardization) TC335 Standards, while others are entirely new ones, all of which intended to reflect current needs and priorities of the solid biofuels industry (Melin et al., 2016). The Standards specify and classify all types of biomass such as woody, herbaceous, fruity and aquatic. The Standards also provide specifications for graded solid biofuels traded in the market, including wood pellets, wood briquettes, wood chips, firewood, as well as non-woody pellets and briquette (Melin et al., 2016).

Federal level

Despite Canada having the greatest quantity of solid biomass per capita in the world, the country, outside of the pulp and paper sector, has been relatively slow to adopt modern solid biomass fuel technologies (Stephen and Wood-Bohm, 2016). The reasons for this include a lack of recognition by policy makers of the important role of solid biomass in decarbonization, erroneous beliefs on the air pollutant emissions performance of modern biomass technologies, and the low cost of the primary competitive fuels – natural gas and coal. However, a variety of successful policy measures have been used by other countries and could serve as examples for Canada's federal policy development (Stephen and Wood-Bohm, 2016).

Since the inception of ISO/TC238, Canada has taken on a leadership role to ensure that these standards are technically sound, do not discriminate against Canadian markets, and that the Canadian solid biofuels industry is well positioned to compete effectively in the global marketplace (Melin et al., 2016).

Canada, largely through work conducted at WPAC and UBC has made significant contributions towards international safety regulations, including:

- Development of MSDS (Materials Safety Data Sheets) for wood pellets around the world and more recently an upgrade to the new Safety Data Sheet (SDS) format;
- Development of the International classification of wood pellets under the International Maritime Organization (IMO) Code for safe transportation of wood pellets;
- Currently developing "Best Practices Guidelines for the Wood Pellet Industry" with participation with the ISO/TC 238 working group on safety; and
- Development of methodologies for determination of self-heating, off-gassing and oxygen depletion (Melin et al., 2016).

The Pan-Canadian Framework for Clean Growth and Climate Change (PFC) mentions that Clean technology, such as lower-carbon bioenergy, and bioproducts that use feedstock from agriculture and forestry waste and dedicated crops to replace higher-carbon fuels can also reduce emissions

(Environment and Climate Change Canada, 2016b). The Government of Canada promotes the use of landfill biomass to create sustainable energy sources, such as renewable natural gas or advanced biofuels, or to create other bioproducts (such as bioplastics and biocomposites) that can also generate new economic opportunities for Canadians (Environment and Climate Change Canada, 2016). The PCF was developed to establish a path forward to meet Canada's commitments under the Paris Agreement (Government of Canada, 2021c).

According to the PFC, Prince Edward Island is home to Canada's longest running, biomass-fired district heating system. Operating since the 1980's, the system has expanded to serve over 125 buildings in the downtown core of Charlottetown, including the University of Prince Edward Island and the Queen Elizabeth Hospital, and cleanly burns 66 000 Mg of waste materials annually (Environment and Climate Change Canada, 2016b).

The proposed Clean Fuel Regulations would require liquid fossil fuel primary suppliers (i.e. producers and importers) to reduce the carbon intensity (CI) of the liquid fossil fuels they produce in and import into Canada from 2016 CI levels by 2.4 gCO_2e/MJ in 2022, increasing to 12 gCO_2e/MJ in 2030 (Government of Canada, 2021c). The proposed Regulations would allow the creation of credits from the production of low CI fuels produced from biomass-based feedstocks. To prevent adverse impacts on land use and biodiversity stemming from the increased harvest and cultivation of these feedstocks, the proposed Regulations would establish land-use and biodiversity (LUB) criteria. Only biofuels made from biomass feedstock that adhere to the LUB criteria would be eligible for compliance credit creation. These criteria apply to feedstock regardless of geographic origin. The criteria do not apply to feedstock that is not biomass (e.g. fuel made from direct air capture) or that is designated "low-concern biomass feedstock" (e.g. municipal solid waste) (Government of Canada, 2021c).

Provincial level

Alberta is one of five provinces that have renewable fuel requirements equal to or higher than the current federal requirements set in the RFR (Government of Canada, 2021c). The Alberta RFS pertains to fuels produced from renewable materials in the form of renewable fuel alcohols, such as ethanol, used in gasoline and bio-based diesel, used in diesel. These products may be produced using traditional technologies or emerging technologies based on advanced chemical and biological processes (Government of Alberta, 2021b).

According to Welling & Shaw (2007), there are several challenges that the province should overcome in order to develop a better policy framework on biomass use in Alberta. The potential of wood-based bioenergy has not been fully explored in rural Alberta yet.

Welling & Shaw (Welling and Shaw, 2007) suggest the following solutions for the use of wood biomass in Alberta:

- Wood biomass must become a profitable business for energy companies, subcontractors, and forest owners to see any sustained success. This is unlikely to develop rapidly or on any sizable scale without the direct involvement of the government. The climate needed to produce economic success is missing many of the positive factors cited in the barriers and recommendations sections.

- The environmental value of using wood heating – GHG neutral status – is not at all understood by consumers and amazingly, also by a large proportion of government employees and officials involved in shaping alternative heating choices.
- Education and training should play a central role in mobilizing the wood-energy resources. Government, academic institutions, and professional bodies should address education, training, and the need for the sensitization of all wood producing stakeholders and energy consumers with regard to wood-energy skills and entrepreneurship. Wood-energy issues should be introduced into forestry training curricula (Welling and Shaw, 2007).

Currently, there are only two examples that have implemented BECCS in Canada at pilot scale. One was related to oil and gas production and the other to Pulp and paper manufacturing. However, many projects around Bioenergy are being deployed and supported country-wide and in Alberta, though not yet incorporating carbon capture. Most actors implementing bioenergy right now belong to the power sector and heavy industry. However, in 2018 the government of Canada created the "Clean Energy for Rural and Remote Communities program" which provides support for communities to deploy their own clean energy projects. Today, there are more than 70 biomass generating power plants with a total installed capacity of 2,408 MW. Wood biomass must become a profitable business for energy companies, subcontractors, and forest owners to see any sustained success (Welling and Shaw, 2007).

To further deploy BECCS, different funding alternatives can arise by the combination of programs supporting growth in bioenergy use and carbon capture and storage. Within the Pan-Canadian Framework for Clean Growth and Climate change, the government of Canada pledged to provide support for the Forestry, Agriculture and Waste sector on the development of advanced bioproducts and bioenergy (Environment and Climate Change Canada, 2016b). As for the 2021 Federal budget, the government of Canada proposed to provide $54.8 million CAD over two years for the forest-based bioeconomy and $67.2 million for seven years on the deployment of a Clean Fuel Standard to increase the use of biofuels. In addition, the government proposed to provide $319 million CAD over seven years to promote the commercial viability of carbon capture, utilization and storage projects, $35 million CAD to support innovation on CCS, plus a tax incentive for CCS whose costs have not been yet determined (Government of Canada, 2021b). At the provincial level, Alberta provides $63 million CAD to support liquid biofuel and bio-power production for 2.5 years (Government of Alberta, 2018b). Also, Alberta is providing $80 million CAD through the "Industrial Energy Efficiency and Carbon Capture Utilization and Storage program (IEE CCUS)" to support industrial energy efficiency and carbon capture, utilization and storage projects and $1.24 billion through 2025 to support two commercial-scale CCS projects, Shell-Quest and Alberta Carbon Trunk Link (ACTL) to reduce GHG from oil sands and fertilizer sectors by 2.76 million Mg per year. This infrastructure cold support deployment of BECCS in the area.

4.4.2 Current land use and potential land-use competition

Currently only two projects on BECCS for Canada have been completed: (i) Husky Energy Lashburn and Tangleflags CO_2 Injection in Heavy Oil with a capacity of 90,000 Mtpa, and (ii) Saint-Felicien Pulp Mill and Greenhouse Carbon Capture Project with a capacity of 90,000 Mtpa. BECCS only negative emissions if used with residues from currently managed forest land and no un-managed land (Withey et al., 2019). Under this scenario, BECCS implementation would be possible on 200 million ha of long-term managed forest which accounts for 57% of total forest land in Canada (Natural Resources Canada, 2020b). However, today only 0.2% of the total forest managed area is harvested.

In Canada, land-use competition for BECCS is associated with those that present risks of deforestation such as Oil and gas exploitation, Agriculture, Hydroelectricity, Urban development. However, Canada's deforestation rate is 0.02% of total forest area, which is relatively low and represents low risks for BECCS. On the other hand, scaling capacity for BECCS depends heavily on the availability of biomass and adequate underground storage space. BECCS sector depends heavily on forestry sector demand and capacity unless other resources are tapped. Within this context, western provinces, such as Saskatchewan, Alberta and British Columbia have better possibilities for large-scale deployment of BECCS (Natural Resources Canada, 2021).

4.4.3 Climate risks & sensitivities

As BECCS in Canada relies mainly on the availability of forestry and agricultural residues, the climate risks for this LMT are linked to its biomass sources as discussed on previously for Forestry and the Agricultural sectors (see sections 3.3 and 3.4). On the other hand, the carbon capture portion of BECCS is an engineered solution. Therefore, its exposure to climate risks may be associated more with potential damages due to wildfires and severe storms. However, the engineered infrastructure would be designed to endure a certain level of stressors, resulting in a lower/more controlled risk exposure.

4.4.4 Economic implications

BECCS could be applied in a competitive way given ideally located hubs/clusters are deployed combining bioenergy with CCS. The provinces of Alberta and Saskatchewan are the best situated since their combination of high bioenergy potential and vast underground storage capacity. With carbon prices above $65 USD, the value of carbon removal from biomass exceeds the energy value of oil. With a carbon price of $170 USD by 2030 as proposed by the federal government, revenue from atmospheric carbon removal would ensure competitive electricity costs (International CCS Knowledge Centre, 2021). If BECCS is deployed, revenues from biomass trade are projected to become a significant share of GDP reaching 6-10% in Canada (Muratori et al., 2016).

Abatement costs for BECCS are estimated between $20-200 USD depending on the energy carrier and sector (Melton et al., 2020) when abatement potential of both bioenergy and CCS are accounted for.

4.4.5 Co-benefits and trade-offs

Assessing the impacts of BECCS requires looking into complex intersectionalities across different sectors. Stoy et al. (Stoy et al., 2018) proposed food, water, energy, biodiversity, and social systems (FWEBS) framework that can be implemented to evaluate the expected impacts of BECCS on different regions. The full implementation of the FWEBS framing will be done during the execution of LANDMARC. However, some insights of the different elements are discussed below.

BECCS could impact food production if specific cropland is developed for bioenergy. For Canada, BECCS is expected to be deployed using forestry and agricultural residue only. Therefore, not major impacts on food production are foreseen thought it should be taken into consideration when developing new policies. Despite of the lower land-use of BECCS with respect to afforestation, this LMT could displace land for other uses such as recreation and urban development. On the other hand, diversification of crops, pulse crop, crop coverage, could bring additional economic benefits for farmers (Stoy et al., 2018).

With regards to water, BECCS would compete with other industrial and agricultural activities in the area. Tough Canada has vast water resources, it is important to assess the effect of BECCS activities in water demand and water quality since will interact with other uses. Also, pollution from neighbouring industrial activities may impact BECCS efficiency. When considering potential opportunities and trade-offs of BECCS on the energy spectrum, it is expected that the major impact could be seen at the Prairie provinces. On one side, these provinces have a strong reliability on fossil-fuel based energy sources while the potential of bioenergy requires further public investment. However, the long history of the region with large-scale energy projects could facilitate the deployment of CCS due to better understanding of communities of the implications. Also, these provinces have more developed regulatory frameworks for the energy sector, forestry and agriculture that share many similarities with BECCS. Improved consultation approaches and incentives to level the playing field for BECCS will be required.

Expanded industrial activity in the region could compromise biodiversity through loss of habitats. Also, the impacts of BECCS deployment should be balanced with the loss of native grasslands and wetlands which are important carbon sinks for the region. Appropriately managed, cropland could foster wildlife habitat but could also decrease biodiversity due to the elimination of native species. In the social aspects, BECCS could bring new economic sources to local communities but could also favour certain stakeholders leading to more inequalities. All the aspects of the FWEBS framework require further study to establish the local context.

4.4.6 Risks associated with scaling up

For scaling up BECCS in Canada, it is important to identify the different potential across regions and the LMT portfolio that is more suitable to the local context. For higher efficiency, BECCS requires appropriate access to biomass feedstocks as well as neighbouring underground storage facilities. So far, the most suitable landscape for this deployment is found mostly at the Prairie provinces. This implies that BECCS potential is restricted to some areas and requires other provinces to utilize different LMT portfolios. In addition, Canada's energy mix is rather mature so BECCS could find some resistance due to the necessary investment in regions that are heavily reliant on carbon intensive energy sources.

4.4.7 Research gaps

From the review of BECCS for Canada, we found knowledge gaps that are important to address to better understand the LMT potential and implications of its deployment. First, considering Canada to be a country with a large extension of land the context on each region can significantly vary. Therefore, it is important to assess the spatial-explicit optimization of BECCS and its real potential per region. Further understanding the opportunities and trade-off of BECCS in the different provinces since each region has their own geographical and socioeconomic dynamics that would be influenced by BECCS.

BECCS will need to be fully integrated with the electricity grid in the case of power generation. That requires proper alignment of different actors and institutions which was not found on during this review. As biomass residue harvesting does not generate visible profit for farmers, it has less interest from farmers than other LMTs. Therefore, there is a need to frame these projects in terms of their economic capacity to generate profits.

All the aspects mentioned above, highlight the need for clear coherent policies at the local, provincial, and federal level to materialize BECCS' potential. Therefore, further studies on socio-economic impacts and policy recommendations are needed and not abundant for the Canadian context.

4.5 Biochar

4.5.1 Policy context

International level

Fourteen governments as well as the United Nations Convention to Combat Desertification (UNCCD) are formally calling for 'biochar' to play a significant role in a post-2012 climate change agreement and in carbon trading (Paul et al., 2009). They have signed up to claims by the International Biochar Initiative (IBI), a lobby organisation made up largely of biochar entrepreneurs as well as scientists, many of them with close industry links. However, the United Nations Environment Programme (UNEP) has warned that biochar is a 'a new and poorly understood technology', that feedstock for large-scale biomass is likely to come from 'biofuels' (agrofuels), i.e. dedicated tree and crop plantations which "should be approached with great caution" and that the impacts on biodiversity and long-term agricultural sustainability are unknown (Paul et al., 2009). When the IPCC finalised its Fourth Assessment Report, it did not find sufficient evidence to reach any conclusion about biochar. UNCCD's claims about IPCC support for biochar, contained in their recent submissions to UNFCCC are therefore incorrect. The IBI argues that applying charcoal to soil creates a reliable and permanent 'carbon sink' and mitigates climate change. It also argues that biochar makes soils more fertile and better able to hold water, thus helping farmers adapt to climate change (Paul et al., 2009). Proposals for 'climate change mitigation' with biochar involve such large quantities of biomass that at least 500 million hectares of dedicated plantations would be required, as well as agricultural land and forests being stripped of so-called ‘residues’. As the experience with agrofuels shows, the creation of a large new market for biomass can be expected to move the ‘agricultural frontier’ (including tree plantations) further into forests and other ecosystems, causing agricultural intensification leading to more nitrous oxide emissions, as well as displacing communities and food production (Paul et al., 2009).

Federal level

Similar to soil carbon and biomass, the Pan-Canadian Framework on Clean Growth and Climate Change mentions biochar in general terms, stating that clean technology, such as lower-carbon bioenergy, and bioproducts that use feedstock from agriculture and forestry waste and dedicated crops to replace higher-carbon fuels can also reduce emissions (Environment and Climate Change Canada, 2016b).

The Canadian Government through its regulating agency, Canadian Food & Inspection Agency (CFIA), has approved the use of biochar in soil. This development is the result of two years of concerted work from organizations such as the Alberta Biochar Initiative (ABI), AirTerra, and other provincial biochar proponents to gain CFIA approval (International Biochar Initiative, 2018).

“Regulatory approval is something ABI has pursued since 2012,” said Don Harfield, who has conducted biochar research and development at Alberta Innovates – Technology Futures for over ten years and serves as ABI’s technical lead (International Biochar Initiative, 2018). “It gives ABI partners the opportunity to pursue a wide range of potential commercial applications for biochar in Alberta and other markets.” (International Biochar Initiative, 2018).

The Canadian Food Inspection Agency (CFIA) requires, by law, that all biochar sold as soil supplement in agriculture and horticulture be certified. To obtain this registration, one must demonstrate that the biochar is harmless for the environment through analyses of carbon, nitrogen and ash contents as well as some toxicological analyses are required such as metal, dioxin and furan contents (Bertrand and Lange, 2019). No Canadian regulation covers the use of biochar pellets as a combustible. However, producers tend to follow technical specifications set by the industry, such as the ISO/TS 17225-8 standard (ISO, 2016), to ensure consistency and to classify their products in compliance with international standards for pellets. These ISO standards refer to several properties that must be declared, namely the origin and source of the organic material, moisture, metal, ash and fines contents, calorific value and density. By respecting these specifications, producers can more easily offer their biochar pellets on the international market (Bertrand and Lange, 2019).

The Canadian Food Inspection Agency (CFIA) requires, by law, that all biochar sold as soil supplement in agriculture and horticulture be certified. The CFIA is responsible for this certification under the Federal Fertilizer Act as a level II soil supplement (CFIA 2017, cited in Bertrand and Lange, 2019). This is applicable for imported and local biochar (Bertrand and Lange, 2019).

Biochar is registered under the list of approved soil supplement materials as part of the Guidance Document repository from the Canadian Food Inspection Agency (CFIA) (Canadian Food Inspection Agency, 2021).

Provincial level

In 2002, Alberta Environment released Standards and Guidelines of the Use of Wood Ash as a Liming Material for Agricultural Soils (Government of Alberta, 2002). This document presents general information on wood ash as well as the regulatory requirements for generators and recommended practices for land managers (Government of Alberta, 2002).

Lakeland College and Alberta Innovates Technology Futures (AITF) with assistance from Western Economic Diversification Canada and industry support have developed the Alberta Biochar Initiative. The ABI is intended to develop and demonstrate technologies that will enable the large-scale commercial deployment of biochar products and biochar applications for the benefit of Albertans (International Biochar Initiative, 2018).

Established in Dec 2011, the ABI consists of small-to-medium sized enterprises (SMEs), industry, academia and government sharing information and producing and generating biochar for end-use applications including soil amendments, reclamation, remediation, horticultural growth media and conducting biochar lifecycle analysis for potential carbon sequestration applications (International Biochar Initiative, 2018). As of 2010, Alberta Innovates Technology Futures pyrolyzers were the only Biochar facility in the province (Anyia, 2010). As of 2016, two ABI demonstration scale pyrolysis units located in Vegreville (commissioned in 2013) (Harfield, 2016). In December 2015, the Canadian federal government approved commercialization of biochar in Alberta, based on a request by the Alberta Biochar Initiative (Davey, 2016). No specific mentioned of biochar on the federal or provincial budget of Alberta.

4.5.2 Current land use and potential land-use competition

Biochar was only allowed for commercialization in recent years. Several applications are being explored including soil amendment, agriculture support, energy use and air and water filtration. However, no clear statistics are available about the country-wide use of biochar. D. Matovic (Matovic, 2011) estimated that there is enough biomass available in Canada to off-set total Canadian GHG emissions when considering both forestry and agricultural residues produced. However, the main limitation is the amount of land on which biochar can be deployed. Considering potential competition of forestry residue for bioenergy generation, Drever et al. 2021 (Drever et al., 2021) considered biochar only from agricultural residues and estimated a mitigation potential of 6.9 MtCO_2e/y spread throughout one fifth of the total arable land of Canada (~67 Mha) where the biomass was harvested. Though there are evidence of growth in the market and interest from the private sector there are no projections for biochar deployment as a carbon sequestration strategy. For biochar, the main competition would be those land uses that compete with agriculture as described on section 3.3.

In Alberta, the Alberta Biochar Initiative, had proposed a desired pathway where 2010-2015 5 $MtCO_2e$ reduced by applying 1.4 Mt of biochar to 280,000 ha of farmland annually. Then, implement a scale-up phase to achieve 10 $MtCO_2e$ reduced by applying 2.8 Mt of biochar to 560,000 ha of farmland annually followed by a full commercial scale aiming for 30 $MtCO_2e$ reduction annually by applying ~8.3 Mt of biochar over 1.6 million ha a year (Anyia, 2010). However, today there is no information about the continuity of the biochar initiative and or continuing support for this initiative.

4.5.3 Climate risks & sensitivities

Climate risks for biochar in Canada are well aligned with those described for agriculture on section 3.3. In addition, the impact of biochar sequestration can also be look from the perspective of soils emissions, soil albedo, and native soil organic carbon (Tisserant and Cherubini, 2019). Climate risks for biochar are not well studied yet and understanding the impacts of changes in soil albedo, transpiration and other short-lived climate forcers (i.e. methane and black carbon) requires coupling of land-climate models. Precipitation, latent heat, surface radiation and clouds could have a complex interaction with soil response. For example, some research as indicated that soil albedo can be reduced offsetting partially or all mitigation potential of biochar for biofuels. Also, evapotranspiration changes from substitution of annual to perennial crops could offset 0.5 °C of warming. In addition, mitigation potential has shown to be very sensitive to the modelling assumptions and study scope taken during life-cycle analysis of biochar (Tisserant and Cherubini, 2019).

4.5.4 Economic implications

Economic viability of biochar depends on feedstock, conversion process, and its connection with carbon sequestration and availability of credits locally (Homagain et al., 2016). Cost analysis for biochar deployment as mitigation practice in Canada showed no possible alternative under \$100 CAD/tCO_2e and it costs were impacted by residue availability and collection efficiency (Drever et al., 2021).

4.5.5 Co-benefits and trade-offs

As a form of carbon, biochar is considered stable, and its carbon storage capacity can be quantifiable serving as a potential offset mechanism. However, once incorporated into the soil biochar decomposes, therefore its permanency is question since it varies on soil type and environmental conditions. Analyses in Canada indicated that assuming stability for 100 years is acceptable since decomposition rates are low in this period. However, further studies are necessary to identify the decomposition of biochar under different soil types and weather conditions which vary significantly across Canada (de Ruiter et al., 2014).

A trade-off of biochar involves the energy use and combustion during its production. Smokeless processes are needed to abate emissions and particles emanated from pyrolysis. Also, measures are needed to abate other potential harmful air pollutants. Also, harvesting forestry residue for biochar may affect ecosystem biodiversity and increase erosion on exposed soil surfaces. Biochar components and heavy metals should be carefully assessed to guaranteed low-toxicity to the remediated environments.

Further studies are being develop which show the potential of biochar to absorber harmful metals, reclaim damaged mine sites and purification of polluted water from heavy industry. The development of a supply chain for biochar could also provide materials to mitigate other environmental issues besides carbon emissions.

Today, uncertainty remains about mitigation potential of biochar. Studies conducted in Canada are not conclusive around the actual capacity for biochar to increase soil carbon in agricultural land or decrease emissions from manure when provided as a feed supplement to cattle. This evidences the susceptibility of biochar to local environmental conditions which proves to be challenging for Canada with a wide variety of climatic zones and soil types (Betkowski, 2021; Briere, 2017; Willis, 2019).

4.5.6 Risks associated with scaling up

As discussed on previous sections, the major risks associated with scaling up involve the wide variety of contexts across regions in Canada. Soil quality varies significantly within and across regions, which impacts the biochar decomposition and efficiency. Also, assumptions of land availability rely on type of crops and farming activities. Also, so far biochar deployment costs are higher than other potential mitigation practices. Therefore, lowering the costs for implementation could provide better opportunities for biochar. Currently, there is no specific federal or provincial polices for biochar for carbon sequestration. Therefore, for scaling up it is required that Canada develops specific policies with regards to Air quality and soil applications.

4.5.7 Research gaps

There is definitely a lack of biochar's recognition as potential technology for carbon emissions' reduction. Pyrolysis process is facilitated by using sophisticated technology that is only located in a few towns in Alberta. At the federal level, biochar is mostly perceived as fertilizer, at the provincial level, the Alberta Biochar Initiative's efforts are not enough to push the government to adopt specific regulations on biochar production that could focus on the role of biochar in land-based mitigation initiatives. Biochar has been commercialized in Alberta since 2015.

Another gap with biochar in Canada involves Quality and Standards definition. Though international and European standards are available, Canadian regulations are needed for carbon sequestration and other energy uses. Also, large scale agronomic field trials needed across climatic zones and soil types to assess stability and large-scale impact.

Lastly, there a big knowledge gaps with regards risks and sensitivities of climate change on biochar as well as comprehensive understanding of the social risks and impacts associated with local implementation.

5. Conclusion

The five LMTs shortlisted for Canada, afforestation/reforestation, soil carbon, wetlands, BECCS and biochar, are commonly related to management of forest areas and agricultural land. Canadian forest expands to 348 Mha of forest which are divided by 226 Mha of managed land and 122 Mha of unmanaged land. Most of the LMTs deployment is expected to occur within managed forest land. On the other hand, Canada has 67 Mha of agricultural land (Matovic 2011) which is considered at least half to be apt for LMT implementation. In addition, wetlands cover ~119 million ha in Canada. Combined, this LMTs could be potentially implemented in ~400 Mha across the country.

Currently the deployment of LMTs in Canada is on very early stage. Significant research efforts and pilot projects have been implemented. However, specific policies are not available though discussions have been taken across different provinces and the federal level. Considering this stage, land use competition is mainly related with the land-use changed around the forestry and agricultural sectors.

For all the shortlisted LMTs, there was consensus that there is enough technical certainty for deployment. Most of this LMTs have been implemented for years, but not with a climate mitigation focus. Therefore, the lack of direct policy to align the different economic sectors with the climate goals represents a barrier. Also, all LMTs were deemed very susceptible to climate risks. That is, the risks of wildfires, floods, draughts, pests, and a changing environment, it is considered to add uncertainty in the potential success of the LMTs. Finally, one of the major barriers identified was associated with the uncertainty around impact monitoring and permanency. When compared to BECCS or DAC, some LMTs are graded very high risks of looking the mitigation capacity due to an unexpected natural disaster. Also, potential biological degradation above- and underground. As a result, LMT mitigation capacity are valued below engineered solutions represented more barrier to access more financing.

As LMTs are deployment, it is expected that the different alternatives compete for land. Despite of a theoretical mitigation potential, the development of different LMTs portfolios at the local level will determine the actual mitigation capacity. Each LMT has its own opportunities and trade-off that are connected with other potential LMTs. Therefore, policies need to be carefully design in order to achieve carbon reduction goals while supporting other sustainability factors such as food, water, energy, biodiversity and socio-economic priorities. Based on its geography, deployment of LMTs will change significantly on the target location. In addition, due to its federal structure, the policies around land-use changes depend of each province which represents a barrier for streamlining efforts to scale LMTs nationally.

The implementation of the shortlisted LMTs is not expected to significantly change the land management framework already in place. In Canada, land management plans are in place at the federal and provincial levels to monitor and regulate the use of the natural resources as well as mitigate the impacts of industrial activities within these areas. Also, federal jurisdiction for applies to support indigenous communities on development land management plans for reserves.

For Afforestation and BECCS, sustainable land management policies – already in place in Canada – require forest to be regenerated and are certified by third-party international organization to review its transparency. Guidelines supporting climate adapted replenish species and implementation of new technologies. Current regulations and guidelines could be adapted to incorporate responsible harvesting of forestry residue as well as location of conversion facilities to mitigate negative impacts on the environment. Canada's forests are an important economic sector and 70% of indigenous peoples live on forest lands or near forest lands. Therefore, all management efforts should consider local communities at the forefront of the decision making since they will be heavily impacted by changes in the sector. The Canadian Forest Service (CFS) is the governmental entity in charge of ensuring forest are sustainable and healthy and oversees the policies to implement management plans. Equivalent institutions are also established across each province to bring the regional perspective.

For Soil carbon and biochar, policies for agricultural land management are under the oversight of Agriculture and Agri-Food Canada (AAFC). This entity keeps monitoring data and establish best practices for managing agricultural land and associated resources. To further implement LMTs within the agricultural sector, clear policies will have to be created to incorporate climate targets in agricultural activities. Currently, an Agricultural Climate Solutions (ACS) program has ben created with the support of $185 million CAD for 10 years to support the development and implementation of farming practices that address climate change. However, further details are needed to create the necessary incentives to achieve the LMTs full potential. For wetlands, new policies are coming online associated with wetlands protection and restoration, which gives an initial framework to start.

The identification of the narratives for the main Canadian LMTs seeks to enable the analysis of the risks and (climate) impacts of LMTs, as well as support the scenario development for modelling and assessment with stakeholders the potential impacts of scaling up LMTs at national and regional scale, which are key objectives of the LANDMARC project.

One of the main challenges with informing these narratives with stakeholder perspectives lies on the disconnection of local perspectives with national/regional perspectives. LMTs have a tangible local impact, that when looking from a regional lens, loses resolution and create risks of national portfolios missing the priorities of the local communities. LANDMARC is looking to address these challenges by evaluating the integration of local, national, and regional perspectives in portfolio design and alignment with global sustainability commitments. Further research necessary to ensure the co-development of portfolios, strategies and policies, relevant at different scales, is being considered within LANDMARC's scope.

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LANDMARC

ANNEX III

OVERVIEW OF INPUT TABLES FOR SIMULATION MODELLING PER COUNTRY

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12.Canada

12.1. Qualitative storylines by identifying measures and actions from interviews for each LMT scenario

Canada LMT 1: Afforestation, Alberta Canada

	1. Wishes of the future for the LMT: include timing	2. How to achieve the wishes • Who pays? • Who implements?	3. Target/Actions • Policies, strategies, projects
Scenario 1: "Go all green" **Stakeholder representations:** Local community, environmental NGOs, green party (provincial/national), oil industry, private sector (forestry services)	• Nearly all cutlines restored by 2050	• Company pays for parts of the restoration • Government to provide part of the funding. • Implemented by local communities for economic diversification • CO2 credits – access to regulated or voluntary markets	• Actions start now with pilot projects • Regulations by 2030 • Tax credits for restoration for industry • Monitoring in place to control progress and CO2 offset credits
Scenario 2:"Halfway is enough" **Stakeholder representations**: Provincial gov't, oil industry, private sector (forestry services)	• Only half of the cutlines need to be restored because nature will take over by 2050 • Some cutlines became transportation infrastructure and communities want to keep them	• Company pays for some • Gov't grants for rest	• Tax credits for reclamation • Regulations to be modified by 2030
Scenario 3: "Reclaim my way" **Stakeholder representations**: Provincial gov't, oil industry, Local community, environmental NGOs	• Regulation requires "reclamation" not "restoration" • Industry wants to reclaim the way it is easiest and lower costs	• Company pays for parts of it • Gov't incentives for the rest	• Tax credits for reclamation • Regulations to be modified by 2030 to allow other forms of reclamation industry wants

Canada LMT 2: Wetland restoration

	1. What are the wishes of the future for the LMT • include timing	2. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	3. Actions • policies, strategies, projects
Scenario 1: "Go all green" **Stakeholder representations:** Local community, environmental NGOs, green party (provincial/national), oil industry, private sector (forestry services)	• Protect all current wetlands and do not allow for new resource development in wetland areas • Restore all degraded wetlands for biodiversity and ecosystems	• Company pays for degraded sites • Gov't pays for protection • CO2 credits – access to regulated or voluntary markets	• Actions start now with pilot projects • Regulations by 2030 • Existing accreditation scheme • Carbon tax
Scenario 2:"Halfway is enough" **Stakeholder representations**: Provincial gov't, oil industry, private sector (forestry services)	• Protect most wetlands allow for some new resource development • Restore some degraded wetlands for biodiversity and ecosystems • Convert other wetlands into forest ecosystem	• Company pays for some • Gov't grants for rest • CO2 credits	• Tax credits for reclamation • Regulations by 2050
Scenario 3: "Reclaim my way" **Stakeholder representations**: Provincial gov't, oil industry, Local community, environmental NGOs	• Industry wants to reclaim (not restore) by forestry or just flooding with water (pit lakes) • Looking for opportunities to use "constructed wetlands" to manage polluted water, not to restore the biological function of the wetlands	• Company pays for some • Gov't expected to provide incentives	• Tax credits for reclamation • Regulations to be modified by 2030 to allow other forms of reclamation industry wants

12.2. Quantitative storylines: pace of implementation for each LMT

Table 3: Quantitative trends/pace of implementation of LMT options

	Current situation (baseline)	**Scenario 1: "Go all green"** **Stakeholders:** Local community, environmental NGOs, green party (provincial/national), oil industry, private sector (forestry services)		**Scenario 2:"Halfway is enough"** **Stakeholders**: Provincial gov't, oil industry, private sector (forestry services)		**Scenario 3: "Reclaim my way"** **Stakeholders**: Provincial gov't, oil industry, Local community, environmental NGOs	
Year	Now (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)
LMT 1: Afforestation	• 1599 km^2 of Northern AB boreal forests leased for oil development [1] • 738.6 km^2 disturbed by mines and plants footprints [1] • 64% of the leased land supports wetland vegetation, 23% supports upland vegetation. • Seismic lines (cutlines) disturbed at least 1,900 km2 of peatlands in Alberta [3]	15% restoration of damaged areas [4]	80% restoration of damage areas [5]	15% restoration of damaged areas [4]	50% restoration of damage areas [6]	• 0% restoration of damaged areas. • 15% of area reclaimed but with no carbon uptake function [1]	• 0% restoration of damaged areas. • 30% of area reclaimed but with no (or very little) carbon uptake function [6]

LMT 2: Wetlands	• (see above)	15% restoration of damaged areas [4]	80% restoration of damage areas [5]	15% restoration of damaged areas [4]	50% restoration of damage areas [6]	• 0% restoration of damaged areas. • 1% of area reclaimed but with no carbon uptake function [1]	• 0% restoration of damaged areas. • 5% of area reclaimed but with no (or very little) carbon uptake function [6]

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[4] TU Delft / Ambienta estimate on potential scale-up of pilot project in the region. LANDMARC consortium. 2022

[5] Interview with elder from local community

[6] TU Delft team. Assumptions based on limitations in policy and as a result of interview with experts.

13.Venezuela

13.1. Qualitative storylines by identifying measures and actions from interviews for each LMT scenario

Venezuela LMT 1: Integrated fire management (IFM) with an Intercultural vision (which considers local knowledge and participation of Indigenous populations and local communities).

	1. Wishes of the future for the LMT: include timing	2. How to achieve the wishes • Who pays? • Who implements?	3. Target/Actions • Policies, strategies, projects
Scenario 1: "IFM Policies at the National Level with an intercultural vision" (more optimistic) **Stakeholder representations:** Indigenous peoples, Local communities, Academia, environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)	1. Development of a plan and a new law about IFM Policies at the National Level with an intercultural vision by 2030 that replace the actual Fire Suppression Policies. 2. Training of new brigades from Forest Fire Department with and holistic formation integrating academic, technical, and local knowledge - cultural heritage, and considering human and ecological dimensions of fire in socio-ecological systems (SES). 3. Include indigenous local communities at all hierarchical levels of decision-making and implementation of these	• International funds for (1) and (2) (e.g., Green Fund), and the government pays for implementation (3). • Bottom-up IFM implementation (including Indigenous peoples and Local communities at all stages of the process)	• Permanent National Working Group on Integrated Fire Management in Venezuela (Grupo de Trabajo MIF-VEN, created under the LANDMARC project) conformed by academics, INPARQUES, Forest Fire Department Coordinators, the Director of Forest Fires of the Ministry of Ecosocialism, National Coordinator of Fire Specialties, National General Directorate of Firefighters (DGNB), Ministry of Interior Affairs, Justice and Peace. • Design and proposal development of a new plan and law about about IFM Policies at the National Level with an

	policies. Promote local governance.		intercultural vision (together with IP and LC) by 2030 that replace the actual Fire Suppression Policies.
Scenario 2: "IFM ghost policies" **Stakeholder representations**: Indigenous peoples, Local communities, Academia, environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)	1. Development of a plan and a new law about IFM Policies at the National Level with an intercultural vision by 2030 that replace the actual Fire Suppression Policies. 2. There are no implementation actions, nor monitoring of IFM plans. Weak relationship between IPs, LCs and government and academic members.	• International funds for (1) and (2) (e.g., Green Fund), but the government does not invest for implementation for the new policies (~~3~~). • Limited IFM implementation and participation of Indigenous peoples and Local communities at all stages of the process.	• Efforts of the National Working Group on Integrated Fire Management in Venezuela (MIF-VEN) unsuccessful for the acceptance of the proposal and implementation of the IFM law.
Scenario 3: "Exclusion - as usual - policies" **Stakeholder representations**: Indigenous peoples, Local communities, Academia, environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)	1. The design of new IFM policies is not achieved and fire suppression policies continue as yore. 2. The traditional practices of the use of fire by IP and LC continue to be prohibited (excluded), and large fires of great magnitude occur due to climate change (fire climate due to great drought, high temperatures and heat waves).	• There is no investment of international funds, and governments maintain fire exclusion policies (although without funds for combat or the implementation of new IFM programs), or • Government asks for loans to equip with high and expensive fire suppression technologies (and increases state indebtedness), or • Government diverts international funds granted to MFIs with local	• Dissolution of the National Working Group on Integrated Fire Management in Venezuela (MIF-VEN). • No formulations of new MFI policies are made. • Restrictions and implementation by the use of fire by IP and CL are accentuated.

		participation, for other programs (or the funds disappear).	

13.2. Quantitative storylines: pace of implementation for each LMT

	Current situation (baseline)	**SCENE- 1"IFM Policies at the National Level with an intercultural vision" SH perspective:** Indigenous peoples, Local communities, Academia. environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)		**SCEN- 2"IFM ghost policies" SH perspective:** Indigenous peoples, Local communities, Academia. environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)		**SCEN- 3": "Exclusion - as usual - policies" SH perspective:** Indigenous peoples, Local communities, Academia. environmental NGOs, INPARQUES (Acronym in Spanish for National Institute of Parks), Forest Fire Department, Ministry of Eco-socialism, Hydroelectric Company, private sector (forestry services)	
Year	Now (Provide sources)	2030 (Change relative to the current situation) (Provide sources)	2050 (Change relative to the current situation) (Provide sources)	2030 (Change relative to the current situation) (Provide sources)	2050 (Change relative to the current situation) (Provide sources)	2030 (Change relative to the current situation) (Provide sources)	2050 (Change relative to the current situation) (Provide sources)
LMT 1: Integrated fire management (IFM) with an Intercultural	Excluding Protected areas (PA) and Indigenous territories (IT) or areas where local	50% of wildfires [5]. The implementation of IFM programme, in savanna areas of Brazil, achieved	Lipsett-Moore et al. [10] estimated a 74% emission	Similar to the current situation, with increases in the trend of	Similar to the current situation, with higher increases in the	Increase of wildfire occurrence with respect to the current situation	Increase of wildfire occurrence with respect to the 2030 situation

vision (which considers local knowledge and participation of Indigenous populations and local communities).	management is allowed, Venezuela shows an increase in its trends of wildfire incidence due to the initial implementation of IFM policies, land use changes and an increase of fire weather (due to climate change). [1],[2], [3], [4]	a 17% reduction in total burned area (from 13766 km2 to 11449 km2), during 2013-2018, in comparison to the previous 5 years (2007-2012), and an estimated abatement potential of 1.71 MtCO2e of non-CO_2 GHG over six years (0.29 $MtCO_2e\ y^{-1}$) [6],[7]. According to Australian experience, shifting the fire regime from an average of 7.6% of area burned early and 32% of area burned late to an average of 20.9% burned early and 10.9% burned late, the fire managers achieved a mean annual emissions reduction of 37.7% (116,968 tCO_2e), relative to the baseline, over the first 7 years of operations [8],[9].	potential, 89.3 Mt $CO_2e\ y^{-1}$ global emissions reductions of the late dry season uncontrolled wildfires through early dry season burning considering 37 countries, including Africa, South America and Australia. .	wildfires, but with more reduced wildfire incidence in IT and PA, where local fire management is allowed) [1] [2] [3], [4]	trend of wildfires, but with more reduced wildfire incidence in IT and PA, where local fire management is allowed [1] [2] [3], [4].	(globally by a factor of 1.08 to 1.4 in the year 2030 [11]), promoted by more intense "fire weather" (under more severe climate change conditions than present), and suppression policies (that promotes fuel accumulation and limit or prohibit use local fire management, and loss of traditional local fire knowledge) [1] [3], [11], [12].	(globally by a factor of 1.21 to 1.27 in the year 2050, and by a factor of 1.3 to 1.57 in the year 2100 [11]), promoted by more intense "fire hazard weather" (under more severe climate change conditions than 2030*), and suppression policies (that promotes fuel accumulation, limit or prohibit use local fire management and loss of traditional local fire knowledge) [1] [3], [11], [12].

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