Parks Canada / Parcs Canada

Canada

Parks Canada Carbon Atlas Series

Carbon Dynamics in the Forests of National Parks in Canada

Catalogue No.: R62-581/2023E-PDF

ISBN 978-0-660-42419-4

For more information, contact Parks Canada at changementclimatique-climatechange@pc.gc.ca.

Office of the Chief Ecosystem Scientist
Protected Areas Establishment and Conservation Directorate
Parks Canada
30 Victoria St., 3rd floor
Gatineau, Quebec
J8X 2A1

Cover images:

Top left: Kat Trivers / ©Parks Canada / Banff National Park

Top right: Éric Le Bel / ©Parks Canada / Kejimkujik National Park and National Historic Site

Bottom: J.F. Bergeron / ENVIROFOTO

Back cover: Karen Best / ©Parks Canada / Mount Revelstoke National Park

Aussi disponible en français sous le titre : Série de l'Atlas du carbone de Parcs Canada : Dynamique du carbone dans les forêts des parcs nationaux du Canada.

Suggested citation:

Sharma, T., Kurz, W.A., Fellows, M., MacDonald, A.L., Richards, J., Chisholm, C., Seutin, G., Richardson, K., Keenleyside, K. (2023). Parks Canada Carbon Atlas Series: Carbon Dynamics in the Forests of National Parks in Canada. Scientific Report. Parks Canada Agency, Gatineau, QC, Canada,104 pp.

Forest Carbon Atlas Team:

Parks Canada
Tara Sharma
Alexander MacDonald
Jennifer Richards
Chelsea Chisholm
Karen Richardson
Gilles Seutin
Karen Keenleyside
Anna Lee-Carswell
Scott Parker

Canadian Forest Service
Werner Kurz
Max Fellows

Contents

List of Tables

List of figures

List of Acronyms

Acronym	Description
AG	Aboveground
BG	Belowground
BIOME-BGC	Biome BioGeochemical Cycle
C	Carbon
CFS	Canadian Forest Service
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DM	Disturbance matrices
DOM	Dead organic matter
FLINT	Full Lands Integration Tool
FORCARB	United States FORest CARBon Budget Model
GCBM	Generic Carbon Budget Model (or the Model)
GHG	Greenhouse Gas
GIS	Geographic information system
GWP	Global Warming Potential
ha	Hectare
HS	Heritage Site
IPCC	Intergovernmental Panel on Climate Change
Mha	Million hectares
Mt C	Megatonne carbon
Mg ha^{-1}	Megagrams per hectare (=tonnes per ha)
Mg ha^{-1} yr^{-1}	Megagrams per hectare per year
Mt C yr^{-1}	Megatonne carbon per year
N_2O	Nitrous oxide
NBP	Net Biome Production
NEP	Net Ecosystem Production

Acronym	Description
NFCMARS	National Forest C Monitoring Accounting and Reporting System
NHS	National Historic Site
NIR	National Inventory Report
NMP	National Marine Park
NP	National Park
NPP	Net Primary Production
NPS	National Park Seaside
NPR	National Park Reserve
NUP	National Urban Park
PC	Parks Canada
PCF	Pan-Canadian Framework on Clean Growth and Climate Change
PF	Prescribed fire
R_h	Heterotrophic respiration
t	Metric tonne = Mg
$t\ C\ ha^{-1}\ yr^{-1}$	Tonnes carbon per hectare per year
UNFCCC	United Nations Framework Convention on Climate Change
yr	year

Photo: C. Cheadle / ©Parks Canada / Gwaii Haanas National Park Reserve and Haida Heritage Site

Executive Summary

The Parks Canada Carbon Atlas Series is the first comprehensive analysis of the amount, distribution and dynamics of natural carbon in Canada's national parks[1]. The objective of the series is to estimate and map the amount of carbon stored, sequestered, and emitted by all ecosystems in national parks. *Carbon Dynamics in the Forests of National Parks in Canada* is the first volume in the series and assesses forested ecosystems. It was prepared in collaboration with the Canadian Forest Service of Natural Resources Canada. Subsequent volumes will assess the carbon dynamics of other major ecosystems.

The national park system in Canada protects outstanding representative examples of the country's distinct natural regions, and the natural processes that help to define them. In addition to protecting biodiversity, maintaining ecological integrity and providing clean water, air and soil, among other ecosystem services, national parks and other protected areas also sequester atmospheric carbon dioxide (CO_2) and store it in trees, other plants, dead organic matter, and soils. In this manner, ecosystems accumulate carbon over time as they remove CO_2, the primary greenhouse gas (GHG) resulting from human activities, from the atmosphere and store carbon in different carbon pools such as living above- and belowground biomass and in dead organic matter, including soils. At the same time, some of this carbon is emitted slowly back into the atmosphere through decomposition of organic matter. Wildfires and other natural disturbances such as insect outbreaks, can also cause rapid emissions of CO_2 and more potent GHGs such

1 For convenience, the term "parks" or "national parks" is used in this report when referring to sites collectively. When the reference is to an individual site, the appropriate designation is used, i.e. (National Park (NP), NP Reserve (NPR), National Marine Park (NMP)).

as methane (CH_4) and nitrous oxide (N_2O) to the atmosphere. Ecosystems are considered a net carbon sink when they sequester more carbon than they emit, and a carbon source when they emit more carbon than they sequester from the atmosphere in a given time period. The ability of ecosystems to regulate climate by sequestering and storing carbon is an important ecosystem service and an essential element of the global carbon cycle. National parks and other protected areas are important milieus in which to study and better understand natural ecosystem carbon dynamics and the role of conservation approaches as natural climate solutions.

This study focuses on the 31 national parks where forest cover represents more than 10% of the total park area. The carbon dynamics of the forested areas were assessed using the latest generation of the spatially-explicit Generic Carbon Budget Model (GCBM) developed by the Canadian Forest Service in collaboration with experts from Moja Global[2]. Carbon stocks in different carbon pools and carbon fluxes and transfers between pools, as well as GHG emissions and removals, were estimated at annual time steps for the period 1990-2020. Results were aggregated at the park level, ecozone level and combined for all 31 parks, and were reported in units of carbon (C) for total stocks (megatonnes or Mt), stock density (tonnes per ha = megagrams per hectare) as well as total fluxes (Mt) and flux density (tonnes per hectare per year), and in units of carbon dioxide equivalents (CO_2e) for GHG emissions to, and removal from the atmosphere.

Main Findings

Carbon Storage and Density

- The 5.6 million hectares of forested ecosystems in **31 national parks stored 1,452 ± 11 Mt C (average of 31 years)**, ranging from 1,431 Mt C in 1990 to 1,466 Mt C in 2002 and then decreasing to 1,438 Mt C in 2020, **with a net gain of around 6.8 Mt C over the 31 years.** Over 70% of stored carbon was in soil, dead wood, and litter pools, with soil being the largest carbon pool (38%).
- **Wood Buffalo National Park forests stored the most carbon (844 ± 11 Mt C)**, representing 58% of the total stored carbon in all national park forests studied. Wood Buffalo National Park (WBNP) is the largest national park in Canada, accounting for 58% of the total forested area in the 31 parks studied. Due to the large amount of area burned, WBNP lost 9.4 Mt C between 1990 and 2020.
- **The average carbon density for forested ecosystems within national parks was 258 ± 2 tonnes carbon/hectare (t C ha^{-1})**. At the ecozone scale, national park forests in the Pacific Maritime Ecozone had the highest carbon density (439 ± 5 t C ha^{-1}), due in part to the very low frequency of wildfires and the presence of old-growth forests. National park forests in the Mixedwood Plains Ecozone had the lowest average carbon density (158 ± 5 t C ha^{-1}). At the individual park level, Pacific Rim National Park Reserve forests had

2 More information on the Moja global organization is available at https://moja.global

the highest average carbon density (477 ± 4 t C ha^{-1}), while Bruce Peninsula National Park forests had the lowest density (150 ± 5 t C ha^{-1}). Gulf Islands National Park Reserve forests showed the greatest increase in carbon density over the study period (39 t C ha^{-1}), while Waterton Lakes National Park forests showed the greatest decrease (18 t C ha^{-1}).

Carbon Fluxes and Greenhouse Gas Emissions

- **The forested ecosystems of 28 national parks were net carbon sinks while those of three national parks** (Wood Buffalo NP, Waterton Lakes NP, and Elk Island NP representing 59% of the total forest area) **were net sources of greenhouse gases (GHG) over the 31-year period**.
  - **Pukaskwa National Park forests were the largest absolute sink of carbon**, removing 0.3 Mt CO_2e per year (1.85 t CO_2e ha^{-1} yr^{-1}) from the atmosphere.
  - **Gulf Islands National Park Reserve forests sequestered the most carbon per unit area** (4.74 t CO_2e ha^{-1} yr^{-1}).
  - **Wood Buffalo National Park forests were the largest absolute source of GHGs into the atmosphere**, emitting 2 Mt CO_2e per year (0.62 t CO_2e ha^{-1} yr^{-1}).
  - **Waterton Lakes National Park forests emitted more GHGs per unit area** (2.41 t CO_2e ha^{-1} yr^{-1}), surpassing even Wood Buffalo National Park on this measure.
- **Overall, forested ecosystems in the 31 national parks were a small carbon sink,** accumulating more carbon than they were releasing during the study period. National park forests showed a cumulative carbon gain of 6.8 Mt C and an average net carbon uptake of 0.22 ± 0.13 Mt C yr^{-1} over the 31-year study.
- **National park forests were overall a net source of greenhouse gas (GHG) emissions during the study period, driven by natural disturbances in just 3 parks**. Cumulatively, national park forests emitted a total of 6.25 Mt CO_2e, or 0.20 ± 0.52 Mt CO_2e yr^{-1} in GHGs. The counter-intuitive fact that parks were a small *sink* of carbon but also a *source* of greenhouse gases (measured in units of carbon dioxide equivalents, CO_2e) is because emissions resulting from decomposition and wildfire included non-CO_2 gases such as methane (CH_4) and nitrous oxide (N_2O) with much higher global warming potentials than CO_2.
- On the annual scale however, parks **were a net sink of GHG emissions in 21 of the 31 years studied and a net source in other years**. Increased natural disturbances (wildfires and insect outbreaks) in a few parks after 2002 resulted in increasing GHG emissions, with the largest emissions occurring in the period from 2012 to 2020, converting parks from a net sink in 1990-2002 to a large source during 2012-2020.
- **Large parks** (e.g., Wood Buffalo National Park**) and large disturbances in parks** (e.g., recent large fires in Wood Buffalo National Park and Waterton Lakes National Park) **dominated the carbon dynamics and GHG emissions balance** at the national level during the study period.

- **Wildfires and insect outbreaks in national park forests were the major factors causing GHG emissions, with wildfires contributing more than insect outbreaks**. Most emissions from wildfires were due to the consumption of dead organic matter (e.g., litter, dead wood) during wildfires.
- **Wildfires also resulted in large transfers from above- and belowground biomass carbon pools to dead organic matter pools.** This was particularly evident in large national parks that experienced large fires such as Wood Buffalo and Waterton Lakes national parks.
- Lastly, **forest age, structure, site characteristics, species composition, and natural disturbance regimes** accounted for most of the variability in carbon storage, removals, and emissions among parks and ecozones.

Potential Implications

This work provides the first estimates of carbon stocks, densities, and fluxes, and their spatial and temporal variability, for forested ecosystems in 31 of Canada's national parks. Notable variations in all measures within and between national parks and ecozones reinforce the importance of adopting a spatially and temporally explicit approach to investigate these characteristics.

Natural climate solutions are increasingly identified as important contributions to GHG emission reduction targets. In that context, protected areas and climate-smart natural resource management are proposed as mechanisms to sustain and enhance natural carbon sinks. This study shows that forests in 28 parks were carbon sinks between 1990 and 2020, while major wildfires and insect outbreaks caused three parks to be net sources. Changing climatic conditions across Canada are projected to increase the severity and frequency of these and other natural disturbances (e.g., extreme weather- or climate-related events), thereby further altering ecosystem carbon dynamics and causing more parks to become sources in some years.

Given the level of detail presented over space and time in this study, the findings can inform site-specific decisions regarding the conservation and restoration of ecosystems in national parks, as well as other management decisions (e.g., siting of new built assets and infrastructure).

The data and information obtained in this and similar studies will help inform ongoing discussions about national carbon inventories, and the systems needed to support monitoring, accounting and reporting of greenhouse gas emissions and removals under various platforms and protocols, including the United Nations Framework Convention on Climate Change (UNFCCC).

Photo: Scott Munn / ©Parks Canada / Gulf Islands National Park Reserve

Chapter 1: Introduction

The Parks Canada Carbon Atlas[3] Series is the first comprehensive analysis of the amount, distribution, and dynamics of natural carbon in Canada's national parks[4]. The objective of the series is to estimate and map the amount of carbon (C) stored, sequestered, and emitted by the major ecosystem types found in Canada's national parks. In addition to providing insight into the role of national park ecosystems in carbon dynamics, this series will provide a comparison of the carbon dynamics between parks and terrestrial ecosystems across Canada. *Carbon Dynamics in the Forests of National Parks in Canada* is the first in the series and assesses forested ecosystems. It was prepared in collaboration with the Canadian Forest Service of Natural Resources Canada. Subsequent volumes will assess the carbon dynamics of other major ecosystems in national parks.

3 The "Atlas" comprises of the digital database and maps of the carbon stocks and GHG emissions which are available on the Government of Canada Open Data portal along with this report.

4 For convenience, the term "parks" or "national parks" is used in this report when referring to sites studied in this report collectively. When the reference is to an individual site, the appropriate designation is used (National Park (NP), NP Reserve (NPR), National Marine Park (NMP)).

Parks Canada Agency

The mandate of the Parks Canada Agency is to protect and present nationally significant examples of Canada's natural and cultural heritage, and foster public understanding, appreciation and enjoyment of those examples in ways that ensure their ecological and commemorative integrity for present and future generations.

The Agency is one of the largest federal Crown land managers, protecting (as of 2020) more than 450,000 km^2 of lands and waters in 47 national parks, five national marine conservation areas that protect marine ecosystems, one national urban park, and 171 national historic sites, including nine historic canals. Parks Canada's network of protected places represents a diversity of natural regions and landscapes, with national parks located in 31 of the 39 terrestrial regions in Canada.

Canada's national park system protects outstanding representative examples of the country's distinct natural regions including forested, grassland, tundra, peatland, wetland, freshwater, coastal and marine ecosystems. In addition to protecting biodiversity, maintaining ecological integrity and providing clean water, air and soil, national park ecosystems also sequester atmospheric carbon dioxide (CO_2) and store it in trees, other plants, dead organic matter, and soils. At the same time, some carbon is emitted slowly back into the atmosphere through decomposition of organic matter. In addition, wildfires and other natural disturbances such as insect outbreaks, cause rapid emissions of CO_2 and more potent GHGs such as methane (CH_4) and nitrous oxide (N_2O) to the atmosphere.

Ecosystems are considered a net carbon sink when they sequester more carbon than they emit, and a carbon source when they emit more carbon than they sequester from the atmosphere in a given time period. The ability of ecosystems to regulate climate by sequestering and storing carbon is an important ecosystem service and an essential component of the global carbon cycle. Understanding the carbon dynamics of different ecosystems and the drivers that impact these dynamics is essential for assessing the carbon balance (carbon sinks and sources) of a given area and over time.

For terrestrial ecosystems, when carbon is sequestered from the atmosphere, it is stored in different carbon pools. There are five main terrestrial carbon pools: aboveground and belowground biomass (which together make up the biomass pool); litter and dead wood (also called the dead organic matter (DOM) pool); and, the soil organic matter (Table 1) (IPCC, 2006).

Table 1. Description of five ecosystem carbon[5] pools defined by the IPCC.

Pool		Description
Biomass	Aboveground biomass	Includes all the living plants and woody forms above the soil (i.e., trees, shrubs, herbs, stems, stumps, branches, and foliage).
	Belowground biomass	Comprises all biomass of live roots.
Dead Organic Matter (DOM)	Litter	Includes all non-living biomass with a diameter greater than the limit for soil organic matter (i.e., 2 mm) and less than the minimum diameter chosen for dead wood (i.e., 10 cm) in various states of decomposition above or within the mineral or organic soil (e.g., detritus of leaves, fruits, flowers, twigs or small branches).
	Dead wood	Comprises all woody debris not included in the litter pool and includes all the dead wood on the forest surface, standing dead trees, stumps, dead logs, coarse woody debris and dead roots that have a diameter larger than or equal to 10 cm.
Soils	Soil organic matter	Includes all organic carbon in mineral soils at the depth of the soil profile limit chosen by country according to their national specifications. Live and dead fine roots with diameters less than the limit for belowground biomass (i.e., 2 mm) can be included when they cannot be distinguished empirically.

Source: Derived from the IPCC guidelines for GHG inventories (IPCC, 2006).

Carbon stored in these different pools is referred to as carbon stocks, defined as the quantity of carbon in a pool, usually measured in megagrams (or tonnes), and also sometimes reported as carbon density measured as megagrams per hectare (Mg ha^{-1}) or tonnes per hectare (t/ha). Carbon is transferred between pools through natural processes, such as litter fall, and from a pool to the atmosphere through decomposition and disturbances (e.g., wildfires). These transfers are called carbon fluxes. Fluxes are usually measured in megagrams per hectare per year (Mg ha^{-1} yr^{-1}), and the sum of all carbon fluxes must equal any changes in carbon stocks over the same time period[6].

5 “Ecosystem carbon” refers to carbon in the forest ecosystem in this report, unless specified otherwise.

6 While this statement is true with respect to carbon, including the carbon contained in CO_2 gas, total GHG emissions are measured in units of CO_2 equivalency and include quantities of CH_4 and N_2O, which have much higher Global Warming Potentials than CO_2 (see section 2.4 below). For this reason, total GHG emissions can exceed the available carbon stocks in an ecosystem.

Different ecosystems store different amounts of carbon in different pools, per unit of area. For example, coastal rainforests store the majority of their carbon in aboveground biomass (e.g., trees, shrubs and other plants), whereas peatlands store the majority of their carbon in deep layers of organic soil (Figure 1).

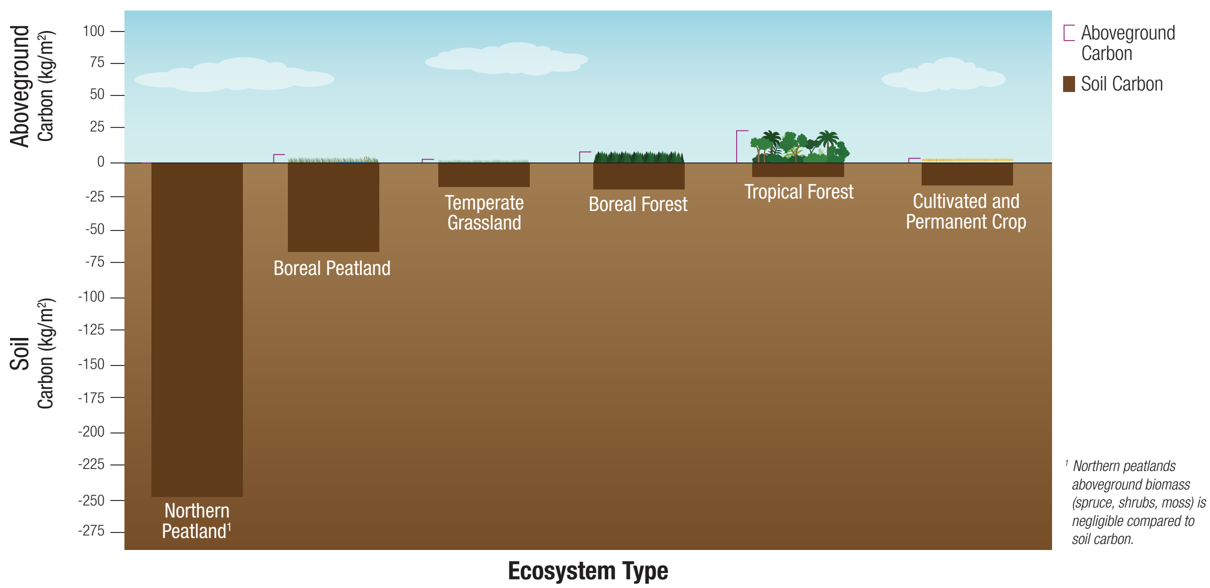


Figure 1. **Aboveground biomass carbon relative to soil carbon, by ecosystem type.** Carbon in each pool is represented using carbon density (kg m^{-2}). Source: Tarnocai et al., 2009 (Northern Peatland); Beaulne et al., 2021 (Boreal Peatland); Bremer et al., 2008 (Temperate Grassland); Stinson et al., 2011 (Boreal Forest); Amthor et al., 1998 (Tropical Forest and Cultivated and Permanent Crop).

Canada compiles and submits national inventories of sources and sinks of greenhouse gases annually to the United Nations Framework Convention on Climate Change (UNFCCC). These National Inventory Reports (NIR) include the carbon balance, as net carbon sequestered or emitted for a given area, for both managed forests and agricultural lands following methods and guidelines of the Intergovernmental Panel on Climate Change (e.g. IPCC, 2003; IPCC, 2006). For the purpose of UNFCCC reporting, "managed forests" are a subset of Canada's forests under direct human influence, which include forests managed for harvesting, forests subject to fire management or management of insect damage, and some protected forests, like those found in national and provincial parks, although this varies by province and territory (Figure 2). Other natural areas, including unmanaged forests, are not included in this reporting even though they play an important role in Canada's carbon balance and ultimately in regulating local to global climatic conditions. Since national parks across Canada fall into both the "managed" and "unmanaged" forest areas for reporting purposes, depending on their location, no systematic estimation of national park carbon dynamics exists. This study seeks to fill this gap.

The Carbon Atlas Series is a contribution to Canada's evolving carbon and climate research agenda (e.g., ECCC, 2020). In addition to providing scientific data and maps to help researchers, managers and others understand and visualise carbon stocks and dynamics in national parks across the country, it will help inform climate change actions that are outlined in the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) and Canada's 2020 Strengthened Climate Plan. The PCF acknowledges the carbon storage potential of ecosystems and includes actions for increasing stored carbon by protecting and enhancing carbon sinks in forests, wetlands, and other ecosystems.

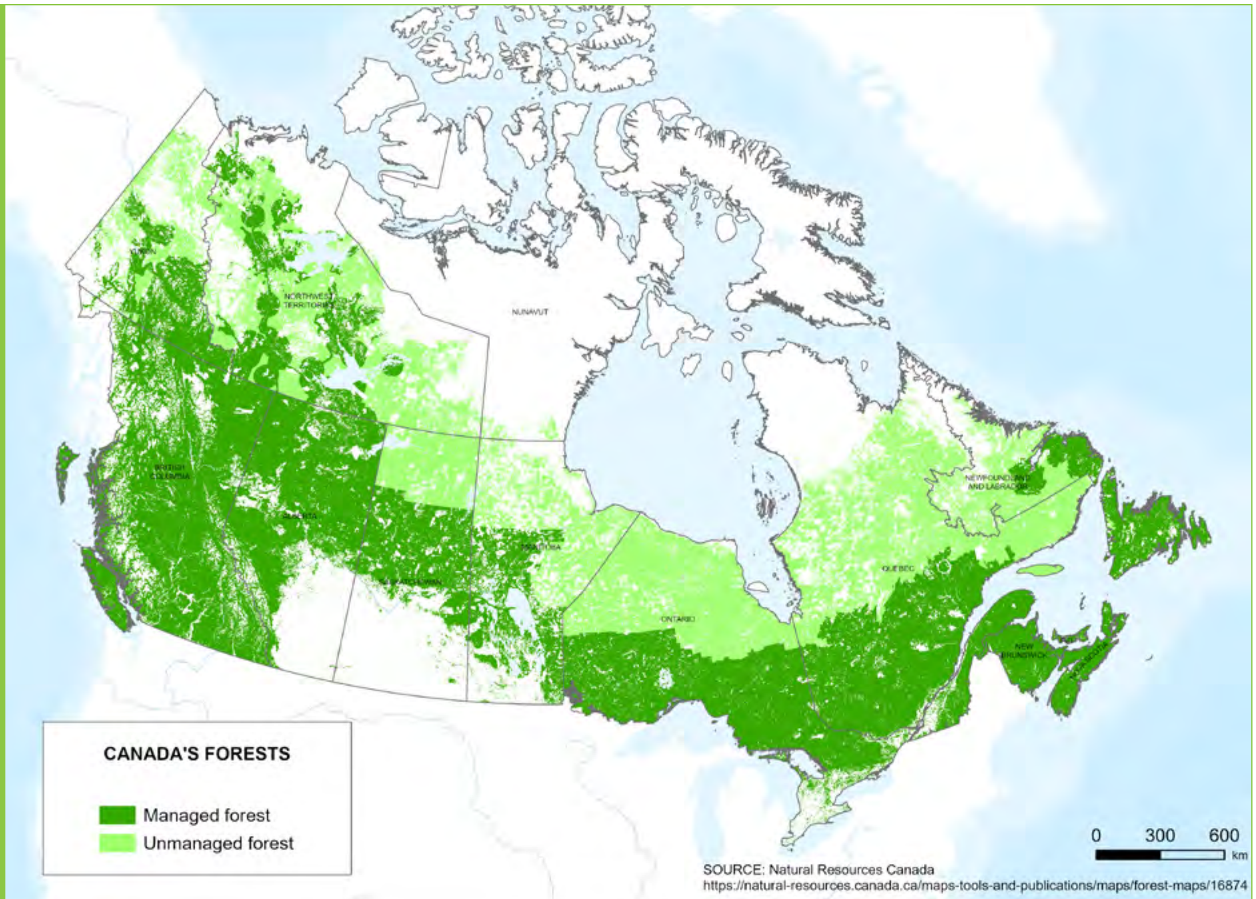


Figure 2. Extent of managed and unmanaged forests in Canada in 2017 as defined for the purpose of estimating and reporting GHG emissions and removals for annual National Inventory Report (NIR) submissions. Light green areas represent unmanaged forest and dark green areas represent managed forest. Source: Natural Resources Canada[7].

7 https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/forest-carbon/reporting-canadas-forest-greenhouse-gas-emissions-and-removals/24187

1.1 Carbon in National Parks

Globally, Campbell et al. (2008) estimated that national parks and other protected areas worldwide contain 312 gigatonnes (Gt) of carbon, representing 15.2% of the global terrestrial carbon stock. More recently, Melillo et al. (2016) estimated that 238 Gt of carbon were stored in 15.5 million km^2 of land identified as protected in the World Database of Protected Areas[8]. Of this, 92 Gt of carbon were estimated to be stored in plant biomass and 146 Gt in soil, together representing about 12% of global terrestrial carbon stocks. Melillo et al. (2016) also concluded that these terrestrial protected areas were a carbon sink, removing about 0.5 Gt of carbon from the atmosphere each year.

For Canada, previous studies that have assessed carbon in national parks or other protected areas were limited in scope to certain regions or provinces (e.g., Morton et al., 2007; Sharma et al., 2013). Kulshreshtha et al. (2000) studied the economic value of carbon sequestration in 39 national parks. They estimated that these parks contain 4.43 Gt of carbon in various pools, with around half stored in northern peatlands and close to another half stored in forest and grassland soils. Their estimates of aboveground biomass were incomplete however, and based on secondary land cover information rather than forest inventories. Recent advances in land cover data and carbon modeling based on detailed forest inventories have significantly improved the capacity to estimate above- and belowground biomass carbon. Estimates of carbon stocks in this Atlas are based on models and data that have benefitted from these recent advances.

8 https://www.protectedplanet.net/c/world-database-on-protected-areas

1.2 Carbon Dynamics in Forested Ecosystems

Forests play a major role in the carbon cycle. Le Quéré et al. (2015) concluded that, globally, forests are the largest terrestrial carbon sink, and over the past two decades have removed more than one-quarter of the emissions worldwide from the burning of fossil fuels (Le Quéré et al., 2015; Pan et al., 2011). Forests naturally cycle carbon between the atmosphere and ecosystem carbon pools through photosynthesis, respiration and decomposition, and periodic disturbances such as fires and insect outbreaks. Carbon is sequestered from the atmosphere through photosynthesis, and a portion of what is removed is converted to primary productivity (growth). The rate of photosynthesis is largely determined by site productivity (including climate and environmental factors), species composition, and vegetation age. Some carbon is emitted by live vegetation to the atmosphere through autotrophic respiration (R_a).

As vegetation dies, carbon is transferred to dead organic matter (DOM). The carbon in this DOM is either transformed into soil organic matter or released to the atmosphere through decomposition. In addition, forests are affected by natural and anthropogenic disturbances that affect carbon stocks and result in transfer of carbon between pools. For example, forest fires release carbon directly from live biomass and DOM pools to the atmosphere, and contribute to the litter pool through tree mortality, either immediately or over time. Insect outbreaks reduce tree growth and may also cause mortality. When forests are harvested, some of the carbon in biomass is transferred to harvested wood products; from there it may be lost to the atmosphere (e.g., burning for bioenergy) or stored for a few years to several decades (e.g., in paper or in buildings) (IPCC, 2006).

Canada's forests cover 347 million hectares of land, and make up approximately 9% of the world's total forest area[9]. For most of the past century, Canada's managed forests (approximately 230 million hectares) have been a significant carbon sink. In recent decades, however, the situation has reversed in some years due largely to a substantial increase in the annual total area burned by wildfires and large insect outbreaks in certain regions. In addition, the economic demand for harvested wood products has shifted over the years, influencing harvest rates[10]. The combination of these factors has resulted in Canada's managed forest now acting as a net source of greenhouse gases (Figure 3)[11].

9 https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/40084.pdf

10 https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-carbon/13085

11 https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-carbon/13085

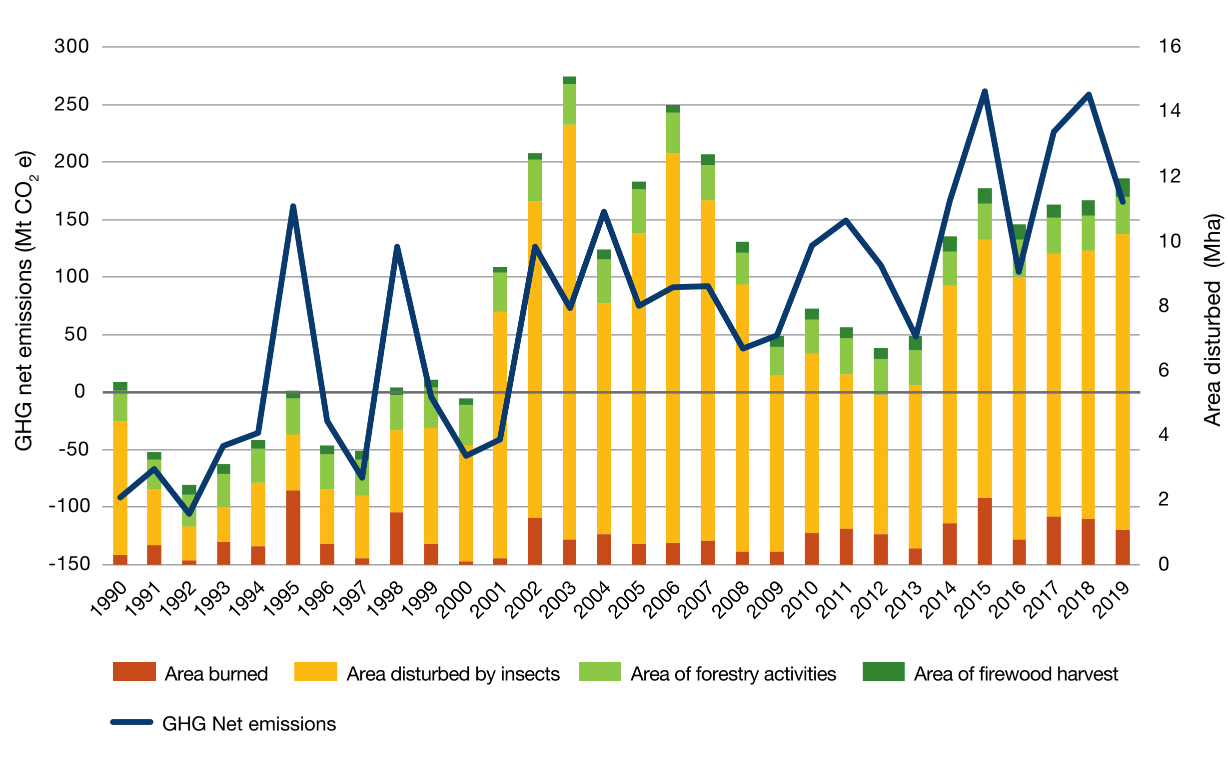


Figure 3. **Net annual GHG emissions and areas impacted by natural disturbances in Canada's managed forest: 1990–2019.** Source: National Inventory Report 1990-2019

Photo: Éric Le Bel / ©Parks Canada / Forillon National Park

Chapter 2: Data and Methods

The Parks Canada Agency currently administers 47 national parks and one national urban park. Thirty-eight of these parks have 10% or more of their geographical area categorized as forest (Figure 4)[12]. We did not have sufficient forest inventory and natural disturbance data for 7 of these 38 parks to consider then in our study. Details on, and the locations of each of the 31 parks considered in this atlas are presented in Table 2 and Figure 4, respectively. Forests in these 31 parks cover 56,000 sq km or 63% of the total area of these parks.

12 The 11 parks with less than 10% of their area as forests are: Aulavik NP, Auyuittuq NP, Grasslands NP, Ivvavik NP, Qausuittuq NP, Quttinirpaaq NP, Sable Island NPR, Sirmilik NP, Torngat Mountains NP, Tuktut Nogait NP, and Ukkusuksalik NP.

Table 2. Forest cover in 31 national parks having 10% or more of their area in forest, grouped by ecozone.

Ecozone	Park Name	Province	Geographic Area (km^2)	Forest Area (km^2)	Forest Area (%)
Atlantic Maritime	Cape Breton Highlands NP	NS	971.7	621.3	64
	Forillon NP	QC	247.6	234.0	95
	Fundy NP	NB	211.8	194.7	92
	Kejimkujik NP & NHS	NS	421.9	308.5	73
	Kouchibouguac NP	NB	242.7	122.7	51
	Prince Edward Island NP	PE	35.7	7.1	20
Boreal Plains	Prince Albert NP	SK	3,882.4	3,462.3	89
	Riding Mountain NP	MB	3,077.2	2,385.7	78
	Wood Buffalo NP[13]	AB	44,236.0	32,870.6	74
Boreal Shield	Georgian Bay Islands NP	ON	14.0	9.8	70
	Gros Morne NP	NL	1,811.6	441.8	24
	La Mauricie NP	QC	547.0	473.2	87
	Mingan Archipelago NPR	QC	96.2	42.4	44
	Pukaskwa NP	ON	1,869.0	1,683.0	90
	Terra Nova NP	NL	408.4	204.5	50
Mixedwood Plains	Bruce Peninsula NP	ON	161.4	132.1	82
	Fathom Five NMP	ON	117.1	13.4	11
	Point Pelee NP	ON	16.0	2.4	15
	Rouge NUP	ON	79.2	18.9	24
	Thousand Islands NP	ON	25.6	13.7	54
Montane Cordillera	Banff NP	AB	6,846.5	3,216.0	47
	Glacier NP	BC	1,344.6	378.9	28
	Jasper NP	AB	11,079.0	5,691.9	51
	Kootenay NP	BC	1,373.5	820.2	60
	Mount Revelstoke NP	BC	261.7	169.1	65
	Waterton Lakes NP	AB	501.9	341.5	68
	Yoho NP	BC	1,280.1	663.0	52

13 Wood Buffalo NP spans two ecozones – Boreal Plains and Taiga Plains – but for reporting purposes it is considered here as being in the Boreal Plains Ecozone only.

Ecozone	Park Name	Province	Geographic Area (km^2)	Forest Area (km^2)	Forest Area (%)
Pacific Maritime	Gulf Islands NPR	BC	37.3	26.5	71
	Gwaii Haanas NPR & Haida HS	BC	1,456.3	1,428.4	98
	Pacific Rim NPR	BC	519.3	270.5	52
Prairies	Elk Island NP	AB	189.8	121.0	64
TOTAL		**Canada**	**83,362.5**	**56,369.1**	**67**

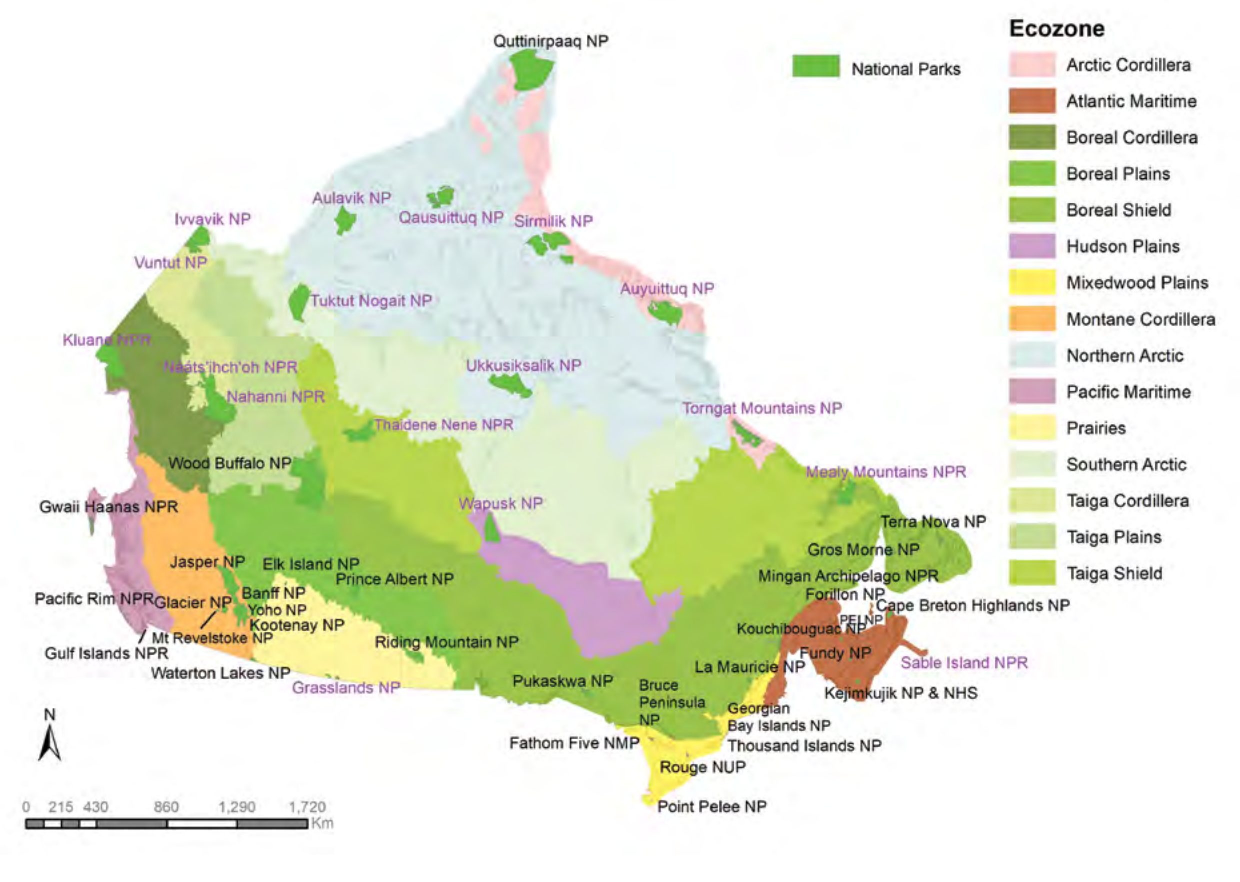


Figure 4. **Distribution of national parks, with 10% or more of area represented by forested ecosystems, across Canada's ecozones.** Parks that have been assessed are labeled in black text, while parks labeled in pink were not assessed in this study.

2.1 Modeling Platform

Two types of models can be used to estimate forest carbon dynamics: *process-based models* that simulate the photosynthesis process (e.g., 3-PG, Landsberg & Waring, 1997; BIOME-BGC, Running & Gower, 1991; CENTURY, Metherell et al., 1993; TEM, Tian et al., 1999); and *empirical models* that use yield curves and field-based inventory data (e.g., EFISCEN, Nabuurs et al., 2000; CO2FIX, Masera et al., 2003; CBM-CFS3, Kurz et al., 2009).

Process-based models require detailed data on many environmental conditions, which were not available at the spatial scale necessary for this study. We therefore used the Generic Carbon Budget Model (GCBM), which is a spatially-explicit version of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009) and has been developed in cooperation with Moja Global[14]. The GCBM uses a combination of spatial forest inventory data, regional mean annual temperature data, and the location and extent of forest disturbances, along with non-spatial or coarsely spatially-referenced modeling parameters (e.g., yield curves, volume to biomass coefficients), to estimate the annual carbon balance of a study area (Figure 5).

Importantly, the GCBM complies with the IPCC guidelines for reporting on carbon stocks and fluxes from land use, land-use change and forestry (IPCC, 2006). It is the core component of Canada's National Forest Carbon Monitoring Accounting Reporting System (NFCMARS) (Kurz & Apps, 2006), and is used by Canada to annually report the GHG emissions and removals for the forest sector (ECCC, 2020).

14 http://moja.global

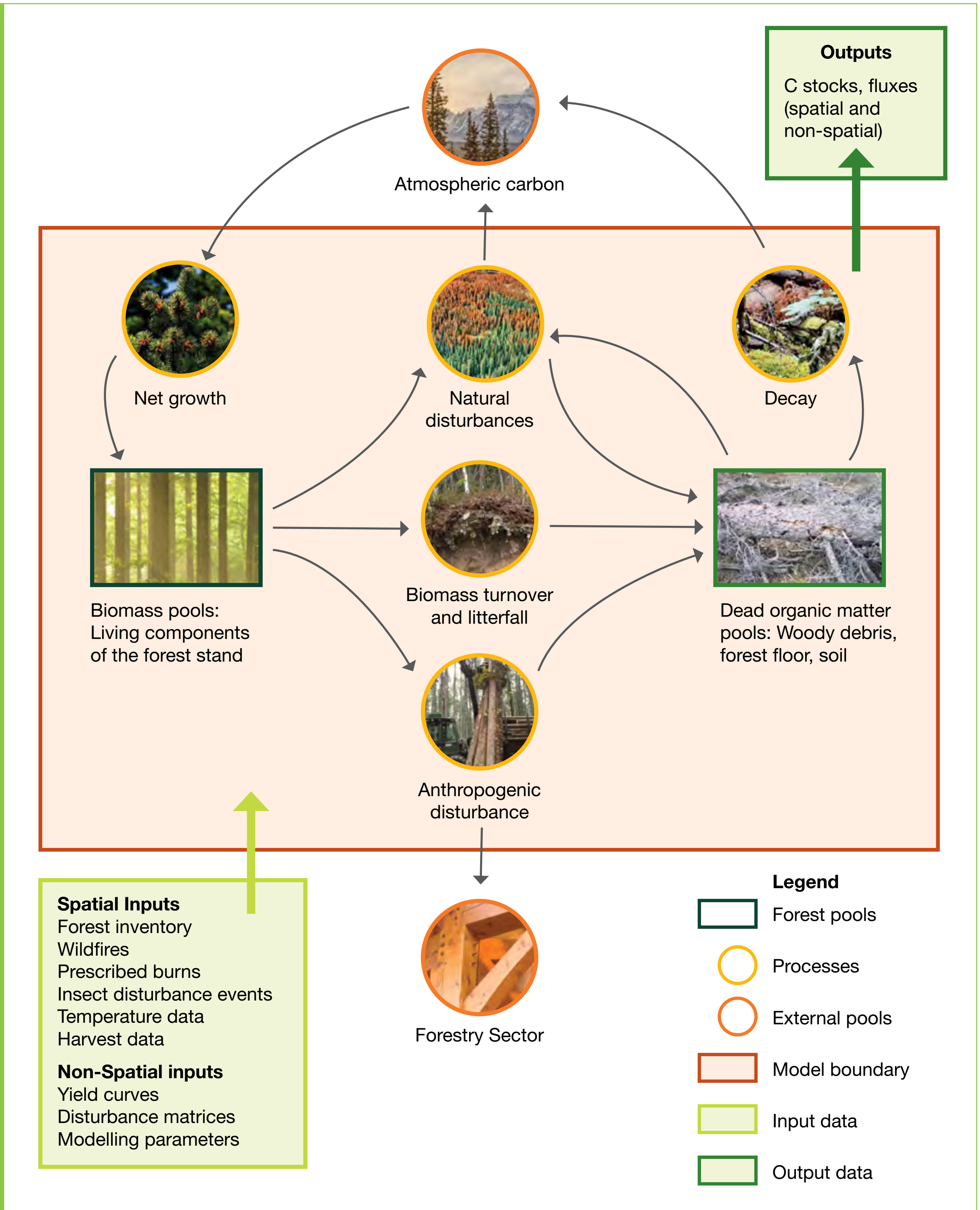


Figure 5. **Schematic of the Generic Carbon Budget Model (GCBM) showing the model inputs and outputs, and the processes simulated.** Adapted from Kurz et al. (2009). The fate of carbon in harvested wood products is not included, given that there is virtually no harvest in national parks.

The GCBM simulates the carbon dynamics in and amongst 10 biomass and 11 DOM[15] pools (Kurz et al., 1996), producing spatially-explicit representations of carbon stocks and fluxes. The model tracks carbon stocks, transfers between pools, and many other carbon flux metrics, such as net primary productivity (NPP), heterotrophic respiration (R_h), net ecosystem productivity (NEP), net biome productivity (NBP), and emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in annual time steps. The carbon stocks and fluxes are also tracked by disturbance event (e.g., forest fires and insect outbreaks).

Carbon stocks and fluxes in the 31 national parks were estimated for the period 1990-2020. The year 1990 marks the beginning of the reporting period for carbon emissions and removals under the UNFCCC, and 2020 is the year with the most recent available data. Effects of both natural disturbances (i.e., wildfires and insect outbreaks) and anthropogenic disturbances (i.e., prescribed fires) on carbon stocks and fluxes were estimated separately using site-specific data obtained from park staff and other sources (section 2.2.2). The spatial resolution used in this study was approximately 30 x 30 m as the spatial data available were compatible at that scale. This resolution also helped capture the impacts of smaller-size disturbances, such as small prescribed fires in parks, which are often only a few hectares in size.

15 The IPCC defines soils as a distinct ecosystem carbon pool (Table 1), while the GCBM combines soils, dead wood and litter together in the DOM pool.

2.2 Spatial Data

2.2.1 Forest Inventory Data

Spatial forest inventory data collected as a part of park monitoring programs and other studies were acquired and compiled for the simulations. In cases where there were no inventory data available for a park, these data were acquired from the province or created using other data sets such as ecological land classification data and/or remote-sensing-based land-cover classification.

The forest inventory layers provide the GCBM with the initial forest stand conditions (i.e., age, species, forest types) and "classifiers" (e.g., site index, ownership, leading species) that are used to couple the inventory data to the yield curves for each spatial unit.

The GCBM requires information on initial forest stand age for the simulation start year. For areas disturbed by wildfires, the forest stand age from the forest inventory data was not always consistent with the date of a known wildfire in a given area. Because Parks Canada monitors and maps all wildfires in national parks every year, the Agency's forest stand age based on fire history was considered to be more accurate, and was therefore used in the GCBM simulation instead of fire age estimated from inventory data.

Calculation of initial forest stand age in 1990 was based on inventory's vintage (Table 3). For example, if a stand was 25 years old in an inventory compiled in 2010, its age in 1990 was set at 5. When the stand was younger than the number of years between 1990 and inventory vintage, the age was set using one or more of the following approaches:

1) Available data prior to 1990 on stand-replacing disturbances (such as wildfires) were used to assign the age in 1990. For example, if the most recent wildfire prior to 1990 occurred in 1950, then the age was set as 40 in 1990.
2) For undisturbed areas, spatial-proximity analysis was used for age estimation, with "missing age" stands being assigned the average age of nearby stands. This approach was used to ensure locational continuity as trees near a disturbed area are typically similar in age to those affected. Proximity analysis was completed using ESRI ArcGIS 10.x software.

In cases where the inventory did not have any age information, wildfire disturbance data were used to assign age to disturbed areas. For undisturbed areas, other products such as remote-sensing-based land-cover classification or broad age classes available from other sources were used.

2.2.2 Disturbances

Disturbance data on wildfires, prescribed fires, a variety of insects, and harvesting were compiled from various sources (Table 3). GCBM links information on the year, type and intensity of disturbance to a disturbance matrix (Kurz et al., 2009) that defines the disturbance-specific resulting flows of carbon between different pools and the atmosphere, by gas type.

Wildfires and Prescribed Fires

Forest fires occurred in 17 national parks with varying frequency and extent during the study period. Other national parks, mostly in Eastern Canada, were not affected by fires during that time. Spatial data on occurrence of wildfires were compiled from information available from each park. To ensure that all wildfires were included, a comparison was made with data from other sources such as the 'Composite2Change' product for 1984-2012 (Hermosilla et al., 2016) and National Burned Area Composite data available from Natural Resources Canada[16]. Missing fires, if any, were added to the fire data from site-specific datasets. All wildfire occurrences were considered stand-replacing events in the simulations.

Parks Canada conducts prescribed fires in parks to help maintain ecological integrity and biodiversity, to promote ecosystem conservation and restoration, and to reduce the risk of wildfire to nearby communities. During the 1990-2020 study period, prescribed fires were undertaken in more than half of the 31 national parks studied. Spatial data on prescribed fires were acquired directly from the appropriate parks. Since data on the objectives and severity of prescribed fires were not readily available, it was assumed for the simulation that 50% of the area of prescribed fire was surface fire and 50% was crown fire.

Insect Outbreaks

In the GCBM simulations, disturbance impacts of 13 species of insects were considered: mountain pine beetle (MPB), Douglas fir beetle (DFB), western balsam bark beetle (WBBB), western black-headed budworm (WBHB), eastern larch beetle (ELB), spruce budworm (SBW), two-year cycle spruce budworm (TSBW), eastern hemlock looper (EHL), emerald ash borer (EAB), forest tent caterpillar (FTC), large aspen tortrix (LAT), aspen two leaf tier (ATT), and European gypsy moth (EGM) (**Appendix A** provides the scientific name for each forest insect). Spatially-explicit data on the extent and severity of these insect outbreaks were compiled from provincial forest-health survey datasets.

16 http://cwfis.cfs.nrcan.gc.ca/datamart

Annual insect aerial surveys are almost never 100% complete (especially in large parks like Wood Buffalo NP) because of poor visibility resulting from forest-fire smoke and adverse weather conditions. In some cases, surveys were not carried out for a few years. In these cases, any available data from provincial surveys conducted in the park were used, even if they did not cover the entire park. For some parks (e.g., Cape Breton Highlands NP), forest-health data were not available in spatial format so insect disturbances were not incorporated in the simulations for those parks.

Mountain Pine Beetle infestations in Jasper National Park where recently killed trees display red foliage. (Photo credit: Chris Maundrell, March 2019).

Table 3. Forest inventory and disturbance data used in the GCBM simulations.

Ecozone	Park Name	Inventory Year	Insects[1]			Wildfires		Prescribed Fires	
			Insect Type	Years	Source	Years	Source	Years	Source
Atlantic Maritime	Cape Breton Highlands NP	2014	No Data	No Data	No Data	2012	PC	--	--
	Forillon NP	2004	EHL, SBW	1995-2020	QC Province	--	--	1990-2020	PC
	Fundy NP	2003	No Data	No Data	No Data	1995-2020	PC	--	--
	Kejimkujik NP & NHS	2014	No Data	No Data	No Data	2016-2020	PC	--	--
	Kouchibouguac NP	2002	No Data	No Data	No Data	1992	PC	--	--
	Prince Edward Island NP	2010	EGM	2014-2017	PEI Province	--	--	--	--
Boreal Plains	Prince Albert NP	2016	ELB, FTC, SBW	1994-2020	SK Province	1995-2020	PC	1990-2020	PC
	Riding Mountain NP	2016	FTC, SBW	2016-2020	MB Province	1990-2020	PC	1995-2020	PC
	Wood Buffalo NP	1975, 2000	WBBB, FTC, LAT, MPB, SBW, TSBW	1990-2019	CFS	1990-2020	PC	1990-2020	PC
Boreal Shield	Georgian Bay Islands NP	2009	EAB, SBW, FTC	1990-2015	ON Province	--	--	--	--
	Gros Morne NP	2010	EHL, SBW	1994-2009, 2020	NL Province	1990-2020	PC	--	--
	La Mauricie NP	2008	EHL, SBW	1995-2020	QC Province	1990-2020	PC	1991-2020	PC
	Mingan Archipelago NPR	2002	EHL, SBW	1995-2020	QC Province	2013	PC	--	--
	Pukaskwa NP	2008	ATT, FTC, EAB,SBW	1990-2015	ON Province	1990-2020	PC	1995-2020	PC
	Terra Nova NP	2010	EHL, SBW	1995	NL Province	1996-2020	PC	2009-2020	PC
Mixedwood Plains	Bruce Peninsula NP	1978, 2006	ATT, EAB	1990-2015	ON Province	--	--	--	--
	Fathom Five NMP	2009	EAB	1990-2015	ON Province	--	--	--	--
	Point Pelee NP	2004	EAB, SBW	1990-2015	ON Province	2017	PC	--	--
	Rouge NUP	2009, 2014	EGM	2008	ON Province	--	--	--	--
	Thousand Islands NP	2006	EAB, SBW	1990-2015	ON Province	--	--	1995-2020	PC

Ecozone	Park Name	Inventory Year	Insects[1]			Wildfires		Prescribed Fires	
			Insect Type	Years	Source	Years	Source	Years	Source
Montane Cordillera	Banff NP	2017	WBBB, FTC, LAT, MPB, SBW, TSBW	1990-2020	CFS	1990-2020	PC	1990-2020	PC
	Glacier NP	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1998-2020	PC
	Jasper NP	2012	WBBB, FTC, LAT, MPB, SBW, TSBW	1990-2020	CFS	1990-2020	PC	1990-2020	PC
	Kootenay NP	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1998-2020	PC
	Mount Revelstoke NP	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1998-2020	PC
	Waterton Lakes NP	2012	WBBB, FTC, LAT, MPB, SBW, TSBW	1990-2020	CFS	1990-2020	PC	1990-2020	PC
	Yoho NP	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1998-2020	PC
Pacific Maritime	Gulf Islands NPR	2006	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1998-2020	PC
	Gwaii Haanas NPR & Haida HS	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1990-2020	PC
	Pacific Rim NPR	2015	MPB, WBBB, DFB, WBHB	1990-2020	BC Province	1990-2020	PC	1990-2020	PC
Prairies	Elk Island NP	1995	WBBB, FTC, LAT, MPB, SBW, TSBW	1990-2020	CFS	1990-2020	PC	1990-2020	PC

Note: -- Represents absence of the disturbance;
[1] Insect types considered are listed by province; not all insects listed for a park are found in that park.

Harvesting

In general, harvesting is not allowed in national parks. Gros Morne NP is an exception where eligible residents are allowed to harvest firewood and saw logs for domestic use[17]. Data for all timber harvested were available and used in the simulation to account for this domestic use. There was commercial logging activity within Wood Buffalo National Park until 1991, but no spatial or volumetric harvest data were available to include in the simulation. Consequently, forest stand age estimates were obtained from inventory data for 2000 for this park.

In a few of the national parks analyzed, small amounts of trees were harvested for the purposes of fuel management and forest restoration. However, the size of these harvested areas, which were not clear-cut, was negligible compared to the total forest area of those parks, and hence the impact of this harvest on carbon dynamics was not included in the simulations.

2.3 Non-spatial Data

2.3.1 Yield curves

Yield curves provide the volume of a forest stand at a particular age, typically at 5- or 10-year intervals (Figure 6). GCBM converts the periodic volume-based curves to annual carbon increments using a set of volume-to-biomass equations and a smoothing algorithm to fill the information gap for young stands with no trees of merchantable size (Kurz et al., 2009).

The yield curves used for parks in the GCBM simulations were obtained from respective provincial agencies for all study sites except Gros Morne NP, where volume tables and yield curves were available specifically for domestic harvest blocks within the park.

17 https://laws-lois.justice.gc.ca/eng/regulations/SOR-2005-204/page-1.html

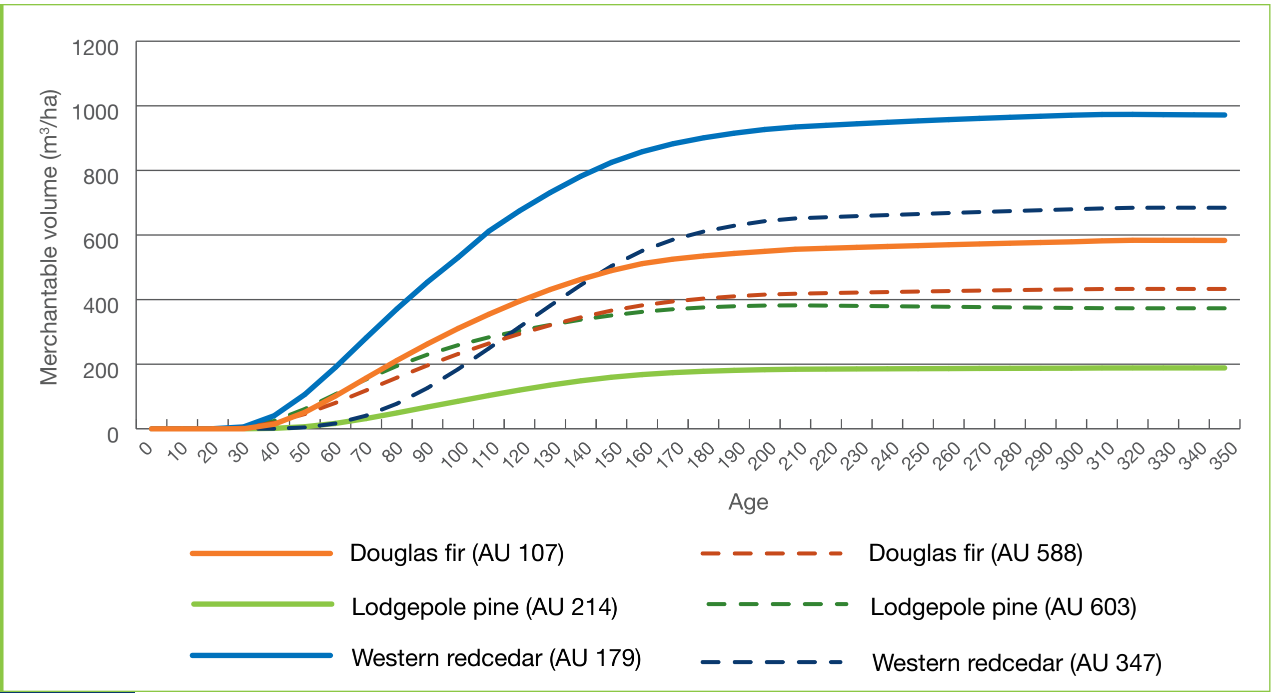


Figure 6. Illustration of yield curves for merchantable timber volume for species in different analysis units (AU) in British Columbia. Solid lines represent curves for species in the Pacific Maritime Ecozone and dashed curves represent corresponding species in the Montane Cordillera Ecozone.

2.3.2 Disturbance Matrices

Disturbance matrices (DM) define the flows between carbon pools in the system resulting from a disturbance, for example, live softwood biomass to snags (Kurz et al., 2009). The disturbance matrices used in this study came from the standard set included with the GCBM, as well as new matrices developed by the authors for some insects (e.g., western balsam bark beetle, Douglas fir beetle) and fire types (e.g., prescribed fires) not already represented. Development of new DMs involved modifying the existing DM of the disturbance type whose impacts most closely resembled the new disturbance. This modification was based on expert knowledge and literature. For example, the DM for prescribed fire was developed by modifying the flow factors in the DM of wildfires. Two examples of the disturbance matrices for mountain pine beetle (very severe) and prescribed fires (crown) are given in **Appendix B**.

2.4 Analysis

Both spatial and non-spatial outputs were generated at annual time steps for the 31-year study period for the following carbon metrics: carbon stocks in IPCC-defined pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and soil); total ecosystem carbon in each pool; net primary productivity (NPP); heterotrophic respiration (R_h); net ecosystem productivity (NEP); net biome productivity (NBP); and greenhouse gas (GHG) emissions and removals[18]. GHG emissions included CO_2, CO, CH_4, and N_2O emissions and were converted to CO_2-equivalent units (CO_2e) using the estimates of 100-year Global Warming Potentials (GWP) for each GHG taken from IPCC AR4 (IPPC, 2007). Inter-annual variability in weather, which affects growth and decomposition rates, was not considered in these analyses.

Results for each metric were aggregated at the park level, ecozone level, and also at the national level across all 31 parks. We assessed the potential effects of spatial and temporal autocorrelation between parks and within the time-series using the Moran's I test (Moran, 1950) and Durbin-Watson test (Durbin & Watson, 1971) respectively.

18 Refer to the Glossary for definitions of these terms.


Photo: Dale Wilson / ©Parks Canada / Fundy National Park

Chapter 3: Results

This study provides the first comprehensive estimates of carbon stocks, densities and fluxes over time for forested ecosystems in Canada's national parks. The following chapter details the carbon stocks in national parks forests, their changes over the period 1990-2020 as a result of natural ecosystem processes and disturbances, and the overall greenhouse gas emissions associated with these dynamics. Notable similarities and differences in the annual and 31-year trends observed between carbon pools, parks and ecozones are illustrated with key examples from the study.

3.1 Carbon Stocks and Density

The average carbon stock contained in the 31 national parks during the study period was 1,452 ±11 Mt C (Table 4). Average ecosystem carbon density during the study period was 258 ± 1.9 t C ha^{-1}.

Table 4. Forest carbon stocks and density in IPCC-defined pools in 31 national parks (average over 1990-2020). The standard deviation represents variability across years.

Pool	Stocks Mt C (±SD)	Density t C ha^{-1} (±SD)
Total Biomass	412 ± 17.7	73 ± 3.1
Dead wood	194 ± 11.8	34 ± 2.1
Litter	300 ± 3.9	53 ± 0.7
Soil	546 ± 0.6	97 ± 0.1
Total Ecosystem	**1452 ± 10.6**	**258 ± 1.9**

Both the carbon stock in different pools and total ecosystem carbon density varied between the forests of different national parks and between ecozones (Table 5). Wood Buffalo NP had the largest total ecosystem carbon stock (844 Mt C) of any park, representing 58% of the total (Figure 7). This finding is not surprising given that Wood Buffalo NP is the largest park in Canada, accounting for 58% of the total forested area in the 31 parks studied. Point Pelee NP, which had the smallest forested area of the 31 parks, also had the smallest total ecosystem carbon stock among all of the parks assessed (0.04 Mt C). National parks in the Boreal Plains Ecozone, including the southern portion of Wood Buffalo NP, comprised 68% of the total forested area of all parks studied, and stored the greatest amount of ecosystem carbon among all ecozones (Table 5).

Among all parks studied, forests in Pacific Rim NPR had the highest ecosystem carbon density (477 ± 4 t C ha^{-1}), while those in Bruce Peninsula NP had the lowest carbon density (150 ± 5 t C ha^{-1}) (Table 5 and **Appendix C**). This relationship was consistent at the ecozone level, with forests of the Pacific Maritime Ecozone (e.g., Pacific Rim NPR) having the highest average carbon density, and those of Mixedwood Plains Ecozone (e.g., Bruce Peninsula NP) having the lowest. The absence of commercial forest harvesting in national parks, coupled with the very low frequency of stand-replacing fires in Pacific Maritime Ecozone sites, resulted in high above- and belowground biomass in these old-growth forests, and consequently high ecosystem carbon densities.

Within a given ecozone, parks with younger forests (e.g., Gulf Islands NPR forests with a median age of 46 years) had lower carbon densities than parks with older forests (e.g., Pacific Rim NPR forests with a median age of 221 years). Glacier NP in the Montane Cordillera ecozone, which had much older forests (median age 164 years) than the other six parks in the same ecozone, also had higher carbon density than the other Montane Cordillera parks.

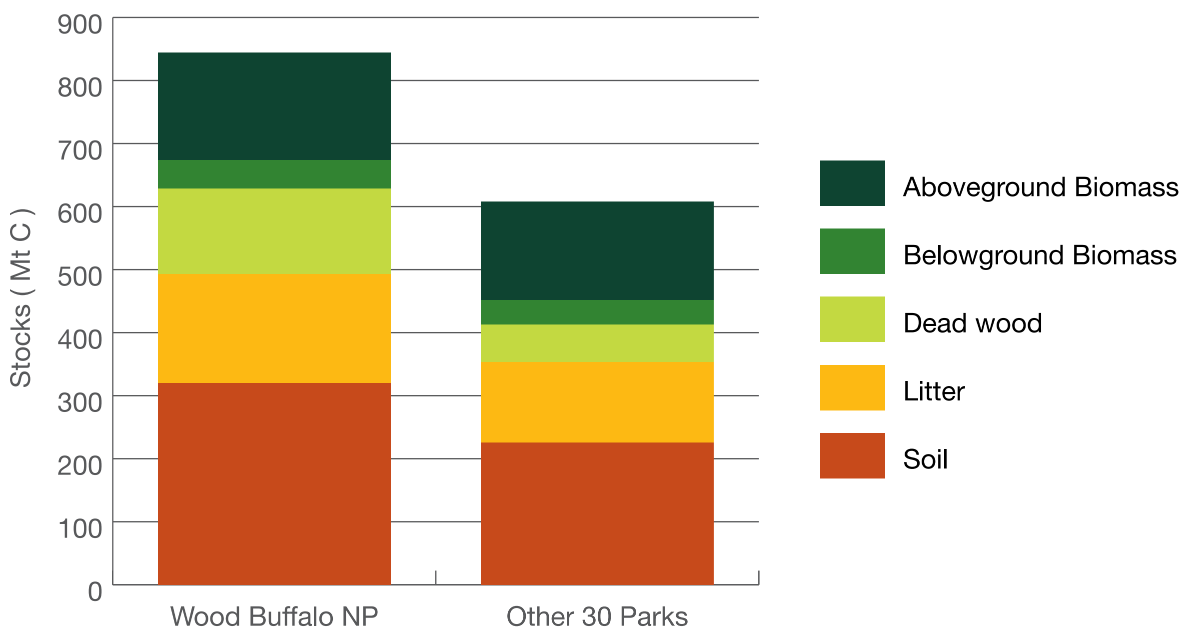


Figure 7. **Forest carbon stocks (average for 1990-2020) in IPCC-defined pools in Wood Buffalo NP versus all other parks combined.**

Table 5. Forest carbon stocks in IPCC-defined pools and ecosystem carbon density, by ecozone and national park (average for 1990-2020).

Ecozone	Carbon Stock (Mt C)							Ecosystem C Density ($t\ C\ ha^{-1}$) [1]
	Park Name	Above-ground Biomass	Below-ground Biomass	Dead wood	Litter	Soil	Total Ecosystem	
Atlantic Maritime		6.52	1.62	2.55	5.79	12.04	28.51	192
	Cape Breton Highlands NP	2.66	0.64	0.91	2.43	4.85	11.48	185
	Forillon NP	0.99	0.28	0.77	0.95	2.11	5.10	218
	Fundy NP	0.78	0.20	0.22	0.78	1.62	3.60	185
	Kejimkujik NP & NHS	1.57	0.37	0.47	1.16	2.40	5.96	199
	Kejimkujik NPS	0.03	0.01	0.01	0.03	0.07	0.15	159
	Kouchibouguac NP	0.46	0.12	0.16	0.41	0.93	2.08	170
	Prince Edward Island NP	0.03	0.01	0.02	0.03	0.06	0.14	203
Boreal Plains		195.90	53.14	148.91	201.99	373.08	973.02	251
	Prince Albert NP	15.81	4.39	8.60	13.37	27.06	69.23	200
	Riding Mountain NP	9.88	2.80	5.28	15.32	26.13	59.41	249
	Wood Buffalo NP	170.21	45.95	135.03	173.30	319.88	844.38	257
Boreal Shield		16.17	4.12	5.93	14.80	27.15	68.16	239
	Georgian Bay Islands NP	0.05	0.01	0.01	0.04	0.07	0.18	183
	Gros Morne NP	2.58	0.59	0.88	2.55	4.36	10.96	248
	La Mauricie NP	3.80	0.94	1.31	2.97	5.58	14.61	309
	Mingan NPR	0.22	0.06	0.08	0.17	0.35	0.88	206
	Pukaskwa NP	8.22	2.21	3.35	8.03	14.88	36.68	218
	Terra Nova NP	1.29	0.31	0.29	1.05	1.91	4.85	238

Ecozone	Carbon Stock (Mt C)							Ecosystem C Density (t C ha^{-1}) [1]
	Park Name	Above-ground Biomass	Below-ground Biomass	Dead wood	Litter	Soil	Total Ecosystem	
Mixedwood Plains		0.69	0.19	0.27	0.50	1.21	2.86	158
	Bruce Peninsula NP	0.46	0.13	0.20	0.35	0.85	1.98	150
	Fathom Five NMP	0.06	0.02	0.01	0.04	0.09	0.22	161
	Point Pelee NP	0.01	0.00	0.00	0.01	0.02	0.04	185
	Rouge NUP	0.10	0.02	0.03	0.06	0.14	0.36	190
	Thousand Islands NP	0.06	0.02	0.03	0.04	0.11	0.25	184
Montane Cordillera		77.92	19.29	31.07	64.43	107.27	299.98	266
	Banff National Park	21.03	5.40	8.33	18.46	31.51	84.72	263
	Glacier NP	4.73	1.05	1.43	2.63	3.37	13.21	349
	Jasper NP	37.73	9.56	14.78	33.14	57.45	152.67	268
	Kootenay NP	6.25	1.39	2.45	3.88	5.83	19.79	241
	Mount Revelstoke NP	1.82	0.40	0.39	0.93	1.28	4.82	285
	Waterton Lakes NP	2.17	0.55	0.73	1.69	3.15	8.29	243
	Yoho NP	5.60	1.25	1.90	3.57	4.70	17.02	257
Pacific Maritime		27.48	6.09	6.05	12.34	23.78	75.73	439
	Gulf Islands NPR	0.35	0.08	0.09	0.16	0.40	1.08	408
	Gwaii Haanas NPR & Haida HS	22.20	4.92	4.98	10.23	19.41	61.75	432
	Pacific Rim NPR	4.92	1.09	0.97	1.95	3.96	12.90	477
Prairies		0.74	0.19	0.37	0.75	1.42	3.47	287
	Elk Island NP	0.74	0.19	0.37	0.75	1.42	3.47	287
National		**326.8**	**84.9**	**194.1**	**300.5**	**545.9**	**1452.3**	**258**

1 Carbon density for each pool is listed in **Appendix C.**

3.1.1 Variation Between IPCC-defined Carbon Pools

Soil carbon was the largest single ecosystem carbon pool within forests for all parks combined (38% of total carbon stocks; Figure 8). This proportion rose to 72 % for DOM (i.e., dead wood, litter, soil carbon: Figure 8). However, the proportions of carbon in different pools varied between ecozones (Figure 9). For example, in Boreal Plains parks, 74% of the total carbon stock occurred in DOM pools and 26% in the biomass pools, whereas in Pacific Maritime parks, 56% of the total carbon stock occurred in the DOM pools, and 44% of the total carbon stock was in the biomass pools.

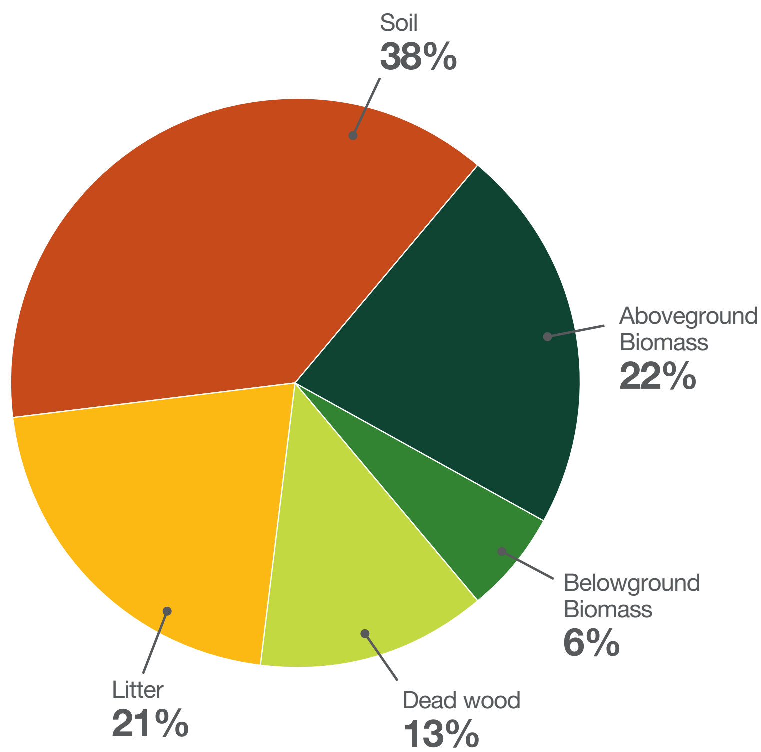


Figure 8. Proportion of forest carbon stocks in IPCC-defined pools across 31 parks (average for 1990-2020).

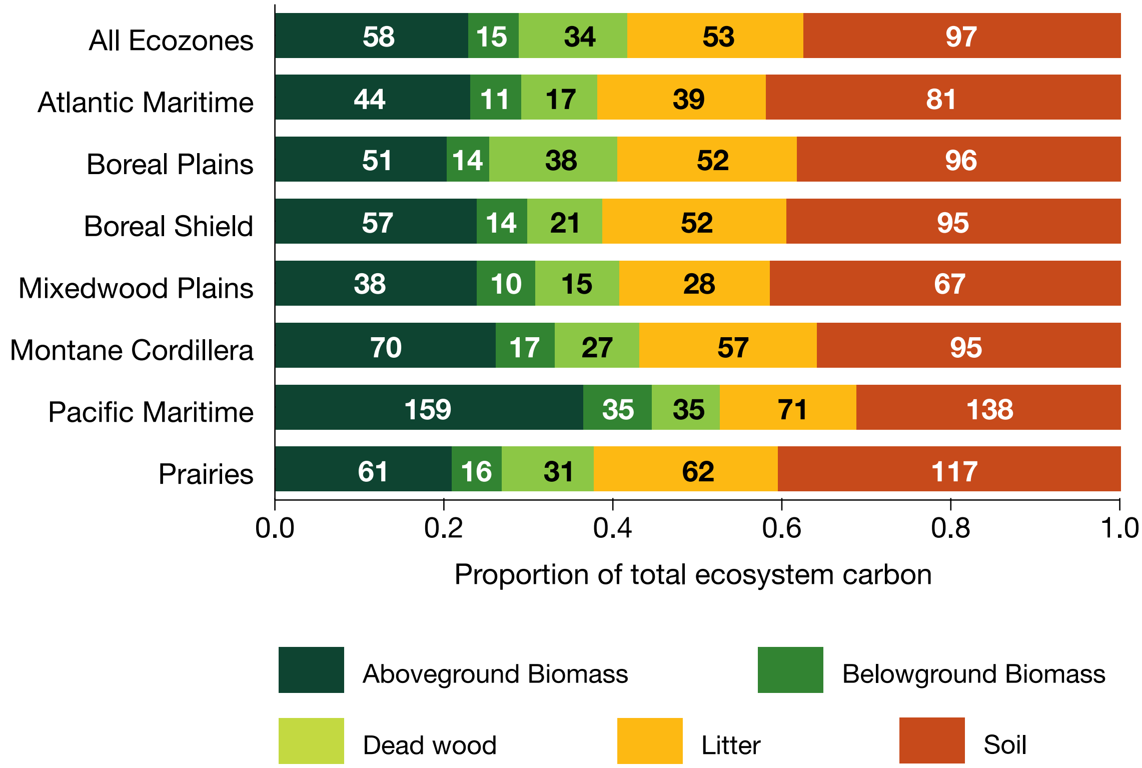


Figure 9. **Forest carbon density proportion in IPCC-defined pools by ecozone.** Numbers in bars represent the average carbon density in that pool during 1990-2020.

3.1.2 Spatial Distribution

There was high variability in carbon density within a single park and between parks. Figure 10 illustrates carbon density distributions for 2020 in the forests of seven national parks, each from a different ecozone. The spatial variability observed can be related to different tree species, forest type and age distribution (largely an indicator of disturbance regime and history) between sites, as well as differences in site quality. For example, Kootenay NP had a mix of young and old forests (age range: 8-371 years), and as a result a mosaic of patches of very high carbon density where older forests occurred, and patches of lower carbon density where younger forests were present. In contrast, Terra Nova NP, which contained more homogeneous and mostly younger forests (age range: 20-100 years), showed a fairly uniform distribution of moderate carbon densities. Despite these contrasting distribution patterns, the two parks had almost the same average carbon density (~240 t C ha^{-1}) in 2020. **Appendix D** provides maps of the spatial distribution of forest carbon density in 2020 for all parks. Using the Moran's I test, we determined weak and/or no significant spatial autocorrelation effects between parks.

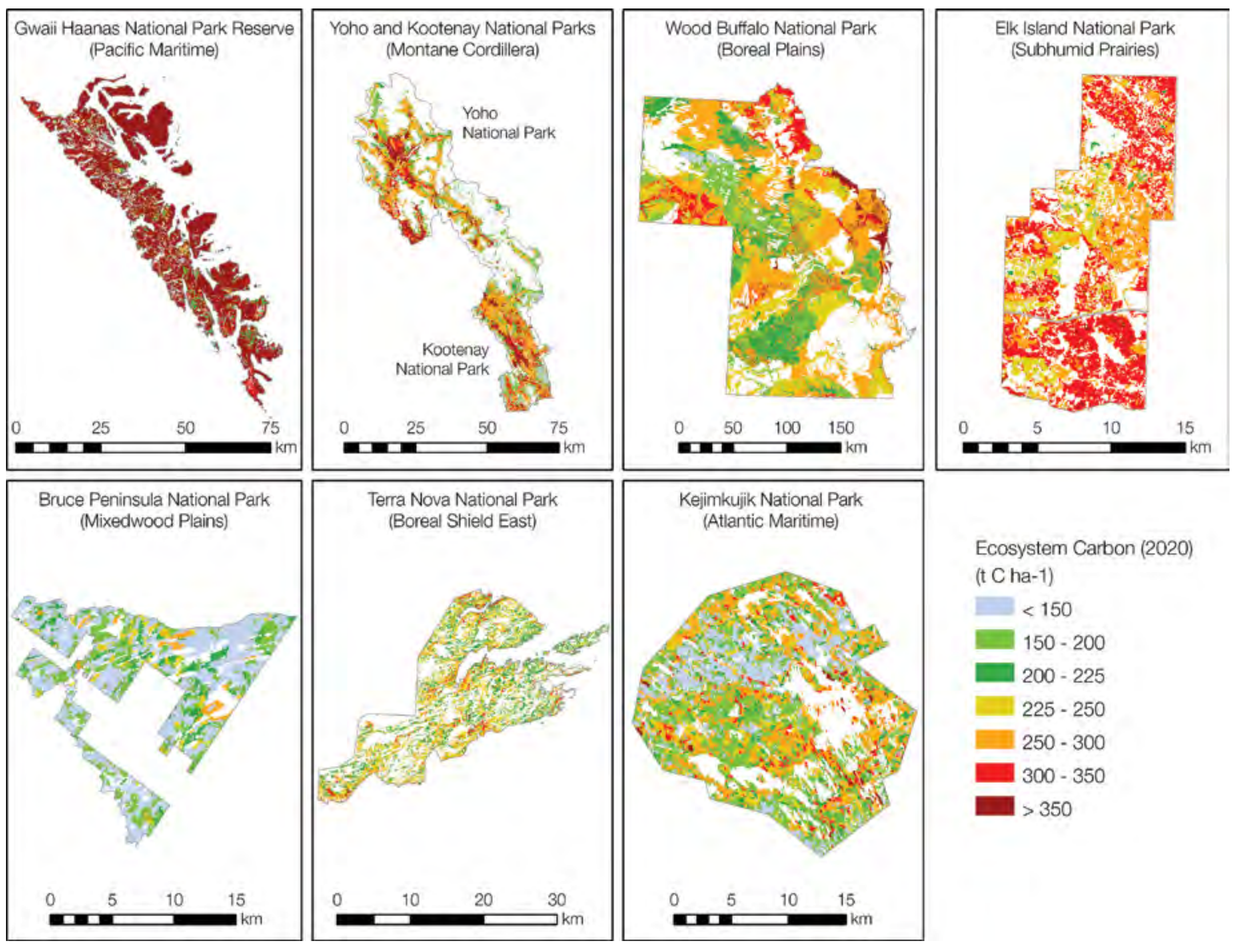


Figure 10. Spatial distribution of forest ecosystem carbon density (t C ha^{-1}) in selected parks and ecozones in 2020

3.1.3 Temporal Changes in Carbon Stocks and Density

The average carbon stocks for the 31 parks ranged from 1431 to 1466 Mt C over the study period (Figure 11). In 1990, the first year of the study, the parks collectively contained 1,431 Mt C in their forested ecosystems. By 2020, the final year of the study, parks collectively contained approximately 1,438 Mt C in their forested ecosystems, representing a net gain of 6.8 Mt C over the 31-year period. The annual breakdown reveals that total ecosystem carbon increased in the first decade of the study period, remained more or less stable in the second decade, and decreased after 2011 returning to almost the same value recorded at the beginning of the study period. Whereas total biomass decreased overall by 5% (21 Mt C) during the study period, dead organic matter (DOM) carbon increased overall by 3% (28 Mt C), and overall ecosystem carbon density was slightly higher in 2020 compared to 1990 (Figure 11).

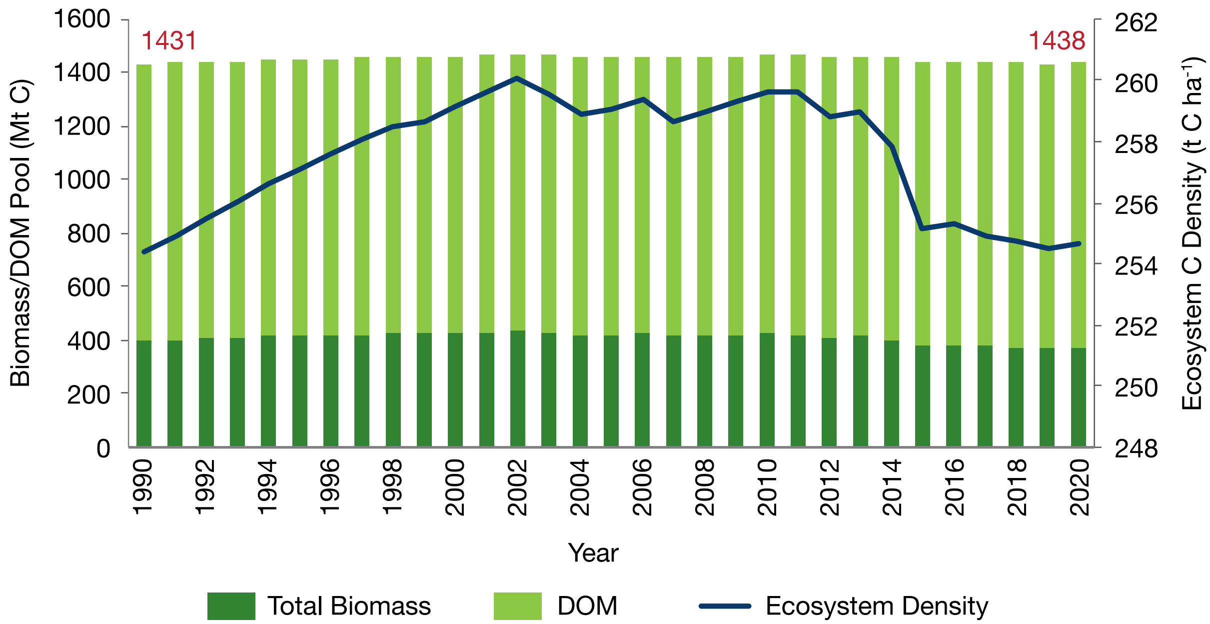


Figure 11. Forest (aboveground + belowground) biomass and dead organic matter (DOM) carbon stocks and total ecosystem carbon density in all 31 national parks over the period 1990-2020. Numbers in red show total ecosystem carbon at the beginning and the end of the study period.

Individually, all parks had higher forest ecosystem carbon densities in 2020 than in 1990, except Waterton Lakes NP and Wood Buffalo NP (Figures 12a, 12b) where wildfires resulted in relatively substantial declines in ecosystem carbon densities during the latter part of the study period. Parks in the Pacific Maritime ecozone not only had the highest densities throughout the study period, but also showed a substantial increase in their density over the period. Gulf Islands NPR showed the greatest increase in carbon density over the study period. Parks in the Mixedwood Plains ecozone had lower carbon densities than most other parks throughout the study period, but they nevertheless showed a substantial increase in densities over time. We did not detect any significant temporal autocorrelation effects in the time-series using Durbin-Watson Test. These results are consistent with Kurz et al. (2008a).

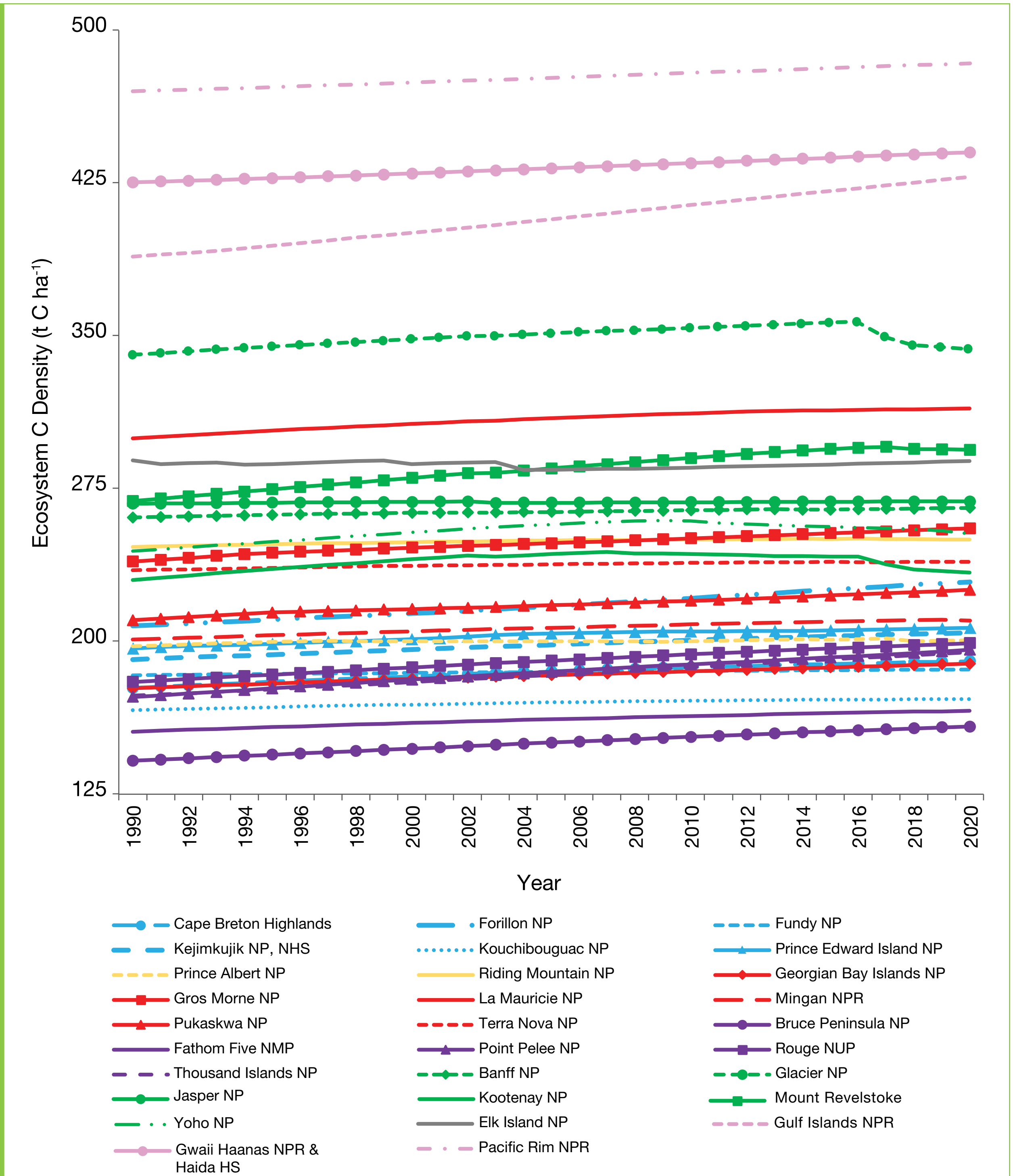


Figure 12a. **Temporal trend in forest carbon density for 29 national parks that showed an overall increase over the period 1990-2020.** Parks are colour-coded by ecozone. Blue – Atlantic Maritime; Yellow – Boreal Plains; Red – Boreal Shield; Purple – Mixedwood Plains; Green – Montane Cordillera; Pink – Pacific Maritime; Grey – Prairies.

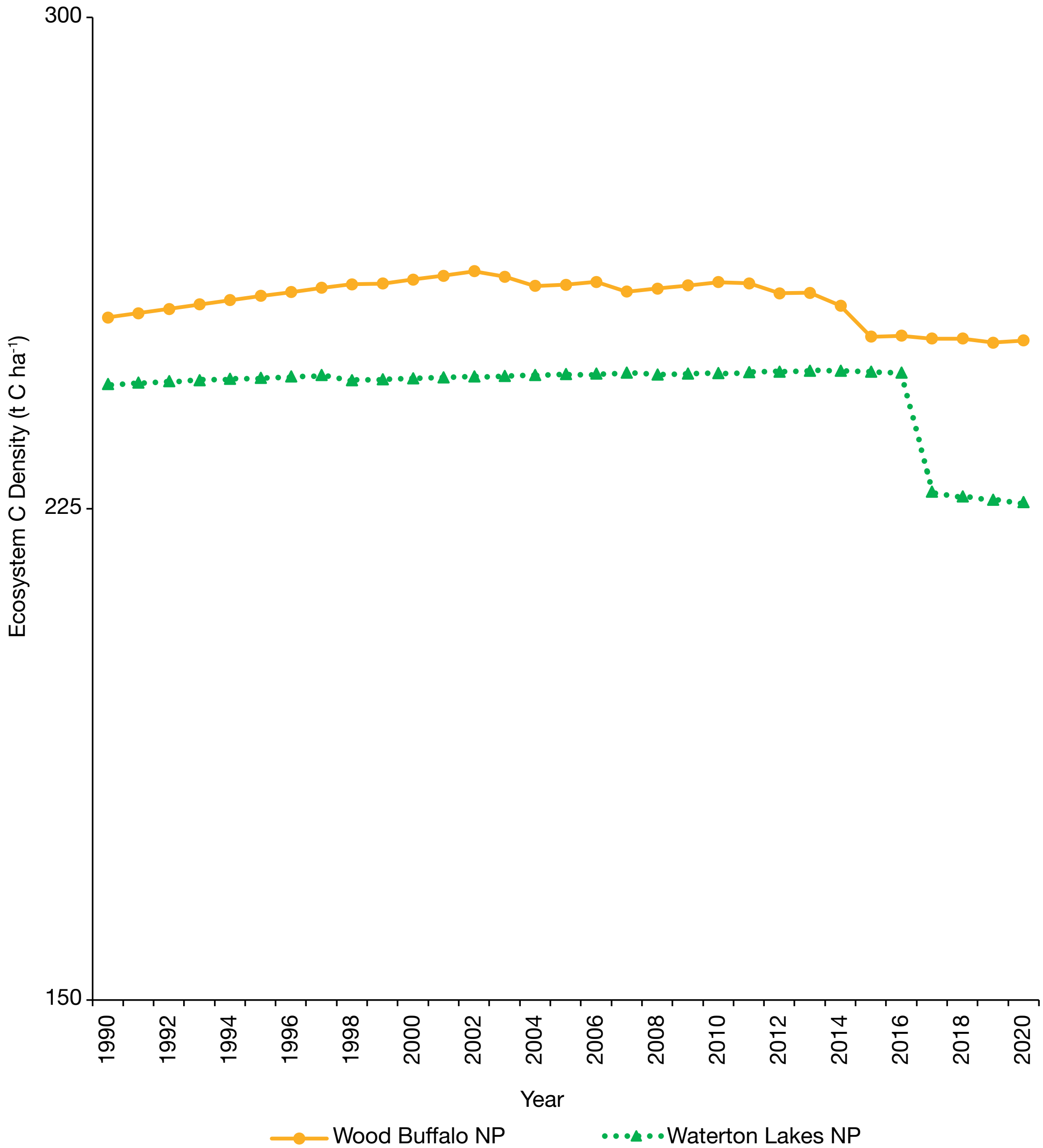


Figure 12b. **Temporal trend in forest carbon density for 2 national parks that showed an overall decrease over the period 1990-2020.** Parks are colour-coded by ecozone. Yellow – Boreal Plains; Green – Montane Cordillera.

Spatial distribution in biomass, DOM, and total ecosystem carbon pools for three years (1990, 2010, 2020) are shown in Figures 13a-d for four parks with different disturbance regimes: Kouchibouguac NP, which was not affected by any measurable disturbances during this period (Figure 13a); Waterton Lakes NP, which was affected by a large wildfire in 2017 (Figure 13b); Pukaskwa NP, which was affected mainly by insect disturbances, some prescribed fires and very few small wildfires during the period (Figure 13c); and Prince Albert NP, which was affected by all three types of disturbances – wildfires, prescribed fires, and insects (Figure 13d).

In Kouchibouguac NP, due to the absence of any significant wildfires and insect outbreaks during the 1990-2020 study period, the biomass and ecosystem carbon density increased slightly in the park. The change in the density of different pools was gradual with no large transfers between carbon pools which, are typically associated with major disturbances (Figure 13a).

In Waterton Lakes NP between 1990 and 2010, some carbon in the biomass pool was transferred to the DOM pools as a result of insect disturbances with no significant changes in total ecosystem carbon (Figure 13b). In 2017, however, there was a large wildfire in the park (15,752 ha affected, i.e., 45% of the forest area in the park) which resulted in losses of living biomass but gains in DOM in the affected areas. These changes are evident in Figure 13b, panel 2020, with the areas of biomass carbon loss indicated in blue, and areas of DOM carbon gain indicated in red. A significant amount of biomass and DOM carbon was also lost through direct GHG emissions associated with the fires, resulting in lower ecosystem carbon stocks in those areas in 2020.

While forests in Pukaskwa NP were not significantly affected by wildfires, they were severely affected by spruce budworm during the late 1990s. Small biomass-to-DOM carbon transfers took place in the southern part of the park which was the most affected by spruce budworm (Figure 13c). Biomass carbon increased in other parts of the park that were less impacted by spruce budworm during 1990-2020. Ecosystem carbon stocks increased in the entire park between 1990 and 2020 (Figure 13c).

Prince Albert NP was affected by wildfires and spruce budworm outbreaks during the study period, and there were also prescribed fires in the park. Losses in biomass carbon in forests were observed over time on the northern side of the park, which was affected by fires, with small increases in DOM in those areas and in areas affected by insects (Figure 13d). As a result, ecosystem carbon stocks decreased in the northern side of the park, while gains in ecosystem carbon were observed in the southern side.

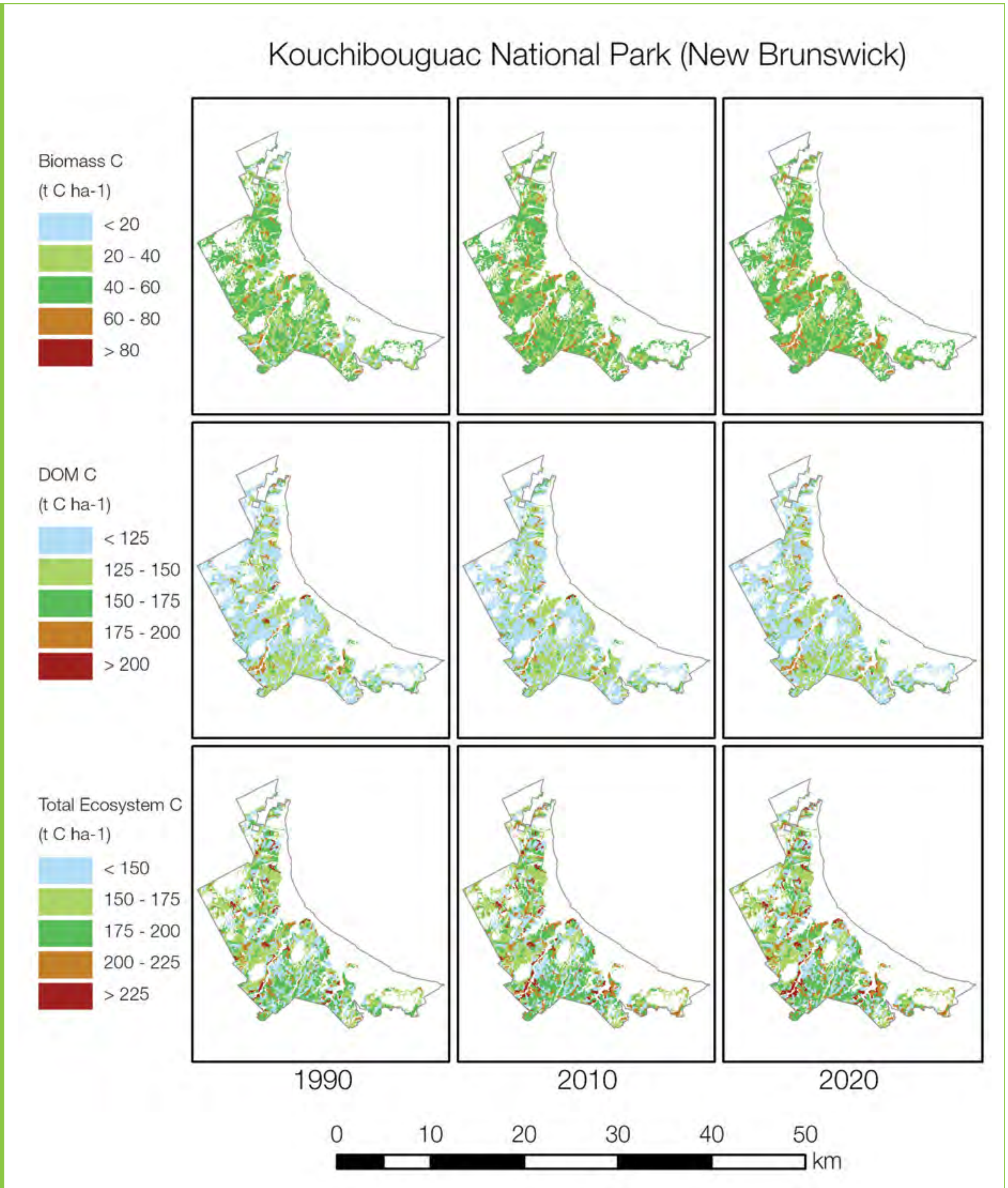


Figure 13a. Temporal changes in biomass, DOM, and total ecosystem carbon density (t C ha^{-1}) in forested ecosystems of Kouchibouguac NP (1990, 2010 and 2020).

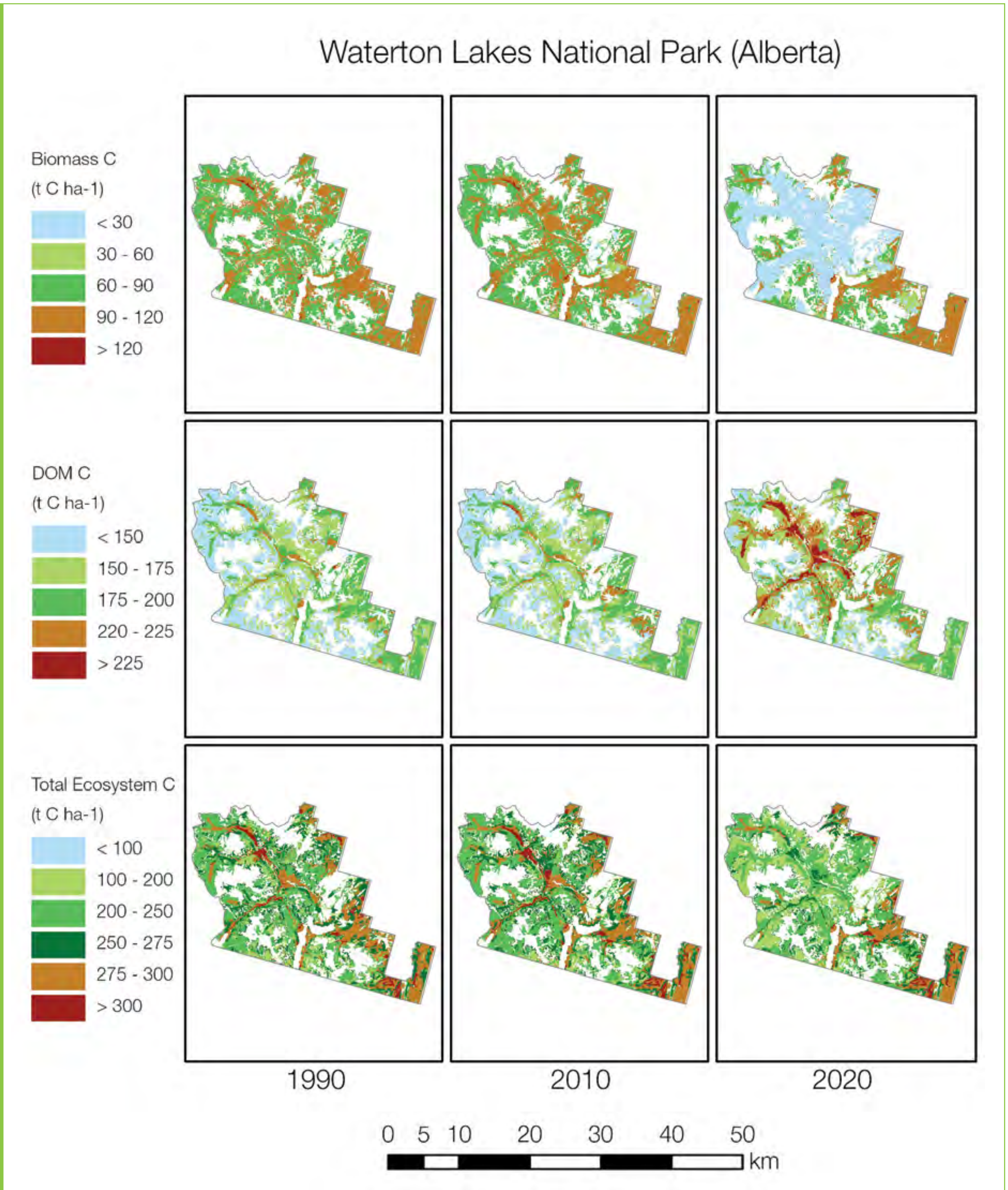


Figure 13b. Temporal changes in biomass, DOM, and total ecosystem carbon density (t C ha^{-1}) in forested ecosystems of Waterton Lakes NP (1990, 2010 and 2020).

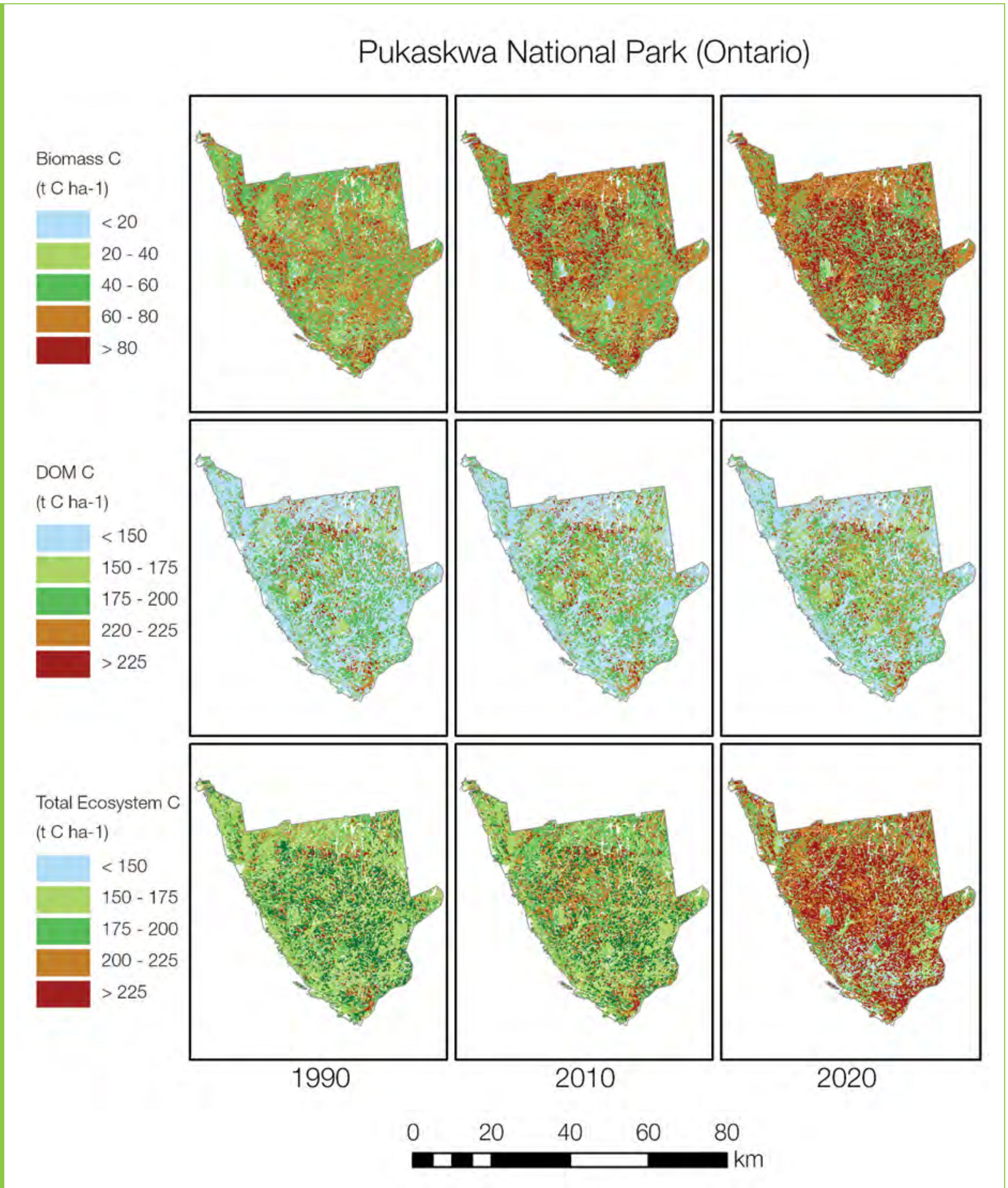


Figure 13c. Temporal changes in biomass, DOM, and total ecosystem carbon density (t C ha^{-1}) in forested ecosystems of Pukaskwa NP (1990, 2010 and 2020).

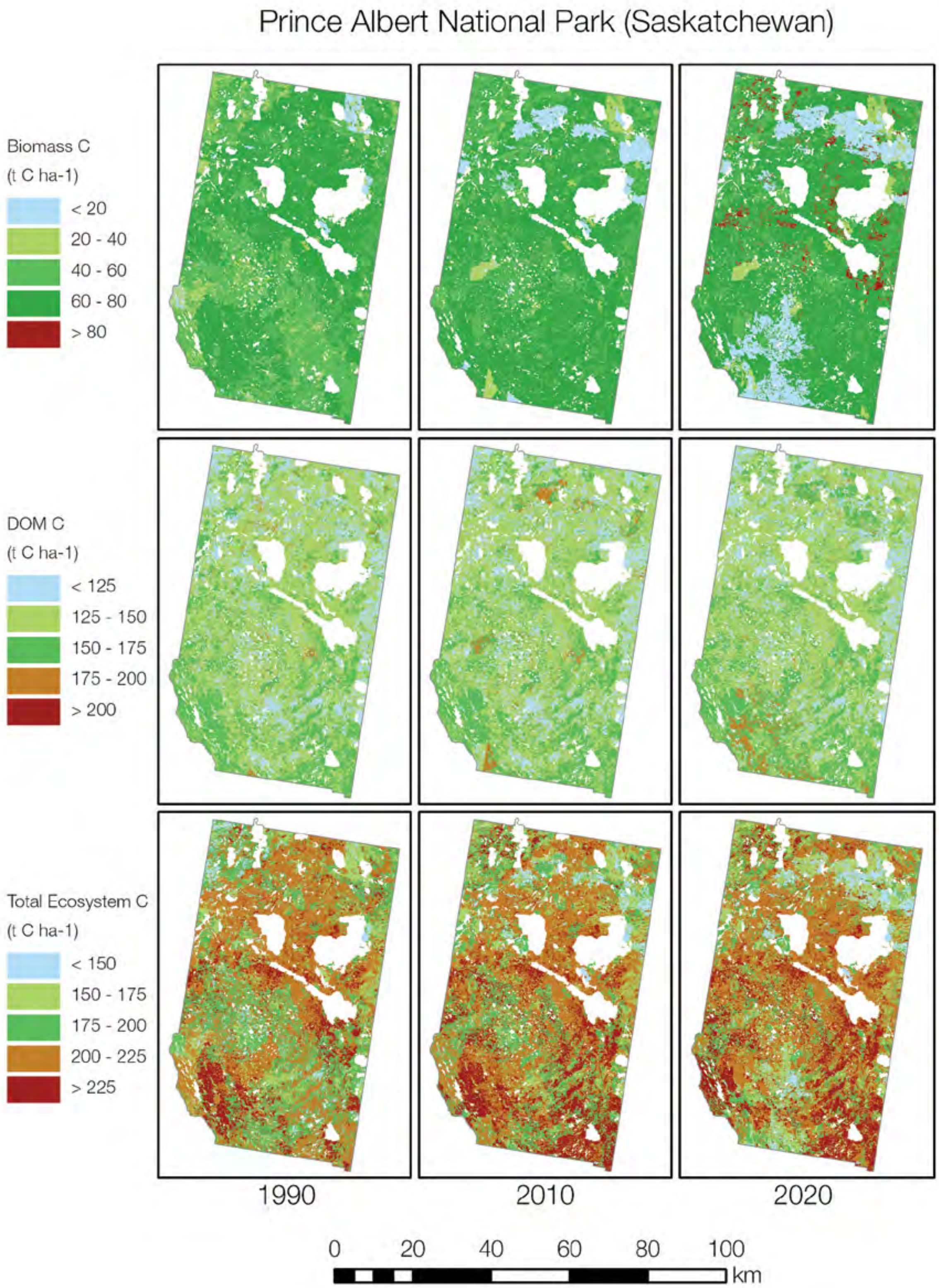


Figure 13d. Temporal changes in biomass, DOM, and total ecosystem carbon density (t C ha^{-1}) in forested ecosystems of Prince Albert NP (1990, 2010 and 2020).

3.2 Carbon Fluxes

3.2.1 Net Primary Production, Heterotrophic Respiration and Net Ecosystem Production

Aggregated results for the forested ecosystems in 31 national parks are summarised for the three main carbon fluxes – net primary productivity (NPP), heterotrophic respiration (R_h) and net ecosystem productivity (NEP) – in Table 6, and shown in Figure 14. The average amount of carbon sequestered annually from the atmosphere through net primary production (NPP) by all national parks was 21.7 Mt C yr^{-1} during the study period. Of this, an average of 19.3 Mt C yr^{-1} was lost to the atmosphere through heterotrophic respiration (R_h). Consequently, on average about 2.4 Mt C yr^{-1} (11%) of NPP accumulated in the ecosystem as net ecosystem productivity (NEP). Most of this NEP was subsequently lost through disturbances leaving an average of approximately 1% of NPP remaining as a fourth carbon flux, net biome productivity (NBP; Table 6), in the forest ecosystems of the 31 parks studied.

Table 6. Forest carbon fluxes and net GHG balance in 31 national parks (1990-2020). Standard deviations represent temporal variability and not statistical uncertainty.

	Indicator	Total Flux (Mt C yr^{-1})	Fluxes per Unit Area (t C ha^{-1} yr^{-1})
Fluxes	NPP	21.7 ± 0.02	3.86 ± 0.01
	R_h	19.3 ± 0.01	3.43 ± 0.01
	NEP	2.40 ± 0.02	0.42 ± 0.01
	NBP	0.22 ± 0.13	0.04 ± 0.02
	Indicator	**Mt CO_2e yr^{-1}**	**t CO_2e ha^{-1} yr^{-1}**
GHG	GHG[19]	0.20 ± 0.52	0.04 ± 0.09

There was little temporal variation in the total NPP for forested ecosystems in all parks during the study period, although it decreased slightly (by 1 Mt C) between 1990 and 2020, whereas R_h increased slightly over the same period (Figure 14). In our model, climate variables were held constant (see methods). Since temperature and water balance can affect both NPP and R_h, the actual temporal variability of these indicators may thus be higher than shown in these estimates.

19 GHG is measured as CO_2e based on IPCC AR4 GWP for CH_4 and N_2O)

Parks in the Mixedwood Plains ecozone had the highest overall NEP per unit area during the study period, followed by parks in the Boreal Shield East ecozone, while parks in the Montane Cordillera ecozone had the lowest NEP per unit area (Figure 15). Old-growth forests in Pacific Maritime ecozone parks contributed to very high annual carbon releases through decomposition (R_h) because their DOM pools were very large. As a result, even though they had the highest NPP, parks in this ecozone had low overall net annual accumulation of carbon. Forests in Montane Cordillera ecozone parks experienced disturbances more frequently and had high decomposition rates (R_h) during the study period, not only in the actual year of a disturbance but also in subsequent years. Consequently, these parks had lowest NEP per unit area. Forests in parks of the Mixedwood Plains ecozone had the lowest NPP but also lowest R_h across all ecozones, which resulted in these forests having highest NEP per unit area. Average NPP, R_h, and NEP values for each park during the study period are provided in **Appendix E**.

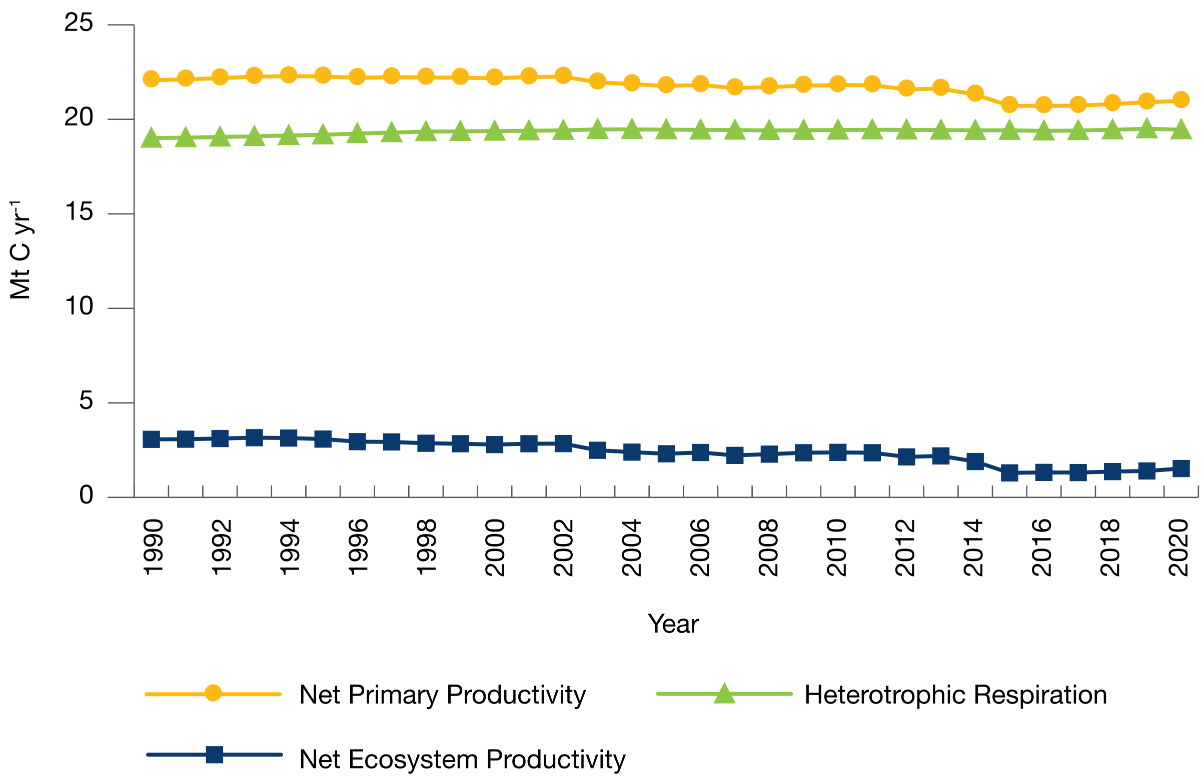


Figure 14. Temporal trend in carbon fluxes (measured as NPP, R_h, NEP) for forested ecosystems in all 31 national parks over the period 1990-2020.

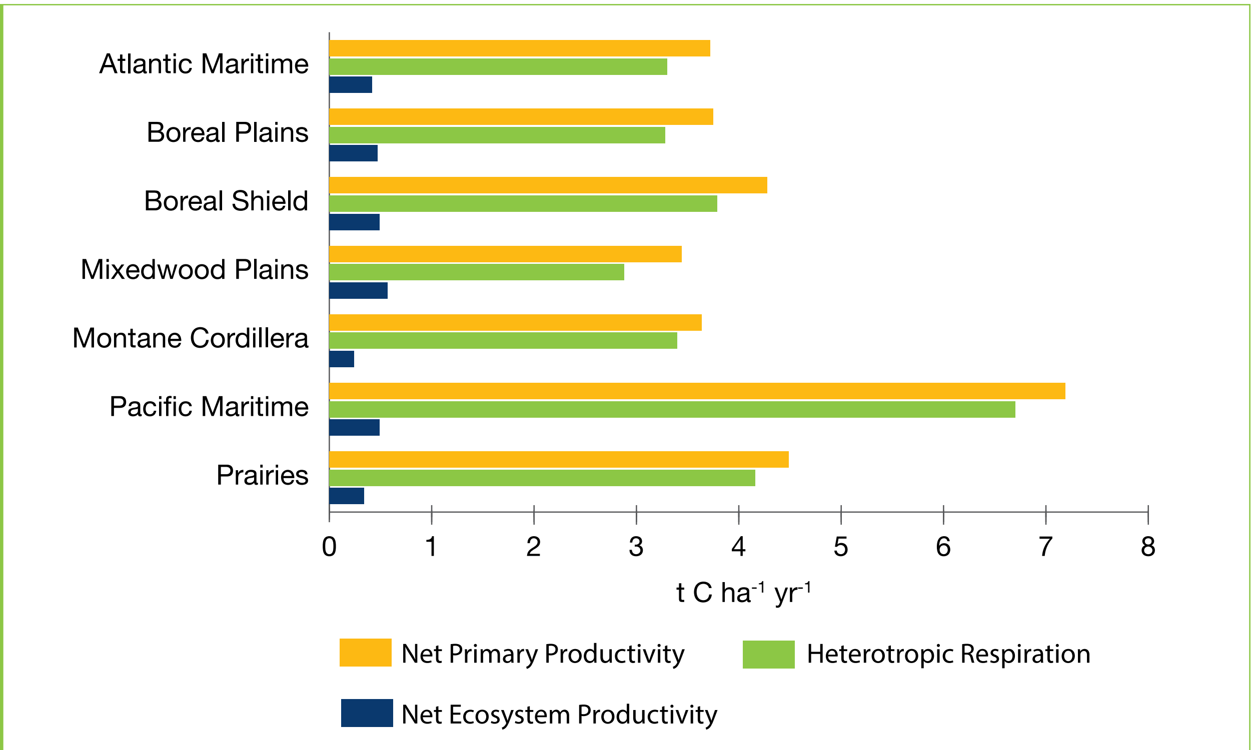


Figure 15. Carbon fluxes per unit area (average for 1990-2020) by ecozone.

Net ecosystem productivity is impacted by forest age and disturbances that affect the forest age-class structure. NEP increased for five parks over the study period (Figure 16a), three of which are found in the relatively undisturbed Pacific Maritime ecozone. NEP increased steadily in Gulf Islands NPR (Figure 16a), which had younger forests (median age 46 years in 1990) experiencing no measurable disturbances. Other parks in the same ecozone (Pacific Maritime) with older forests but no measurable disturbances (i.e., Pacific Rim NPR and Gwaii Haanas NPR, both with mean stand ages greater than 180 years in 1990) also showed an increase in NEP, albeit at a much lower rate than Gulf Islands NPR. For these parks, the rate of decomposition from natural processes (R_h) approached that of biomass production, which resulted in smaller rate of increase in NEP.

Net ecosystem productivity decreased between 1990-2020 for the parks that were affected more frequently by disturbances (Figure 16b). As expected, NEP decreased in the year in which a disturbance occurred and the magnitude of the decrease depended on the total area affected by the disturbance. NEP then increased after a few years to the point where biomass production (NPP) was greater than losses from decomposition (R_h; see Wood Buffalo NP example in Figure 17). Disturbances in a given year (such as wildfires that led to tree mortality) led to lower NPP in that year and to increased R_h, and result in low NEP values in the same year. Parks in Montane Cordillera ecozone were more frequently affected by fires after 2000 (e.g., Kootenay NP, Glacier NP, Yoho NP, Waterton Lakes NP), and consequently showed not only a continuous decline in

NEP values, but also negative NEP values during the study period. Decomposition rates in the forests of these parks were much higher than their biomass production, resulting in negative NEP values (e.g., Glacier NP, Waterton Lakes NP and Mingan NPR).

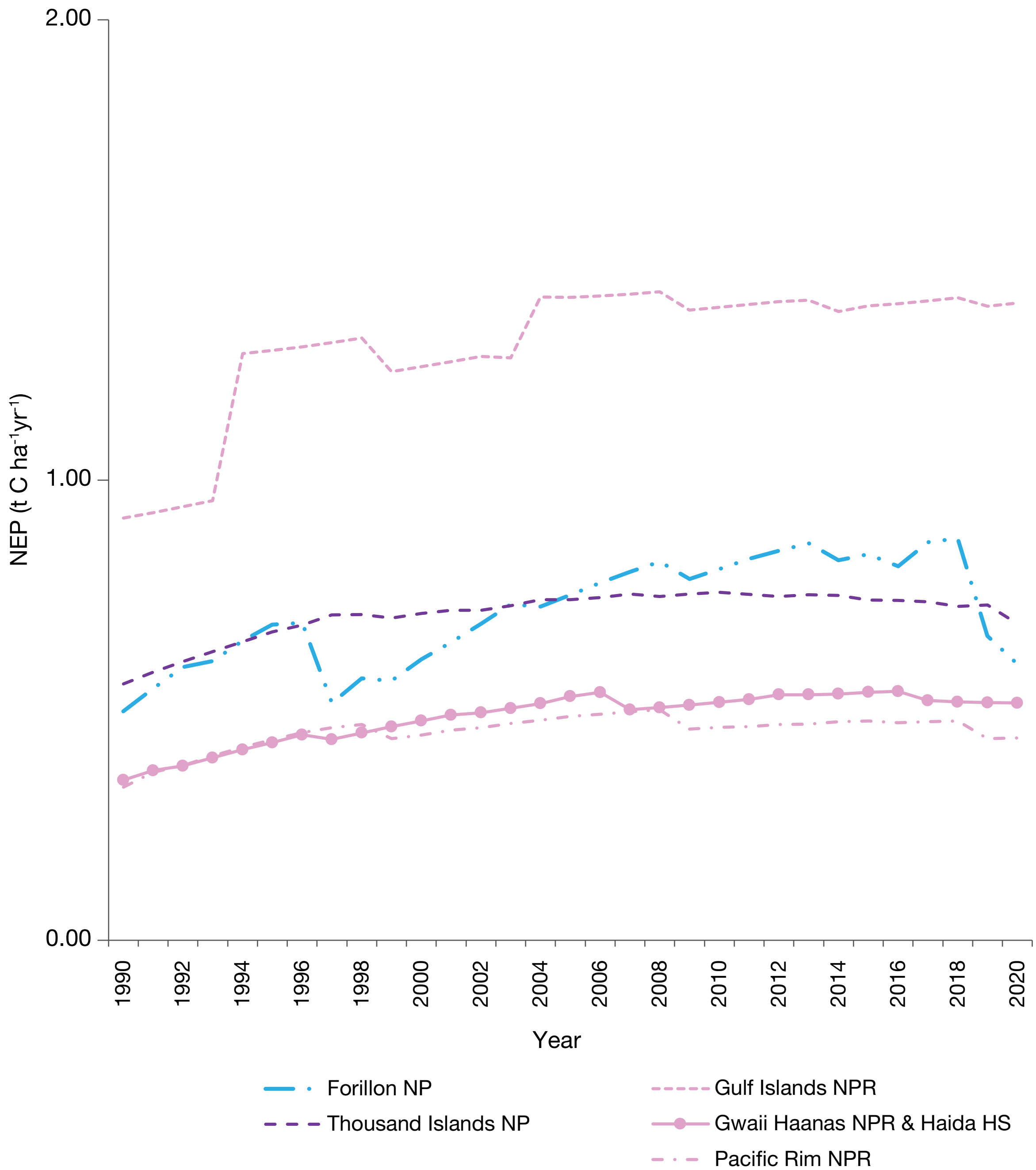


Figure 16a. **Net ecosystem productivity for 5 national parks that showed an increase over the period 1990-2020.** Parks are colour-coded by ecozone. Blue – Atlantic Maritime; Purple – Mixedwood Plains; Pink – Pacific Maritime.

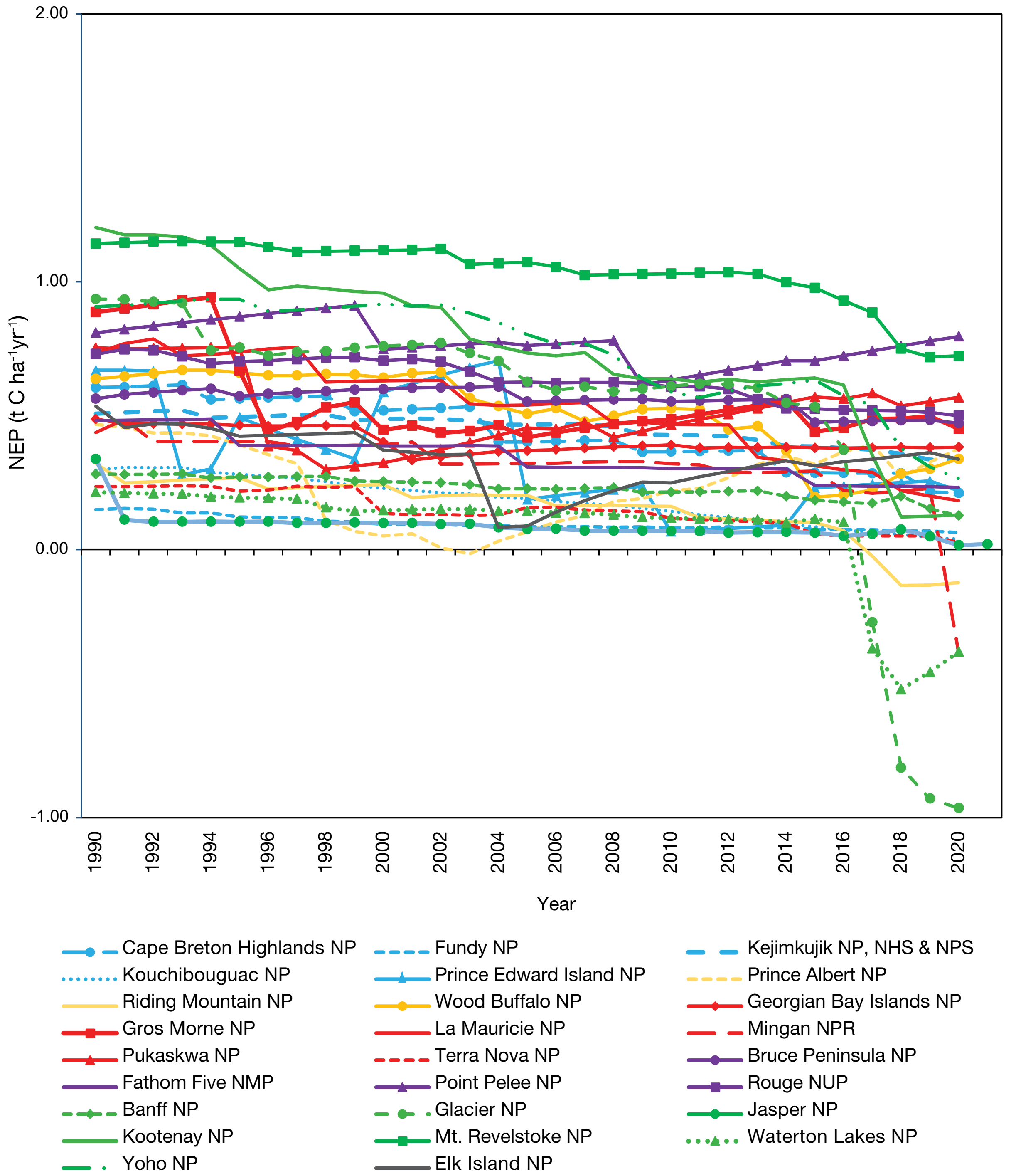


Figure 16b. **Net ecosystem productivity for 26 national parks that showed a decrease over the period 1990-2020. Parks are colour-coded by ecozone.** Blue – Atlantic Maritime; Yellow – Boreal Plains; Red – Boreal Shield; Purple – Mixedwood Plains; Green – Montane Cordillera; Grey – Prairies. Average NEP values by park are provided in Appendix E.

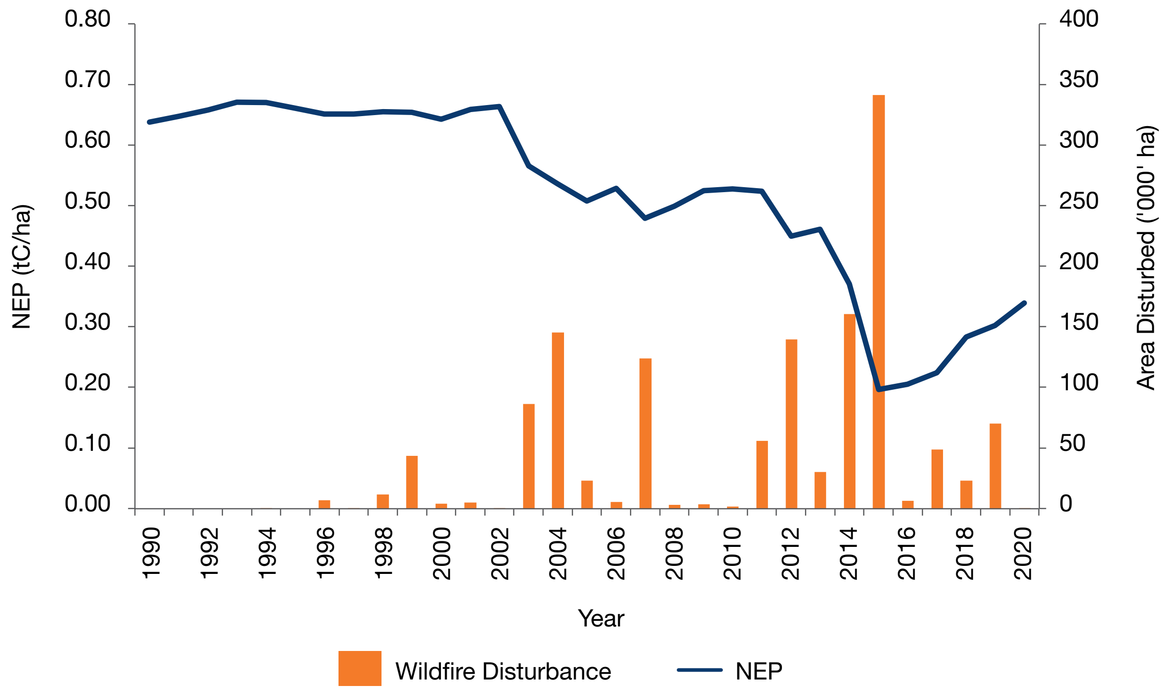


Figure 17. Impacts of changes in wildfire-disturbed area on net ecosystem productivity (NEP) for forested ecosystems in Wood Buffalo NP (1990-2020).

3.2.2 Effects of Disturbances on Carbon Fluxes

Wildfires were the source of the highest direct carbon releases to the atmosphere from disturbances (Table 7). Most of these carbon releases were from combustion of dead organic material during wildfires. Prescribed fires in parks also resulted in releases but these were small compared to those from wildfires. Emissions due to insect outbreaks were negligible compared to those from wildfires.

Table 7. Forest carbon fluxes and transfers (kt C) resulting from disturbances in 31 national parks (total for the period 1990-2020).

Disturbance Type	Direct carbon releases	Biomass carbon releases	DOM carbon releases	Biomass to DOM transfers
Wildfire	65,996	12,832	53,164	95,280
Insects	14	14	0	17,282
Prescribed Fire	1,495	287	1,208	1,180
Harvesting	0	0	0	1
Total	**67,505**	**13,132**	**54,372**	**113,742**

Note: 1 kt = 1000 tonnes

Transfers of carbon from biomass to DOM pools were the largest carbon fluxes from disturbances, with wildfires resulting in highest transfers of carbon to DOM (Table 7). Insect outbreaks resulted in substantive but smaller overall transfers of carbon from biomass to DOM. These transfers to DOM will contribute to future carbon releases from the decomposition or burning of dead organic matter. Among insects, mountain pine beetle and forest tent caterpillar in the west, and spruce budworm in the east contributed the most to transfers from biomass to DOM (assessed as 9 Mt C, 2.2 Mt C and 3.5 Mt C, respectively, over 31 years).

Transfers from biomass to DOM pools varied each year (Figure 18) depending on the area affected by disturbances, and were higher during years of large wildfire occurrences. (**Appendix F** provides area affected by disturbances for all 31 parks). The total area affected by wildfires each year during the study period increased significantly after 2002, resulting in increased transfers of carbon from biomass to DOM. Insect outbreaks affecting park forests increased significantly after 2003, again resulting in increased transfers from biomass to DOM.

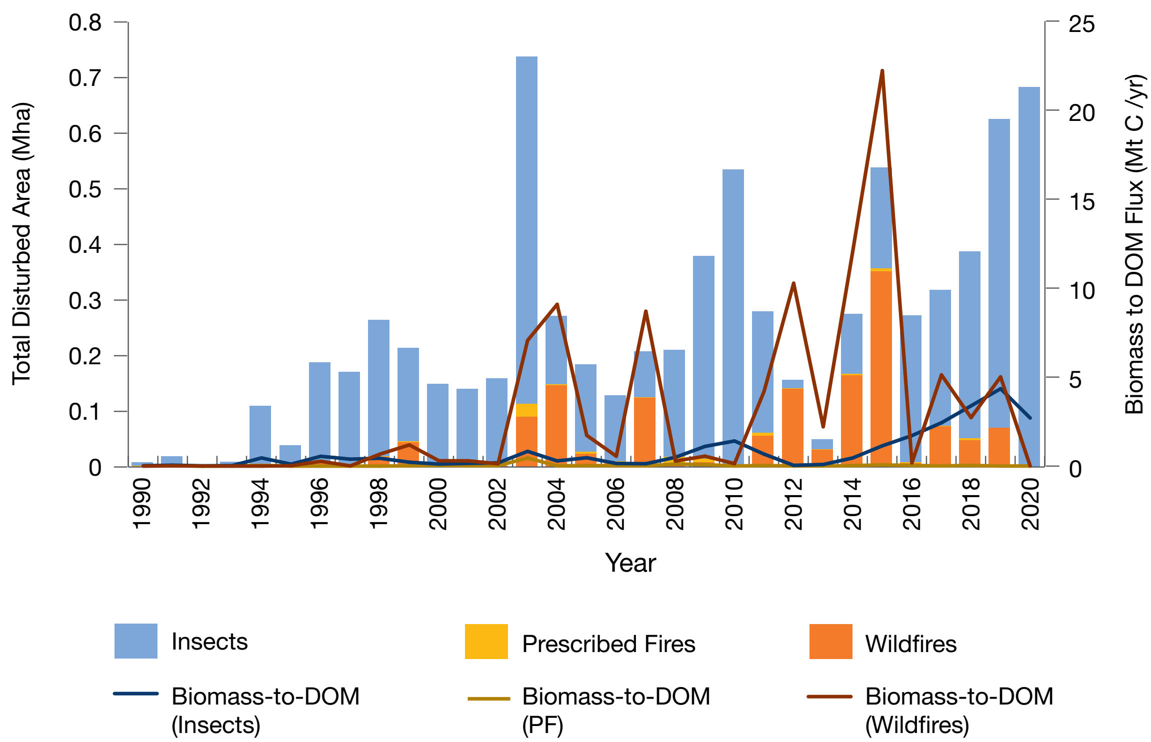


Figure 18. Biomass-to-DOM carbon transfers (right vertical axis) and area affected by wildfires and other disturbances in 31 parks (1990-2020). Insects-disturbed area refers to the total amount of new area affected in a given year. Bars represent area (Mha) affected by different types of forest disturbance (left vertical axis). Lines represent the biomass-to-DOM carbon transfer (Mt C yr^{-1}) for respective disturbance. PF = Prescribed Fire.

3.2.3 Net Biome Productivity

At the park level, total NBP during the study period was positive for forests in 29 parks, indicating they were carbon sinks. Only two parks, Wood Buffalo NP and Waterton Lakes NP showed negative total NBP during the study period, indicating that these sites were net sources of carbon (Figure 19). At the ecozone level, the Boreal Plains ecozone, which included the largest park area affected by frequent and large disturbances during the study, was the only ecozone that showed an overall negative NBP value, a result driven by the pattern observed at Wood Buffalo NP.

Annual NBP was predominantly positive for all parks that were affected by infrequent or small disturbances over the period 1990-2020 (Figure 20a). By contrast, annual NBP was negative in several years for parks that were affected by frequent or large disturbances, in particular, those in the Montane Cordillera and Boreal Plains ecozones (Figure 20b) that were affected by wildfires. **Appendix G** provides annual NBP values over the study period for each park assessed.

Overall, forested ecosystems in the 31 national parks were a small carbon sink, with a cumulative net biome productivity (NBP) of 6.8 Mt C and an average net carbon uptake of 0.22 Mt C yr^{-1} over the 31-year study period (Table 6; Figure 21). However, on an annual scale the 31 parks were a net source of carbon in nine different years (i.e., 2003, 2004, 2007, 2012, 2014, 2015, 2017, 2018, and 2019), releasing on average 4.1 Mt C yr^{-1} during those years (Figure 21). Cumulative NBP showed a fairly smooth pattern of rise-plateau-fall corresponding to three distinct periods in the time-series. From 1990-2002, annual NBP was positive and cumulative NBP increased on average 2.7 Mt C yr^{-1} across all 31 parks. During this period, there were relatively few disturbances in the parks and there was a net gain in carbon. From 2003-2011, annual NBP was positive in some years and negative in others, with cumulative NBP remaining more or less constant with minimal change overall (0.1 Mt C yr^{-1}). From 2012 onward there were large fluctuations in the annual NBP due to frequent disturbances, including large wildfires in 2 national parks in Alberta. As a result, cumulative NBP steadily decreased until 2020 (-2.4 Mt C yr^{-1}). Most of the carbon gained in the initial period (1990-2002) was subsequently lost by 2020 due to increases in fire and insect disturbances.

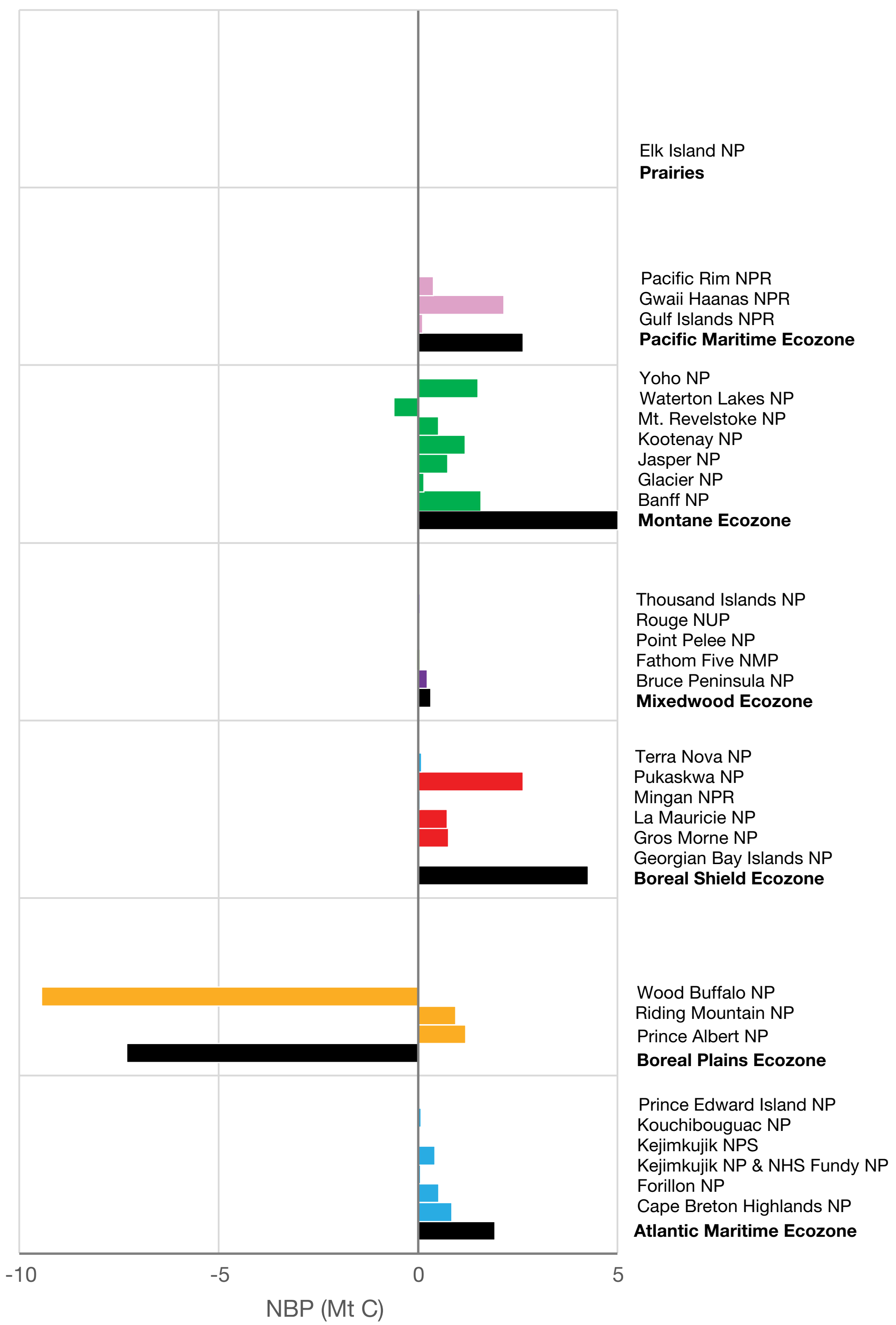


Figure19. **Total NBP for forested ecosystems, by park and ecozone over the period 1990-2020.** Parks are grouped by ecozone, with ecozone names in bold. Black bars represent the total NBP for the ecozone for each group. Positive values of NBP denote ecosystem carbon stock increases (net sinks) and negative values denote ecosystem carbon losses (net sources).

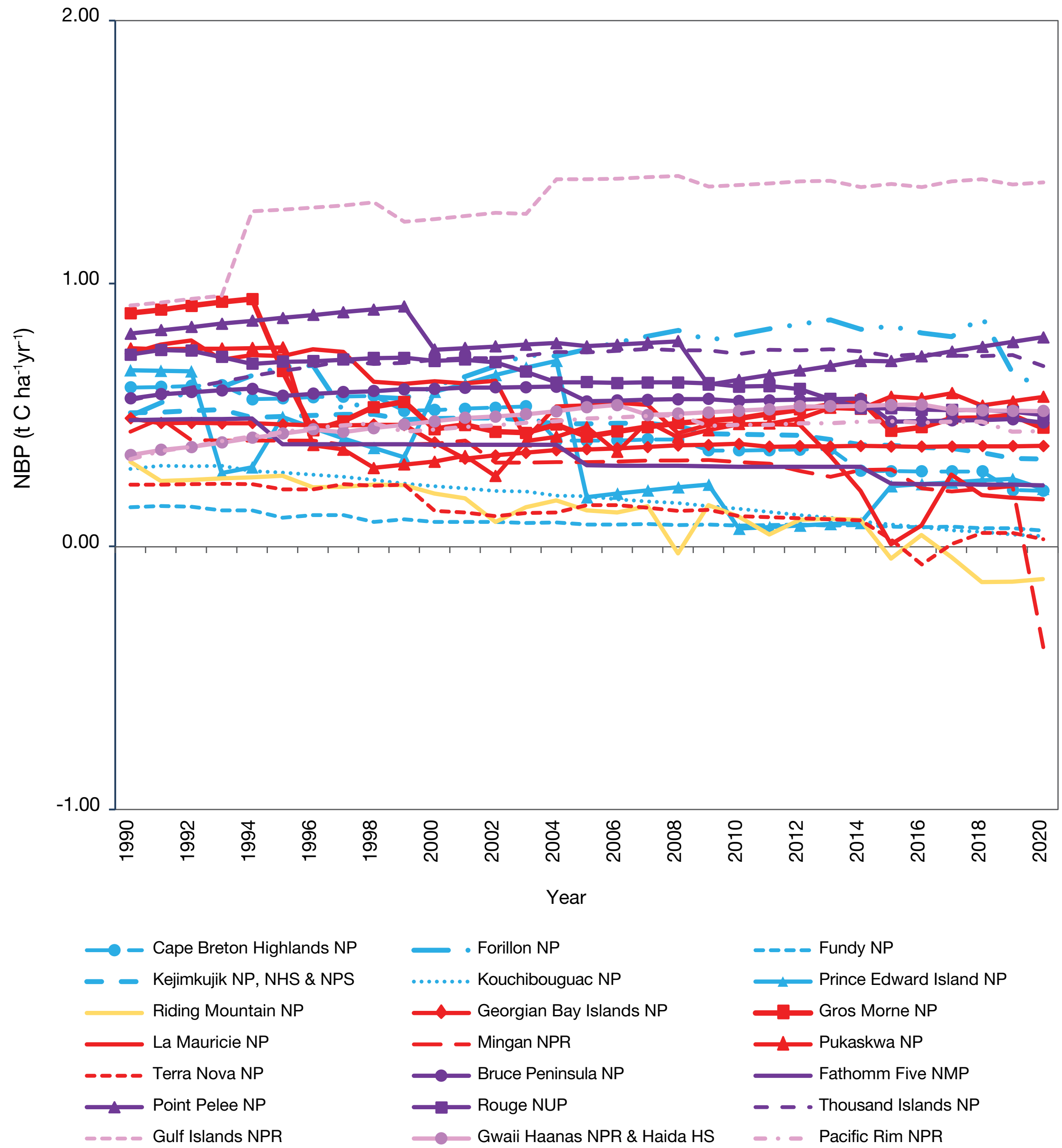


Figure 20a. **Net biome productivity for 21 national parks affected by infrequent or small disturbances over the period 1990-2020.** Parks are colour-coded by ecozone. Blue – Atlantic Maritime; Yellow – Boreal Plains; Orange – Boreal Shield; Purple – Mixedwood Plains; Pink – Pacific Maritime. Positive values of NBP denote ecosystem carbon stock increases (net carbon sinks) while negative values denote ecosystem carbon losses (net GHG sources).

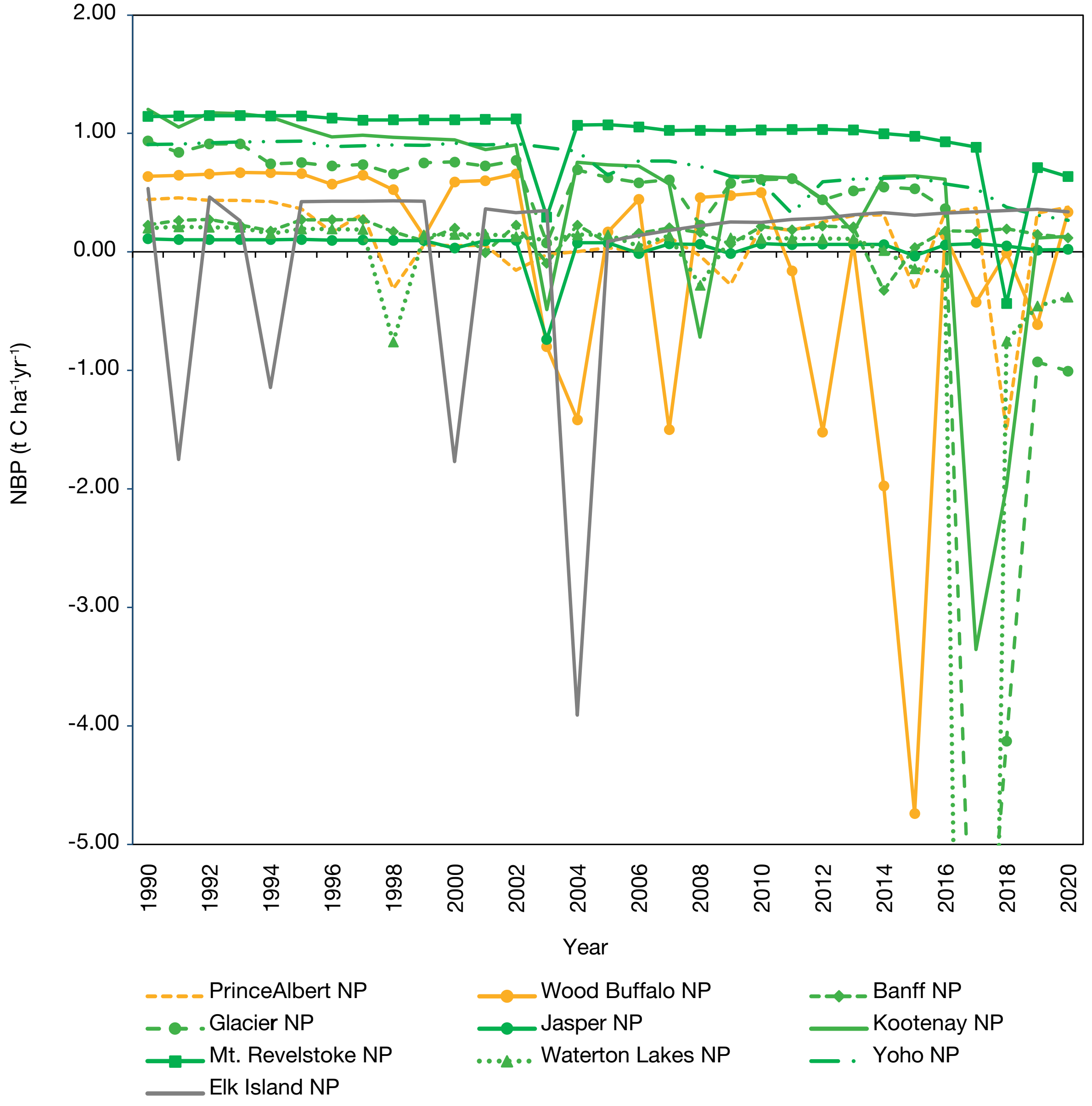


Figure 20b. **Net biome productivity for 10 national parks affected by frequent or large disturbances over the period 1990-2020.** Parks have been colour-coded by ecozone. Yellow – Boreal Plains; Green – Montane Cordillera; Grey – Prairies; Positive values of NBP denote ecosystem carbon stock increases (net carbon sinks) while negative values denote ecosystem carbon losses (net GHG sources).

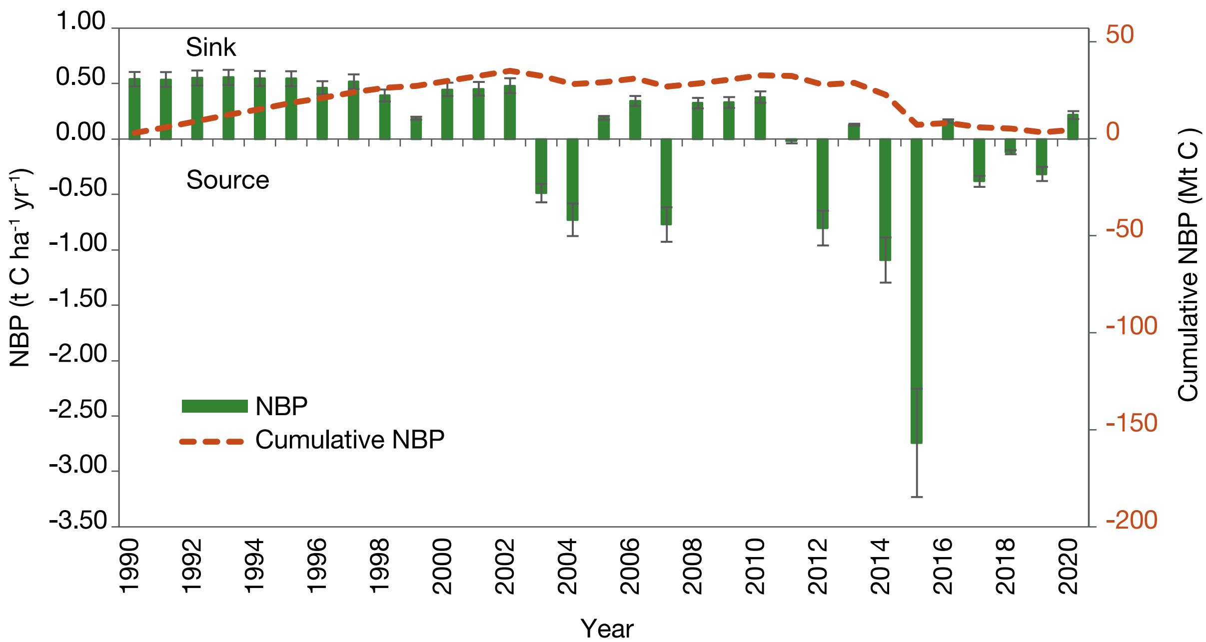


Figure 21. Annual variation in NBP (left axis) and cumulative NBP (right axis) for forested ecosystems in 31 parks over the period 1990-2020.

3.2.4 Greenhouse Gas Emissions

While NBP quantifies the net gain or loss of carbon in the ecosystem net GHG emissions (GHG balance) is the metric reported at a national scale following IPCC reporting standards. The GHG balance considers the global warming potential of each greenhouse gas, including CO_2, CH_4, CO, and N_2O, emitted through natural processes and disturbances, and is reported in units of carbon dioxide equivalents (CO_2e). Negative values represent removals (sinks) from atmosphere and positive values represent emissions (sources) into the atmosphere.

The forested ecosystems of 28 parks were net sinks of GHGs over the study period (Figure 22). The forests of Pukaskwa NP were the largest net sink of carbon (9.63 Mt CO_2e), removing on average 0.31 Mt CO_2e yr^{-1} from the atmosphere, while forests in the Gulf Islands NPR sequestered the most carbon per unit of forest area (4.74 t CO_2e ha^{-1} yr^{-1}) (Table 8). Two-thirds of the Gulf Islands NPR forest was less than 50 years old in 1990, which contributed to its high carbon sequestration rate as the young forest was in its maximum carbon uptake period. Similarly, two-thirds of the forest in Pukaskwa NP was between 50–70 years old in 1990. Because of its larger area, Pukaskwa NP sequestered more carbon overall than Gulf Islands NPR, even though its sequestration rate was lower than that of Gulf Islands NPR.

Forested ecosystems in three parks were net sources of GHG emissions during the study period – Wood Buffalo NP, Waterton Lakes NP, and Elk Island NP (Figure 22). Wood Buffalo NP was the largest source, emitting on average 2 Mt CO_2e yr^{-1} during the study period, while Waterton Lakes NP emitted on average more GHGs per unit area, 2.41 t CO_2e ha^{-1} yr^{-1}, than Wood Buffalo NP (0.62 t CO_2e ha^{-1} yr^{-1})(Table 8). Over 31 years, Wood Buffalo NP emitted approximately 63 Mt CO_2e of GHGs in total, while Waterton Lakes NP emitted 2.5 Mt CO_2e, and Elk Island NP released 0.05 Mt CO_2e of GHGs (Table 8).

At the ecozone level, forested ecosystems of Boreal Plains parks were together the largest emitters of GHGs, while those of Boreal Shield parks sequestered the greatest amount of carbon (Figure 22). This is expected since Wood Buffalo NP (largest source) and Pukaskwa NP (largest sink) represent approximately 60% of the area of these ecozones, respectively.

Overall, park forests were a carbon sink in 21 years and a net source of GHGs in ten years (i.e., 2003, 2004, 2007, 2011, 2012, 2014, 2015, 2017, 2018, 2019) when there were large wildfires in 10 parks (Figure 23). Looking at specific time intervals, cumulative carbon sequestration increased in the 31 parks studied from 1990 to 2002, with forests representing a net sink of about 10 Mt CO_2e yr^{-1}. Between 2003 and 2011, due to increases in natural disturbances, carbon sequestration and emissions alternated over this period and national park forests were a small net source of GHGs. They emitted an average of 2.0 Mt CO_2e yr^{-1} during this period. From 2012 to 2020 however, they were a larger source, and emitted on average 12.9 Mt CO_2e yr^{-1} due to further increases in disturbances. Cumulatively, over the 31-year study period, national park forests were a net source of 6.2 Mt CO_2e of GHGs.

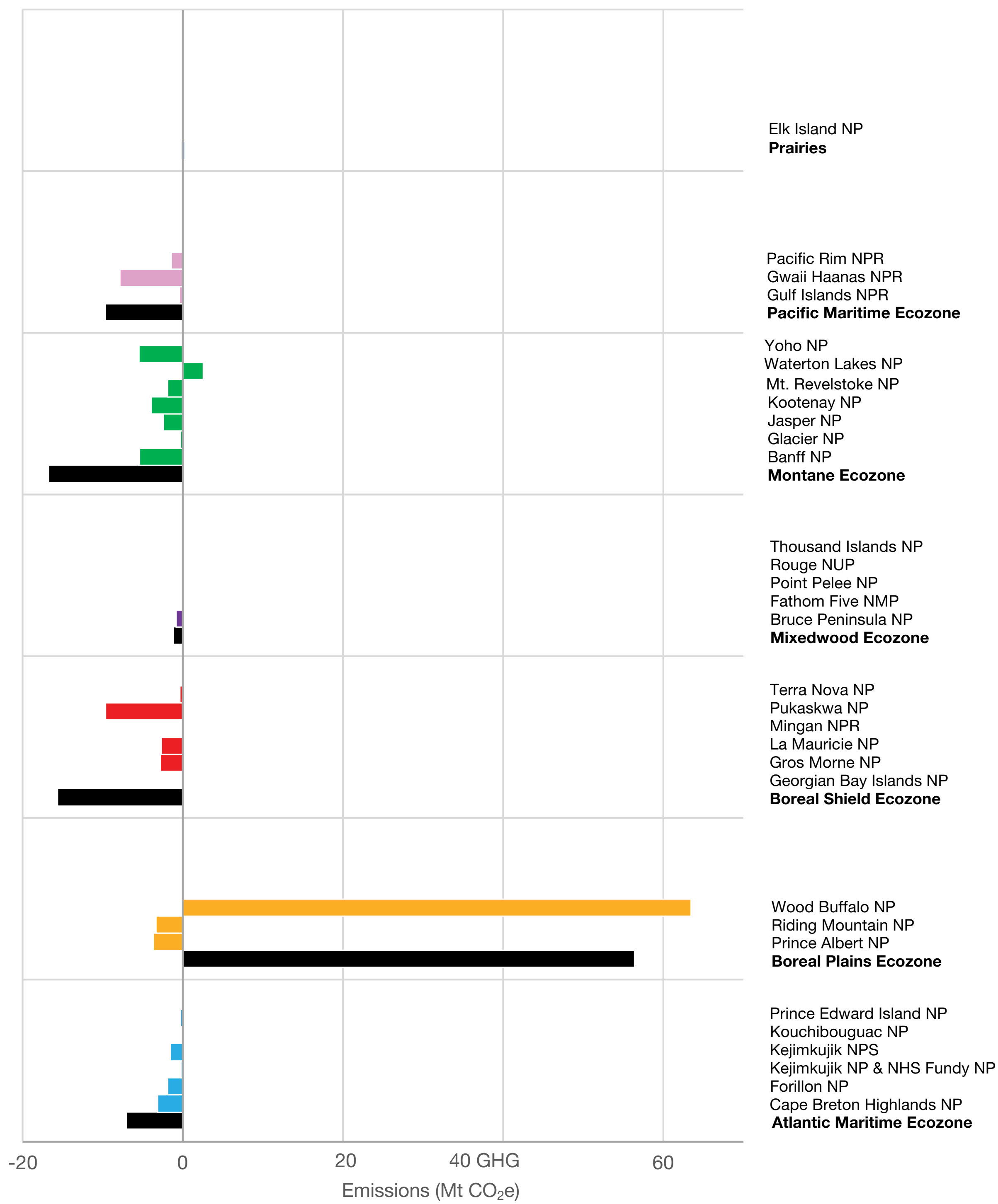


Figure 22. **Total GHG emissions (Mt CO_2e) from forested ecosystems, by park and ecozone for the period 1990-2020.** Parks are grouped by ecozone, with ecozone names in bold. Black bars show the total emissions for each ecozone. Negative values represent removals from atmosphere and positive represent emissions into the atmosphere.

Table 8. Total and average annual GHG emissions from forested ecosystems in 31 national parks

Ecozone	Park Name	Total GHG emissions (Mt CO_2e)	Annual GHG emissions (t CO_2e yr^{-1})	GHG emissions per unit area (t CO_2e $ha^{-1}yr^{-1}$)
Atlantic Maritime	Cape Breton Highlands NP	-3.11	-100,172	-1.61
	Forillon NP	-1.89	-60,887	-2.60
	Fundy NP	-0.22	-6,938	-0.36
	Kejimkujik NP & NHS	-1.54	-49,787	-1.61
	Kouchibouguac NP	-0.26	-8,307	-0.68
	Prince Edward Island NP	-0.03	-913	-1.28
Boreal Plains	Prince Albert NP	-3.69	-118,994	-0.34
	Riding Mountain NP	-3.36	-108,238	-0.45
	Wood Buffalo NP	63.45	2,046,651	0.62
Boreal Shield	Georgian Bay Islands NP	-0.05	-1,467	-1.49
	Gros Morne NP	-2.79	-89,879	-2.03
	La Mauricie NP	-2.65	-85,562	-1.81
	Mingan Archipelago NPR	-0.15	-4,909	-1.16
	Pukaskwa NP	-9.63	-310,722	-1.85
	Terra Nova NP	-0.32	-10,462	-0.51
Mixedwood Plains	Bruce Peninsula NP	-0.84	-27,105	-2.05
	Fathom Five NMP	-0.05	-1,711	-1.28
	Point Pelee NP	-0.02	-686	-2.84
	Rouge NUP	-0.14	-4,415	-2.33
	Thousand Islands NP	-0.11	-3,545	-2.58
Montane Cordillera	Banff NP	-5.36	-172,837	-0.54
	Glacier NP	-0.32	-10,277	-0.27
	Jasper NP	-2.38	-76,865	-0.14
	Kootenay NP	-3.94	-127,009	-1.55
	Mount Revelstoke NP	-1.85	-59,762	-3.53
	Waterton Lakes NP	2.55	82,178	2.41
	Yoho NP	-5.47	-176,563	-2.66
Pacific Maritime	Gulf Islands NPR	-0.39	-12,572	-4.74
	Gwaii Haanas NPR & Haida HS	-7.85	-253,307	-1.77
	Pacific Rim NPR	-1.39	-44,881	-1.66
Prairies	Elk Island NP	0.05	1,493	0.12
TOTAL		**6.25**	**201,549**	**0.04**

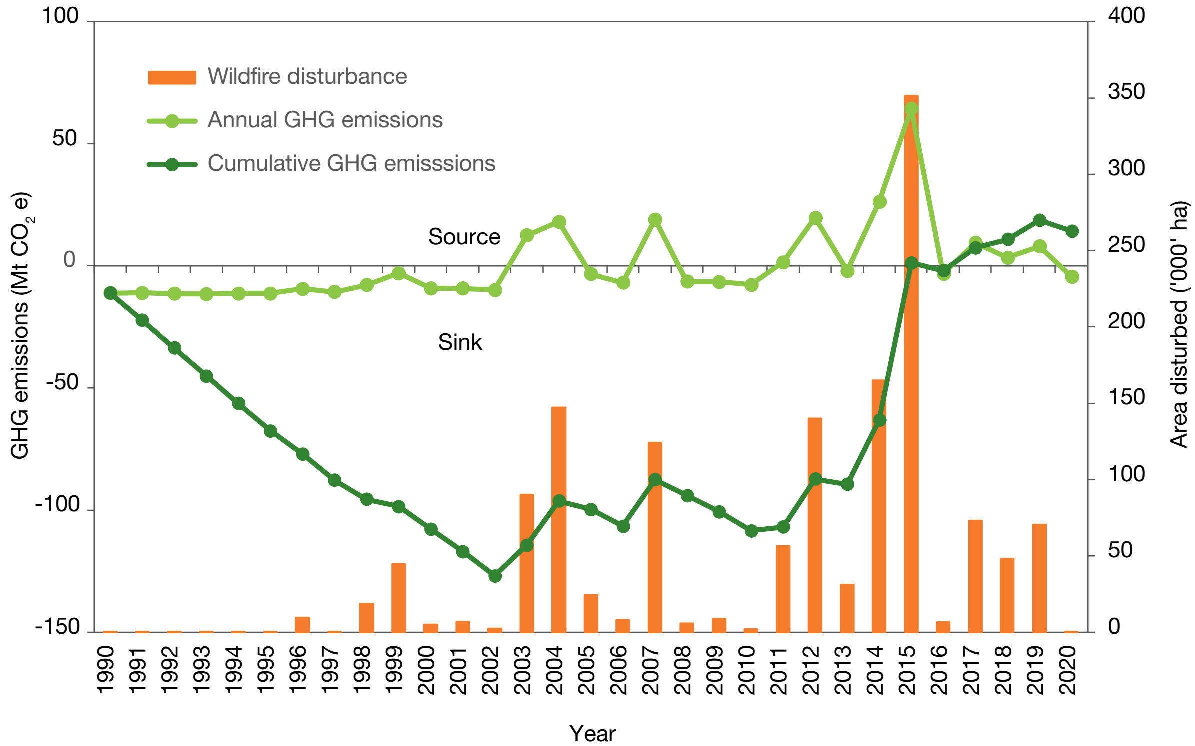


Figure 23. **Annual and cumulative net GHG emissions (Mt CO_2e) for forested ecosystems, and wildfire-affected areas, for all 31 national parks over the period 1990-2020.** Negative values represent net removals of atmospheric carbon, while positive values represent net GHG emissions into the atmosphere.

Photo: M. Hamel / ©Parks Canada / La Mauricie National Park

Chapter 4: Discussion

In this study, we present the results of the first installment in the Parks Canada Carbon Atlas Series, a suite of studies to assess the carbon storage and dynamics, where possible, of major ecosystems found within national parks across Canada. This study focused on forested ecosystems across 31 parks, including estimation of the impacts of natural disturbances on carbon storage and GHG emissions. We discuss below, in sequence, carbon stocks and density, carbon fluxes, and GHG emissions, in each case considering status and trends through the 31-year period covered by our study. We then identify the potential limitations of our study and present some implications of our findings for the stewardship of protected and conserved areas in Canada.

4.1 Spatial Distribution of Carbon Stocks and Densities

Collectively, this study estimated that forests in 31 of Canada's national parks contain 1,452 Mt C, equivalent to the annual emissions from 1.16 billion vehicles[20]. This is lower than the 2,419 Mt C estimated by Kulshreshtha et al. (2000), however, that estimate was based on additional carbon pools in 39 national parks across Canada and included other ecosystems such as grasslands (plant biomass), peatlands (plant biomass), and relatively carbon-dense regions in Arctic parks (soil carbon). Our study focused on temperate and southern boreal forested areas but excluded forested areas within the seven national parks in the Yukon, the Northwest Territories, and Newfoundland and Labrador, due to lack of data. Inclusion of these northern parks would likely have increased our carbon stock estimates, but by how much is unknown given the different biophysical factors influencing forests in those sub-arctic ecozones.

Forests in the 31 national parks assessed were estimated to have a mean carbon density of 258 t C ha-1 (range 150-477 t C ha-1), averaged across sites and years during the study period. This is higher than the average density of 170 t C ha-1 estimated by Kulshreshtha et al. (2000) for protected areas in Canada. The disparity likely results from their inclusion of grassland and peatland carbon pools alongside forests in the calculations, and from incomplete input data on forest inventory and land cover, as reported by the authors. Our estimate is also higher than the 220 t C ha-1 estimate reported by Stinson et al. (2011) for managed forests in Canada for the period 1990-2008. The difference can largely be explained by the fact that national parks are not subject to large-scale timber harvesting and, as a result, typically contain older, more carbon-dense forests than surrounding unprotected or differently managed landscapes.

Another indication of higher forest carbon density in national parks compared to surrounding forests is demonstrated through carbon density estimates at the ecozone scale. The carbon densities for different pools we report in this study were similar but consistently higher than those observed in previous research focused on broader forested landscapes encompassing protected areas and various other land uses. Total ecosystem carbon densities were similar to previous studies in the Boreal Plains ecozone (251 t C ha-1 compared to 230 t C ha-1 estimated by Kurz et al., 2013). For parks in the Mixedwood Plains ecozone, our biomass carbon density estimates of 45-64 t C ha-1 were in line with those obtained by Chen et al. (2010) of 52 t C ha-1 for all forests of Ontario using the FORCARB model. Finally, our soil carbon density estimates for the Boreal Plains and Boreal Shield East ecozones were consistent with previously reported estimates for boreal forest soils (93 t C ha-1 from Jobbagy & Jackson, 2000; 96 t C ha-1 compared to 86 t C ha-1 from Stinson et al., 2011). As observed for carbon densities at the park or site-scale, our estimation of higher carbon densities at the ecozone scale was likely due to a lack of harvesting and, thus, the inclusion of older and more carbon-dense stands.

20 Source: EPA Greenhouse Gas Equivalencies calculator https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

Large differences were observed in forest carbon stocks and densities between different ecozones, reflecting differences in forest age and type, site characteristics, and disturbance regimes among these regions. Site characteristics vary by ecozone and are influenced regionally and locally by relatively "definitive and enduring" biophysical characteristics and the relationships between them (Wiken et al., 1996). These characteristics are accounted for in how the GCBM simulates forest growth and productivity over time based on the input data provided. For example, the Pacific Maritime ecozone is characterized by older forest stands, long warm and wet growing seasons, and infrequent natural disturbances, resulting in high biomass production (Wiken et al., 1996) and consequently yielded the highest estimated total ecosystem carbon density of all the ecozones (also reported by Smithwick et al., 2002; Sothe et al., 2022; Stinson et al., 2011; Trofymow & Blackwell, 1998; Trofymow et al., 2008). These old-growth forests also had the highest DOM carbon density (244 t C ha-1). The forests in this ecozone, including coastal temperate rain forests, showed the highest root and leaf litter production as well as accumulation of coarse woody debris per unit area, which contributed to increased DOM carbon density. Conversely, national park forests in the Mixedwood Plains ecozone were estimated to have the lowest densities of biomass and total ecosystem carbon of all ecozones. Ecosystem carbon density was only slightly higher for park forests in the Atlantic Maritime ecozone. Parks in both these ecozones contain relatively shallow, nutrient-poor soils limiting vegetation growth and productivity, resulting in low biomass densities (Wiken et al., 1996) and low ecosystem carbon densities.

In the forests we studied, the proportion of carbon stored in different pools varied across ecozones, as expected from the patterns observed in previous studies (e.g., Stinson et al., 2011). This was mainly due to differences in disturbance regimes between ecozones. Our results for parks in the Pacific Maritime ecozone aligned with previous research (Trofymow & Blackwell, 1998), where we estimated an above-average proportion of total carbon in forest biomass pools (i.e., 44%, compared to an average of 28 % across the ecozones assessed) due to infrequent natural disturbances. In contrast, we found below-average amounts of carbon (26%) in biomass pools and above-average (74%) in DOM pools for parks in the Boreal Plains ecozone. Forests in this ecozone were affected more frequently and widely by natural disturbances than park forests in other ecozones, resulting in large transfers of biomass carbon to DOM carbon pools, over half of which was to soil carbon.

4.2 Temporal Trends in Carbon Stocks and Density

In most forested areas of the parks studied, carbon stocks increased consistently at a slow rate. Twenty nine of the 31 parks studied contained higher forest ecosystem carbon stocks in 2020 than in 1990. The magnitude of increase in carbon stocks was associated with the age of the forests and the extent of natural disturbances impacting them. Older forests experiencing fewer natural disturbances accumulated less carbon than younger forests. For example, in the Pacific Maritime ecozone, Pacific Rim NPR, with a median forest age of 221 years in 1990, accumulated less carbon per hectare over the study period than the forests of Gulf Islands NPR, which had a median age of 46 years in 1990. Similarly, Glacier NP forests (median age 164 years in 1990), which were the oldest in the Montane Cordillera ecozone, accumulated less carbon than the forests of other parks in this ecozone. In their study of three mountain parks, Sharma et al. (2013) observed a similar pattern between forest age and changes in ecosystem carbon density over time. In their study of Pacific Northwest forests, Gray et al. (2016) reported that the decline in carbon accumulation rate with stand age was primarily due to increased decomposition-related losses of dead wood. Our results appear to reflect that finding, whereby the increase in carbon stocks over the study period was relatively small in parks such as Glacier NP (median age 164 years in 1990) where decomposition losses in dead wood were higher, almost nullifying the carbon sequestration in that park in those years.

In sharp contrast with the other 29 parks, forest carbon stocks in Waterton Lakes NP and Wood Buffalo NP notably decreased in the second half of the study period. These decreases were associated with increases in wildfire frequency and area burnt by wildfires, which converted the accumulated carbon stock gains into losses from the forested ecosystems. Over 16,000 hectares of forest were burnt in Waterton lakes NP in 2017, and over 1.3 million hectares in Wood Buffalo NP from 2002 to 2020. Substantial GHG emissions from these wildfires surpassed the estimated carbon sequestration during those years, resulting in a net decrease in carbon stock over the entire study period. The decrease in carbon density over time was greater for Waterton Lakes NP as 50 % of its forest were burnt in one year compared to 2% per year in Wood Buffalo NP.

The cumulative effect of carbon accumulation and losses across all parks in our study was that overall forest carbon stocks increased in parks over the first third of the study period (1990-2002) and remained more or less constant from 2003 to 2011. They then decreased thereafter, reaching a level slightly higher than the 1990 value by 2020. Forested ecosystems within national parks therefore remained a carbon sink for the 31-year period assessed (netting a gain of 6.8 Mt C over time), but as more parks experience increased disturbances associated with future climate change (e.g., Boulanger et al., 2013), national park forests are likely to become a carbon source.

4.3 Carbon Fluxes and GHG Emissions

Beyond gradual changes in respiration and decomposition rates as ecosystems mature, disturbances drive the major or sudden shifts in forest carbon and GHG dynamics (e.g., Giles-Hansen & Wei, 2022; Kurz et al., 2008a). In Canada's national park forests, our modeling results indicated that wildfires were by far the most important driver determining whether parks were a net source or sink of GHGs, both at the site level and aggregated at the national level. Our results further indicated that prescribed fires and insect outbreaks also contributed to changes in forest carbon dynamics, through direct and indirect emissions. These results are consistent with multiple previous studies focused on the impact of disturbances on temperate and boreal forest ecosystems (see a review by Thom & Seidl, 2016).

Wildfire impacts on carbon dynamics are significant not only as they lead to carbon losses in the year of occurrence, but also because they substantially impact forest productivity and releases of carbon from decomposition of DOM for years after each fire event. For example, national park forests affected by wildfires showed low NEP in the year of fire and several years post-fire (Figure 18, curve for Wood Buffalo NP, years 2015 to 2017) due to the negative NEP of fire-affected stands. NEP for the park then increased slowly due to post-fire regeneration of forest stands, a finding that is consistent with earlier studies (e.g., Amiro et al., 2010). Recent wildfires (i.e., post-2017) that occurred in some of the studied parks would likely affect carbon dynamics at those sites for several more years, initially through emissions resulting from decomposing burnt biomass, and then through increasing carbon sequestration through the establishment and continued growth of young trees.

The absence of large, stand-replacing wildfires in 28 parks during the study period made them net carbon sinks over time. Nonetheless, several of those parks were annual sources of carbon in the years when they were most affected by large natural disturbances, demonstrating the effect of site-level interannual variability in the area affected by natural disturbance on carbon fluxes and GHG emissions.

In contrast, the forests of Wood Buffalo NP, Waterton Lakes NP, and Elk Island NP were overall net sources of GHG emissions during the study period. Emissions from relatively frequent and large fires in the boreal forests of Wood Buffalo NP made the park a net source in multiple years. In contrast, the Montane Cordilleran forests of Waterton Lakes NP were a carbon sink each year until 2017, when the large Kenow wildfire event resulted in a significant one-time forest loss and associated high GHG emissions, nullifying that site's carbon gains over previous decades, and converting the park into an overall net source of GHGs late in the study period (see Figure 23). In 2004, a single large wildfire event in the forests of Elk Island NP, on the northern edge of Prairie ecozone, resulted in high GHG emissions that slightly surpassed the park's carbon sequestration in all other years, causing Elk Island NP forests to be a small net source of GHGs. Several authors have previously discussed the role of historic fire suppression and exclusion, settlement patterns, and other land-use changes as the key factors that altered the natural fire regime in Canadian temperate and boreal forests (e.g., McGee et al., 2015; Wang et al., 2022; White et al., 2011). Climate change is now known to further contribute to changes in forest disturbance regimes (for example, in wildfire regimes: see Halofsky et al., 2020 for an assessment of the Pacific Northwest; Seidl et al., 2020 for a global analysis). Changing climatic conditions are also contributing to a decrease in forest resiliency to disturbances (Forzieri et al., 2022), however, this finding is biome specific, with boreal forests showing an increase in resiliency (see also Johnstone et al., 2010). Stevens-Rumann et al. (2017) found climate change affected post-fire recovery of forests, with impacts ranging from declining regeneration, changes in species composition and density, and potential conversion to non-forested states.

A full and detailed understanding of the impacts of fire on forest carbon dynamics requires fine-scale data on the severity and type of fire affecting the forests studied (Wiedinmyer & Neff, 2007). In our study, wildfire severity was held constant because we lacked consistent data for multiple parks over time. This led to uncertainties in estimates of fire-related carbon transfers and emissions, likely resulting in an underestimation of GHG emissions in years of major fires. Notwithstanding this methodological bias, emissions from just two parks, Wood Buffalo NP and Waterton Lakes NP, outweighed the combined forest carbon sequestration in the other 29 parks, resulting in park forests being a net GHG source at the national level over the 31-year study period. The relatively recent fires in Wood Buffalo NP and Waterton Lakes NP not only highlight how large disturbances can convert individual parks into net sources of GHGs, but also how disturbances in one large park or region can significantly impact the GHG balance of all national parks combined.

Prescribed fire is an ecosystem management tactic that seeks to address forest health and ecosystem integrity issues associated with historic fire suppression and exclusion, in addition to reducing the conditions for and likelihood of severe wildfire events that could damage communities and infrastructure (Wang et al., 2022; White et al., 2011). Prescribed fires in the parks we studied also resulted in GHG emissions, but these represented only about 2% of the total GHG emissions from wildfires during the study period. In our modeling, we assumed that areas affected by prescribed fire disturbances experienced a 50-50 split of surface and crown fire, respectively. Although this assumption is valid for some parks (V. Kafka, personal communication, August 2020), it may have resulted in a small overestimation of emissions for other parks where prescribed fires were almost exclusively surface fires. Thus, if anything, this methodological bias reinforces our conclusion that prescribed fires during this study period contributed little to the overall carbon balance of Canada's park forests.

Insect outbreaks affected relatively large areas (Appendix F) and resulted in large carbon transfers from biomass to DOM pools, due to tree mortality and subsequent decay (see also Dymond et al., 2010; Kurz et al., 2008b; Sharma et al., 2013). These transfers toward DOM pools have the potential to lead to GHG releases through decomposition or wildfire over time (Raffa et al., 2008; Sharma et al., 2013). Nevertheless, our results indicate that insect outbreaks, like prescribed fires, as accounted for in our study resulted in small direct GHG emissions compared to wildfires. Two factors may have led us to underestimate GHG emissions from insect outbreaks. First, although we considered the 13 insect species that had the greatest potential to impact forests in national parks, small areas were affected by other insects in some parks, resulting in some unaccounted-for emissions. Second, no usable forest health data were available for some parks (e.g., Cape Breton Highlands NP) preventing consideration of insect outbreak in our GCBM simulation for those sites. However, because each factor only affected a small fraction of the total area under study, their combined impact should have only resulted in a small underestimation of the actual emissions resulting from insect outbreaks. Our conclusion that wildfires, not insect outbreaks, drove the carbon and GHG emissions dynamics of Canada's national parks forests between 1990-2020 thus remains valid.

Our results highlight an important distinction when reporting ecosystem carbon fluxes and GHG emissions. Although the overall NBP of the forests we studied was net positive, indicating that they were a net sink of carbon over time, their calculated GHG emissions in CO_2-equivalent over the same time period led us to conclude that they were a net source of GHGs. This is because GHG emissions during wildfires include non-CO_2 emissions such as methane (CH_4) and nitrous oxide (N_2O) gas, which have much higher global warming potentials than CO_2. Thus, the GHG emissions from large wildfires in the system we studied, calculated in CO_2-equivalent, ended up being higher than the amount of carbon sequestered and recorded as NBP.

Forest ecosystem carbon and GHG dynamics can provide insights into the potential role of protected areas as nature-based solutions for climate change mitigation and how this role may vary over space and time. Collectively, the forests of Canada's national park system were a net source of GHG emissions over the period 1990-2020. However, this status shifted over time from being a net sink of GHG every year between 1990 and 2002, to alternating between being a small net sink or a small net source annually between 2003 and 2011, to becoming an overall larger net source thereafter. A similar shift has also been reported for portions of Canada's managed forests, for example the Montane Cordillera, which converted to net sources of GHGs after 2002 (Kurz et al., 2018). In both cases the shift was associated primarily with large-scale changes in natural disturbance regimes. Although the potential for Canadian park forests to contribute to GHG sequestration at the national and global scale is currently impaired, their role in preventing stored carbon from being released following land use conversion remains. Active forest management options, in particular those aimed at restoring ecosystem- and site-specific natural fire regimes, need to be devised to restore the sequestration capacity of park forests and, accordingly, their full potential as nature-based solutions for climate change mitigation.

4.4 Gaps and Future Directions

Several factors may affect the accuracy of the results obtained in this study. These include lack of complete input data, limitations in the consideration of multiple natural disturbances and their interactions, model limitations and assumptions, and a lack of consideration of the impacts of climate change on current and future forest carbon dynamics. With regards to inputs, the GCBM simulation relies on consistent and complete forest inventory, climatic, and disturbance-related data to generate accurate estimates of forest growth and productivity. These data requirements limited the geographic scope of this study as there was a paucity of data available in northern regions, and therefore the analysis was restricted to parks in Canada's southern latitudes where data were more readily available. The resulting gap in our assessment is an important one, as northern forests are carbon-rich ecosystems and are experiencing higher rates of warming than other regions in Canada (Bush & Lemmen, 2019).

Our study focused on the major disturbances from fire and certain insects that are known to drive forested ecosystems dynamics at a landscape scale in Canada (see a review by McCullough et al., 1998), and thereby ecosystem carbon dynamics in these forests (Kurz et al., 2013). Smaller disturbances by other insects, wind throw, plant pathogens, and drought are causing further losses of carbon and can combine to generate cumulative impacts of natural disturbances on forested areas (e.g., Boucher et al., 2018). This implies that our carbon flux results somewhat underestimate the actual GHG emissions from the forests studied. This also highlights the need to consider future projections of carbon dynamics in parks. The collection and inclusion of additional data on different types and extent of natural disturbances – including fire severity – in the future will also allow for more accurate estimation of emissions.

Our findings provide important insights on forest carbon dynamics in Canada's national parks, but it should be noted that the full influence of climate variability on these dynamics was not directly assessed in this study. The GCBM simulation uses constant average climate conditions and is therefore not designed to consider the response of growth and decomposition rates due to changes in temperature and precipitation regimes and ongoing increases in atmospheric CO_2 concentration resulting from anthropogenic climate change. These constraints are likely to have had some effect on the modeled estimates of inter-annual variability, regional distribution and trends in ecosystem carbon dynamics (Kurz et al., 2013). Enhancements to the GCBM to account for climate-induced changes in growth rates, species composition, and disturbances would be valuable to improve its application as a dynamic ecosystem carbon accounting tool.

While this atlas has examined historical (1990-2020) changes in carbon stocks and dynamics within the forested regions of the parks, it has not attempted to assess future changes in carbon stocks and sequestration. Climate change is projected to shift climatic regimes across protected areas globally (Dobrowski et al., 2021; Elsen et al., 2020). These new climatic conditions are expected to have a severe impact on the capacity of national parks to sequester carbon, with a study by Melillo et al. (2016) projecting a 40% reduction in carbon sequestration in protected areas by 2100 under the RCP8.5 scenario. The projected changes in climate will not only impact carbon dynamics directly, but will cause shifts in the growth, demography, and composition of forested ecosystems (McDowell et al., 2020). Climate change is also anticipated to intensify wildfire regimes and other landscape-level disturbances over time (Descals et al., 2022; Flannigan et al., 2005), which would result in further increases in GHG emissions (Davis et al., 2019; Halofsky et al., 2020). Therefore, gaining a better understanding of the projected changes in forests under different climate change scenarios is increasingly crucial for predicting the subsequent range of direct and indirect impacts on forest carbon stocks and dynamics. This knowledge will help ascertain the potential role of parks as natural climate solutions. The baseline data and analyses produced through our study for the time period 1990-2020 provide a useful benchmark for monitoring future impacts of climate change on carbon dynamics within Canada's forest landscape.

As is true with most regional or national estimates of ecosystem carbon balance, the forested ecosystem carbon stocks and dynamics calculated in this study are difficult to verify at large spatial scales. Undertaking in situ sampling to verify and validate these estimates would require a resource-intensive sampling and monitoring program that does not currently exist in Canada or elsewhere, to the authors' knowledge. Finally, this work does not consider the GHG emissions avoided related to the conservation status of the forested ecosystems assessed, for example in limiting land-use and land cover change or other carbon-intensive activities. Altogether, these gaps may contribute to underestimating the contribution of protected and conserved areas to climate change mitigation.

4.5 Implications for Management

While protected areas remain a critical mechanism to conserve biodiversity and ecosystem services, including carbon sequestration and storage, this study demonstrates that protection of forests within national parks is not alone a guarantee that carbon sequestration can be sustained as a co-benefit of biodiversity protection over time. New approaches that mainstream climate change considerations in the planning, stewardship, and active management of parks will be important in addressing climate change-related risks that can compromise the role of park forests and other ecosystems as carbon sinks. These approaches should be designed to address biodiversity conservation and climate change in an integrated manner, as articulated in the United Nations Environment Assembly (UNEA)'s March 2022 definition of "nature-based solutions" (UNEA, 2022), and previously in the 2021 International Protected and Conserved Area Joint Statement on Climate Change and Biodiversity Crises, signed by 26 governments and conservation organizations during the UNFCCC COP26 (Parks Canada Agency, 2021).

Our spatially-explicit, site-level findings can inform active management decisions, built asset and infrastructure considerations, and biodiversity conservation planning to favour carbon conservation and sequestration. Our analyses identified and described spatial distributions of both carbon stocks and densities in individual national parks, with some parks showing moderate spatial variability while many others showed high variability, even over relatively short distances. Ecosystem carbon maps (e.g., Figure 11) can help identify where, in a park and across the network of parks, ecosystem conservation and restoration activities have the greatest potential to augment carbon sequestration and reduce the risk of releasing stored carbon. Similarly, these maps can help inform site-specific management decisions, such as the siting of new built assets and above- and/or below-ground infrastructure.

4.6 Summary

Increasingly, nature-based climate solutions are recognized as important approaches to achieve GHG emission reduction targets both in Canada (Drever et al., 2021) and globally (Griscom et al., 2017). Protected areas are an important component of this but until now, the role of Canada's protected areas and their component ecosystems as nature-based solutions for climate change mitigation has not been comprehensively assessed. Here we used a carbon budget model, the GCBM, to provide the first comprehensive estimates and spatially-explicit data on carbon stocks, densities, and fluxes for forested ecosystems within national parks across Canada and over time. Notably, this study shows both the "when" and the "where" associated with forest ecosystem carbon dynamics at fine temporal and spatial resolutions for protected area ecosystems, and the carbon pools therein, that have never before been reported at the national level. Knowing the location and density of those carbon stocks, and their temporal dynamics, can inform decisions on ecosystem management and restoration to safeguard large natural carbon stores, and help to reduce the risks of carbon losses and GHG emissions due to natural and other disturbances.

This study shows that national park forests contained a substantial amount of carbon accumulated over decades and centuries, but that changes in natural disturbance regimes have caused them to become, in certain areas, a net source of GHG emissions in recent years. This finding highlights the importance of considering future climate change impacts on forest carbon dynamics in protected areas, as projected increases in the severity and frequency of natural disturbances have the potential to further shift the carbon balance in national parks. This new knowledge addresses a gap in the collective understanding of protected areas as nature-based solutions in the face of climate change.

This 31-year record of forest carbon storage and fluxes for national parks across Canada answers key questions that will enable considering inclusion of the mitigation potential of protected areas into Canada's nationally determined contributions under the Paris Agreement, and illustrates the challenges associated with measuring these contributions from one year to the next. The findings of this report and others will support Canada's efforts under the UNFCCC and inform discussions around national carbon inventories and the infrastructure and data required to monitor, account, and report GHG emissions for protected area networks. Parks Canada continues to work with partners and collaborators to comprehensively study carbon dynamics in other ecosystems including peatland, grassland, and coastal ecosystems within national parks, national historic sites, and national marine conservation areas. These studies will help to place the carbon fluxes and GHG emissions associated with forested ecosystems in a broader, more complete context. This work will further demonstrate the important and dynamic role protected areas and their component ecosystems can play as nature-based solutions for climate change mitigation, and more broadly in addressing the dual crises of climate change and biodiversity loss.

Acknowledgments

This work could not have been completed without the help and support provided by many individuals and organizations, and the funding support from Parks Canada and Natural Resources Canada. Our thanks to all of the following:

Parks Canada Agency

- The geomatics specialists, ecologists, and other staff in all parks for providing various data required for the project and responses to queries about these data sets.
- Peter Demontigny for providing GIS mapping support, and Alice Yue and Linda Dam for their help with creating charts and figures.
- Victor Kafka and Michel Theriault for advice and suggestions on use of fire data in this study, and Lakmal Ratnayake for help with fire data compilation.
- Queenie Gray for reviewing the initial draft report. Anna Lee-Carswell, Hilary Ta, Danielle Yetman, Michelle Macullo and Rik Van Bogaert for reviewing subsequent drafts and supporting the copy-editing, translation processes, and formatting of the report.
- Scott Parker for networking support and advice on the project during its initial period.
- Marlow Pellatt for his expertise on Blue Carbon and the insights and feedback provided on the first draft of this report.
- Julia Thomas for outreach within and outside the Agency.

Provincial Governments

- Lane Gelhorn and Nancy Podbielski from SK Ministry of Environment, Forest Service, for yield curves, ecosite mapping, and insect defoliation layers for Prince Albert NP.
- James Steenberg from NS Department of Lands and Forestry and Derek Gilby and James Bruce from NS Department of Natural Resources for forest inventory, insect data, yield curve estimations and other assistance for Kejimkujik and Cape Breton NPs data.
- Antonio Viveiros from MB Sustainable Development, Forestry and Peatlands for forest inventory, yield curves and other assistance for Riding Mountain NP.
- Ron Fournier from Natural Resources Canada for insect disturbance data in Ontario Parks; Adam Hogg and Mike Vanderdoelen from ON Ministry of Natural Resources; Land Information Ontario for fire and insect disturbance data for Ontario parks.
- Andrew Ing from PEI Department of Communities, Land, and Environment, Resource Inventory and Modeling section for yield curves and insect disturbance data in Prince Edward Island NP.

Canadian Forest Service Carbon Accounting Team

- Mark Hafer, Eric Neilson, Benjamin Hudson, Byron Smiley, Mihai Voicu, and Stephen Kull for yield datasets and explanations, scripts for data extraction, and information on the GCBM.
- Roger Brett for the compiled dataset on insect disturbances for all mountain parks.
- Mike Wulder and his team for data from the composite-to-change product for disturbances.
- Laurie McCormick for assistance with literature reviews.

Others

- "Moja global" for maintenance and assistance of the open source FLINT platform that hosts the GCBM.
- Risa Smith, International Union for Conservation of Nature, for reviewing the draft and providing valuable suggestions.
- Florence Daviet, Canadian Parks and Wilderness Society, for reviewing the draft and providing valuable suggestions.

References

Amiro, B. D., Barr, A. J., Barr, J. G., Black, T. A., Bracho, R., Brown, M. A., Chen, J. C., Clark, K. J., Davis, K. L., Desai, A. R., Dore, S., Engel, V., Fuentes, J. D., Goldstein, A. H., Goulden, M. L., Kolb, T., Lavigne, M. B., Law, B. E., Margolis, H. A., . . . Xiao, J. Q. (2010). Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research*, *115*, G00K02. **https://doi.org/10.1029/2010jg001390**

Amthor, J. S., Dale, V. H., Edwards, N. T., Garten, C. T., Gunderson, C. A., Hanson, P. J., Huston, M. A., King, A. W, Luxmoore, R. J., McLaughlin, S. B., Marland, G., Mulholland, P. J., Norby, R. J., O'Neill, E. G., O'Neill, R. V., Post, W. M., Shriner, D. S., Todd, D. E., Tschaplinksi, T. J., ... Wullschleger, S. D. (1998). *Terrestrial ecosystem responses to global change: a research strategy* (Publication No. 4821). Oak Ridge National Laboratory. **https://info.ornl.gov/sites/publications/Files/Pub57658.pdf**

Beaulne, J., Garneau, M., Magnan, G., & Boucher, É. (2021). Peat deposits store more carbon than trees in forested peatlands of the boreal biome. *Scientific Reports*, *11*, 2657. **https://doi.org/10.1038/s41598-021-82004-x**

Boucher, D., Boulanger, Y., Aubin, I., Bernier, P. Y., Beaudoin, A., Guindon, L., & Gauthier, S. (2018). Current and projected cumulative impacts of fire, drought, and insects on timber volumes across Canada. *Ecological Applications*, *28*(5), 1245–1259. **https://doi.org/10.1002/eap.1724**

Boulanger, Y., Gauthier, S., Gray, D. R., Le Goff, H., Lefort, P., & Morissette, J. (2013). Fire regime zonation under current and future climate over Eastern Canada. *Ecological Applications, 23*(4), 904–923. **https://doi.org/10.1890/12-0698.1**

Bremer, E. (2008). *Potential of rangelands to sequester carbon in Alberta*. Alberta Sustainable Resource Development. **https://open.alberta.ca/publications/9780778582045**

Bush, E., & Lemmen, D. S. (Eds.). (2019). *Canada's changing climate report*. Natural Resources Canada. **https://changingclimate.ca/CCCR2019/**

Campbell, A., Miles, L., Lysenko, I., Hughes, A., & Gibbs, H. (2008). *Carbon storage in protected areas: Technical report*. United Nations Environment Programme World Conservation Monitoring Centre. **https://resources.unep-wcmc.org/products/WCMC_RT140**

Canadian Interagency Forest Fire Centre Inc. Training Working Group. (2023). *Canadian wildland fire glossary*. Canadian Interagency Forest Fire Centre Inc. **https://www.ciffc.ca/sites/default/files/2023-05/CWFM_glossary_v2023-04-24-EN.pdf**

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C. J., Aber, J. L., Cole, J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P., McGuire, A. D., . . . Schulze, E.-D. (2006). Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems*, *9*, 1041–1050. **https://doi.org/10.1007/s10021-005-0105-7**

Chen, J., Colombo, S. J., Ter-Mikaelian, M. T., & Heath, L. S. (2010). Carbon budget of Ontario's managed forests and harvested wood products, 2001–2100. *Forest Ecology and Management*, *259*(8), 1385–1398. **https://doi.org/10.1016/j.foreco.2010.01.007**

Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., Parks, S. A., Sala, A., & Maneta, M. P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, *116*(13), 6193–6198. **https://doi.org/10.1073/pnas.1815107116**

Descals, A., Gaveau, D. L. A., Verger, A., Sheil, D., Naito, D., & Peñuelas, J. (2022). Unprecedented fire activity above the Arctic Circle linked to rising temperatures. *Science, 378*(6619), 532–537. **https://doi.org/10.1126/science.abn9768**

Dobrowski, S. Z., Littlefield, C. E., Lyons, D. S., Hollenberg, C., Carroll, C., Parks, S. A., Abatzoglou, J. T., Hegewisch, K., & Gage, J. (2021). Protected-area targets could be undermined by climate change-driven shifts in ecoregions and biomes. *Communications Earth & Environment, 2*, 198. **https://doi.org/10.1038/s43247-021-00270-z**

Drever, C. R., Cook-Patton, S. C., Akhter, F., Badiou, P. H., Chmura, G. L., Davidson, S. J., Desjardins, R. L., Dyk, A., Fargione, J. E., Fellows, M., Filewod, B., Hessing-Lewis, M., Jayasundara, S., Keeton, W. S., Kroeger, T., Lark, T. J., Le, E., Leavitt, S. M., LeClerc, M.-E., … Kurz, W. A. (2021). Natural climate solutions for Canada. *Science Advances*, *7*(23), eabd6034. **https://doi.org/10.1126/sciadv.abd6034**

Durbin J., & Watson, G. S. (1971). Testing for serial correlation in least squares regression (III). *Biometrika*, *58*(1), 1–19. **https://doi.org/10.1093/biomet/58.1.1**

Dymond, C. C., Neilson, E. T., Stinson, G., Porter, K., MacLean, D., Gray, D., Campagna, M., & Kurz, W. A. (2010). Future spruce budworm outbreak may create a carbon source in eastern Canadian forests. *Ecosystems, 13*, 917–931. **https://doi.org/10.1007/s10021-010-9364-z**

Elsen, P. R., Monahan, W. B., Dougherty, E. R., & Merenlender, A. M. (2020). Keeping pace with climate change in protected areas. *Science Advances, 6*(25), eaay0814. **https://doi.org/10.1126/sciadv.aay0814**

Environment and Climate Change Canada. (2020). *Climate science 2050: Advancing science and knowledge on climate change*. **https://publications.gc.ca/collections/collection_2020/eccc/En4-414-2020-eng.pdf**

Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., & Stocks, B. J. (2005). Future area burned in Canada. *Climatic Change, 72*, 1–16. **https://doi.org/10.1007/s10584-005-5935-y**

Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A., & Cescatti, A. (2022). Emerging signals of declining forest resilience under climate change. *Nature, 608*, 534–539. **https://doi.org/10.1038/s41586-022-04959-9**

Giles-Hansen, K., & Wei, X. (2022). Cumulative disturbance converts regional forests into a substantial carbon source. *Environmental Research Letters, 17*(4), 044049. **https://doi.org/10.1088/1748-9326/ac5e69**

Gray, A. N., Whittier, T. R., & Harmon, M. E. (2016). Carbon stocks and accumulation rates in Pacific Northwest forests: Role of stand age, plant community, and productivity. *Ecosphere*, *7*(1) e01224. **https://doi.org/10.1002/ecs2.1224**

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645–11650. **https://doi.org/10.1073/pnas.1710465114**

Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology, 16*, 4. **https://doi.org/10.1186/s42408-019-0062-8**

Hermosilla, T., Wulder, M. A., White, J. C., Coops, N. C., Hobart, G. W., & Campbell, L. B. (2016). Mass data processing of time series Landsat imagery: Pixels to data products for forest monitoring. *International Journal of Digital Earth*, *9*(11), 1035–1054. **https://doi.org/10.1080/17538947.2016.1187673**

Intergovernmental Panel on Climate Change. (2003). *Good practice guidance for Land Use, Land-Use Change and Forestry*. Institute for Global Environmental Strategies. **https://www.ipcc.ch/publication/good-practice-guidance-for-land-use-land-use-change-and-forestry/**

Intergovernmental Panel on Climate Change. (2006). *IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies. **https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/**

Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. **https://www.ipcc.ch/report/ar4/syr/**

Intergovernmental Panel on Climate Change. (2013). *Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. **https://www.ipcc.ch/report/ar5/wg1/**

Jobbagy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423–436. **https://doi.org/10.2307/2641104**

Johnstone, J. F., Chapin, F. S., Hollingsworth, T. N., Mack, M. C., Romanovsky, V., & Turetsky, M. (2010). Fire, climate change, and forest resilience in interior Alaska. *Canadian Journal of Forest Research, 40*(7), 1302–1312. **https://doi.org/10.1139/X10-061**

Kull, S. J., Rampley, G. J., Morken, S., Metsaranta, J. M., Neilson, E. T., & Kurz, W. A. (2019). *Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2: user's guide*. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. **https://d1ied5g1xfgpx8.cloudfront.net/pdfs/39768.pdf**

Kulshreshtha, S. N., Lac, S., Johnston, M., & Kinar, C. (2000). *Carbon sequestration in protected areas of Canada: an economic valuation* (Economic Framework Project, Report No. 549). The Canadian Parks Council. **https://www.nswooa.ca/uploads/5/9/6/9/59690537/canadian_parks_council_carbon-sequestration-in-protected-areas-of-canada-an-economic-valuation.pdf**

Kurz, W. A., & Apps, M. J. (2006). Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to meet the reporting requirements of the Kyoto Protocol. *Mitigation and Adaptation Strategies for Global Change*, *11*, 33–43. **https://doi.org/10.1007/s11027-006-1006-6**

Kurz, W. A., Beukema, S. J., & Apps, M. J. (1996). Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector. *Canadian Journal of Forest Research, 26*(11), 1973–1979. **https://doi.org/10.1139/x26-223**

Kurz, W. A, Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., & Safranyik, L. (2008b). Mountain pine beetle and forest carbon feedback to climate change. *Nature, 452*, 987–990. **https://doi.org/10.1038/nature06777**

Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw, C., Rampley, G. J., Smyth, C., Simpson, B., Neilson, E. G., Trofymow, J. A., Metsaranta, J. M., & Apps, M. J. (2009). CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modeling*, *220*(4), 480–504. **https://doi.org/10.1016/j.ecolmodel.2008.10.018**

Kurz, W. A., Hayne, S., Fellows, M., MacDonald, J. D., Metsaranta, J. M., Hafer, M., & Blain, D. (2018). Quantifying the impacts of human activities on reported greenhouse gas emissions and removals in Canada's managed forest: Conceptual framework and implementation. *Canadian Journal of Forest Research*, *48*(10), 1227–1240. **https://doi.org/10.1139/cjfr-2018-0176**

Kurz, W. A., Shaw, C. H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., & Neilson, E. T. (2013). Carbon in Canada's boreal forest—A synthesis. *Environmental Reviews*, *21*(4), 260–292. **https://doi.org/10.1139/er-2013-0041**

Kurz, W. A., Stinson, G., Rampley, G. J., Dymond, C. C., & Neilson, E. T. (2008a). Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences, 105*(5), 1551–1555. **https://doi.org/10.1073/pnas.0708133105**

Landsberg, J. J., & Waring, R. H. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management*, *95*(3), 209–228. **https://doi.org/10.1016/S0378-1127(97)00026-1**

Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., Jones, S. D., Sitch, S., Tans, P., Arneth, A., Boden, T. A., Bopp, L., Bozec, Y., Canadell, J. G., Chini, L. P., Chevallier, F., Cosca, C. E., Harris, I., Hoppema, M., … Zeng, N. (2015). Global carbon budget 2014. *Earth System Science Data, 7*(1), 47–85. **https://doi.org/10.5194/essd-7-47-2015**

Masera, O., Garza-Caligaris, J., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G., Pussinen, A., De Jong, B., & Mohren, G. M. J. (2003). Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modeling*, *164*(2–3), 177–199. **https://doi.org/10.1016/s0304-3800(02)00419-2**

McCullough, D. G., Werner, R. A., & Neumann, D. (1998). Fire and insects in northern and boreal forest ecosystems of North America. *Annual Review of Entomology, 43*, 107–127. **https://doi.org/10.1146/annurev.ento.43.1.107**

McDowell N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., …, Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science, 368*(6494), eaaz9463. **http://doi.org/10.1126/science.aaz9463**

McGee, T., McFarlane, B., & Tymstra, C. (2015). Chapter 3–Wildfire: A Canadian perspective. In J. F. Shroder, & D. Paton (Eds.), *Wildfire hazards, risks and disasters* (pp. 35–58). Elsevier. **https://doi.org/10.1016/B978-0-12-410434-1.00003-8**

Melillo, J. M., Lu, X., Kicklighter, D. W., Reilly, J. M., Cai, Y., & Sokolov, A. P. (2016). Protected areas' role in climate-change mitigation. *Ambio*, *45*, 133–145. **https://doi.org/10.1007/s13280-015-0693-1**

Metherell, A. K., Harding, L. A., Cole, C. V., & Parton, W. J. (1993). *CENTURY Soil Organic Matter Model Environment, Technical Documentation, Agroecosystem Version 4.0* (Technical Report No. 4). Great Plains System Research Unit, Colorado State University. **https://www.nrel.colostate.edu/projects/century/manual/html_manual/man96.html**

Moran, P. A. P. (1950). Notes on continuous stochastic phenomena. *Biometrika*, *37*(1–2), 17–23. **https://doi.org/10.2307/2332142**

Morton, C. J., Cameron, R., & Duinker, P. (2007). Modeling carbon budgets in four protected wilderness areas in Nova Scotia. In S. Bondrup-Nielsen, K. Beazley, G. Bissix, D. Colville, S. Flemming, T. Herman, M. McPherson, S. Mockford, & S. O'Grady (Eds.), *Ecosystem based management: Beyond boundaries. Proceedings of the Sixth International Conference of Science and the Management of Protected Areas, 21–26 May 2007, Acadia University, Wolfville, Nova Scotia* (pp. 429–440). Science and Management of Protected Areas Association.

Nabuurs, G.-J., Schelhaas, M.-J., & Pussinen, A. (2000). Validation of the European Forest Information Scenario Model (EFISCEN) and a projection of Finnish forests. *Silva Fennica*, *34*(2), 638. **https://doi.org/10.14214/sf.638**

Natural Resources Canada, & Canadian Forest Service. (2020). *The state of Canada's forests: Annual report 2020*. **https://d1ied5g1xfgpx8.cloudfront.net/pdfs/40219.pdf**

Parks Canada. (2021, November 5). *Parks Canada and Protected and Conserved Areas Around the World Sign First Ever Joint Statement on Climate Change and Biodiversity* [Press release]. **https://www.canada.ca/en/parks-canada/news/2021/11/parks-canada-and-protected-and-conserved-areas-around-the-world-sign-first-ever-joint-statement-on-climate-change-and-biodiversity.html**

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, *333*(6045), 988–993. **https://doi.org/10.1126/science.1201609**

Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. A., Turner, M. G., & Romme, W. H. (2008). Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience, 58*(6), 501–517. **https://doi.org/10.1641/B580607**

Running, S. W., & Gower, S. T. (1991). FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology*, *9*(1–2), 147–160. **https://doi.org/10.1093/treephys/9.1-2.147**

Seidl, R., Honkaniemi, J., Aakala, T., Aleinikov, A., Angelstam, P., Bouchard, M., Boulanger, Y., Burton, P. J., De Grandpré, L., Gauthier, S., Hansen, W. D., Jepsen, J. U., Jõgiste, K., Kneeshaw, D., Kuuluvainen, T., Lisitsyna, O. V., Makoto, K., Mori, A., Pureswaran, D. S., . . . Senf, C. (2020). Globally consistent climate sensitivity of natural disturbances across boreal and temperate forest ecosystems. *Ecography*, *43*(7), 967–978. **https://doi.org/10.1111/ecog.04995**

Sharma, T., Kurz, W. A., Stinson, G., Pellatt, M. G., & Li, Q. (2013). A 100-year conservation experiment: Impacts on forest carbon stocks and fluxes. *Forest Ecology and Management*, *310*, 242–255. **https://doi.org/10.1016/j.foreco.2013.06.048**

Smithwick, E. A. H., Harmon, M. E., Remillard, S. M., Acker, S. A., & Franklin, J. F. (2002). Potential upper bounds of carbon stores in forests of the Pacific Northwest. *Ecological Applications*, *12*(5), 1303–1317. **https://doi.org/10.2307/3099973**

Sothe, C., Gonsamo, A., Arabian, J., Kurz, W. A., Finkelstein, S. A., & Snider, J. (2022). Large Soil Carbon Storage in Terrestrial Ecosystems of Canada. *Global Biogeochemical Cycles, 36*(2), e2021GB007213. **https://doi.org/10.1029/2021gb007213**

Stevens-Rumann, C. S., Kemp, K. B., Higuera, P. E., Harvey, B. H., Rother, M. T., Donato, D. C., Morgan, P., & Veblen, T. T. (2018). Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, *21*(2), 243–252. **https://doi.org/10.1111/ele.12889**

Stinson, G., Kurz, W. A., Smyth, C., Neilson, E. G., Dymond, C. C., Metsaranta, J. M., Boisvenue, C., Rampley, G. J., Li, Q. J., White, T. M., & Blain, D. (2011). An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, *17*(6), 2227–2244. **https://doi.org/10.1111/j.1365-2486.2010.02369.x**

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, *23*(2), GB2023. **https://doi.org/10.1029/2008gb003327**

Thom, D., & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological Reviews, 91*(3), 760–781. **https://doi.org/10.1111/brv.12193**

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., & Helfrich, J. (1999). The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States. *Tellus B: Chemical and Physical Meteorology*, *51*(2), 414–452. **https://doi.org/10.3402/tellusb.v51i2.16318**

Trofymow, J. A., & Blackwell, B. A. (1998). Changes in ecosystem mass and carbon distributions in coastal forest chronosequences. *Northwest Science, 72*(2), 40–42. **https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/5091.pdf**

Trofymow, J. A., Stinson, G., & Kurz, W. A. (2008). Derivation of a spatially explicit 86-year retrospective carbon budget for a landscape undergoing conversion from old-growth to managed forests on Vancouver Island, BC. *Forest Ecology and Management*, *256*(10), 1677–1691. **https://doi.org/10.1016/j.foreco.2008.02.056**

United Nations Environmental Assembly. (2022, March 2). *Nature-based solutions for supporting sustainable development* (Resolution No. 5/5). United Nations Environment Programme. **https://wedocs.unep.org/bitstream/handle/20.500.11822/39752/K2200677%20-%20UNEP-EA.5-Res.5%20-%20Advance.pdf?sequence=1&isAllowed=y**

United States Global Change Research Program. (2018). *Second State of the Carbon Cycle Report (SOCCR2): A sustained assessment report*. **https://doi.org/10.7930/SOCCR2.2018**

Wang, W., Wu, W., Guo, F., & Wang, G. (2022). Fire regime and management in Canada's protected areas. *International Journal of Geoheritage and Parks*, *10*(2), 240–251. **https://doi.org/10.1016/j.ijgeop.2022.04.003**

White, C. A., Perrakis, D. D. B., Kafka, V. G., & Ennis, T. (2011). Burning at the edge: Integrating biophysical and eco-cultural fire processes in Canada's parks and protected areas. *Fire Ecology,* 7, 74–106. **https://doi.org/10.4996/fireecology.0701074**

Wiedinmyer, C., & Neff, J. C. (2007). Estimates of CO_2 from fires in the United States: Implications for carbon management. *Carbon Balance and Management*, *2*, 10. **https://doi.org/10.1186/1750-0680-2-10**

Wiken, E. B., Gauthier, D., Marshall, I., Lawton, K., & Hirvonen, H. (1996). *A perspective on Canada's ecosystems: An overview of the terrestrial and marine ecozones* (Occasional Paper No. 14). Canadian Council on Ecological Areas. **https://ccea-ccae.org/wp-content/uploads/2015/10/P14_A-prespective-on-Canadas-Ecosystems.pdf**

Glossary

Term	Description
Autotrophic respiration	Respiration by photosynthetic organisms (e.g., plants and algae; IPCC, 2013, Annex III).
Biomass	The mass of living forest vegetation, which includes trees of merchantable size, and below merchantable size, broken down by components: merchantable stemwood, foliage, coarse and fine roots, and other (treetops, stumps, and trees of sub-merchantable size; Kull et al., 2019).
Carbon balance (or Carbon budget)	The balance of the exchanges (uptake and release) of carbon between the carbon reservoirs in the carbon cycle.
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, natural gas, and coal; burning biomass; land-use changes; and industrial processes (e.g., cement production). Carbon dioxide is the principal anthropogenic greenhouse gas that affects Earth's radiative balance. As the reference gas against which other greenhouse gases are measured, it has a global warming potential of 1 (United States Global Change Research Program [USGCRP], 2018, Section G).
Carbon dioxide equivalent (CO_2e)	A measure used to compare different greenhouse gases based on their contribution to radiative forcing. The UNFCCC uses global warming potentials (GWPs) as factors to calculate carbon dioxide equivalent (IPCC, 2006, Glossary).
Crown Fire	A fire that advances through the crown fuel layer, usually in conjunction with a surface fire (Canadian Interagency Forest Fire Centre Inc. Training Working Group [CIFFC Training Working Group], 2023).
Dead Organic Matter (DOM)	A generic term for all dead organic compounds in the ecosystem, including standing dead trees, downed trees, coarse and fine woody debris, litter, soil carbon, and peat (Kull et al., 2019).
Disturbance Matrix (DM)	A matrix defining the proportion of each biomass and DOM pool that is transferred to other pools, the atmosphere, and the forest product sector at the time of a disturbance, according to disturbance type and terrestrial ecozone (Kull et al., 2019).
Ecosystem carbon density	Mass of carbon per unit area (carbon density) contained in biomass and dead organic matter pools.
Flux	Carbon flux refers to the direction and rate of transfer of carbon between pools (USGCRP, 2018, Section G).

Term	Description
Global warming potential (GWP)	An index that measures how much energy one [metric] ton of a greenhouse gas will absorb and subsequently release throughout a specified time horizon. The heating potentials of GHGs are standardized relative to the radiative forcing of CO_2 which has a GWP value of 1. The time period usually used for GWPs is 100 years, which is inclusive of the combined effects of GHGs in the atmosphere over their lifetime (USGCRP, 2018, Section G).
Greenhouse Gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the atmosphere itself and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. In addition to CO_2, N_2O, and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs; IPCC, 2013, Annex III).
Gross primary production (GPP)	The gross uptake of carbon dioxide through photosynthesis (USGCRP, 2018, Section G).
Heterotrophic respiration (R_h)	The conversion of organic matter (in litter, dead wood, and soils) to carbon dioxide by organisms other than plants and algae (IPCC, 2013, Annex III).
Managed forests	Managed forests include forests managed for harvesting, forests subject to fire or insect management, and protected forests, such as those found in national and provincial parks. The managed forest area in Canada is 226 million hectares. All other forests in Canada are considered "unmanaged" (Natural Resources Canada & Canadian Forest Service, 2020).
Merchantable volume	Merchantable volume is the sum of the stem volume of trees larger than a specified diameter at breast height (1.3m). The diameter threshold varies by region across Canada.
Mitigation (of climate change)	A human intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2013, Annex III).

Term	Description
Net biome productivity (or production) (NBP)	Net biome productivity (NBP) is net ecosystem carbon balance (NECB) estimated at large temporal and spatial scales (Chapin et al., 2006). It is estimated as NEP minus carbon losses from disturbance (e.g., fire), harvesting, and land clearing during land-use change. It is equivalent to the annual total ecosystem carbon stock change. If the ecosystem carbon balance results in a net uptake from the atmosphere (positive NBP), the ecosystem is said to be a carbon sink; if the balance results in net emissions to the atmosphere (negative NBP), the ecosystem is said to be a source of carbon.
Net ecosystem carbon balance (NECB)	The net rate of carbon accumulation in (or loss from [negative sign]) ecosystems. NECB represents the overall ecosystem carbon balance from all sources and sinks—physical, biological, and anthropogenic (Chapin et al., 2006).
Net ecosystem exchange (NEE)	The net CO_2 exchange with the atmosphere – that is, the vertical and lateral CO_2 flux from the ecosystem to the atmosphere. It differs from NEP in being opposite in sign and in including non-respiratory CO_2 fluxes such as those from fire. Positive values refer to carbon released to the atmosphere (i.e., a source), and negative values refer to carbon uptake (i.e., a sink; Chapin et al., 2006).
Net ecosystem productivity (or production) (NEP)	NEP is defined as net primary productivity minus all losses of carbon due to decomposition.
Net primary productivity (or production) (NPP)	The net uptake of carbon dioxide by plants through gross primary production in excess of losses from plant, or autotrophic respiration (USGCRP, 2018, Section G).
Pool	A compartment, or reservoir, within the Earth system where carbon can be taken up, stored, and/or released within a carbon budget (USGCRP, 2018, Section G).
Prescribed Fire	Fire deliberately utilized in a predetermined area in accordance with a specified and approved burning prescription to achieve set objectives (CIFFC Training Working Group, 2023).
Removal (of CO_2 or GHG)	Withdrawal of a GHG and/or a precursor from the atmosphere by a sink (IPCC, 2013, Annex III).
Sawlogs	Sawlogs are logs of particular diameter that can be used for lumber production. By contrast, firewood can be wood of any diameter size.

Term	Description
Sequestration	Storage of carbon through natural, deliberate, or technological processes in which carbon dioxide is diverted from emission sources or removed from the atmosphere and stored biologically in the ocean and terrestrial environments (e.g., vegetation, soils, and sediments), or in geological formations (USGCRP, 2018, Section G).
Sink	Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere (IPCC, 2013, Annex III).
Site quality	Site quality is a measure of the productivity of a site, often expressed as site index which is defined as the average height at some fixed age (commonly 50 years at breast height) attained by dominant and co-dominant site trees for any given species.
Soil Carbon	Carbon in soil, including various forms of organic and inorganic soil carbon and charcoal but excluding soil biomass, such as roots and living organisms (Kull et al., 2019).
Stock	The mass of carbon contained within a particular pool within the Earth system (USGCRP, 2018, Section G).
Surface Fire	A fire that burns in the surface fuel layer, excluding the crowns of the trees, as either ahead fire, flank fire, or backfire (CIFFC Training Working Group, 2023).

Appendix A: Scientific names for forest insects

Common Name	Scientific Name
Aspen two-leaf tier	*Enargia decolor*
Douglas fir beetle	*Dendroctonus pseudotsugae*
Eastern hemlock looper	*Lambdina fiscellaria*
Eastern larch beetle	*Dendroctonus simplex*
Emerald ash borer	*Agrilus planipennis*
European gypsy moth	*Lymantria dispar*
Forest tent caterpillar	*Malacosoma disstria*
Large aspen tortrix	*Choristoneura conflictana*
Mountain pine beetle	*Dendroctonus ponderosae*
Spruce budworm	*Choristoneura fumiferana*
Two-year cycle budworm	*Choristoneura biennis*
Western balsam bark beetle	*Dryocoetes confusus*
Western black-headed budworm	*Acleris gloverana*

Appendix B: Disturbance matrices for prescribed fires (crown) and mountain pine beetle (very severe)

Prescribed Fires (Crown)

Source[a]	Sink[a] (proportion of carbon transferred)																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-
2	-	0.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.81	0.01	0.08	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.75	-	-	-	-	0.22	0	0.02	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.75	-	-	-	-	0.22	0	0.02	-	-
5	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.81	0.01	0.08	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	-	-	-	0.81	0.01	0.08	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.21	-	-	-	-	-	-	-	-	-	-	0.71	0.01	0.07	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.8	-	-	0.2	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.8	-	-	-	-	-	0.2	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.9	-	-	-	-	0.1	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.9	-	-	-	-	-	-	-	0.1	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-

[a] Source [a] Sink [b] – zero value

Mountain Pine Beetle (Very Severe)

Source[a]	Sink[a] (proportion of carbon transferred)																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0.5	-[b]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-
2	-	0.5	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-
4	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	0.5	-	-	-	-	-	-	-	-	-	0.25	0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	0.5	-	-	-	-	-	-	0.25	0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-

[a] Source [a] Sink [b] – zero value

Row	Description	Column	Description
1	Softwood Merchantable	1	Softwood merchantable
2	Softwood Foliage	2	Softwood foliage
3	Softwood Other	3	Softwood others
4	Softwood Submerchantable	4	Softwood sub-merch
5	Softwood Coarse Roots	5	Softwood coarse roots
6	Softwood Fine Roots	6	Softwood fine roots
7	Hardwood Merchantable	7	Hardwood merch
8	Hardwood Foliage	8	Hardwood foliage
9	Hardwood Other	9	Hardwood other
10	Hardwood Submerchantable	10	Hardwood submerch
11	Hardwood Coarse roots	11	Hardwood coarse roots
12	Hardwood Fine Roots	12	hardwood fine roots
13	Aboveground Very Fast DOM	13	Above Ground Very Fast soil C
14	Belowground Very Fast DOM	14	Below Ground Very Fast soil C
15	Aboveground Fast DOM	15	Above Ground Fast soil C
16	Belowground Fast DOM	16	Below Ground Fast soil C
17	Medium DOM	17	Medium Soil C
18	Aboveground Slow DOM	18	Above Ground slow soil C
19	Belowground Slow DOM	19	Below Ground Slow soil C
20	Softwood Stem Snag	20	Softwood Stem Snag
21	Softwood Branch Snag	21	Softwood Branch Snag
22	Hardwood Stem Snag	22	Hardwood Stem Snag
23	Hardwood Branch Snag	23	Hardwood Branch Snag
24	Black Carbon	24	Black C
25	Peat	25	Peat
		26	CO_2
		27	CH_4
		28	CO
		29	N_2O
		30	products

Appendix C: Average carbon density (t C ha^{-1}) in IPCC-defined pools in parks (1990-2020)

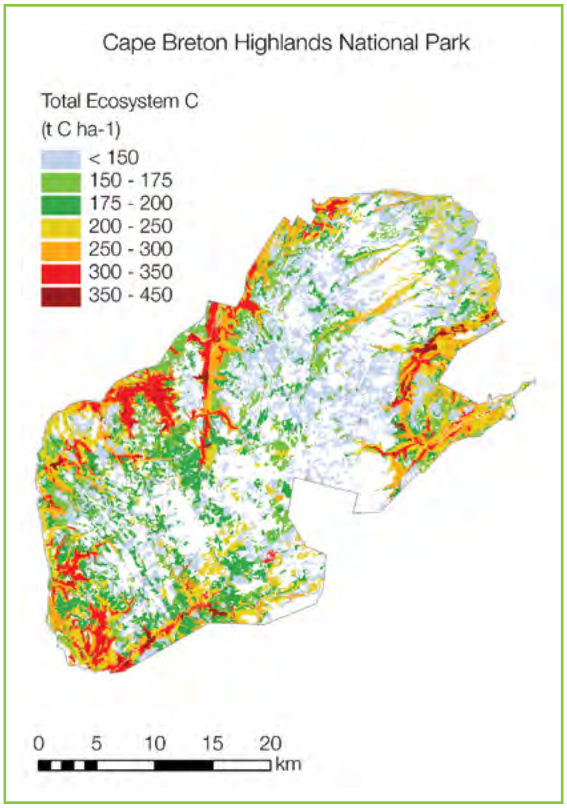
Park Name	AG* Biomass	BG* Biomass	Dead wood	Litter	Soil C	Total Ecosystem
Banff NP	65	17	26	57	98	263
Bruce Peninsula NP	35	10	15	26	64	150
Cape Breton Highlands NP	43	10	15	39	78	185
Elk Island NP	61	16	31	62	117	287
Fathom Five NMP	43	12	11	31	65	161
Forillon NP	42	12	33	41	90	218
Fundy NP	40	10	11	40	83	185
Georgian Bay Islands NP	49	13	10	37	74	183
Glacier NP	125	28	38	69	89	349
Gros Morne NP	58	13	20	58	99	248
Gulf Islands NPR	132	29	35	59	152	408
Gwaii Haanas NPR & Haida HS	155	34	35	72	136	432
Jasper NP	66	17	26	58	101	268
Kejimkujik NP, NHS & NPS	52	12	15	39	80	198
Kootenay NP	76	17	30	47	71	241
Kouchibouguac NP	37	10	13	34	76	170
La Mauricie NP	80	20	28	63	118	309
Mingan NPR	52	13	18	41	82	206
Mount Revelstoke NP	107	24	23	55	76	285
Pacific Rim NPR	182	40	36	72	146	477
Point Pelee NP	49	13	15	30	77	185
Prince Albert NP	46	13	25	39	78	200
Prince Edward Island NP	47	11	22	39	84	203
Pukaskwa NP	49	13	20	48	88	218
Riding Mountain NP	41	12	22	64	110	249
Rouge NUP	51	13	17	33	76	190
Terra Nova NP	63	15	14	51	93	238
Thousand Islands NP	44	12	19	32	77	184
Waterton Lakes NP	64	16	21	50	92	243
Wood Buffalo NP	52	14	41	53	97	257
Yoho NP	84	19	29	54	71	257
National	**58**	**15**	**34**	**53**	**97**	**258**

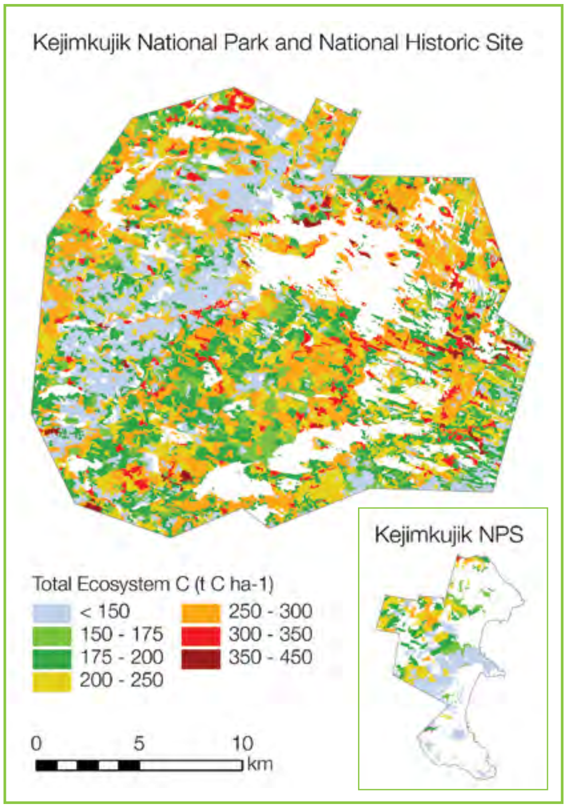
*AG – Aboveground; BG – Belowground

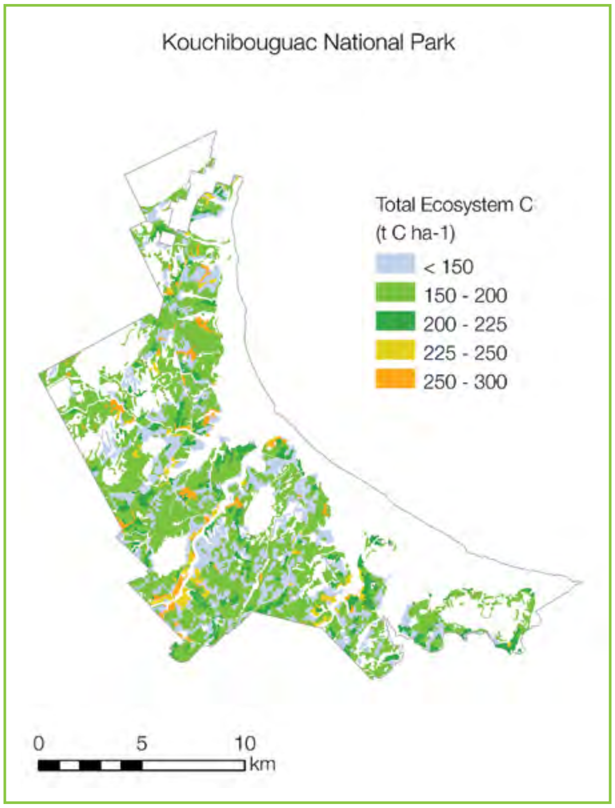
Appendix D: Spatial distribution of total ecosystem carbon density in 2020 (parks grouped by ecozone)

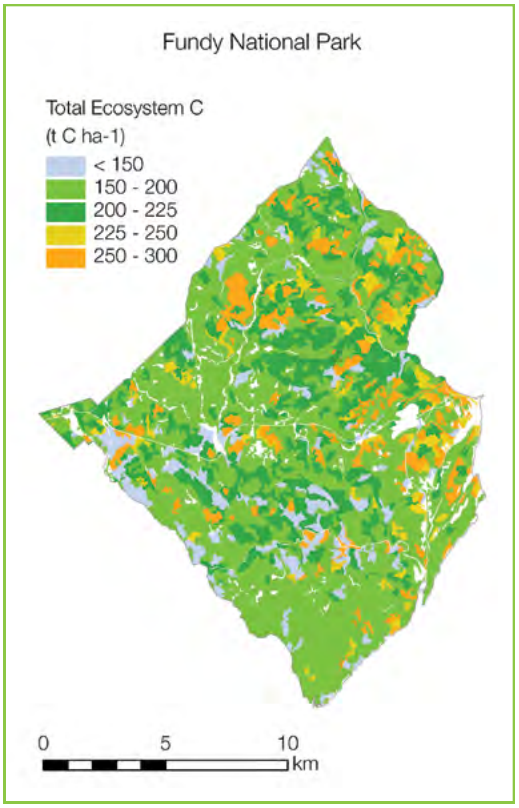
Appendix	Ecozone
Di	Atlantic Maritime
Dii	Boreal Plains (including Wood Buffalo National Park)
Diii	Boreal Shield
Div	Mixedwood Plains
Dv	Montane Cordillera
Dvi	Pacific Maritime
Dvii	Prairies

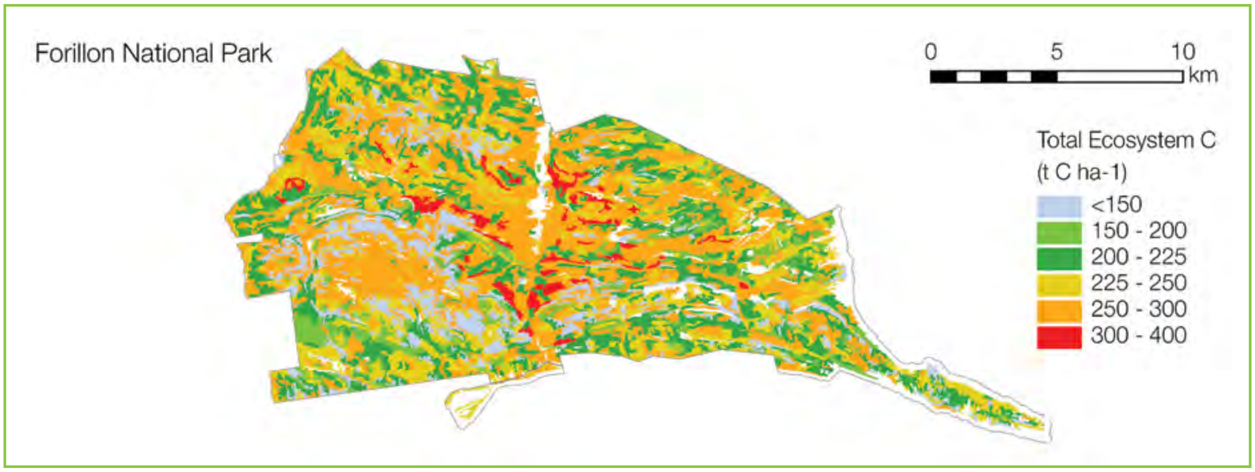
Appendix Di: Atlantic Maritime Ecozone

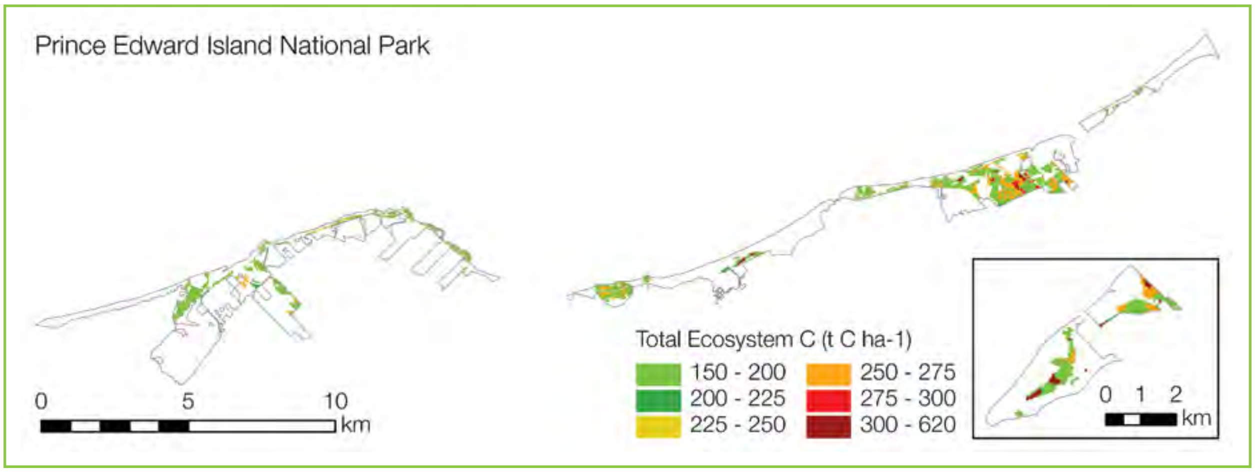




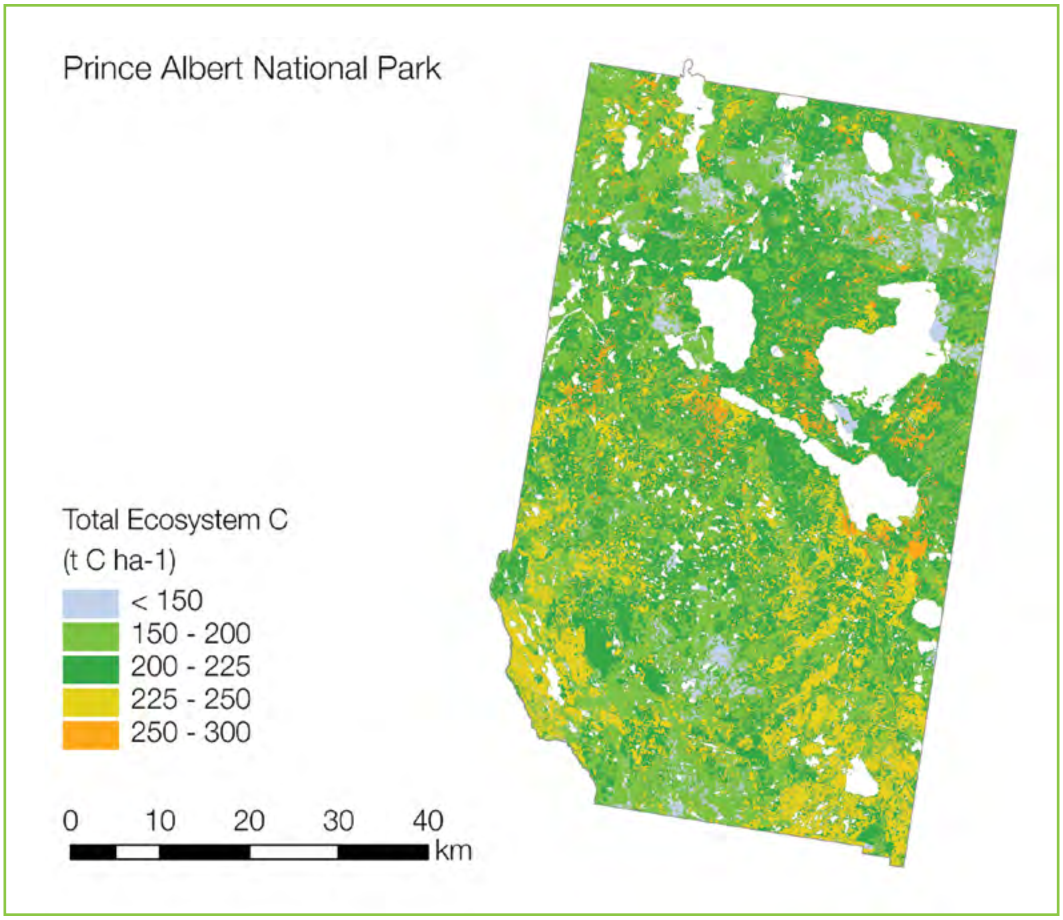


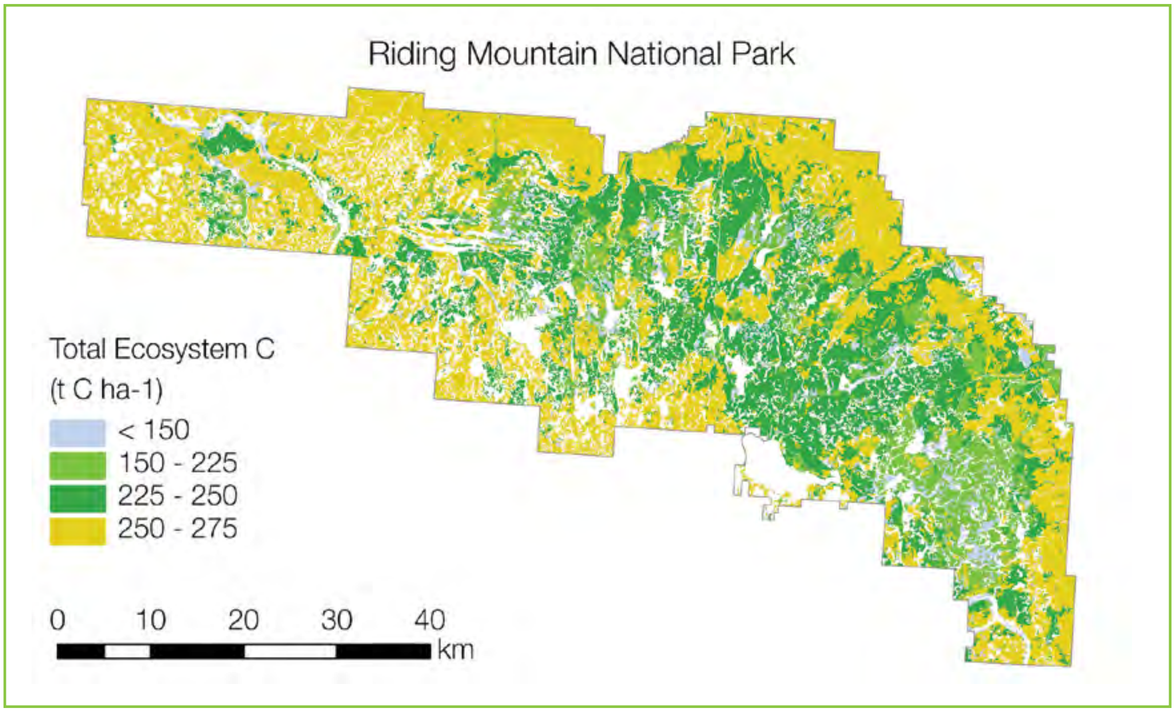


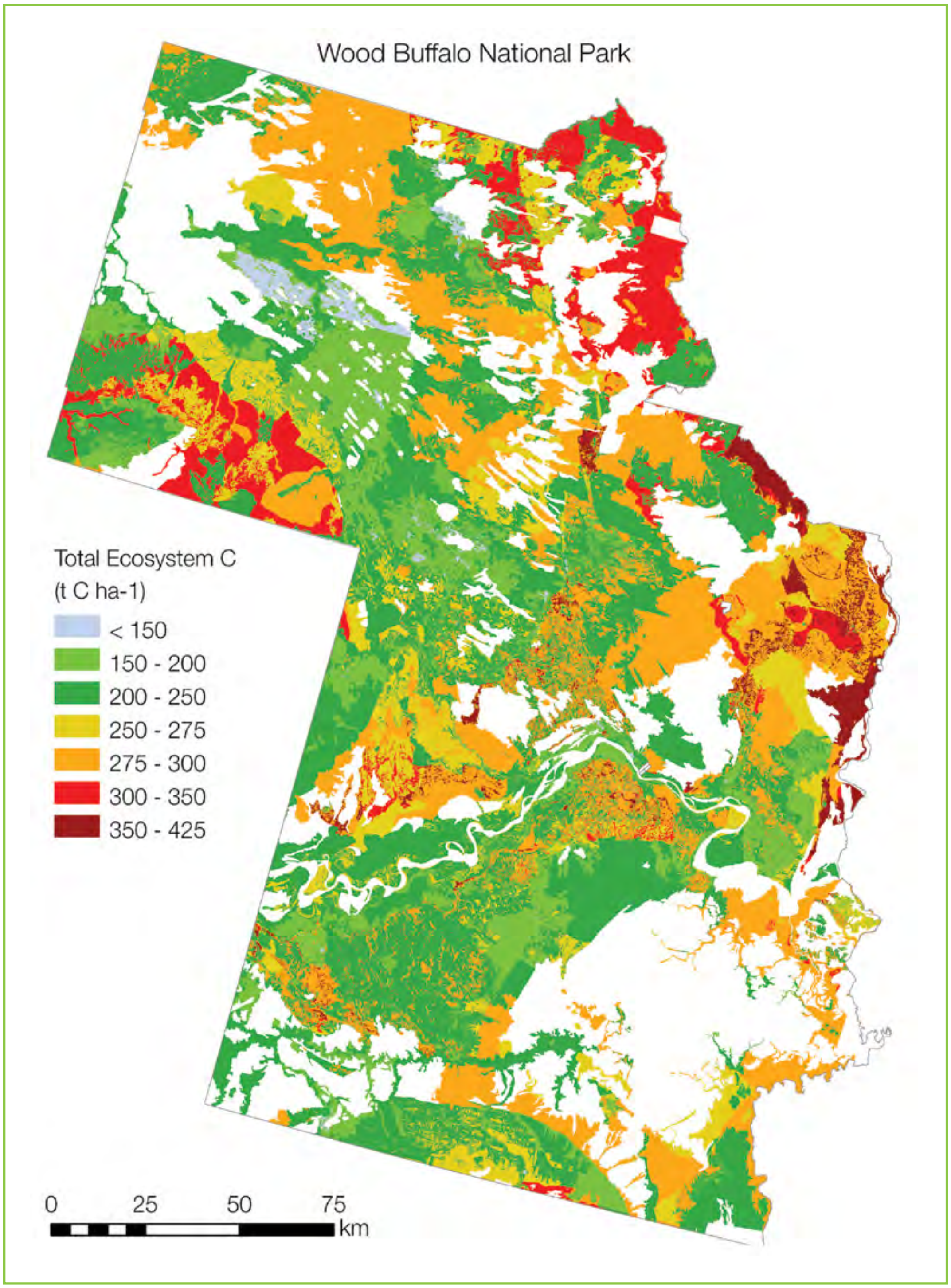

Forillon National Park
0
5
10
km
Total Ecosystem C
(t C ha-1)
<150
150 - 200
200 - 225
225 - 250
250 - 300
300 - 400


Prince Edward Island National Park
0
5
10
km
Total Ecosystem C (t C ha-1)
150 - 200
200 - 225
225 - 250
250 - 275
275 - 300
300 - 620
0
1
2
km

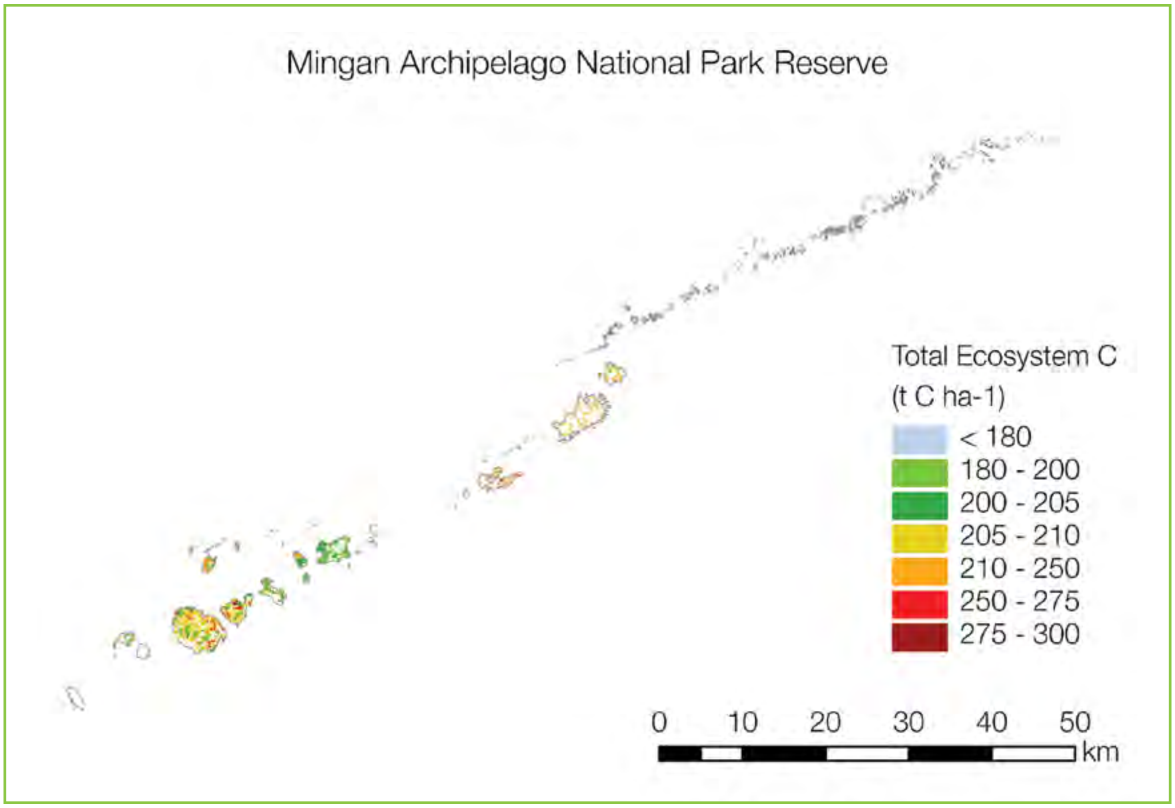
Appendix Dii: Boreal Plains Ecozone

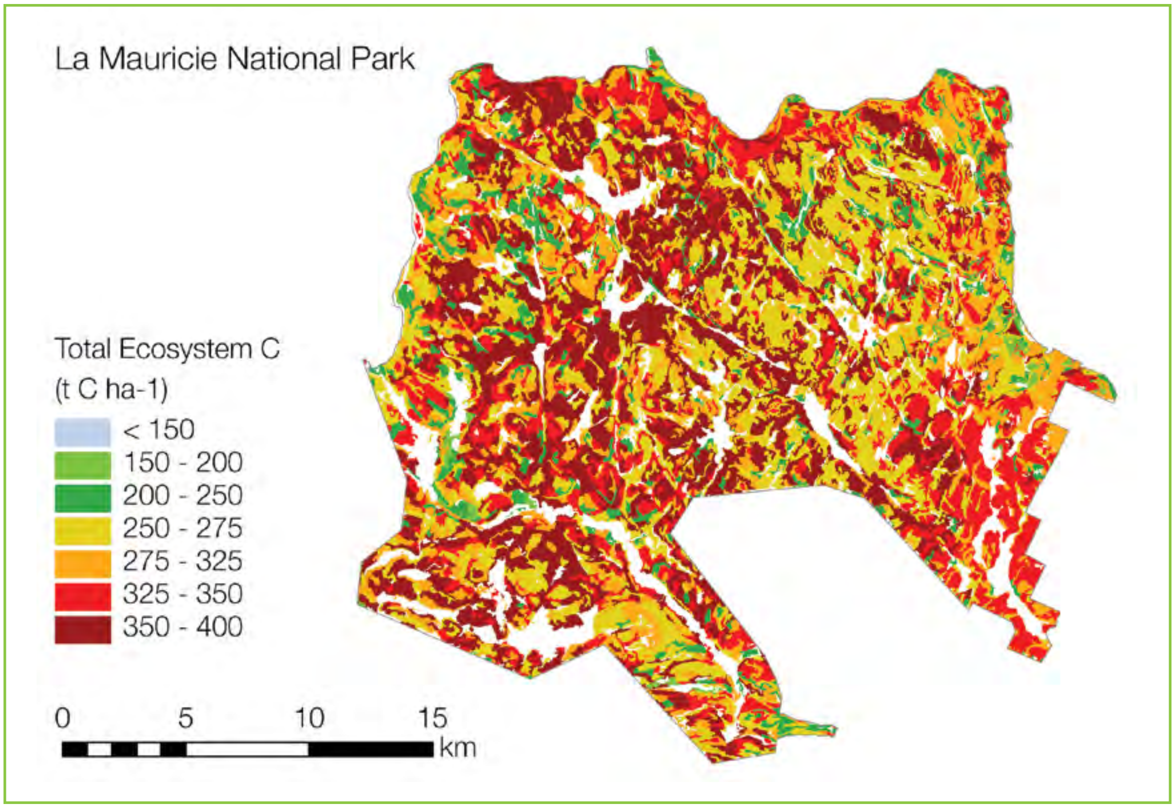


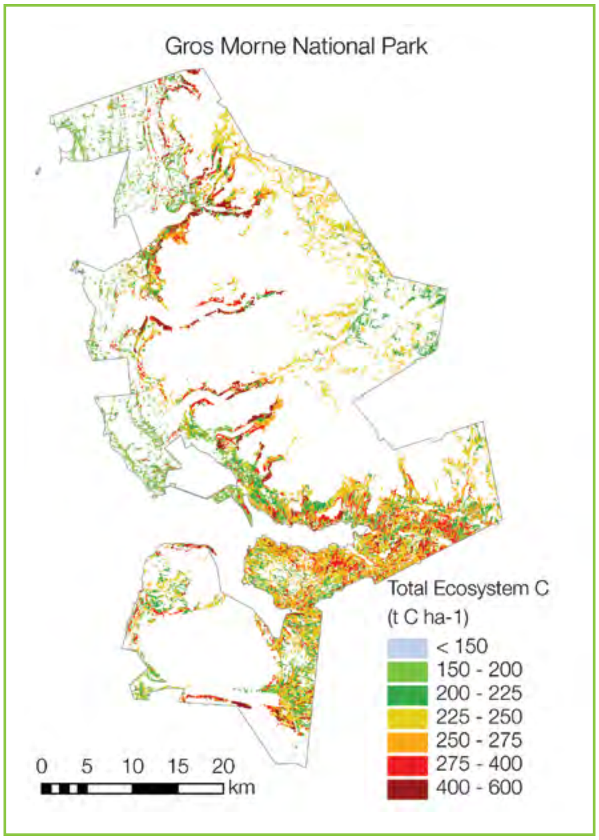


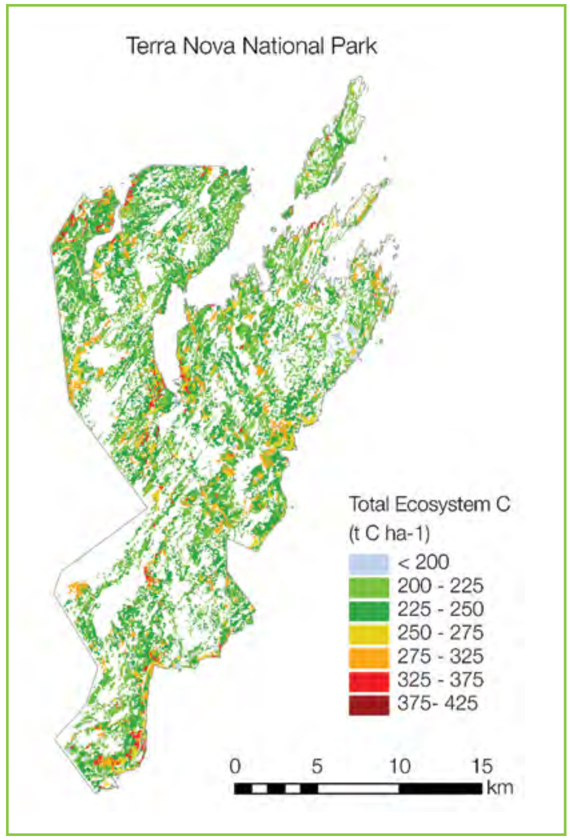


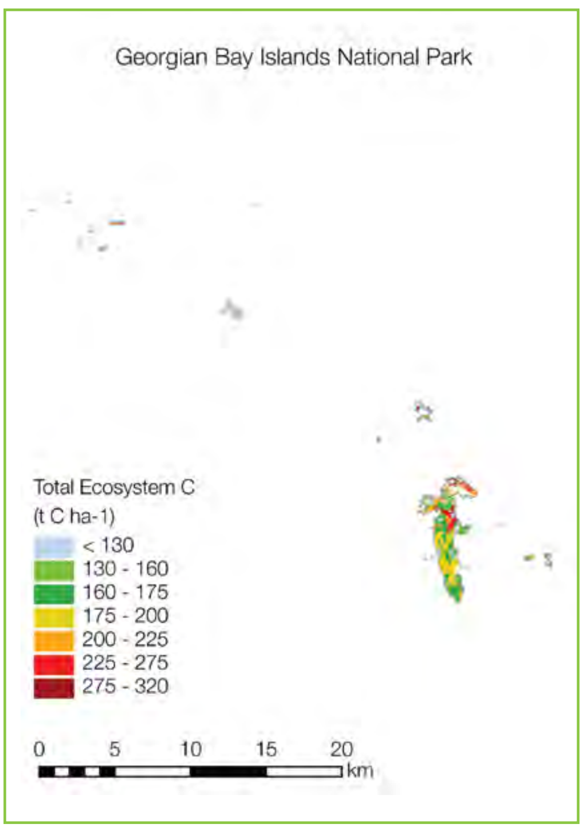
Wood Buffalo National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 200
200 - 250
250 - 275
275 - 300
300 - 350
350 - 425
0
25
50
75
km

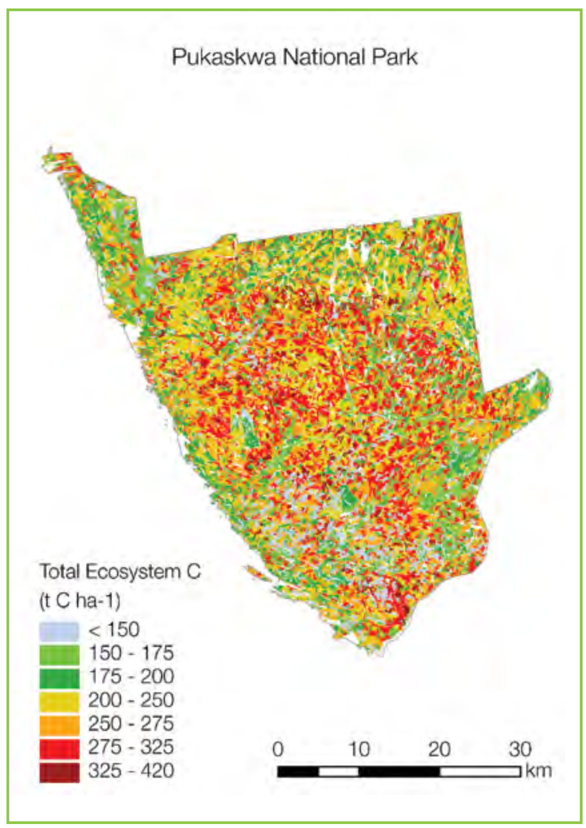

Mingan Archipelago National Park Reserve
Total Ecosystem C
(t C ha-1)
< 180
180 - 200
200 - 205
205 - 210
210 - 250
250 - 275
275 - 300
0
10
20
30
40
50
km


La Mauricie National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 200
200 - 250
250 - 275
275 - 325
325 - 350
350 - 400
0
5
10
15
km

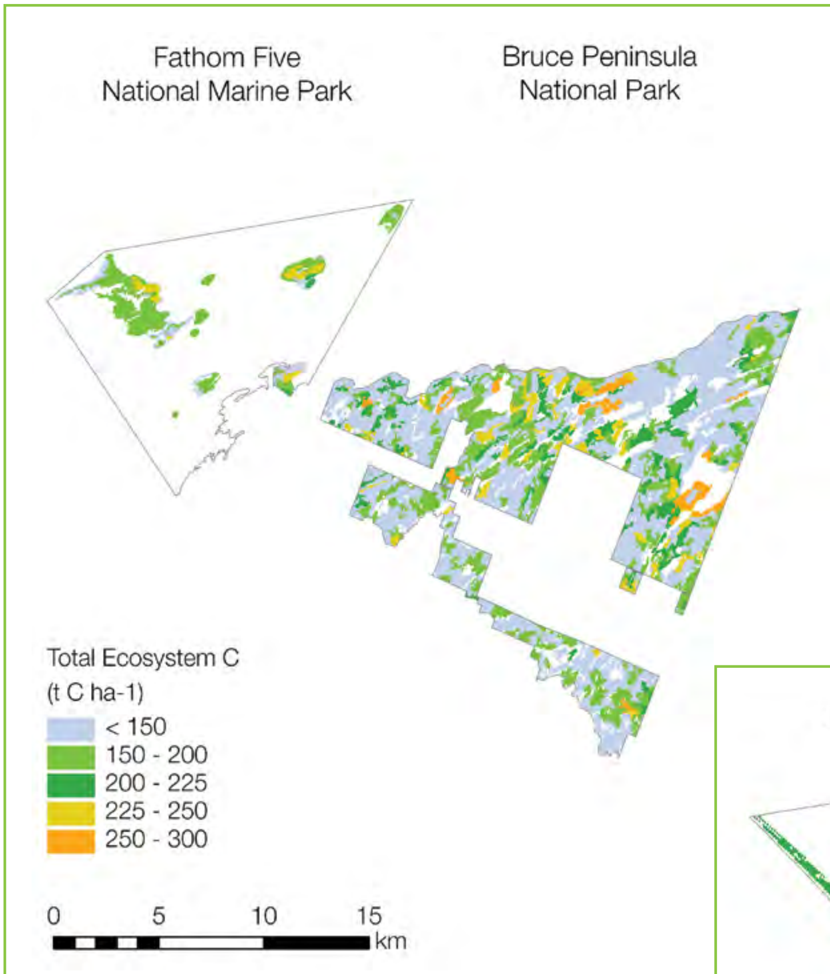

Gros Morne National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 200
200 - 225
225 - 250
250 - 275
275 - 400
400 - 600
0 5 10 15 20 km

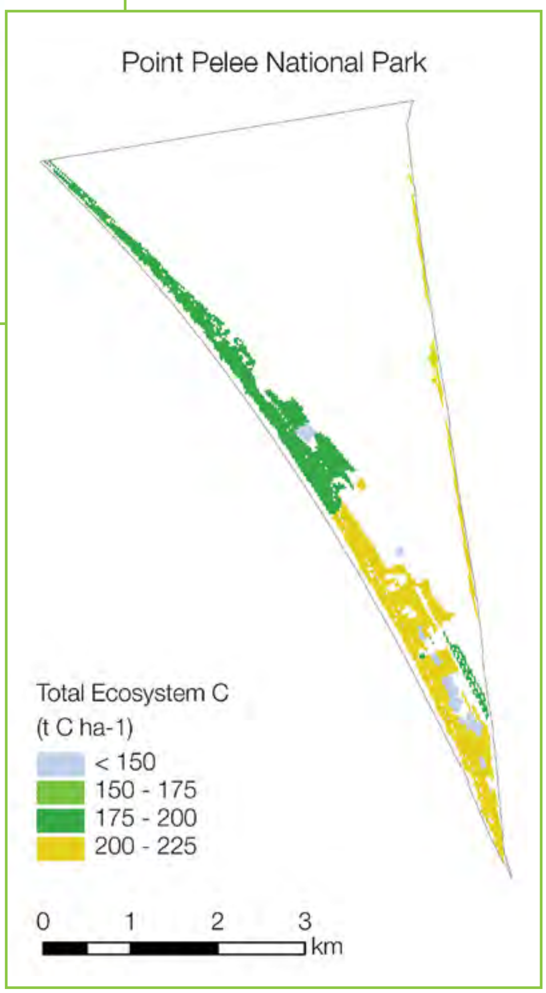

Terra Nova National Park
Total Ecosystem C
(t C ha-1)
< 200
200 - 225
225 - 250
250 - 275
275 - 325
325 - 375
375- 425
0 5 10 15 km

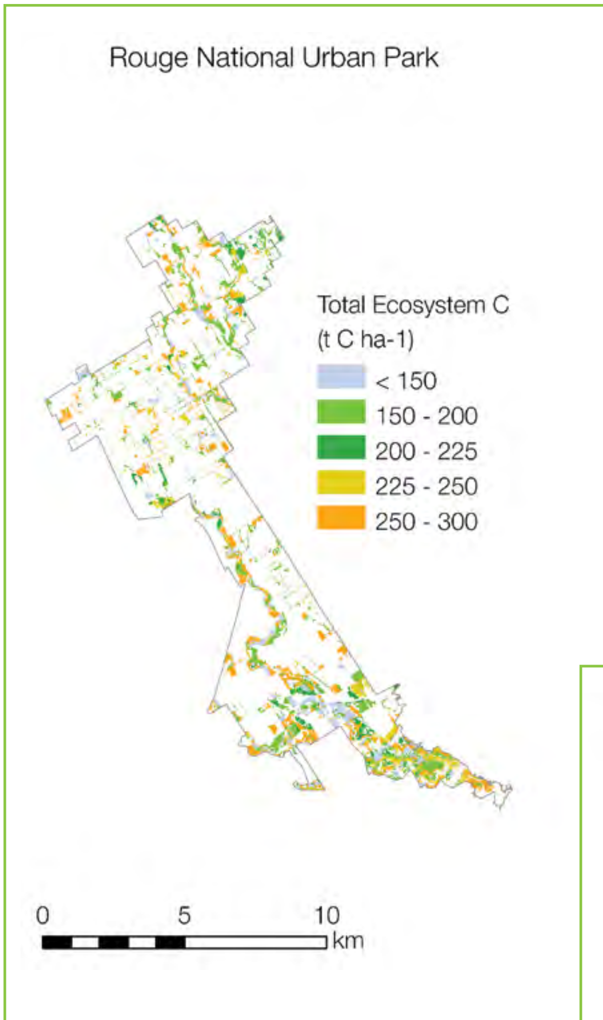

Georgian Bay Islands National Park
Total Ecosystem C
(t C ha-1)
< 130
130 - 160
160 - 175
175 - 200
200 - 225
225 - 275
275 - 320
0 5 10 15 20 km

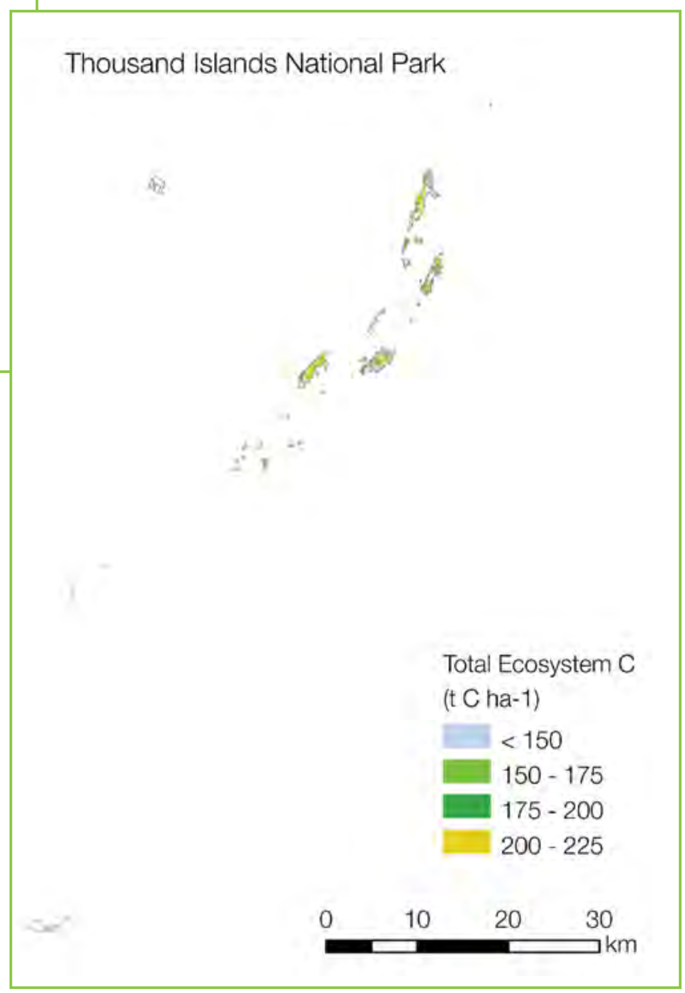

Pukaskwa National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 175
175 - 200
200 - 250
250 - 275
275 - 325
325 - 420
0 10 20 30 km

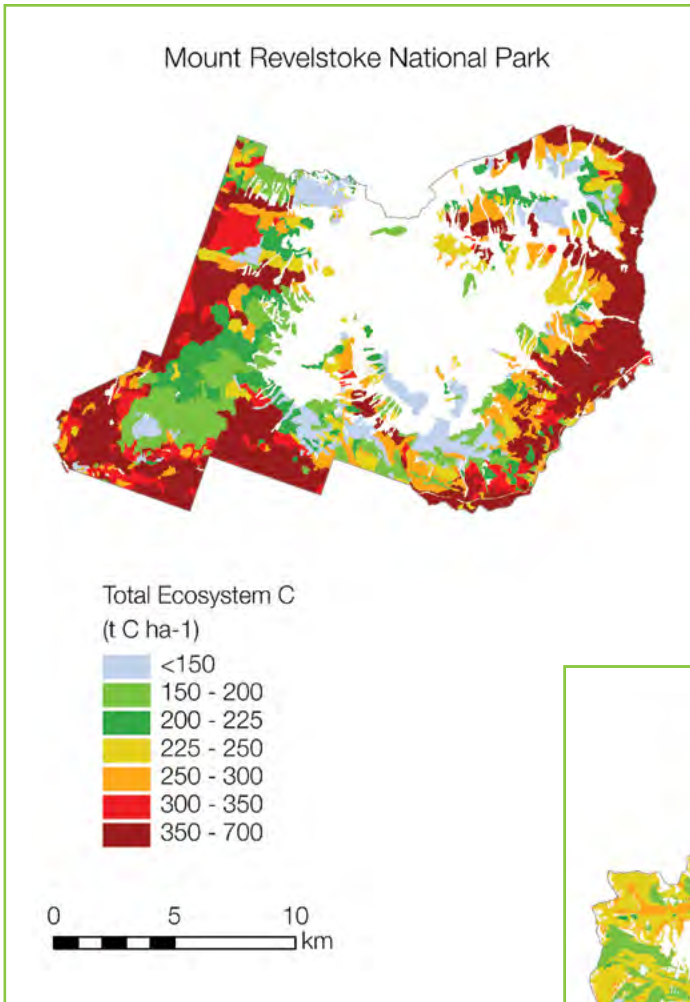
Appendix Div: Mixedwood Plains Ecozone

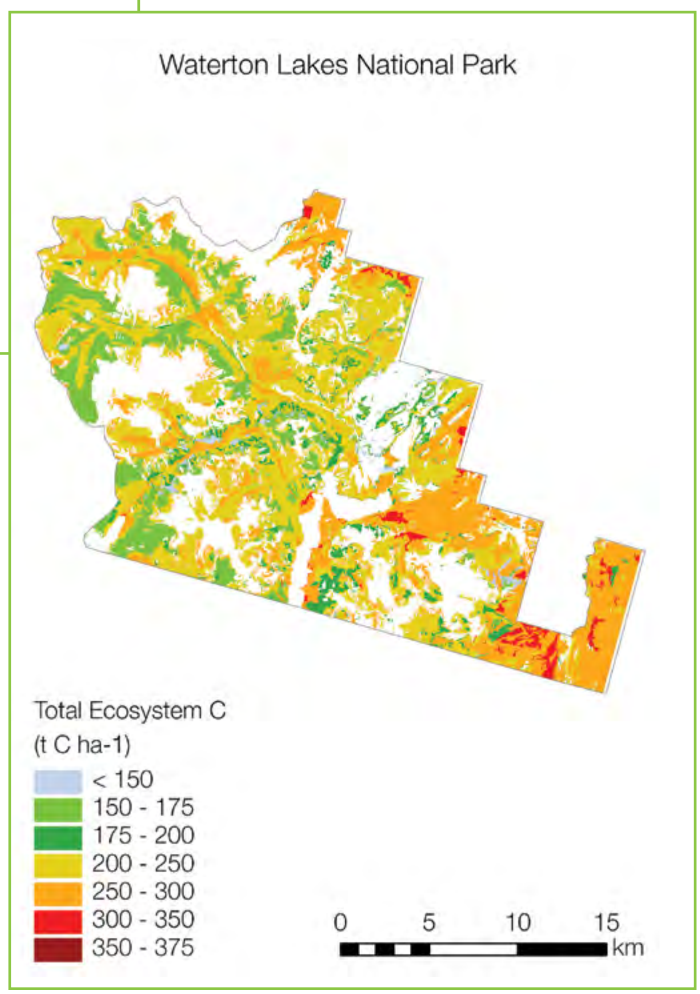


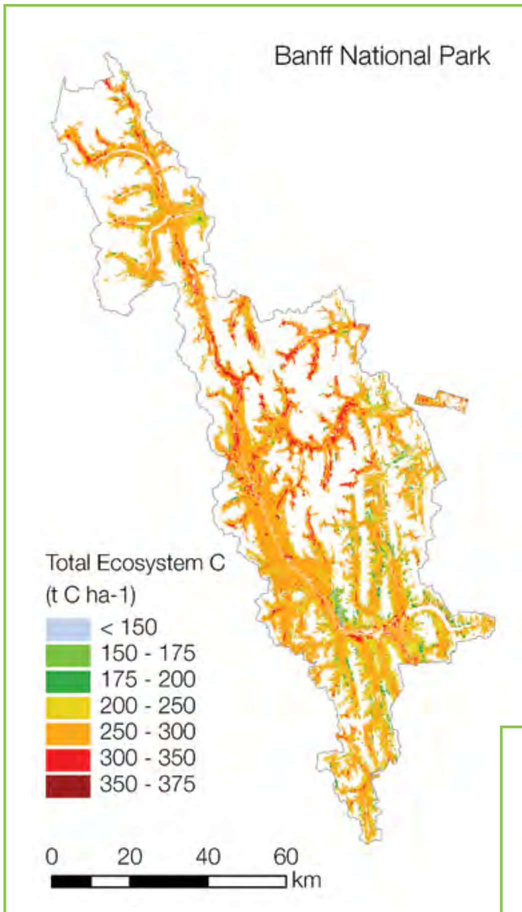


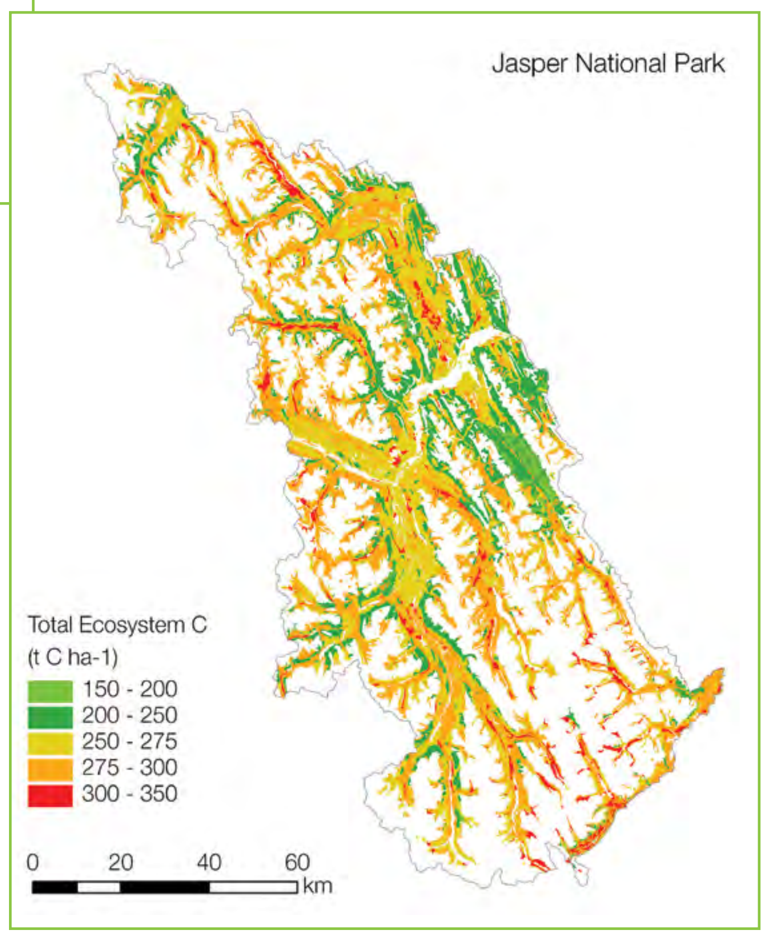

Rouge National Urban Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 200
200 - 225
225 - 250
250 - 300
0
5
10
km

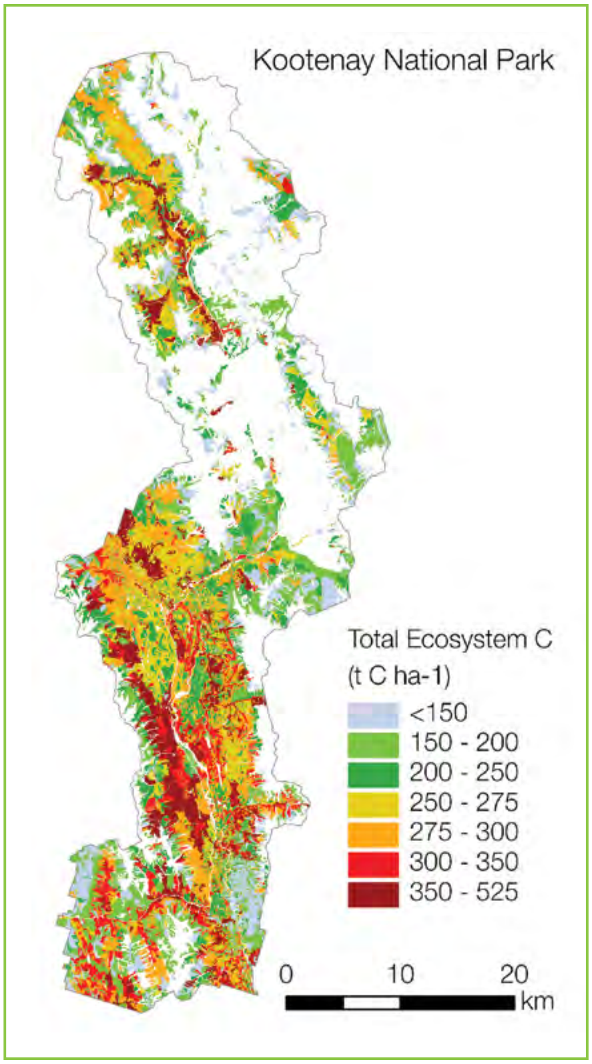

Thousand Islands National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 175
175 - 200
200 - 225
0
10
20
30
km

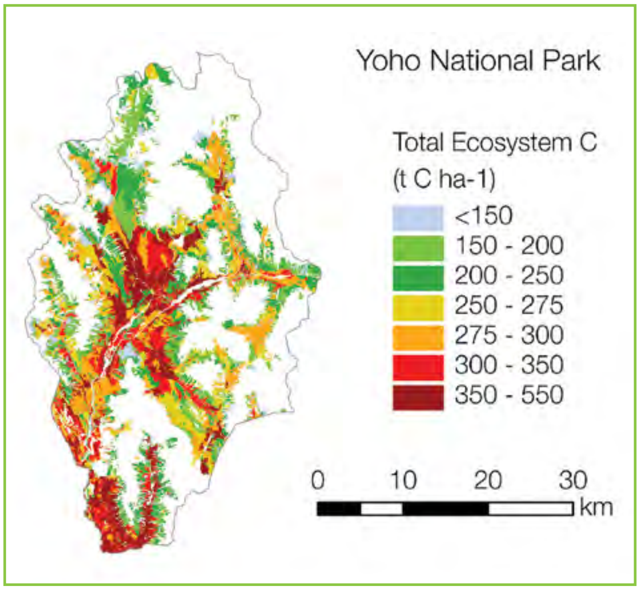

Mount Revelstoke National Park
Total Ecosystem C
(t C ha-1)
<150
150 - 200
200 - 225
225 - 250
250 - 300
300 - 350
350 - 700
0
5
10
km

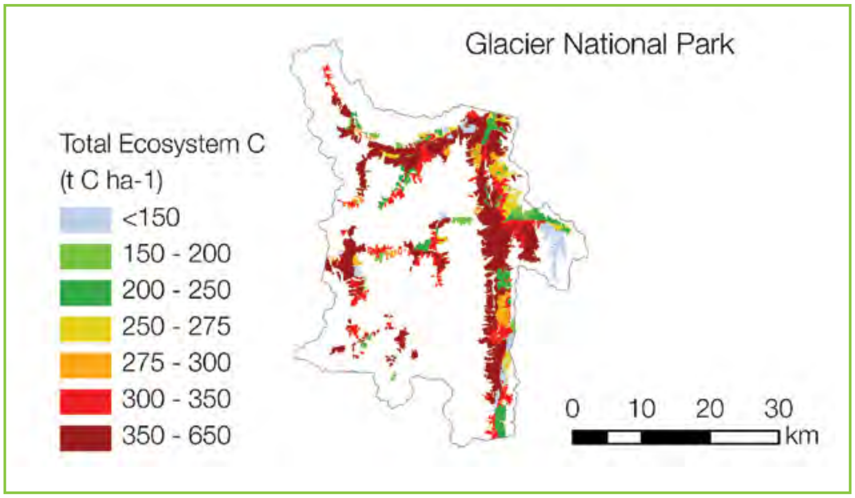

Waterton Lakes National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 175
175 - 200
200 - 250
250 - 300
300 - 350
350 - 375
0
5
10
15
km


Banff National Park
Total Ecosystem C
(t C ha-1)
< 150
150 - 175
175 - 200
200 - 250
250 - 300
300 - 350
350 - 375
0
20
40
60
km

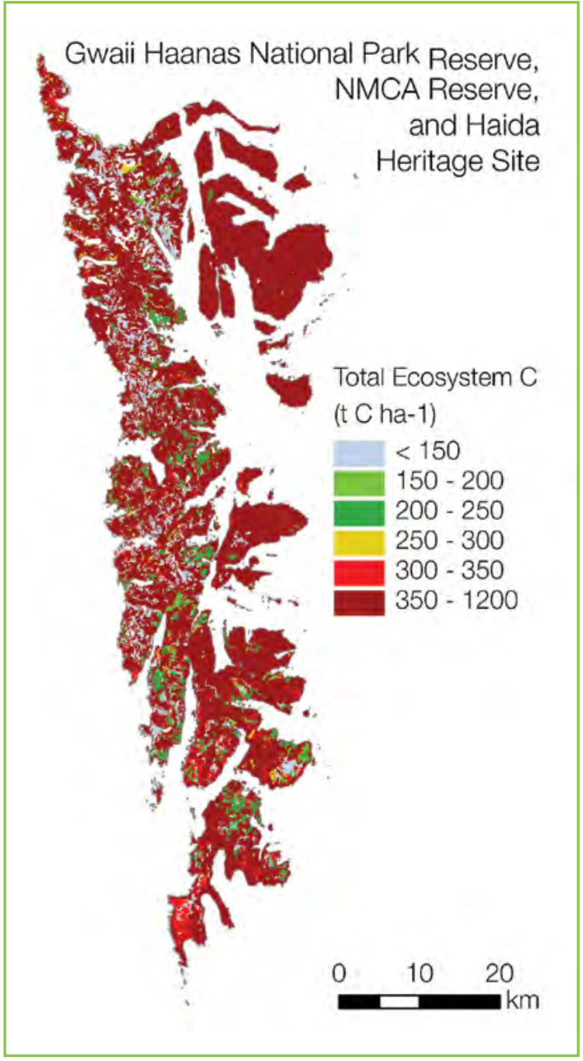

Jasper National Park
Total Ecosystem C
(t C ha-1)
150 - 200
200 - 250
250 - 275
275 - 300
300 - 350
0
20
40
60
km

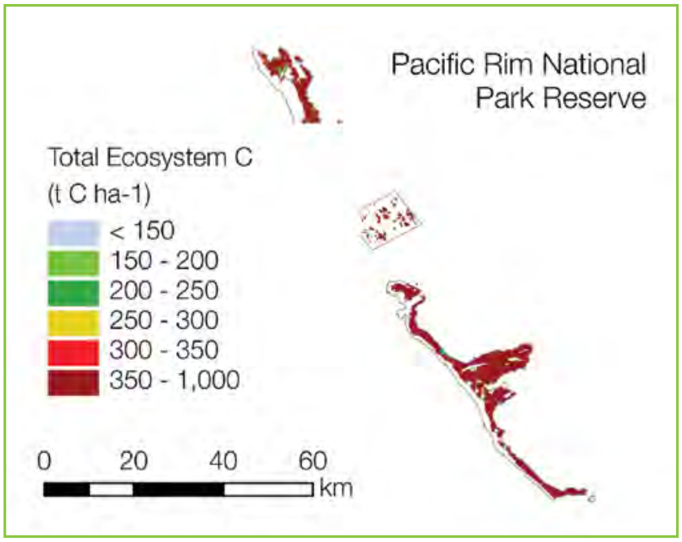

Kootenay National Park
Total Ecosystem C
(t C ha-1)
<150
150 - 200
200 - 250
250 - 275
275 - 300
300 - 350
350 - 525
0
10
20
km

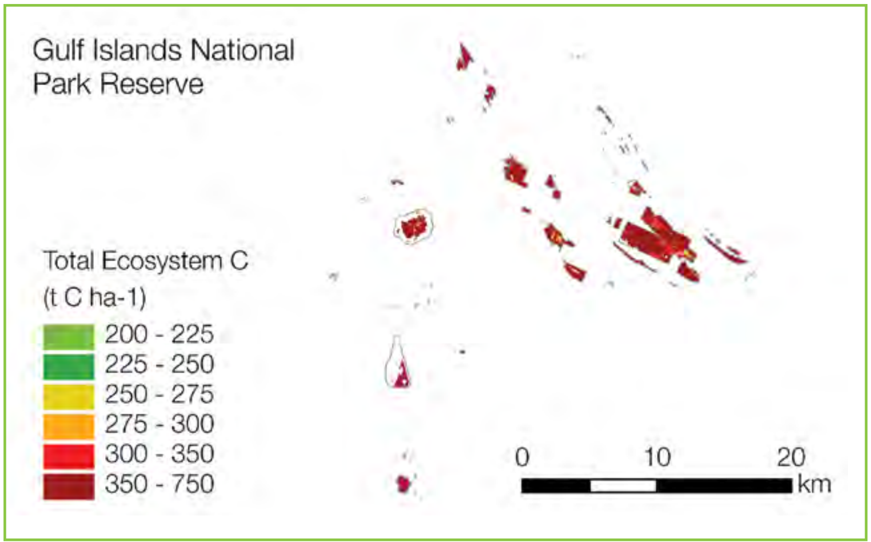

Yoho National Park
Total Ecosystem C
(t C ha-1)
<150
150 - 200
200 - 250
250 - 275
275 - 300
300 - 350
350 - 550
0
10
20
30
km


Glacier National Park
Total Ecosystem C
(t C ha-1)
<150
150 - 200
200 - 250
250 - 275
275 - 300
300 - 350
350 - 650
0
10
20
30
km

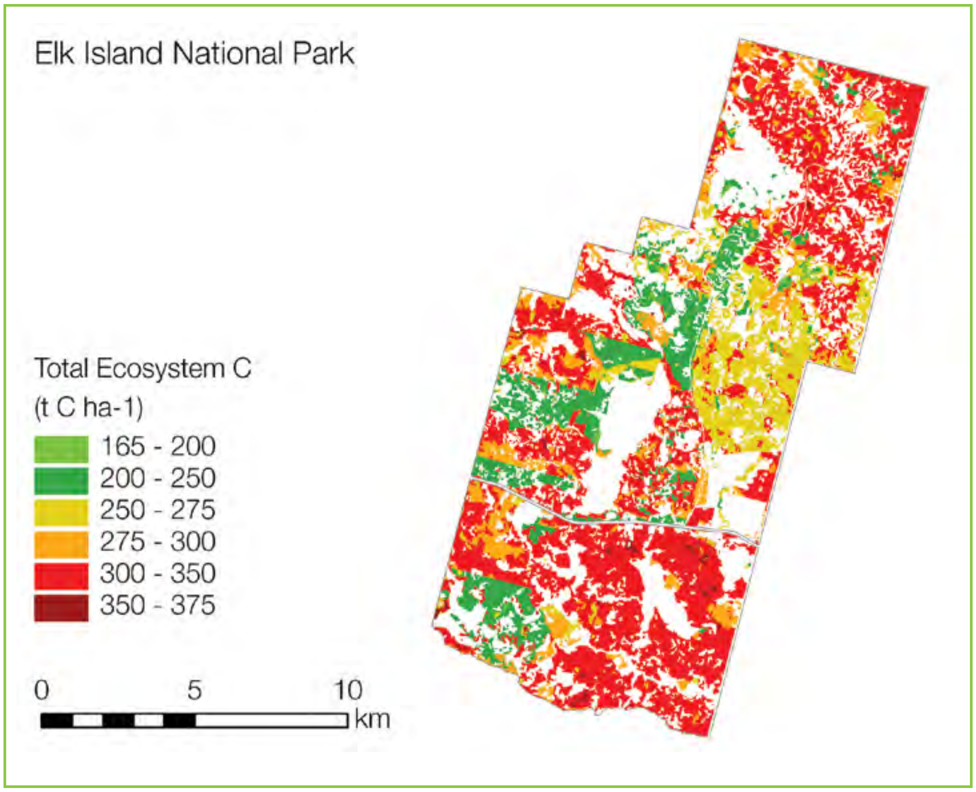
Appendix Dvi: Pacific Maritime Ecozone







Appendix Dvii: Prairies Ecozone



Appendix E: Average carbon fluxes by park (1990-2020)

Park Name	Area (km^2)	NPP ($t\ C\ yr^{-1}$)	R_h ($t\ C\ yr^{-1}$)	NEP ($t\ C\ yr^{-1}$)	NPP ($t\ C\ ha^{-1}\ yr^{-1}$)	Rh ($t\ C\ ha^{-1}\ yr^{-1}$)	NEP ($t\ C\ ha^{-1}\ yr^{-1}$)
Banff NP	3,216	1,118,182	1,043,562	74,620	3.48	3.25	0.23
Bruce Peninsula NP	132	42,975	35,583	7,392	3.25	2.69	0.56
Cape Breton Highlands NP	621	229,411	202,091	27,320	3.69	3.25	0.44
Elk Island NP	121	54,348	50,271	4,077	4.49	4.16	0.34
Fathom Five NMP	13	4,479	4,013	467	3.34	2.99	0.35
Forillon NP	234	93,807	77,144	16,663	4.01	3.30	0.71
Fundy NP	195	64,743	62,833	1,910	3.33	3.23	0.10
Georgian Bay Islands NP	10	3,777	3,376	400	3.83	3.43	0.41
Glacier NP	379	194,908	175,519	19,388	5.14	4.63	0.51
Gros Morne NP	442	214,420	189,907	24,513	4.85	4.30	0.55
Gulf Islands NPR	27	21,742	18,311	3,430	8.19	6.90	1.29
Gwaii Haanas NPR & Haida HS	1,428	1,004,765	935,681	69,084	7.03	6.55	0.48
Jasper NP	5,692	1,966,185	1,921,005	45,180	3.45	3.38	0.08
Kejimkujik NP, NHS & NPS	308	126,074	112,441	13,633	4.09	3.65	0.44
Kootenay NP	820	340,708	277,830	62,877	4.15	3.39	0.77
Kouchibouguac NP	123	36,999	34,734	2,265	3.02	2.83	0.18
La Mauricie NP	473	244,334	219,309	25,025	5.16	4.63	0.53
Mingan NPR	42	13,368	12,026	1,342	3.15	2.83	0.32
Mount Revelstoke NP	169	88,219	70,656	17,562	5.22	4.18	1.04
Pacific Rim NPR	271	214,723	202,483	12,240	7.93	7.48	0.45
Point Pelee NP	2	1,123	936	187	4.64	3.87	0.77
Prince Albert NP	3,462	1,029,778	943,527	86,251	2.97	2.73	0.25
Prince Edward Island NP	7	2,796	2,547	249	3.92	3.57	0.35
Pukaskwa NP	1,683	659,825	573,381	86,443	3.92	3.41	0.51
Riding Mountain NP	2,385	952,319	915,049	37,270	3.99	3.84	0.16
Rouge NUP	19	7,958	6,754	1,204	4.21	3.57	0.64
Terra Nova NP	204	86,813	83,792	3,021	4.25	4.10	0.15
Thousand Islands NP	14	5,677	4,706	971	4.14	3.43	0.71
Waterton Lakes NP	341	117,921	115,282	2,639	3.45	3.38	0.08
Wood Buffalo NP	32,871	12,523,697	10,822,380	1,701,316	3.81	3.29	0.52
Yoho NP	663	283,393	234,209	49,183	4.27	3.53	0.74

Appendix F: Total forest area (km²) affected by disturbances (1990-2020)

Park Name	Wildfire	Prescribed Fire	Insects	Total
Banff National Park	119.5	128.2	969.4	1,217.1
Bruce Peninsula NP			1.5	1.5
Elk Island NP	16.3	37.2		53.5
Forillon NP		1.0	417.9	418.9
Fundy NP	0.3			0.3
Georgian Bay Islands NP			0.6	0.6
Glacier NP	58.7	0.5	423.9	5,266.5
Gros Morne NP			68.6	68.6
Gulf Islands NPR*				0.0
Jasper NP	42.3	207.3	5,293.7	5,543.3
Kejimkujik NP, NHS & NPS	0.5	0.1		0.6
Kootenay NP	124.4	35.4	666.5	9,813.2
La Mauricie NP	1.2	23.0	48.1	72.3
Mingan NPR	0.0		44.5	44.5
Mount Revelstoke NP	5.5	0.6	48.5	880.5
Point Pelee NP			0.0	0.0
Prince Albert NP	436.0	252.3	8,551.0	9,239.3
Pukaskwa NP	0.6	29.5	2,265.4	2,295.4
Riding Mountain NP	2.3	113.2	298.2	413.6
Terra Nova NP	0.1	2.1	4.4	6.6
Thousand Islands NP		0.1	0.0	0.1
Waterton Lakes NP	167.5	25.8	71.8	265.1
Wood Buffalo NP	13,425.9	0.0	17,645.8	31,071.8
Yoho NP	0.2	9.9	842.6	10,503.6
Grand Total	**14,401.4**	**866.2**	**37,662.4**	**52929.0**

*Prescribed fire area was very small (1.28 ha)

Note: Parks which were not affected by any disturbances or for which disturbance data were not available for this study are not included in this table.

Appendix G: Annual net biome productivity by park (in t C ha^{-1} yr^{-1})

Year	Banff NP	Bruce Peninsula NP	Cape Breton Highlands NP	Elk Island NP	Fathom Five NMP	Forillon NP	Fundy NP
1990	0.23	0.56	0.61	0.54	0.48	0.50	0.15
1991	0.27	0.58	0.61	-1.75	0.48	0.55	0.16
1992	0.27	0.59	0.61	0.47	0.48	0.59	0.15
1993	0.23	0.59	0.61	0.26	0.49	0.61	0.14
1994	0.18	0.60	0.56	-1.14	0.49	0.65	0.14
1995	0.27	0.57	0.56	0.42	0.39	0.69	0.11
1996	0.27	0.58	0.57	0.43	0.39	0.69	0.12
1997	0.27	0.59	0.57	0.43	0.39	0.51	0.12
1998	0.17	0.59	0.57	0.43	0.39	0.57	0.09
1999	0.09	0.60	0.52	0.43	0.39	0.56	0.10
2000	0.20	0.60	0.52	-1.77	0.39	0.61	0.09
2001	-0.01	0.60	0.52	0.36	0.39	0.65	0.09
2002	0.23	0.61	0.53	0.33	0.39	0.69	0.09
2003	-0.09	0.61	0.53	0.35	0.39	0.73	0.09
2004	0.23	0.61	0.40	-3.91	0.39	0.72	0.09
2005	0.08	0.55	0.40	0.09	0.31	0.75	0.09
2006	0.16	0.56	0.40	0.14	0.31	0.78	0.09
2007	0.20	0.56	0.41	0.18	0.31	0.80	0.09
2008	0.16	0.56	0.41	0.22	0.31	0.82	0.08
2009	0.07	0.56	0.37	0.25	0.31	0.78	0.09
2010	0.22	0.55	0.37	0.25	0.30	0.81	0.08
2011	0.19	0.56	0.37	0.27	0.30	0.83	0.08
2012	0.22	0.56	0.37	0.28	0.30	0.85	0.09
2013	0.21	0.56	0.37	0.31	0.30	0.86	0.08
2014	-0.32	0.56	0.29	0.33	0.30	0.83	0.08
2015	0.04	0.48	0.29	0.31	0.24	0.84	0.08
2016	0.18	0.48	0.29	0.33	0.24	0.81	0.08
2017	0.17	0.48	0.29	0.34	0.24	0.80	0.08
2018	0.19	0.48	0.29	0.35	0.24	0.87	0.07
2019	0.15	0.48	0.22	0.36	0.24	0.66	0.07
2020	0.12	0.47	0.21	0.34	0.23	0.60	0.06

Year	Georgian Bay Islands NP	Glacier NP	Gros Morne NP	Gulf Islands NPR	Gwaii Haanas NPR & Haida HS	Jasper NP	Kejimkujik NP & NHS
1990	0.49	0.94	0.89	0.92	0.35	0.11	0.51
1991	0.47	0.84	0.90	0.93	0.37	0.10	0.51
1992	0.47	0.91	0.92	0.94	0.38	0.10	0.52
1993	0.47	0.91	0.93	0.96	0.40	0.10	0.52
1994	0.47	0.74	0.94	1.28	0.41	0.10	0.49
1995	0.46	0.75	0.67	1.28	0.43	0.11	0.50
1996	0.46	0.73	0.44	1.29	0.45	0.10	0.50
1997	0.46	0.74	0.48	1.30	0.44	0.10	0.50
1998	0.46	0.66	0.53	1.31	0.45	0.10	0.50
1999	0.46	0.75	0.55	1.24	0.46	0.10	0.48
2000	0.40	0.76	0.45	1.25	0.48	0.03	0.49
2001	0.33	0.73	0.46	1.26	0.49	0.10	0.49
2002	0.35	0.77	0.44	1.27	0.49	0.10	0.49
2003	0.36	0.08	0.43	1.27	0.50	-0.74	0.48
2004	0.37	0.69	0.46	1.40	0.51	0.08	0.47
2005	0.37	0.63	0.42	1.40	0.53	0.08	0.47
2006	0.37	0.58	0.44	1.40	0.54	-0.01	0.47
2007	0.38	0.61	0.46	1.40	0.50	0.07	0.47
2008	0.38	0.23	0.47	1.41	0.51	0.06	0.46
2009	0.39	0.58	0.48	1.37	0.51	-0.01	0.43
2010	0.39	0.61	0.49	1.38	0.52	0.07	0.43
2011	0.38	0.62	0.50	1.38	0.52	0.06	0.43
2012	0.38	0.44	0.52	1.39	0.53	0.07	0.42
2013	0.38	0.52	0.54	1.39	0.53	0.06	0.41
2014	0.38	0.55	0.56	1.37	0.54	0.06	0.39
2015	0.38	0.53	0.44	1.38	0.54	-0.03	0.39
2016	0.38	0.37	0.45	1.37	0.54	0.06	0.38
2017	0.38	-7.39	0.49	1.39	0.52	0.07	0.37
2018	0.38	-4.13	0.49	1.40	0.52	0.05	0.36
2019	0.38	-0.93	0.50	1.38	0.52	0.02	0.34
2020	0.38	-1.01	0.45	1.38	0.52	0.02	0.33

Year	Kejimkujik NPS	Kootenay NP	Kouchi-bouguac NP	La Mauricie NP	Mingan NPR	Mount Revelstoke NP	Pacific Rim NPR	Point Pelee NP
1990	0.26	1.20	0.30	0.73	0.44	1.14	0.33	0.81
1991	0.27	1.05	0.31	0.77	0.49	1.15	0.36	0.82
1992	0.27	1.17	0.31	0.78	0.40	1.15	0.38	0.84
1993	0.27	1.17	0.31	0.71	0.40	1.15	0.40	0.85
1994	0.25	1.14	0.29	0.73	0.40	1.15	0.42	0.86
1995	0.25	1.05	0.28	0.72	0.40	1.15	0.44	0.87
1996	0.25	0.97	0.27	0.75	0.40	1.13	0.45	0.88
1997	0.25	0.99	0.27	0.74	0.39	1.11	0.46	0.89
1998	0.25	0.97	0.25	0.63	0.39	1.11	0.47	0.90
1999	0.22	0.96	0.24	0.62	0.39	1.12	0.44	0.91
2000	0.22	0.95	0.23	0.63	0.39	1.12	0.45	0.75
2001	0.22	0.86	0.22	0.62	0.40	1.12	0.46	0.75
2002	0.22	0.90	0.21	0.63	0.32	1.12	0.46	0.76
2003	0.22	-0.49	0.21	0.41	0.32	0.29	0.47	0.77
2004	0.17	0.76	0.20	0.53	0.32	1.07	0.48	0.77
2005	0.17	0.73	0.19	0.54	0.32	1.07	0.49	0.76
2006	0.17	0.72	0.18	0.55	0.32	1.06	0.49	0.77
2007	0.17	0.58	0.17	0.54	0.33	1.03	0.50	0.78
2008	0.17	-0.72	0.17	0.43	0.33	1.03	0.50	0.78
2009	0.14	0.64	0.16	0.46	0.33	1.03	0.46	0.62
2010	0.14	0.64	0.14	0.46	0.32	1.03	0.46	0.63
2011	0.14	0.63	0.13	0.47	0.32	1.03	0.46	0.65
2012	0.14	0.45	0.12	0.46	0.29	1.04	0.47	0.67
2013	0.14	0.17	0.11	0.35	0.27	1.03	0.47	0.69
2014	0.07	0.64	0.10	0.21	0.29	1.00	0.47	0.71
2015	0.07	0.64	0.08	0.01	0.29	0.98	0.48	0.71
2016	-1.52	0.61	0.07	0.08	0.22	0.93	0.47	0.72
2017	-0.11	-3.35	0.06	0.27	0.21	0.89	0.47	0.74
2018	-0.08	-1.98	0.06	0.20	0.22	-0.44	0.48	0.76
2019	-0.08	0.12	0.05	0.19	0.23	0.71	0.44	0.78
2020	-0.07	0.13	0.04	0.18	-0.38	0.64	0.44	0.80

Year	Prince Albert NP	Prince Edward Island NP	Pukaskwa NP	Riding Mountain NP	Rouge NUP	Terra Nova NP	Thousand Islands NP
1990	0.44	0.67	0.75	0.32	0.73	0.24	0.56
1991	0.46	0.67	0.75	0.25	0.75	0.24	0.58
1992	0.44	0.67	0.75	0.25	0.74	0.24	0.61
1993	0.44	0.28	0.75	0.26	0.72	0.24	0.63
1994	0.43	0.30	0.76	0.26	0.70	0.24	0.65
1995	0.37	0.49	0.76	0.27	0.70	0.22	0.67
1996	0.17	0.45	0.39	0.23	0.71	0.22	0.68
1997	0.32	0.41	0.37	0.23	0.71	0.24	0.71
1998	-0.31	0.38	0.30	0.24	0.72	0.23	0.69
1999	0.06	0.34	0.31	0.24	0.72	0.24	0.70
2000	0.05	0.59	0.32	0.20	0.71	0.14	0.71
2001	0.06	0.62	0.35	0.18	0.71	0.13	0.72
2002	-0.16	0.65	0.27	0.10	0.70	0.12	0.72
2003	-0.02	0.68	0.40	0.15	0.67	0.13	0.73
2004	0.00	0.71	0.42	0.18	0.62	0.13	0.74
2005	0.04	0.19	0.45	0.14	0.63	0.16	0.74
2006	0.01	0.20	0.36	0.13	0.62	0.16	0.74
2007	0.12	0.21	0.48	0.15	0.62	0.15	0.75
2008	-0.03	0.23	0.42	-0.03	0.63	0.14	0.75
2009	-0.28	0.24	0.44	0.16	0.62	0.14	0.75
2010	0.21	0.07	0.47	0.11	0.61	0.12	0.73
2011	0.18	0.07	0.47	0.05	0.61	0.11	0.75
2012	0.25	0.08	0.49	0.10	0.60	0.11	0.75
2013	0.31	0.09	0.53	0.11	0.56	0.10	0.75
2014	0.31	0.09	0.52	0.10	0.53	0.10	0.74
2015	-0.32	0.23	0.57	-0.05	0.53	0.03	0.73
2016	0.33	0.24	0.56	0.04	0.52	-0.07	0.73
2017	0.37	0.24	0.58	-0.04	0.52	0.01	0.73
2018	-1.51	0.25	0.54	-0.13	0.52	0.05	0.73
2019	0.33	0.26	0.55	-0.13	0.51	0.05	0.73
2020	0.38	0.22	0.57	-0.12	0.50	0.03	0.69

Year	Waterton Lakes NP	Wood Buffalo NP	Yoho NP
1990	0.20	0.64	0.91
1991	0.21	0.65	0.91
1992	0.21	0.66	0.92
1993	0.21	0.67	0.93
1994	0.15	0.67	0.93
1995	0.19	0.66	0.94
1996	0.19	0.57	0.89
1997	0.19	0.65	0.90
1998	-0.76	0.53	0.90
1999	0.14	0.13	0.90
2000	0.15	0.59	0.92
2001	0.15	0.60	0.90
2002	0.13	0.66	0.91
2003	0.10	-0.80	0.88
2004	0.15	-1.42	0.85
2005	0.14	0.17	0.65
2006	0.05	0.44	0.77
2007	0.14	-1.50	0.77
2008	-0.28	0.46	0.72
2009	0.12	0.48	0.64
2010	0.12	0.50	0.59
2011	0.11	-0.16	0.32
2012	0.11	-1.52	0.59
2013	0.11	0.07	0.61
2014	0.01	-1.97	0.62
2015	-0.14	-4.74	0.63
2016	-0.17	0.14	0.58
2017	-18.14	-0.42	0.54
2018	-0.75	-0.01	0.38
2019	-0.46	-0.61	0.31
2020	-0.38	0.34	0.27

Canada