Nova Scotia's Carbon Sinks and Pathways to Net-Zero by 2050

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Abstract

In Nova Scotia, *An Act to Achieve Environmental Goals and Sustainable Prosperity* provided legislated greenhouse gas emissions targets for 2020, 2030, and 2050. Work has been done in finding various carbon sinks and practices to enhance them and determining ways to meet the 2030 emissions target. There is a lack of clarity regarding how many emissions sinks and sources are required to meet the 2050 target of having net-zero emissions; this needs to be resolved. This report examines what the maximum allowable anthropogenic emissions are at 2050 when following various scenarios. A baseline year for anthropogenic emissions and carbon sinks was established and scenarios for different trends in sink strengths were developed to project the sinks to 2050. Threats to and vulnerabilities of the sinks were provided to illustrate the risks inherent of following the pathways. The results of these scenarios showed that anthropogenic emissions need to be reduced by about 14% to 51% of 2019 emissions by 2050 in order to meet the legislated net-zero target. Also, it was determined that 1 $MtCO_2e$ over or under net-zero could result in a cost or revenue of approximately $120 million to $1.2 billion in 2019 CAD, respectively. The clarity that this report provides allows policymakers to better plan for meeting the legislated 2050 emissions target. Additionally, this report gives recommendations regarding its findings.

1 Introduction

In 2016, the Paris Agreement came into effect with the purpose of (United Nations Climate Change, n.d.-b):

> Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change (United Nations, 2015, p. 3)

In 2020, the average global temperature was approximately 1.2°C above pre-industrial levels (Lindsey & Dahlman, 2021). According to the Intergovernmental Panel on Climate Change (IPCC) models, in order to limit global warming to 1.5°C or have minimal increase over this temperature, the world must have reduced net anthropogenic CO_2 emissions to roughly 55% of 2010 levels by 2030 and achieved net-zero CO_2 emissions by around 2050 (IPCC, 2018).

Net-zero emissions occurs when the amount of CO_2e captured by carbon sinks is subtracted from the amount of CO_2e emitted into the atmosphere and the result is zero. It is important to note that reaching net-zero emissions does not necessarily require that all anthropogenic emissions are eliminated, it just means that the same amount of emissions that are released by a source are absorbed by sinks. In 2019, global CO_2 emissions were approximately 43 $GtCO_2$ (Hausfather, 2019). To reach net-zero emissions by 2050, CO_2 emissions must be both reduced (through the use of zero-emissions energy sources and potentially through energy efficiency measures) and removed (using CO_2 sinks) (Hughes & McCoy, 2021). While CO_2 is not the only greenhouse gas emission that is contributing to climate change, it is the most dominant, responsible for 80% of Canada's greenhouse gas emissions in 2019 (ECCC, 2021a).

In late 2020, Canada announced that it plans to achieve net-zero by 2050 (ECCC, 2020). All provinces and territories have made similar announcements (Hughes, 2021). For example, in 2019, the Nova Scotia legislature passed *An Act to Achieve Environmental Goals and Sustainable Prosperity* (Government of Nova Scotia, 2019). The Act (Government of Nova Scotia, 2019) states that:

> The Government's goals in relation to greenhouse gas emissions reductions are that greenhouse gas emissions in the Province are
>
> (a) by 2020, at least 10% below the levels that were emitted in 1990;
>
> (b) by 2030, at least 53% below the levels that were emitted in 2005; and

> (c) by 2050, at net zero, by balancing greenhouse gas emissions with greenhouse gas removals and other offsetting measures. (p. 2)

Based on the 2030 goal in the Act (Government of Nova Scotia, 2019), 2030 emissions should be at most approximately 10.9 MtCO$_2$e (ECCC, 2021b). A concern with the 2050 goal is that it does not specify what the anthropogenic emissions should be at in 2050 (Government of Nova Scotia, 2019). In order for the 2050 target to be met, Nova Scotia will need to have sufficient sinks to counter the remaining emissions or be prepared to purchase negative emissions credits from other jurisdictions or construct facilities to capture CO$_2$ (Hughes & McCoy, 2021). Depending on the remaining emissions to reduce and the demand for negative emissions credits or technologies, this could be expensive for the province (Hughes & McCoy, 2021).

The purpose of this report is to evaluate Nova Scotia's current net emissions and estimate future net emissions. This is done by determining current estimates for certain carbon sinks in Nova Scotia and projecting the sinks into the future under different scenarios. The maximum allowable anthropogenic emissions that meet the climate targets will be determined based on the projections of the sinks, providing clarity for the legislation and what is allowable.

The report first provides a review of carbon sinks, their processes and, in some cases, technologies. Following this, a 2019 Nova Scotian baseline of known carbon sinks and the province's geological sequestration capacity will be presented along with the threats and vulnerabilites to those sinks and potential solutions to reducing the impacts of the threats and vulnerabilities. Once the baseline is established, the sinks will be projected under different scenarios to determine the maximum allowable anthropogenic emissions that still meet the province's climate targets. Finally, recommendations that were produced as a result of this research will be provided. Sections of this report were used in a submission to the Province of Nova Scotia as part of public consultations regarding the Sustainable Development Goals Act.[1] All conversions from carbon to CO$_2$e were calculated using atomic mass information from National Center for Biotechnology Information (2021).

2 Review of Carbon Sinks

A sink is "any process, activity or mechanism which removes a greenhouse gas from the atmosphere" (United Nations Climate Change, n.d.-a, para. 1). Carbon dioxide sinks (also referred to as carbon sinks in this report) are sinks that remove CO$_2$ (United Nations Climate Change, n.d.-a). Konyn (2021) describes two kinds of carbon sinks: natural and artificial (United Nations Climate Change, n.d.-a). Carbon sinks require the sequestration of the CO$_2$

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[1] The report submission is "An Analysis of the Greenhouse Gas Emissions Reduction Targets in Nova Scotia's Environmental Goals and Sustainable Prosperity Act of 2019" by Larry Hughes and Mark McCoy (URL: http://dclh.electricalandcomputerengineering.dal.ca/enen/2021/210726_HUGHES_NS_EnvGoalsAndSustProspAct.pdf)

they capture for an acceptable amount of time if they are to be considered for mitigating climate change. Ideally, the CO_2 would be sequestered permanently or for thousands of years. In this report, a natural sink is a carbon sink that captures CO_2 using processes that occur naturally on Earth.

If a sink is enhanced by humans, but its main process is naturally occurring, this report will consider the sink as natural. In this report, an artificial sink is a carbon sink that captures CO_2 using methods developed by humans. There are three natural sinks that are examined in this report which are relevant to Nova Scotia: forests, croplands, and wetlands. The artificial sink that is examined in this report is direct air capture in combination with carbon sequestration in geological formations. Finally, some other carbon sinks that were not the focus of this report will be discussed. All monetary figures presented in this section are in 2019 USD (NASEM, 2019).

2.1 Forests, Croplands, and Wetlands

The land sink was the largest carbon sink available globally in 2019 (Hausfather, 2019). This subsection of the report will examine how forests, croplands, and wetlands work as carbon sinks, their ability to capture and sequester carbon, and the advantages and disadvantages to them working as carbon sinks.

2.1.1 How it Works

Various forms of vegetation absorb carbon dioxide from the atmosphere through direct contact. Aquatic plants obtain CO_2 through contact with CO_2 in water, air, or both (if not fully submerged) (Mentzer, 2018). Plants breathe in CO_2 and some is released back to the atmosphere when the plants breathe out (Riebeek et al., 2011). The retained CO_2 is eventually converted into materials for the structural material of the plant, such as bark or leaves; this is how carbon is stored in plants (Riebeek et al., 2011). When vegetation dies, it decomposes and begins to release the carbon that it stored (Riebeek et al., 2011). When plant products burn, such as in wildfires or intentional burning, carbon that the plant stored is also released (NASEM, 2019). The soil that vegetation is in can also contain a significant amount of the carbon in a vegetated area in the form of soil organic matter (44% of forest carbon is stored in the live vegetation and 45% of forest carbon is stored in the form of soil organic matter) (Mulhern, 2020).

Three major areas of vegetation for carbon sinks are forests, croplands, and wetlands. There are various proposals on how best to capture carbon by managing these three areas of vegetation, such as coastal blue carbon and terrestrial carbon removal and sequestration (TCRS) (NASEM, 2019).

Coastal blue carbon is a carbon capture and sequestration (CCS) method that involves tidal wetlands and seagrasses capturing carbon and storing it in the structural material of the plants as well as burying plant organic carbon in their soils (NASEM, 2019; Riebeek et al., 2011). Tidal wetlands can expand both along the sea floor and vertically (they have to expand vertically at the same or greater rate of rising sea levels) (NASEM, 2019), potentially increasing the amount of carbon they can capture and sequester. Most of the organic carbon collected in tidal wetlands is a product of the wetlands themselves (NASEM, 2019). While coastal blue carbon is a natural process, with human involvement, its ability to capture and store carbon can be improved: such as restoring coastal wetlands; improving the carbon storage of coastal areas by burying high-carbon materials – that were not made in the coastal ecosystems – in them; managing coastal wetlands in such a way that allows their area to increase with rising sea levels and that increases or maintains the rate at which organic carbon is buried as time goes on (NASEM, 2019); and preventing wetlands from being drained (Minnesota Board of Water and Soil Resources, n.d.).

TCRS is a CCS method that involves land-based plants capturing CO_2 and storing it in the structural materials of the plants as well as storing carbon in the soil. Increasing the amount of carbon stored in forests requires planting and preserving more carbon-dense trees, or protecting more trees from being lost (through natural death, harvesting, or fire), or both. Increasing the amount of carbon stored in soil requires adding more plant matter to the soil, decreasing the decomposition rate of soil organic matter into CO_2, or both. As with coastal blue carbon, TCRS is a natural process, but humans can improve its ability to capture and store carbon. Various practices of TCRS can be divided into the types of the land that they are used on, such as forests, grasslands, and croplands. Some forestry practices include avoiding deforestation; afforestation and reforestation; management of forests to restore and maintain their health, and increase their growth; increasing the time before harvest of trees to maintain the carbon capture ability of the trees; and preserving more harvested wood and wood products (a developing practice which may improve carbon/CO_2 removal). These practices have the potential to increase carbon capture and reduce CO_2 emissions associated with wood products. In terms of grassland/cropland practices that help remove and reduce CO_2 emissions, they can be divided into two categories: conventional (already established) and frontier (developing). Some conventional grassland/cropland practices are including trees in agricultural land and management techniques such as not tilling the ground as frequently or at all before planting crops (the CCS ability of tilling practices varies based on the climate and soil characteristics). Some frontier grassland/cropland practices include: adding biochar (solid carbon by-product resulting from the biomass-to-fuel process) to soil to store carbon and increase crop productivity; placing high-carbon surface soils deeper underground and low-carbon soils near the surface to allow more carbon to be absorbed and potentially increase the amount of time carbon remains in the soil; and modifying current agricultural plants to increase the amount of carbon sent to the plant roots (NASEM, 2019).

2.1.2 Carbon Capture Ability

In 2019, the global land sink captured an estimated 11.50 $GtCO_2$ which is approximately 27% of the global CO_2 emissions that year (Hausfather, 2019). Land-use changes were responsible for 6.60 Gt of CO_2 emissions in 2019 (Hausfather, 2019). The potential annual CCS ability and CO_2 capacity of coastal blue carbon with the technology and knowledge in 2019 was 0.13-0.80 $GtCO_2$/y globally and 8-65 $GtCO_2$ globally, respectively (NASEM, 2019). The potential annual CCS ability and CO_2 capacity of TCRS practices with the technology and knowledge in 2019 was 5.5-12 $GtCO_2$/y globally and 660-1215 $GtCO_2$ globally, respectively (NASEM, 2019). Qualifiers for the values provided from NASEM (2019) can be found on pages 356-357 of that source. There are significant variations in the carbon absorbed by the land between years, with variation reaching as high as 4.62 $GtCO_2$/y in the previous decade (Hausfather, 2019). This variation is connected to changes in temperatures and stored water in tropical regions, and can result from weather events (Yue et al., 2020).

There are multiple factors that affect the carbon capture ability of vegetation and the land sink. The amount of carbon absorbed by vegetation on the land is believed to increase when higher atmospheric CO_2 concentrations increase photosynthesis, causing more plant growth and thus, more carbon to be stored (NASEM, 2019; Smith, 2020), and when forests reclaim some former agricultural land (NASEM, 2019). While increased CO_2 allows for plants to grow more, plants are still limited by other materials that may not be as plentiful in order to grow (Smith, 2020). It has been recently found that globally, the effectiveness of 86% of terrestrial ecosystems at capturing CO_2 is decreasing (Smith, 2020). The vegetation sink can be divided into two categories: vegetation that quickly acts to reach equilibrium with the CO_2 in the atmosphere and the vegetation that is not in equilibrium with the CO_2 in the atmosphere (NASEM, 2019). Types of vegetation that fall into the first category are leaves and small roots (NASEM, 2019), whereas those that fall into the second category are live wood and long-lasting, land-based dead organic matter (NASEM, 2019). Should the CO_2 concentration in the atmosphere decrease over a century, the land is predicted to remain a carbon sink due to the absorption of CO_2 by the vegetation that does not reach equilibrium with the atmosphere, despite the vegetation that releases CO_2 during this time (NASEM, 2019). When more CO_2 is removed from the atmosphere, the effectiveness of vegetation as a carbon sink will decrease (NASEM, 2019). In a business-as-usual scenario, it is predicted that the land carbon sink will become a land carbon source as a result of factors such as plants lacking resources other than CO_2 to grow (NASEM, 2019; Smith, 2020) and the death of forests to high temperatures and drought (NASEM, 2019). The removal of the trees through methods such as harvesting, natural death, or fire affects the carbon capture ability of trees (NASEM, 2019; Natural Resources Canada, 2020a). Also, due to changes in albedo when conducting afforestation/reforestation at high latitudes, the result is an overall increase in temperature even after taking into account the temperature decrease from the emissions reduction from the trees (NASEM, 2019).

2.1.3 Advantages/Disadvantages

Some advantages to coastal wetlands are that they help to protect coasts during storms, provide homes for wildlife, and reduce the strength of waves. Coastal blue carbon practices can also reduce the flood risk to humans by reducing the population of regions that are becoming more prone to flooding. Another major disadvantage to coastal blue carbon is that there is risk that the practices used, such as shoreline modification, will ultimately harm the coastal ecosystem. Some advantages to TCRS practices are that the practices can be viewed as repairing damage done to the ecosystem, they may improve ecosystem diversity, and improve soil quality. A significant disadvantage to these practices is that there might be competition for land with other economic needs, such as food production, so what is technically possible for carbon capture may not be necessarily feasible. Another major disadvantage is that the effects of the practices can be reversed by methods such as harvesting, where the carbon that was stored gets released. One final disadvantage to some terrestrial practices is that adoption rates for some of these practices are low, preventing the effects from being realized. The estimated costs to implement the CO_2 removal practices of coastal blue carbon and TCRS span a relatively small range. The cost for coastal blue carbon burial is estimated to be \$10/tCO_2 and the cost for TCRS is estimated to range \$15-\$100/tCO_2 (NASEM, 2019, p. 356).

2.2 Direct Air Capture

As the name suggests, direct air capture (DAC) technology captures CO_2 from the air. While DAC is not a sink by itself, the combination of DAC with carbon sequestration in geological formations is a carbon sink. DAC has the potential to provide massive carbon capture abilities (NASEM, 2019). This subsection examines how DAC works, the ability of DAC to capture carbon, and its advantages and disadvantages.

2.2.1 How it Works

In the DAC systems presented in NASEM (2019), air is pulled from the atmosphere into an air contactor where CO_2 is removed from the air. DAC systems are carbon capture systems; they do not store CO_2. At present, DAC systems can capture CO_2 using liquid solvents or solid sorbents.

Carbon Engineering's DAC systems use a liquid solvent in the form of a KOH solution and capture 75% of the CO_2 passing through their DAC system (Carbon Engineering, n.d.). The liquid solvent DAC system described in NASEM (2019) uses an aqueous solution of KOH as well and can capture 75% of atmospheric CO_2 passing through the air contactor at an ambient concentration of 400 ppm. In the NASEM (2019) liquid solvent DAC system, there are five further processes, including causticizing, calcinating, slaking, clarification and filtering, and air separation of O_2, where the KOH is recovered, and high-concentration CO_2 gas is produced. The following are the reactions for the different processes:

Air Contactor: $2\mathrm{KOH}_{(aq)} + \mathrm{CO}_{2\,(g)} \rightarrow \mathrm{H_2O}_{(g)} + \mathrm{K_2CO}_{3\,(aq)}$

Causticizer: $\mathrm{K_2CO}_{3\,(aq)} + \mathrm{Ca(OH)}_{2\,(aq)} \rightarrow 2\mathrm{KOH}_{(aq)} + \mathrm{CaCO}_{3\,(s)}$

Calciner: $\mathrm{CaCO}_{3\,(s)} \rightarrow \mathrm{CaO}_{(s)} + \mathrm{CO}_{2\,(g)}$

Slaker: $\mathrm{CaO}_{(s)} + \mathrm{H_2O}_{(l)} \rightarrow \mathrm{Ca(OH)}_{2\,(aq)}$

Not only is KOH recovered through these processes, but materials for the various processes are recovered throughout the system reactions shown above (NASEM, 2019).

In DAC systems that use solid sorbents, air is brought into contact with a solid, CO_2-adsorbing material which captures the CO_2 on its surface. The material is then heated, or placed in a vacuum, or both which releases the CO_2 from the material at which point it can be processed for sequestration. The CO_2-adsorbing material is then cooled to begin capturing more CO_2 (NASEM, 2019).

Once CO_2 is captured through either type of DAC system, it must be stored; for example, in geological formations (covered later in this report) (IEA, 2020; NASEM, 2019).

2.2.2 Carbon Capture Ability

The carbon capture ability of DAC is mainly constrained by finances rather than technical constraints. The sequestration of the CO_2 that is captured by DAC systems does have limitations in the form of feasible geological sequestration locations and safe storage capacity. DAC systems can be constructed anywhere, but the infrastructure and resources to operate DAC systems must be in place as well, potentially limiting DAC locations. The energy that is required to run the DAC systems could be obtained from renewable and/or non-renewable sources, the use of renewables increasing the net CO_2 capture ability of the DAC system and the use of non-renewables decreasing that ability. To increase the net CO_2 capture ability of DAC systems, non-emitting energy sources should be employed (NASEM, 2019).

If natural gas was used as a thermal energy source for liquid solvent DAC system presented in NASEM (2019), the system could absorb the CO_2 produced by the combustion of the natural gas while also absorbing as much atmospheric CO_2 as possible. This reduces the volume of atmospheric CO_2 that can be captured. The employment of power sources at the location of the DAC system has the potential to be limited by land availability. If there are multiple air intake points, it is important to place them such that the air being pulled in by the air intakes at each point has an ambient concentration of CO_2, allowing for optimal carbon capture.

2.2.3 Advantages/Disadvantages

The major advantages of DAC are its potentially large annual CO_2 capture abilities and relatively small land usage to achieve those ends (NASEM, 2019). Also, DAC allows for CO_2 product at various purities to be sold to the market. The most significant disadvantage to DAC is that it is presently an expensive technology for CO_2 removal, with average costs ranging from roughly $90/t to $900/t of net CO_2 captured.

The limited deployment of DAC systems has resulted in a lack of data for analyses to help policymakers understand the costs of negative emissions through DAC systems that are required to meet the climate goals of the Paris Agreement (NASEM, 2019; United Nations Climate Change, n.d.-b). One advantage is that it does not seem to be a lack of fundamental understanding of the technology that is slowing its uptake (NASEM, 2019).

Some disadvantages of DAC include the significant reduction in local CO_2 concentrations may have a detrimental impact to local ecosystems; potential chemical emissions from solid sorbent DAC systems may harm the environment; more research needs to be conducted into water production and use in DAC; and to reach large scale CO_2 capture via DAC, a significant amount of money needs to go towards research and development. Another significant disadvantage of DAC systems is that they are not carbon sequestration technologies themselves – they need another method to store the carbon they capture in order to be useful (NASEM, 2019). Looking past 2050, it has been recently found that DAC could decrease the costs of meeting international climate targets, but doing so would demand up to 25% of worldwide energy in 2100 (Evans, 2019); this is a significant potential disadvantage.

2.3 Carbon Sequestration in Geological Formations

Carbon sequestration in geological formations (CSGF) is an artificial carbon sink support method that works with bioenergy with carbon capture and sequestration (BECCS) and DAC by acting as the storage method (NASEM, 2019). Here we examine how CSGF works as a carbon sink, the ability of CSGF to sequester carbon, and the advantages and disadvantages to CSGF working as a carbon sink.

2.3.1 How it Works

CSGF is a primary CO_2 storage method for both BECCS and DAC systems (NASEM, 2019). This technology is simply a storage method for the CO_2 that other technologies capture (NASEM, 2019). Captured CO_2 must first be compressed into a supercritical fluid before it can be sequestered, allowing for more CO_2 to be stored (NASEM, 2019). The fluid is then pumped into an underground geological formation for long-term storage (NASEM, 2019). The formation must be deep enough that the underground pressure and temperature causes the fluid to stay compressed and supercritical (NASEM, 2019; National Energy Technology Laboratory, n.d.). The geological formations that can be used for CSGF must have porous rock that fluids can pass into and their tops must be sealed by rock that is difficult or impossible for fluids to pass through (NASEM, 2019). Due to the density of supercritical CO_2 in relation to fluids that fill the rock pores, the CO_2 will rise to the top of the rock formation and be stored permanently if there are no leakage pathways (NASEM, 2019). Sedimentary rocks can be used for CSGF (Grant Wach (Dalhousie University), personal communication, June 23, 2021; NASEM, 2019). Some reservoirs for CO_2 storage include depleted oil/gas deposits and deep saline aquifers – both onshore and offshore locations (NASEM, 2019). One method of CSGF injects CO_2 into oil/gas reserves to increase extraction while also storing CO_2 – this process is called enhanced oil/gas recovery (NASEM, 2019). To increase the trapping ability of CO_2 in the underground reservoirs, multiple methods can be implemented, such as CO_2 (or carbon) mineralization (as will be discussed in the section 2.4.2 of this report) (NASEM, 2019).

2.3.2 Carbon Storage Ability

By 2019, major saline aquifer CSGF projects sequestered individual amounts between 0.3-1.2 $MtCO_2/y$ (NASEM, 2019). The potential global CO_2 capacity of saline aquifer CSGF given the knowledge and technology in 2019 was 5000-25000 $GtCO_2$. Enhanced oil recovery projects can be carbon sinks provided that substantially more CO_2 is injected into the reservoir per barrel of oil produced.

One factor that affects the ability of CSGF to store CO_2 is the potential for leaks in the CO_2 reservoir. Leaks could be the result of cracks in the low permeable rock. If the sequestration site is not near the capture site, transportation will be required to the sequestration site, potentially resulting in CO_2 emissions (i.e., transportation on a ship burning fossil fuels). Consequently, the net CO_2 captured and sequestered could decrease. Ideally, sequestration sites would be near to the location of carbon capture to avoid transportation costs and potential emissions. It is important to note that there is a maximum sequestration rate for CO_2 in CSGF that is capped where unsafe pressure build-up in a reservoir is not reached. An important factor which limits the CO_2 sequestration capacity of CSGF is that injecting CO_2 into reservoirs can result in a build-up of pressure that may cause seismic activity or break the reservoir seal. Once stored in the reservoir, unless there is leakage, the CO_2 will remain in the reservoir for an indefinite period (NASEM, 2019).

2.3.3 Advantages/Disadvantages

The most significant advantages of CSGF are: it has a large potential CO_2 storage capacity; there is a significant amount of research and experience with CSGF; and storage of CO_2 is permanent provided there are no leaks. Additionally, the cost of CO_2 sequestration is very low at \$7-\$13/tCO_2. Major disadvantages of CSGF include implementation of CSGF may result in further seismic activity; leakage of the CO_2 reservoir may contaminate groundwater; it requires a significant amount of research to scale up CSGF and guarantee its safe and consistent application; and a sequestration site may not necessarily be near high-emissions sources. Given the use of CSGF in enhanced oil recovery, another advantage of CSGF is that the oil industry could play a role in carbon sequestration should it make sense to do so, improving their oil extraction. Another significant disadvantage to CSGF is that, depending on a country's laws, it may not be explicit who is financially liable for CO_2 reservoirs long after a sequestration project has ended; this has been a major contributor to preventing large-scale deployment of CSGF. Another barrier to scaling up CSGF is the potential issue of gaining permission to conduct CSGF under lands that are owned by potentially many people, which expends time and money (NASEM, 2019).

2.4 Other Sinks

Some other sinks which were not examined in relation to Nova Scotia, but which may have carbon capture potential once looked at, are bioenergy with carbon capture and sequestration (BECCS) and carbon mineralization. BECCS is a mix between an artificial sink and a natural sink while carbon mineralization is a sink following a natural process (NASEM, 2019). In their respective subsections, how the technologies work will be explained and their global carbon capture potential will be provided.

2.4.1 Bioenergy with Carbon Capture and Sequestration

Generally, BECCS is the process in which CO_2 is captured from the air via growing vegetation, the vegetation is used in bioenergy power plants, CO_2 is captured from the power plants, and CO_2 is then stored in geological formations (American University, 2020; NASEM, 2019). As explained in section 2.1, plants capture CO_2 via respiration and store it in the materials that constitute the vegetation (Riebeek et al., 2011). While some carbon can be stored in the soil at this step, the sequestration of carbon for BECCS is focused on geological formations (NASEM, 2019).

Some other methods of BECCS are: the vegetation is fermented into fuel and CO_2 from the fermentation process is captured and sequestered; and the vegetation is converted to fuel and the biochar product of this conversion is sequestered in soil as in the TCRS practice (NASEM, 2019). Sources that could be used for BECCS include: energy crops grown on marginally productive cropland (of which there is a substantial amount globally); forestry plant residues; crop plant residues; and organic waste from cities (BECCS Task Force, 2018; NASEM, 2019). When biomass is collected from the source, it must then be transported to a consumer (including industrial consumers) for conversion into its next product (i.e., fuel, energy, and/or biochar) (NASEM, 2019). If the product is fuel, that fuel must be transported to the consumer (NASEM, 2019). Transportation adds CO_2 emissions to the atmosphere which BECCS can absorb (NASEM, 2019). It is important to note that emissions will vary depending on the mode of transportation as well as the distance travelled (NASEM, 2019). The biomass can be converted to various products (such as heat and fuel) using multiple methods that fall under thermochemical or biological classifications, such as pyrolysis, fermentation, gasification, and simply combustion (NASEM, 2019).

When biomass combustion is used for thermal or electrical power, CO_2 will be produced and the methods for capturing this CO_2 are typically no different than the developing methods for CCS in a fossil fuel power plant (NASEM, 2019). Some methods in which power plant CO_2 emissions are removed are where CO_2 is separated either before or after combustion (NASEM, 2019). One technology of CCS used in fossil fuel power plants is CO_2 scrubbers, which remove a net of 80-90% of CO_2 emitted by the plant when including the extra energy and emissions for running the scrubbers (Horton, 2008). Once the CO_2 is captured from these processes, it can be sequestered in geological formations (NASEM, 2019). When biomass is converted to fuel, carbon can be stored in biochar which can be added to soil for sequestration as well as a potential benefit to the productivity of the land (NASEM, 2019).

The potential annual carbon capture ability of BECCS with the technology and knowledge in 2019 was 3.5-15 $GtCO_2$/y globally. Qualifiers for these values from NASEM (2019) can be found on page 357 of that source. Like DAC, the CO_2 capacity for BECCS methods that store CO_2 in geological formations is constrained by the space in geological formations to store CO_2 safely and feasible geological sequestration locations. The CO_2 capacity for the BECCS method that produces fuel along with biochar seemingly does not have capacity constraints. As discussed previously, the mode of transportation and the transportation distance for biomass can decrease the net CO_2 removal ability of BECCS to varying degrees. Truck transportation has the highest rate of CO_2 emissions per kg of biomass per km travelled, followed by train and then sea freight. A significant factor that affects the carbon capture ability of BECCS is carbon losses: for a bioenergy integrated gasification combined cycle power plant that uses CO_2 capture and sequestration and burns switchgrass, from the point of carbon capture in switchgrass to the point of sequestration of that carbon, over half of the original carbon can be lost. It is important to note that the combustion, degradation, and respiration of living things contribute to CO_2 and CH_4 emissions (NASEM, 2019).

2.4.2 Carbon Mineralization

Carbon mineralization is a natural process that occurs when various kinds of silicates and rocks high in calcium or magnesium content are weathered (NASEM, 2019). Natural carbon mineralization can capture 30 $GtCO_2$ over a century (Hills et al., 2020; NASEM, 2019). CO_2 can be stored as carbonates by reacting with the previously described materials (NASEM, 2019). Some preferred types of minerals for carbon mineralization are mantle peridotite and basaltic lavas. Some of the mineralization reactions are shown below:

$$\mathrm{CaSiO_3 + CO_2 \rightarrow CaCO_3}$$

$$\mathrm{Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2}$$

$$\mathrm{Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O}$$

Humans can get involved with carbon mineralization to achieve two outcomes: sequestering CO_2 in carbonate materials or both capturing and sequestering CO_2 in carbonate materials – each outcome has methods that can be taken to achieve them (NASEM, 2019).

For storing CO_2, three methods can be used: ex situ, in situ, and surficial carbon mineralization (NASEM, 2019). For ex situ carbon mineralization, material used in the CO_2 to carbonate reaction is brought to locations of CO_2 capture where it is reacted with CO_2 in its temporary storage substance. For in situ carbon mineralization, CO_2 that is temporarily stored in fluids are passed through viable underground rock formations to react and store CO_2 in carbonate materials. For surficial carbon mineralization, CO_2 that is temporarily stored in fluids are passed over a high surface area of certain industrial waste products (such as mining tailings) or a high surface area of reactive rocks where CO_2 can react with the material. The method for both carbon capture and storage could use in situ or surficial mineralization along with surface water as the temporary storage substance for CO_2. CO_2 from the atmosphere will dissolve in surface water naturally, so the surface water for this carbon mineralization process acts as the carbon capture component (NASEM, 2019; Riebeek & Simmon, 2008).

There is a wide range and some unknown quantities for the carbon capture ability of the various methods of carbon mineralization, given the technology and knowledge of 2019. The known values for individual sequestration-only carbon mineralization methods could be as high as 32 $GtCO_2$/y for annual CO_2 removal and as high as roughly one million $GtCO_2$ for global capacity. Two potential limiters of the carbon capture ability of in situ carbon mineralization are that the pores of rocks could be clogged by carbonates, preventing further carbon storage, and that the reactions that produce the carbonate materials could form a layer that protects the reactants from further reacting, potentially slowing or stopping further carbon storage. Certain kinds of rocks have higher rates of carbonation, so their abundance (or lack thereof) is important to consider when choosing a rock for carbon mineralization. For surficial carbon mineralization, some industrial waste products do not contain much calcium or magnesium, thus reducing the carbon storage capability of this method (NASEM, 2019).

3 Nova Scotia’s Carbon Sinks Baseline

To develop emissions scenarios that extend decades into the future, it is critical to establish a baseline of the province’s current carbon sinks. This section will examine Nova Scotia’s forests, croplands, and wetlands as carbon sinks and Nova Scotia’s geological sequestration potential. The baseline year will be 2019 as that is the most recent year for which key data involved in this report is available, such as the annual GHG emissions for Nova Scotia (ECCC, 2021b).

3.1 Nova Scotia’s Forests

According to the provincial Ecological Landscape Analysis (ELA) reports for Nova Scotia’s ecodistricts, which use data from 2015 and 2017, the total area of Nova Scotia’s forests is approximately 4.3 Mha (found by summing the forest areas provided in the ELA report for each ecodistrict (Bush & Baldo, 2019)). Assuming that this area is the area of the province’s forests in 2019 and using the ELA data (Bush & Baldo, 2019), it was determined that forests constituted approximately 78.3% of the land area of Nova Scotia in 2019; this makes the forests Nova Scotia’s largest carbon sinks by land area. This subsection will discuss the ability of forests to absorb carbon as well as the threats to the forest and vulnerabilities to events that will impact this ability.

3.1.1 Forest Sink Ability

The average CO_2 flux (i.e., change in CO_2 emissions) of Nova Scotia’s forests was approximately -9.38 $MtCO_2/y$ between 2013 and 2017 and approximately -9.06 $MtCO_2/y$ between 2008 and 2012. This report assumes that the change in these values is linear to get the CO_2 flux for the next five-year period (2018-2022), resulting in a CO_2 flux of approximately -9.70 $MtCO_2/y$ for the baseline year. The data used to determine this value were collected from permanent forest sample plots (PSPs) in the province. The PSP-based estimations show only change in carbon stocks between measurement periods. Therefore, if a given plot is harvested, it is assumed that all emissions associated with the harvested wood products are emitted entirely at harvest, which will lead to an overestimation of emissions from harvested wood products that store carbon for a longer period as they decompose (James Steenberg (Nova Scotia Department of Lands and Forestry), personal communications, July 26, 2021).

Additionally, forests and PSPs were stratified by ecoregion and it is therefore assumed that the sample plots share the same carbon capture characteristics of a given ecoregion. Moreover, emissions from dead organic matter only include coarse woody debris and standing dead trees (i.e., snags) and not litter, fine woody debris, dead tree roots, or soils, which will lead to an underestimation of emissions from forests due to the decomposition of these dead organic matter pools. The total net removal of carbon from forests and harvested wood products is likely overestimated by the PSP-based data (J. Steenberg, personal communications, July 26, 2021).

Given that the carbon capture value for Nova Scotia’s forests is likely overestimated (J. Steenberg, personal communications, July 26, 2021), it is important to compare it to the carbon capture value of the forests of a jurisdiction that is geographically close to Nova Scotia. Such a jurisdiction is the state of Maine. The area of Maine’s forests is 17.30M acres (approximately 7.00 Mha) and Maine’s forests captured an estimated average net of about 15.1 $MtCO_2e/y$ between 2006 and 2016 (value obtained by subtracting wood product emissions from net forest uptake and converting from carbon to CO_2e) (Bai et al., n.d.). From this data, the per hectare carbon capture of Maine’s forests can be estimated to be approximately 2.16 $tCO_2e/ha/y$. Comparing this to Nova Scotia’s forests in a similar time period (2013-2017) which have an estimated net per hectare carbon capture of 2.17 $tCO_2e/ha/y$ (when taking the 2013-2017 flux data for the province’s forests provided in the previous paragraph and dividing it by the forest area in Nova Scotia from the 2019 ELA reports), it is clear that they have very similar values, so the estimate for Nova Scotia is likely reasonable.

3.1.2 Threats and Vulnerabilities

There are multiple threats to Nova Scotia's forests that could reduce their ability to capture and store carbon, such as drought, fires, pests, and strong weather events (McCurdy & Stewart, 2003).

Some potential solutions to reducing the threat of droughts to Nova Scotia's forests are to thin or intentionally burn the forest to decrease the forest density and to promote trees that can resist the effects of droughts (Myers, 2019). The likelihood of droughts happening in Nova Scotia's future is likely given that there has been a drought of any intensity during six years of the last decade (Agriculture and Agri-Food Canada's National Agroclimate Information System, 2021) and that temperatures increase with global warming.

Reducing the threat of drought consequently reduces the threat of fires to the province's forests (Climate Change Unit, n.d.-e). The risk of potentially high-damaging fires can be reduced through management practices such as prescribed burning (Natural Resources Canada, 2021). The likelihood of forest fires happening in Nova Scotia's future is almost certain given that there have been wildfires reported every year for the past five years (Nova Scotia Department of Lands and Forestry, 2020) and that in the rapid emissions reduction climate scenario, the province's fire season is expected to get longer (Natural Resources Canada, 2020b).

Pests, including new pests introduced from southern climates, are considered by the province to be the highest threat to Nova Scotia's forests (Climate Change Unit, n.d.-e). To reduce the threat of pests that may arrive from southern climates (Climate Change Unit, n.d.-e), the province should prepare and research forest management practices to reduce the impact of the most likely pests on Nova Scotia's forests. To reduce the threat of pests that currently inhabit the province's forests, practices to reduce their impact which already exist (such as those meant to deal with the spruce beetle (Nova Scotia Department of Natural Resources, 1998)) should be used (if not currently practised) and research should be conducted to improve their effectiveness or to find more effective practices. A vulnerability of Nova Scotia's forests is the vulnerability of all spruce trees to the spruce beetle during spruce beetle outbreaks (Taylor et al., 2020). The likelihood of new pests is almost certain since it is already occurring (i.e., the hemlock woolly adelgid was reported in Nova Scotia in 2017 (Taylor et al., 2020)). The likelihood of spruce budworm infestations is likely to decrease in the future should temperatures at their southern limit rise (Taylor et al., 2020). Currently, certain spruce budworm infestations cause low amounts to significant amounts of damage to large quantities of spruce-fir forests in 30-40 year intervals (Taylor et al., 2020). To reduce the vulnerability of Nova Scotia's forests to pest infestations, various forest management practices can be conducted, such as decreasing the number of a pest's host trees in a forest through thinning and predicting when and where pest infestations will occur so that action can be taken to prevent further infestation (Climate Change Resource Center, n.d.). An example of a practice that is currently implemented to reduce the potential of spruce beetle infestations is removing blown down trees from an area of forest (Nova Scotia Department of Natural Resources, 1998).

Some other vulnerabilities of Nova Scotia's forests are the vulnerability of tall stands of mostly spruce or balsam fir to wind damage (Taylor et al., 2020), and the vulnerability of shallow rooted trees to wind damage (Neily et al., 2007). In Nova Scotia, between 2008 and 2012, two softwood tree species that were among the highest in commercial populations were red spruce and balsam fir, and a hardwood tree species that was among the highest in commercial population was red maple (Nova Scotia Department of Natural Resources: Renewable Resources Branch, 2017). The trees listed all have shallow roots (McGrath, 2018) which means that the province's commercial trees with some of the highest populations in their respective category were vulnerable to wind damage (Neily et al., 2007) and likely still are. A potential solution to reducing the vulnerability of the province's forests to wind damage would be to assess areas that are high-risk and ensure that the trees do not grow too tall (since some tall trees are more vulnerable to wind damage (Taylor et al., 2020)). The likelihood of strong weather events is almost certain since hurricanes hit Nova Scotia every seven years on average (Taylor et al., 2020). The likelihood of extra-tropical cyclones that have winds that could result in significant damage is almost certain since cyclones of this strength hit Nova Scotia roughly once every two years (Taylor et al., 2020).

Other threats to the province's forests are: anthropogenic actions which help the forest sink can be undone deliberately (i.e., forest clearing) or through natural disturbances (i.e., fires or windstorms (Taylor et al., 2020)), thus reversing progress; and the potential to increase the amount of harvested wood to decrease emissions by replacing higher-emissions materials like steel and concrete with harvested wood products (NASEM, 2019). To reduce the threat of actions that improve the forest sink being intentionally undone, a potential solution would be to produce legislation that "locks in" the action unless the scientific community decides, in the future, that the action is ultimately harmful to the forest sink. The increase in emissions resulting from an increase in the production of harvested wood products would have to be offset by increasing the net carbon uptake of the forest through various methods such as improved forestry management practices as well as afforestation/reforestation (NASEM, 2019). A serious impact from climate change is potential changes in growing season length: while potentially longer growing seasons could increase plant growth, warmer temperatures could increase carbon loss from plant respiration enough to offset some of or exceed the carbon capture from the increased growing season length (Zhu (ed.) et al., 2010); this presents a significant challenge.

3.2 Nova Scotia's Croplands

In 2011, the area of cropland in Nova Scotia was 280 889 acres (Statistics Canada, 2016), and the area decreased by 4.8% to approximately 267 406 acres (or 108 218 ha) in 2016 (Statistics Canada, 2018). For the baseline year of this report, the cropland area will be assumed to be the same as the area in 2016. When comparing this value to the total area of Nova Scotia calculated from the data in the ELA reports (Bush & Baldo, 2019), cropland constituted approximately 1.96% of Nova Scotia's land area in 2016. This subsection will discuss the ability of cropland to absorb carbon as well as the threats to cropland and vulnerabilities to events that will impact this ability.

3.2.1 Cropland Sink Ability

Due to insufficient data available about the ability of Nova Scotia's croplands to absorb or emit carbon, a coarse estimate was made. The most specific data provided regarding the carbon capture ability for cropland is the Land-Use, Land-Use Change, and Forestry (LULUCF) data for the Atlantic Maritime Ecozone (AME), which is that the cropland for this region released approximately 541 ktCO$_2$e in 2019 (ECCC, 2021c). This value was scaled down linearly from the cropland data of the AME to the cropland data of Nova Scotia by using the ratio of the area of Nova Scotia (O'Grady & Moody, 2021) to the area of the AME (ESTR Secretariat, 2014).[2] The result of this calculation is that Nova Scotia's croplands are a source of approximately 145 ktCO$_2$e/y rather than a sink in 2019. Due to the coarseness of this estimate, it does not provide an accurate depiction of Nova Scotia's cropland sink. Since it is relatively small in comparison to other sinks and sources, this inaccuracy does not have a significant impact on Nova Scotia's carbon sink baseline. Currently, there is no incentive for cropland owners to focus on carbon sequestration on their cropland (Derek Lynch (Dalhousie University), personal communication, June 30, 2021).

3.2.2 Threats and Vulnerabilities

Like the forests, there are multiple threats to Nova Scotia's croplands that could make them emit more carbon via degradation of the ecosystem's ability to capture carbon. Climate change could result in an increased quantity and strength of droughts that reduce the productivity of the cropland (Agriculture and Agri-Food Canada, 2020); this means that the plants on the cropland would not be absorbing as much carbon. To reduce the effect of

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[2] The area information reproduced in the calculations is a copy of an official work that is published by the Government of Canada and the reproduction has not been produced in affiliation with or with the endorsement of the Government of Canada.

droughts on crops, cropland, livestock, and forestry systems can be combined in various ways on one farm (Calmon & Feltran-Barbieri, 2019). A cropland management practice that can reduce the effects of floods and droughts on croplands is planting cover crops (McLellan, 2015). Another effect of climate change is that it could increase pest infestations which may require the use of pesticides – the use of which could increase energy usage for their production and distribution and potentially GHG emissions depending on the energy source used (Agriculture and Agri-Food Canada, 2020). Efforts should be made to avoid the potential emissions connected to the production and distribution of pesticides (Agriculture and Agri-Food Canada, 2020) or to capture them at source points. Another threat to the productivity and survivability of cropland plants is the potential introduction of salt water to cropland (Climate Change Unit, n.d.-a; Weissman et al., n.d.). To reduce the impact of salt water intrusion, various adaptation actions can be taken, such as adding gypsum to the soil and planting cover crops; however, these are only short-term solutions (Weissman et al., n.d.).

Nova Scotia’s croplands have some vulnerabilities, such as having low-lying coastal cropland (e.g., parts of the Annapolis valley) being prone to saltwater intrusion as sea levels rise (Weissman et al., n.d.). To prevent the intrusion, sufficiently high dykes should be constructed or maintained, or both, in areas that are at risk of saltwater intrusion. Other vulnerabilities are that: Nova Scotia uses unirrigated farming, making the cropland susceptible to drought; the province’s soils are coarse and sloped, making them vulnerable to erosion; and the soils are low in soil organic matter, reducing their water holding capacity and structure related to water infiltration capacity (D. Lynch, personal communication, August 15, 2021; Marshall et al., 2021). This reduction in soil health related to water infiltration and retention has multiple detrimental effects: it leaves the land vulnerable to both flooding and drought (D. Lynch, personal communication, August 15, 2021). The adoption of cropland management practices that increase soil organic matter would decrease the risk of both flooding and drought (D. Lynch, personal communication, June 30, 2021). Some potential examples of management practices to increase soil carbon would be to include trees on cropland and the planting of cover crops (NASEM, 2019) and diverse crop rotations to allow inclusion of some perennial crops (D. Lynch, personal communication, August 15, 2021). Increasing the amount of soil organic matter in cropland soils would increase soil structure and thus, decrease erosion (D. Lynch, personal communication, June 30, 2021).

The likelihood of droughts occurring in the province’s future is already discussed in the Nova Scotia’s Forests subsection of this report. As long as sea barriers are not constructed to prevent the sea from reaching inland, the likelihood of salt water intrusion is likely given the expected sea level rise and that Nova Scotia is slowly losing land (Graham & Musselman, n.d.). The likelihood of flooding occurring in Nova Scotia in the future is likely given that the annual precipitation is predicted to increase in the future (Climate Change Unit, n.d.-b) and that more intense rainfalls are predicted (Climate Change Unit, n.d.-c).

3.3 Nova Scotia’s Wetlands

According to the most recent provincial ELA reports for Nova Scotia’s ecodistricts, which use data from 2015 and 2017, the total area of Nova Scotia’s wetlands is approximately 383 kha (found by summing the wetland areas provided in the ELA report for each ecodistrict (Bush & Baldo, 2019)). For maps of the ecodistricts, see the ELA reports by Bush and Baldo (2019). Assuming that this area is the area of the province’s wetlands in 2019 and using the ELA data (Bush & Baldo, 2019), it was determined that wetlands constituted approximately 6.9% of the land area of Nova Scotia in 2019; this makes the wetlands Nova Scotia’s second largest carbon sink by land area. This subsection will discuss the ability of wetlands to absorb carbon as well as the threats to the wetlands and vulnerabilities to events that will impact this ability.

3.3.1 Wetland Sink Ability

A study of Nova Scotian wetlands examined 55 wetlands consisting of five kinds of wetland across the province during summer of 2017 (Gallant et al., 2020). One portion of the study was to determine the GHG flux from Nova Scotian wetlands and it was determined that the wetlands emit an average of 1.46 $tCO_2e/ha/y$ in the form of methane and capture 6.45 $tCO_2e/ha/y$ in the form of CO_2e, resulting in an average net capture of 4.99 $tCO_2e/ha/y$ (Gallant et al., 2020). For this report, the net capture rate is assumed to be the same as the baseline year. With this assumption, the net capture rate along with the area of wetlands were used to calculate the net carbon capture ability of Nova Scotia’s wetlands. The province’s wetlands were calculated to be a sink of approximately 1.91 $MtCO_2e/y$ (Bush & Baldo, 2019; Gallant et al., 2020) for the baseline year.

3.3.2 Threats and Vulnerabilities

Given how climate change will affect the CO_2 and CH_4 fluxes in wetlands in certain climate change scenarios for Australia (ADSEWPC & WWT, 2012), we believe the most significant threat to the ability of the province’s wetlands to absorb carbon is climate change. According to the Australian Department of Sustainability, Environment, Water, Population, and Communities and the Wetlands and Waterbirds Taskforce (2012), these are potential changes to the GHG fluxes in wetlands:

- Warmer climates will accelerate the rate of production of carbon dioxide and methane from wetland soils, but may also increase primary production.

> - Wetter climates will increase wetland surface areas and promote carbon sequestration and increased primary production, but may increase methane emissions.
> - Drier climates will increase the oxidation of carbon stores but reduce methane emissions. (p. 8)

Dry and wet environments could be created by droughts and floods, respectively, potentially resulting in changes to the GHG flux of Nova Scotian wetlands (ADSEWPC & WWT, 2012). Before any solution is chosen to counter the effects of increased wetness or dryness, an assessment of the GHG fluxes from a wetland in its original state should be made along with an estimate of the GHG fluxes with the solutions applied. If a solution will have lower net emissions or be a greater net sink than the original state, then the solution should be applied. An example of a solution to counter the effects of wetland soil drainage (which may result from excessive dryness) would be to rewet the soil of the wetland (NASEM, 2019). A potential solution to counter the effects of wet environments on wetlands would be to drain the excess water, though the ecological effects of such an action requires further research. Some threats to coastal wetlands are coastal erosion (Climate Change Unit, n.d.-d) and "sea-level rise, where inundation will threaten the survival of the largely intertidal wetland plants" (ADSEWPC & WWT, 2012, p. 8). To control the erosion of coastal wetlands, sediments can be added to a region (NASEM, 2019). According to ADSEWPC & WWT (2012):

> If continued input of suspended sediment from rivers is sufficient for sediment accretion to keep pace with a steadily rising sea-level, then carbon dioxide emissions could decrease as the tidally-flooded coastal areas increase in area and plant population size and existing inundated carbon pools are buried even deeper – provided that such landward movement of intertidal areas is not prevented by coastal squeeze such as the presence of hard sea-defences and other infrastructure. (p. 8)

Management practices should be developed and adopted to allow coastal wetlands to move inland with rising sea levels and to maintain the sink. A potential technological solution to impacts of rising sea levels is to use control gates to maintain the current tides into the future; however, this should be considered a last resort (Sadat-Noori et al., 2021).

We believe that the greatest vulnerability of the wetlands carbon sink is that its GHG fluxes are influenced by its climate (ADSEWPC & WWT, 2012). This means that unless climate change is reversed, there are a couple measures that could be taken to reduce the impacts on the sink that are described in ADSEWPC & WWT (2012). These measures are to estimate the GHG fluxes under the new climate and attempt to modify the environment where necessary and possible (as described in the previous paragraph). The vulnerability of coastal wetlands is their location – they are susceptible to both coastal erosion (Climate Change Unit, n.d.-d) and flooding from rising sea levels (ADSEWPC & WWT, 2012). The potential solutions for both issues are discussed in the previous paragraph.

The likelihood of droughts which may cause wetlands to dry was already discussed in the Nova Scotia’s Forests subsection of this report. As noted in the Nova Scotia’s Croplands subsection of this report, there is more annual precipitation expected in Nova Scotia’s future (Climate Change Unit, n.d.-b) which means that the province’s wetlands could experience the GHG flux changes associated with a wet environment as described in ADSEWPC & WWT (2012). The likelihood of sea level rise is considered by the IPCC to be virtually certain (IPCC, 2021). The likelihood of coastal erosion continuing in the future is certain since it is considered an inevitable process (Tsoukala et al., 2015).

3.4 Nova Scotia’s Geological Sequestration Sites

While geological sequestration sites do not capture carbon on their own (NASEM, 2019) and as such, are not technically sinks (United Nations Climate Change, n.d.-a), it is important to discuss them as they make up Nova Scotia’s “natural” carbon storage capacity for artificially captured carbon (NASEM, 2019). Nova Scotia has the potential to be an important location for CO_2 sequestration given the number of offshore sedimentary basins in the region, which have excellent potential for carbon sequestration (G. Wach, personal communication, June 23, 2021).

While work is being done to determine an estimate for the CO_2 sequestration potential in and around Nova Scotia (G. Wach, personal communication, July 5, 2021), an estimate can be made for some potential sites that are known, namely the depleted offshore oil and gas fields (G. Wach, personal communication, July 5, 2021). For example, the volumes of oil or gas that were extracted from the Sable Offshore Energy Project, the Deep Panuke Offshore Gas Development Project, and the Cohasset-Panuke Project are 60 billion m^3 (CNSOPB, n.d.-c), approximately 4.2 billion m^3 (CNSOPB, n.d.-b), and 7.1 million m^3 (CNSOPB, n.d.-a), respectively. Assuming that the volume that can be injected into the depleted reservoirs is equivalent to the volume that was extracted, that the density of supercritical CO_2 being injected into the reservoirs is 600 kg/m^3, and that the reservoirs can retain supercritical CO_2 (NASEM, 2019), the potential CO_2 storage capacity of Nova Scotia’s depleted offshore oil/gas fields is approximately 38.5 $GtCO_2$. Given that Canada’s total anthropogenic GHG emissions were 730 $MtCO_2e$ in 2019 (ECCC, 2021a), this is a huge storage potential. This potential storage capacity could hold about 53 years’ worth of Canada’s 2019 anthropogenic GHG emissions.

3.5 Summary of Nova Scotia's Carbon Sinks

Nova Scotia has significant natural carbon sinks and a huge storage potential for captured CO_2. While other sinks do exist, such as carbon mineralization and seagrasses (NASEM, 2019), they were not the focus of this report. Research to quantify these other sinks could be used to enhance the accuracy of the pathways that will be provided in this. Of the three sinks examined, Nova Scotia's forests were found to be the largest sink by far, followed by the province's wetlands. Nova Scotia's croplands were estimated to be a source rather than a sink, though not a significant one in comparison to other emissions sources. Table 1 provides a summary of the 2019 baseline for Nova Scotia's carbon sinks.

Table 1: Nova Scotia's carbon sinks baseline summary

Carbon Storage/Sinks	Carbon Storage/Sink Potential
Forests	9.701 $MtCO_2$/y absorbed
Cropland	0.145 $MtCO_2e$/y released
Wetlands	1.911 $MtCO_2e$/y absorbed
Carbon Storage	38.505 $GtCO_2$ storage capacity

The vulnerabilities, threats, and likelihoods of those threats are important to present so that they are taken into consideration when examining the net-zero pathways. They show how the strengths of the sinks may not arrive at the projected values so that policymakers understand the risks with attempting to follow one of the provided pathways. It is important that the quantities provided in Table 1 are kept up-to-date and accurate so that progress can be measured and goals can be adjusted accordingly.

4 Pathways to Net-zero by 2050

The pathways to net-zero by 2050 will each have a different trend in the sink strengths that will be used to determine the maximum anthropogenic emissions in 2030 and 2050 to meet the targets of those years. These targets are outlined in *An Act to Achieve Environmental Goals and Sustainable Prosperity* (Government of Nova Scotia, 2019). The Act states that Nova Scotia's GHG emissions should be reduced by at least 53% of 2005 levels by 2030 (Government of Nova Scotia, 2019) (emissions at approximately 10.9 $MtCO_2e$ (ECCC, 2021b)) and the net emissions by 2050 should be zero (Government of Nova Scotia, 2019).

The carbon sink baseline established in the previous section will be the starting point from which the trends in the sink strengths will be applied. The baseline year anthropogenic emissions can be used as a reference to compare the maximum anthropogenic emissions found. In the emissions projections figures, the anthropogenic emissions in 2050 are the maximum allowable anthropogenic emissions. The baseline year anthropogenic emissions is the same for all pathways and is provided in the 2019 GHG emission summary of the EN_GHG_IPCC_NS spreadsheet (total emissions of about 16.2 $MtCO_2e$) in ECCC (2021b). Figure 1**Error! Reference source not found.** details the 2019 GHG emissions based on sector, using the data provided in ECCC (2021b).

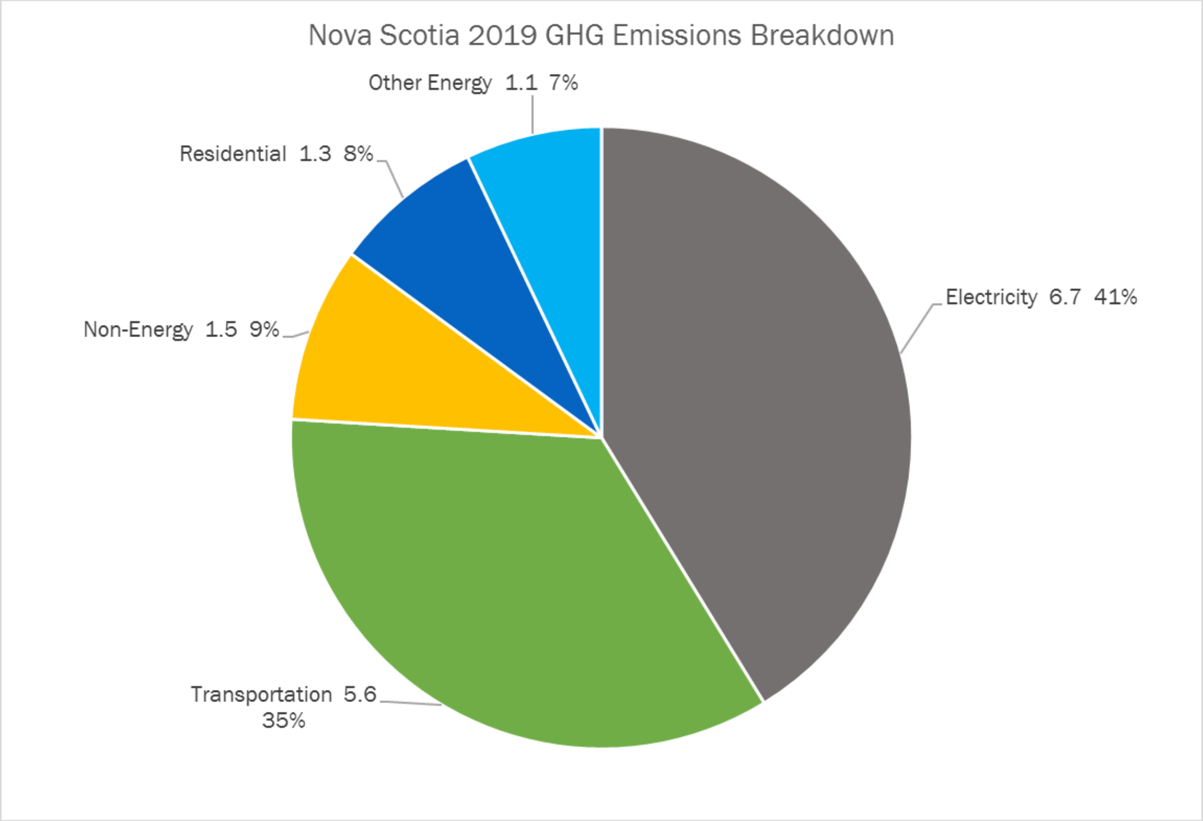

Figure 1: Nova Scotia 2019 GHG emissions breakdown. All units are in MtCO2e. Data from ECCC (2021b).

The emissions resulting from Land-Use, Land-Use Change, and Forestry (LULUCF) are only included in the estimate for the GHG flux for the province's croplands. The three trends for sink strengths involved in the pathways are: the strength of the sinks remain steady at their baseline strength; the strength of the sinks increases by a certain amount each decade; and the strength of the sinks decreases by a certain amount each decade. This section will also discuss the potential cost of direct air capture. It is important to note that these pathways could be disturbed by an unexpected, high-impact event at any point (such as the Covid-19 Pandemic), potentially resulting in changes to net annual emissions that are far from the projected values. The first pathway that will be examined is the steady-sinks pathway.

4.1 Pathway 1: Steady Sinks

In this pathway, the forests and wetlands remain constant as sinks, and croplands remain constant as a source. The steady-sinks pathway would be a difficult pathway to maintain, especially given all the threats to and vulnerabilities of the sinks. Figure 2 shows the emissions projections for the steady-sinks pathway and the associated data.

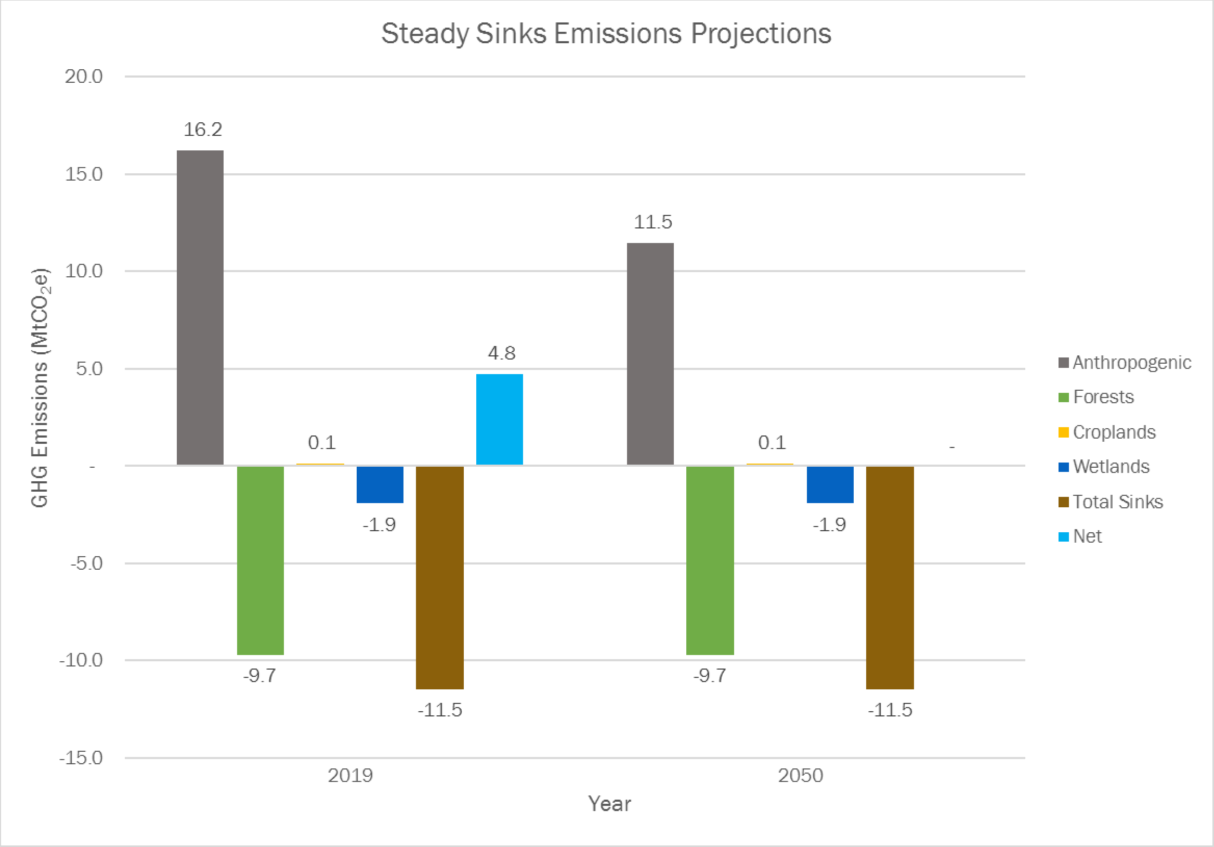

Figure 2: Emissions projections for the steady-sinks pathway.

At the baseline year of 2019, the net emissions are approximately 4.8 MtCO$_2$e after summing the anthropogenic emissions with the total GHG fluxes of the sinks. By 2050, emissions reductions will have to take place to meet the 2050 goal of net-zero emissions. The maximum anthropogenic emissions in 2050 is about 11.5 MtCO$_2$e, a reduction of roughly 29% from

2019. Even this value is higher than what emissions should be reduced to in the 2030 target without sinks. An emissions reduction of about 4.8 $MtCO_2e$ is possible given the scenarios outlined in Hughes & McCoy (2021).

4.2 Pathway 2: Increasing Sinks

In this pathway, the strengths of the sinks increase to 2050. The assumption for the forest sink is that the change in the CO_2 flux of the forest sink between the 2008-2012 and the 2013-2017 intervals is constant (i.e., each five-year interval has the same change in CO_2 flux). In the case of Nova Scotia's croplands, the following assumptions are made: improved cropland practices (cover crops, no tilling, and improved rotations) are fully implemented by 2050 and are implemented at one third of the total value each decade; the change in soil organic carbon resulting from each practice (0.36 t C/ha/y for cover crops in the US, 0.14-0.18 t C/ha/y for improved rotations in the US, and 0.33 t C/ha/y for no tilling in the US) is the same in Nova Scotia as it is in the US (NASEM, 2019); the cropland area of Nova Scotia does not change; and the maximum value for carbon sequestration of improved rotations is used. The increase in soil organic carbon is converted to CO_2 sequestered when calculating the CO_2 flux for the decades. The assumptions made for the wetlands sink are that the net carbon sequestration rate presented by Gallant et al. (2020) remains constant and that wetlands are restored such that the sink increases by 4% of the baseline value every decade. The increasing sinks pathway would be the most difficult pathway to achieve because the impact of the threats to and vulnerabilities of the biological sinks would have to be reduced while also increasing the carbon captured in them.

Figure 3 shows the emissions projections for the increasing sinks pathway and the associated data.

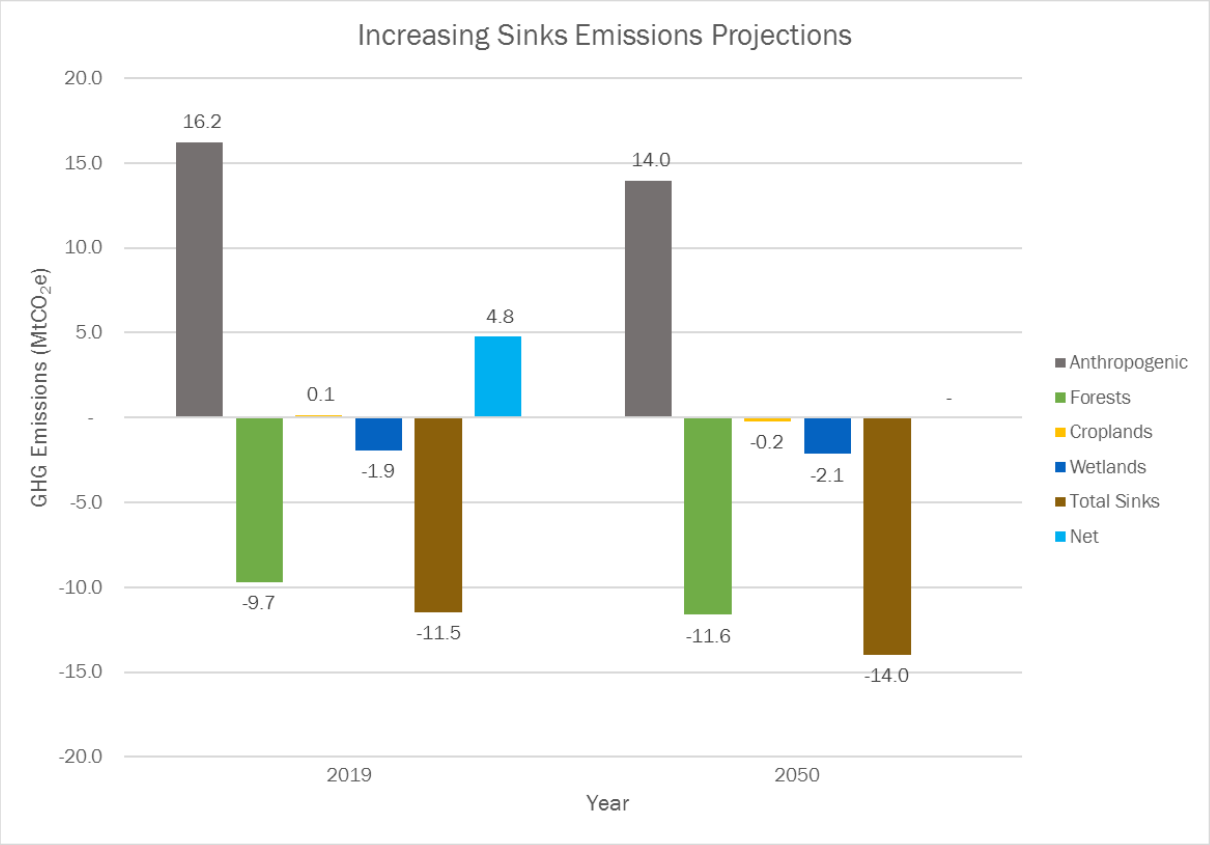

Figure 3: Emissions projections for the increasing sinks pathway.

By 2050, few emissions reductions will have to take place to meet the 2050 goal of net-zero emissions. The maximum anthropogenic emissions in 2050 is about 14.0 MtCO$_2$e, a reduction of nearly 14% from 2019. This value is significantly higher than what emissions should be reduced to in the 2030 target without sinks. An emissions reduction of about 2.3 MtCO$_2$e is highly likely given the scenarios outlined in Hughes & McCoy (2021). The main issue with making this scenario possible is ensuring that the sinks' strengths increase while their threats potentially reduce their strengths.

4.3 Pathway 3: Decreasing Sinks

In this pathway, the sinks decrease in strength by a certain amount. The decreasing sinks pathway may be considered a more plausible pathway than Pathways 1 and 2. Should the sink strengths decrease, the degree to which they decreases may be hard to predict; this report will assume how much they decrease by. This pathway assumes that the strengths of the sinks decrease by 10% of the baseline value each decade regardless of human intervention. For forests and wetlands, this means that the magnitudes of negative emissions decrease by 10% of their baseline values each decade. For croplands, this means that the positive emissions increase by 10% of the baseline value each decade. Figure 4 shows the emissions projections for the decreasing sinks pathway and the associated data.

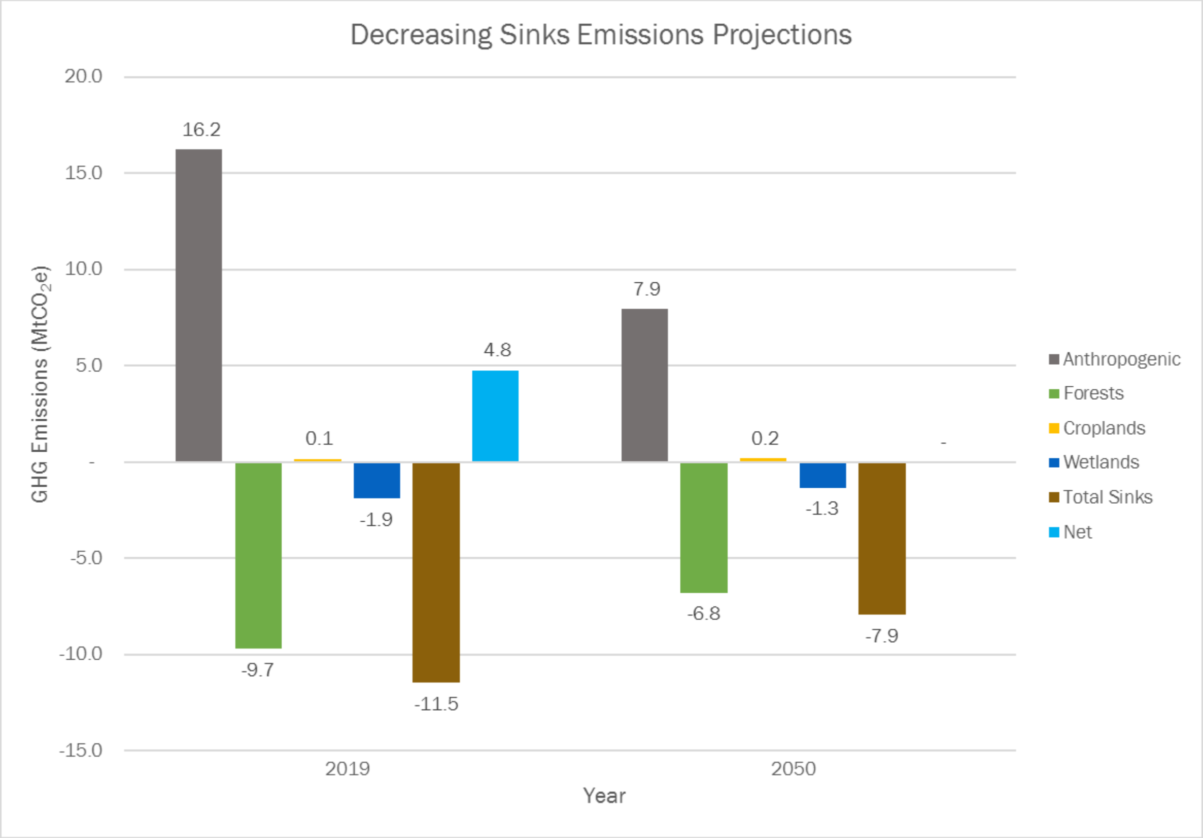

Figure 4: Emissions projections for the decreasing sinks pathway.

Unlike the other pathways, significant reductions must take place to achieve net-zero emissions by 2050. The maximum anthropogenic emissions in 2050 is about 7.9 $MtCO_2e$, a reduction of about 51% from 2019. An emissions reduction of about 8.2 $MtCO_2e$ may be possible if the necessary effort and policy is implemented.

4.4 Summary

All pathways require some level of anthropogenic emissions reduction to achieve the 2050 emissions target when including sinks in the total emissions. The anthropogenic emissions reductions for the various pathways range from a 14% to 51% reduction from 2019 emissions and the projected total GHG flux of all sinks in 2050 ranges from approximately -7.9 $MtCO_2e$ to -14.0 $MtCO_2e$. Table 2 details key information from the net-zero emissions pathways. The projected total GHG flux of all carbon sinks in 2050 is always equal to the maximum anthropogenic emissions in 2050 in order for net-zero to be achieved. Values in Table 2 may not align with data presented in the emissions projections graphs due to rounding.

Table 2: Key results from the net-zero emissions pathways.

Pathway	Projected Total GHG Flux of All Sinks in 2050 ($MtCO_2e$)	Max Anthropogenic Emissions for 2050 Target ($MtCO_2e$)	2019 to 2050 Decrease in Anthropogenic Emissions
Steady Sinks	-11.5	11.5	-29% (-4.8 $MtCO_2e$)
Increasing Sinks	-14.0	14.0	-14% (-2.3 $MtCO_2e$)
Decreasing Sinks	-7.9	7.9	-51% (-8.3 $MtCO_2e$)

The purpose of this report is not to determine how these reductions are made; it is to simply state them. For information on determining how reductions might be made for 2030 when sinks are not included, see Hughes & McCoy (2021). The ideas for how reductions might be made for 2030 in Hughes & McCoy (2021) gives some ideas for how to approach reducing emissions to 2050. As Figure 1 shows, the two highest emitting sectors which collectively constitute roughly 76% of the province's emissions in 2019 are electricity and transportation (ECCC, 2021b).

Reducing the emissions in these two sectors (ECCC, 2021b) will be critical to achieving the emissions reduction for the 2050 target. Both maintaining and increasing sinks could be a major problem given all the vulnerabilities of sinks and the threats they face, such as the threats of fires and pests to the forests (McCurdy & Stewart, 2003). Preventing sinks from decreasing in strength any further than the assumptions made for the decreasing sinks pathway could also be difficult depending on the impacts of the threats to and vulnerabilities of the sinks. It is important to note that, for the decreasing sinks pathway, the maximum anthropogenic emissions will continue to decline past 2050 if the sink strengths decline as well. This means that efforts to reduce emissions should not be given up once 2050 is reached.

If Nova Scotia is unable to achieve the emissions reduction necessary to meet the 2050 emissions target, it will either have to purchase negative emissions from another jurisdiction (Hughes & McCoy, 2021) or construct direct air capture facilities. The cost of direct air capture ranges from 2019 values of roughly \$90-\$900 USD per net tonne of CO_2 captured (NASEM, 2019). It is assumed that the amount of CO_2 that is captured in a year by direct air capture can be geologically sequestered in that same year. For this report, it is assumed that these prices are both the cost of negative emissions (through purchasing or direct air capture) and the sale price of negative emissions. If the province needs to remove 1 $MtCO_2e$ of emissions to reach the maximum anthropogenic emissions, the cost would be approximately \$120 million to \$1.2 billion in 2019 CAD (exchange rate used from Bank of Canada (2020). Similarly, if the province was able to sell 1 $MtCO_2e$ of negative emissions, its revenue would be approximately \$120 million to \$1.2 billion in 2019 CAD (exchange rate used from Bank of Canada (2020). At the maximum cost of roughly \$900 2019 USD per net tonne of CO_2 captured (NASEM, 2019), the cost or revenue could be significant, especially if there is more than 1 $MtCO_2e$ that needs to be removed or can be sold. Work should be done to maintain and increase the biological sinks while also reducing anthropogenic emissions so that negative emissions can be sold, providing another revenue stream to the province.

5 Conclusion and Recommendations

This report provides an estimated baseline of Nova Scotia’s natural carbon sinks and its geological sequestration capacity, showing that Nova Scotia has significant carbon sinks and geological capacity in relation to its annual greenhouse gas (GHG) emissions. Included in this baseline were the carbon capture ability of the sinks, the province’s carbon storage capacity, the potential threats to the natural sinks, vulnerabilities of the natural sinks, and potential solutions to reduce the impact of the threats and vulnerabilities. A background was provided to the natural sinks (forests, croplands, and wetlands), direct air capture, and carbon sequestration in geological formations to allow for a better understanding of their concepts and carbon capture and sequestration potential.

Alternative sinks were provided to show the opportunity for further research. With the baseline established, three different trends (i.e., steady, increasing, and decreasing) were applied to the sinks in focus to determine the maximum allowable anthropogenic emissions to meet the 2030 and 2050 climate targets outlined in *An Act to Achieve Environmental Goals and Sustainable Prosperity* (Government of Nova Scotia, 2019) with the assumption that the remaining emissions after the 2030 reductions take place are net emissions rather than just anthropogenic emissions. The results for all trends indicate that anthropogenic emissions can increase from 2019 levels by about 31-43% and still meet the 2030 net emissions target. The results for the steady sinks, increasing sinks, and decreasing sinks pathways indicate that emissions will need to reduce by about 29%, 14%, and 51% from 2019 levels, respectively, to meet the 2050 net emissions target. The ranges of costs associated with purchasing negative emissions through direct air capture or credits when the province's anthropogenic emissions are 1 $MtCO_2e$ over the maximum allowable anthropogenic emissions were presented. The ranges of revenues associated with selling negative emissions credits when the province's anthropogenic emissions are 1 $MtCO_2e$ under the maximum allowable anthropogenic emissions were also presented. The magnitude of both the cost and revenue ranges were found to be about $120 million to $1.2 billion in 2019 CAD. From the results of this research and analysis, a series of recommendations have been developed and are presented below.

1. *Conduct a complete and accurate assessment of the annual greenhouse gas (GHG) fluxes of Nova Scotia's biological sinks (such as forests, croplands, wetlands, and seagrass meadows) every two years.*
   - This assessment should be released as an inventory report available to the public.
   - Each sink should be mapped and have their GHG flux displayed in a publicly available map. The associated data tables should be released alongside the map. This will provide a visualization to areas that need work.
   - The following information should be determined: locations of sink; area of sink; annual GHG flux of sink; and maximum annual GHG flux of sink. These can provide better estimates of the maximum anthropogenic emissions for the 2030 and 2050 targets. The data must be verifiable.
   - Trends in the strength of the biological sinks should be monitored and appropriate action should be taken if the strengths decrease. Threats that might decrease sink strength and potential solutions to those threats are discussed in section 3 of this report.
2. *Quantify the carbon-related impacts of the threats to Nova Scotia's biological sinks and conduct an economic and carbon flux assessment of the potential solutions to reducing the threats and vulnerabilities of the sinks.*
   - The potential impact on the carbon flux of any of the biological sinks as a result of their threats should be quantified.
   - Research should be conducted into potential solutions (including those presented in this report) to the threats and vulnerabilities.

- Potential solutions to reduce the impact of threats and vulnerabilities of biological sinks should be evaluated for economic feasibility and changes in carbon flux from implementation.

3. *A 2040 emissions reduction target should be established between 53% and 100% emissions reduction.*
   - Establishing a target between the 2030 and 2050 targets will allow for a closer milestone to achieve when 2030 is reached, creating a greater sense of urgency.
   - The target can provide a reference to measure progress in emissions reductions.
4. *Efforts should continually be made to reduce emissions beyond 2050.*
   - According to the IPCC (2018), net negative global anthropogenic CO_2 emissions may need to be maintained in the long term to prevent increases in temperature.
   - Reducing emissions so that net negative emissions are achieved allows environmental security if the sinks decrease in strength.
   - Maintaining net negative emissions allows for a potential revenue stream to the province and helps other jurisdictions reach their climate targets.
5. *Introduce a tax incentive for carbon captured in natural sinks to promote the maintenance of or efforts to increase their carbon capture ability.*
   - Nova Scotia or the Government of Canada should provide a tax incentive to managers of forests, croplands, wetlands, and seagrasses on a per verified tonne of carbon captured basis. This incentive should be less than the annual cost range for DAC; otherwise, it might be more financially reasonable to spend the government funds on DAC.
   - This will motivate land managers to manage their lands in a way to maintain carbon capture levels or to increase them.
   - The incentive could provide funding to land managers to implement the practices that preserve or improve carbon capture.
6. *If the purchase of negative emissions is necessary, it must be sustainable.*
   - Nova Scotia should not save up money to 2050 to pay for negative emissions to reach net-zero for only the year of 2050.
   - If the entirety of the remaining emissions is not economically feasible to be reduced by negative emissions purchases, then the negative emissions that are

economically feasible to purchase must be purchased annually and in perpetuity. This will reduce the remaining emissions that need to be removed to reach net-zero by 2050.

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