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A National Assessment of Wetland Status and Trends for Canada's Forested Ecosystems Using 33 Years of Earth Observation Satellite Data

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Abstract: Wetlands are important globally for supplying clean water and unique habitat, and for storing vast amounts of carbon and nutrients. The geographic extent and state of wetlands vary over time and represent a dynamic land condition rather than a permanent land cover state. Herein, we combined a time series of land cover maps derived from Landsat data at 30-m resolution to inform on spatial and temporal changes to non-treed and treed wetland extents over Canada's forested ecosystems (>650 million ha) from 1984 to 2016. Overall, for the period, 1984 to 2016, we found the extent of wetlands (non-treed and treed combined) in Canada's forested ecosystems to be stable, with some regional variability, often resulting from offsetting decreases and increases within a given ecozone. Notwithstanding difficulties in using optical satellite data for mapping a land condition, by accumulating wetland evidence via earth observations consistently through multiple decades, our results capture the trends in wetland cover over a previously unmapped, national extent at a level of spatial detail and temporal reach suitable for further focused interpretations of wetlands and drivers and projections of wetland dynamics.

Keywords: Landsat; time series; ecosystem dynamics; Canada; boreal; wetland

1. Introduction

Wetlands are significant global contributors to the supply of clean, fresh water and they regulate the hydrological cycle to mitigate floods and protect shorelines. Wetlands also store notable amounts of carbon and other nutrients, thus influencing both water and nutrient cycles as well as modulating climate [1–4]. Wetlands are the transitional areas between terrestrial uplands and deep, open water [5]. Wetlands range from permanently flooded lands to areas where water is at or near the land surface and soils remain saturated just long enough to develop hydrophytic vegetation and other biological activities adapted to wet/aquatic environments [6]. The global importance of wetlands is reflected through their designation for conservation under an international convention: Nation signatories to the Ramsar Convention, including Canada, indicating a commitment to "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world" [7].

Wetlands cover about 13% of Canada (1.29 million km^2) and constitute about a quarter of the world's documented wetlands [8]. The Canadian National Wetland Working Group [6] adopted a hierarchical classification systems composed of five broad wetland classes that, in turn, are characterized by 49 wetland forms (based on surface morphology), and further refined by 72 wetland types (based on physiognomic characteristics). By virtue of this structural diversity, Canadian wetlands provide habitat for many wildlife species, including moose and migratory birds, and a wide array of products (e.g., cranberries, fowl, peat, wild rice) of regional and local importance. The five major wetland classes include swamps (which are dominated by trees or tall shrubs, e.g., *Salix* spp.), bogs, fens, marshes, and shallow water/ponds (which are dominated by low shrubs, graminoids such as sedges, and aquatic plants) [6,8]. These five broader class definitions can also be considered more simply as treed wetlands (e.g., swamps) and non-treed wetlands (or open water, e.g., bogs, fens, marshes, and shrub-dominated ponds) [9].

The societal value of wetlands is a relatively recent realization. Not so long ago, wetlands in proximity to populated areas were considered impediments to development and were often drained and converted to lands that could be built upon or farmed. Land use changes have resulted in notable wetland alteration, degradation, or loss due to urbanization and agricultural development that has occurred over the last century in southern Canada where human populations are high [8]. Natural resource exploration and extraction has caused the degradation or loss of wetlands in more remote regions (oil and gas, mining) [10]. Additionally, climate change may substantially alter wetlands across Canada (i.e., stability, growth, or contraction) and is expected to vary regionally [1,4]. Alterations to wetland ecosystems can also result in public safety concerns as well as impacts to infrastructure where wetlands have previously provided natural mechanisms for reducing flooding in some regions [8]. Befitting their importance, federal, provincial, and territorial governments have common interests and share responsibility for the conservation and management of Canada's wetlands. As a result, wetlands are a key element of federal environmental sustainability responsibilities involving water quality and availability, wildlife habitat, natural resource protection, and climate change [11], with regulations to protect wetlands for administration under a mix of legislative vehicles (e.g., Department of the Environment Act, Canadian Environmental Protection Act, Fisheries Act, Species At Risk Act). Canada's performance on environmental sustainability is measured by several indicators, including wetland extent [8]. In documenting policy specific to wetlands, Canada's "Federal Policy on Wetland Conservation" [12] advocates "no net loss" of wetland ecosystem services and supports the Ramsar Convention by securing protection for, restoring, and monitoring wetlands of international importance. Although now somewhat dated and subject to change by subsequent governments, the implementation of the policy on federal lands and lands subject to federally funded projects indicates the importance of conducting wetland inventories.

As noted above, natural resource managers and policy-makers over a wide-range of governance (local through to federal) can benefit from accurate annual wetland maps over large areas to monitor, conserve, restore, and manage wetlands; to characterize historical wetland dynamics over long periods; and to quantify rates of wetland loss or conversion caused by human disturbances and environmental change. However, wetlands are inherently challenging to map due to potentially large seasonal and annual fluctuations in size and permanence [13]. Maps produced from traditional aerial photography precisely delineated wetlands, but reproducibility of these delineations were subject to human error and long intervals between aerial surveys. Therefore, such map production could not adequately contribute to an understanding of seasonal and inter-annual wetland dynamics or long-term trends in wetland condition. Digital analysis of annual satellite imagery reduces human sources of errors in wetland delineation and provides the temporal resolution needed to detect intra- and inter-annual and longer temporal trends in wetland dynamics [14]. It also enables assessments of variability in wetland extents over large spatial scales, which are essential to the development and application of national and international policies on water, biodiversity, climate, and carbon management [8]. The challenges of using remotely sensed data for monitoring wetlands is presented by Gallant [15] and Special Issue citations therein, including approaches, technologies, and data products, and monitoring opportunities. The value of long-term monitoring of wetlands was shared by Moffett et al. [16], with provisional trends from remote sensing offered as a means to test ecological theory and to motivate continued remote sensing-based monitoring advancements. Gallant [15] shared the importance of wetland monitoring, followed with a description of how broad scale information, such as from remote sensing, can complement costly and spatially and temporally limited in situ measures. Also indicated was a diversity of methodological approaches and data options, rather than coalescence on standards, underlining the complexity of wetland mapping and monitoring. Several recent regional-scale analyses of annual satellite imagery, sometimes combined with ancillary topo-edaphic data, have been used to map wetlands with pixel-by-pixel accuracy of 83–97% [17,18]. Given the interest in capturing not only wetland area, but also change in wetland status and extent over time, multi-temporal investigations are increasingly of interest. The use of time series satellite imagery has been demonstrated [17,19,20]. Dingle Robertson et al. [19] showed for two wetland complexes in Ontario, Canada, over a 26-year period using Landsat-5 Thematic Mapper data, an ability to capture a range of wetland dynamics as well as inference of the drivers of change. Li and Chen [21] identified the scope and described the value and necessity of using satellite remotely sensed data for practical and timely wetland mapping in Canada.

Despite the benefits and values of remote sensing-based wetland mapping illustrated by past studies, challenges remains for large-area and long-term wetland mapping with earth observation data because (a) wetlands represent a land condition and not a singular land cover state [22], with different types of wetlands containing different vegetation and a range of moisture conditions [15], and (b) they vary spatially, temporally (between years), and seasonally (within years) [13,15,22,23]. The lack of a consistent vegetation pattern can lead to errors when using automated or semi-automated methods designed for remotely sensed data such as aerial photographs or satellite imagery, and intensive ground campaigns are often required to produce maps with lower error rates [19] and are typically limited to smaller spatial extents. Natural resource managers and policy makers are interested in deriving reliable wetland maps over large areas in a consistent manner for a single year, as well as in characterizing wetland dynamics over time [8]. Addressing both of these information needs for wetland status and dynamics are facilitated by the availability of Landsat time series data and related improved processing and analysis opportunities [24,25].

The goal of this research was to demonstrate the utility of a multi-decadal time series of land cover derived from optical remotely sensed data to inform on the status and trends of wetlands over large areas. We acknowledge the challenges with mapping a land condition and propose the accumulation of land cover change evidence over time to increase confidence in the trends captured. To offer a novel approach to wetland characterization, we use a 33-year disturbance-informed and harmonized annual land cover mapping product [26] to isolate and characterize wetlands over a large area and multiple decades. In so doing, we demonstrate for the 650 million hectares of forested ecosystems of Canada, as represented by the forested terrestrial ecozones, a capacity for wetland mapping and related assessment of changes in wetland extents over time. After addressing the methodological aspects related to data characteristics and analyses, we enumerate the outcomes, and follow with insights on changes in wetland extents for the forest-dominated ecozones of Canada.

2. Methods

2.1. Study Area

Our study area encompassed Canada's forest-dominated ecozones [27], which represents ~65% of Canada's total area (i.e., ~650 million hectares) [9]. Following Stinson et al. [28] and Frazier et al. [29], we divide the Boreal Shield and Taiga Shield ecozones into east and west compartments (as listed in Table 1) because of regional differences in temperature, precipitation, and disturbance regimes. Within these forested ecozones, landscapes are mosaics of treed land (represented by >347 million ha treed and other wooded land) [30] interspersed largely with lakes, wetlands, and herbaceous vegetation and shrubs [9,26]. The climatic conditions across all of Canada's 12 forested-dominated ecozones are highly variable. In general, the northern parts of the study area are highly seasonal, typically with snow cover through the winter and short growing seasons. Coastal regions are typically warmer, with longer growing seasons and more productive ecosystems. Central areas of Canada have a continental climate, characterized by long, cold winters and hot summers (for ecozone summaries, see Coops et al. [31]).

Table 1. Summary statistics of wetland area (millions of hectares, Mha), by ecozone, for the period, 1984–2016. Numbers in the parentheses are the percentage of an ecozone covered by wetlands.

	Ecozone	Mean ± SD [1] (Mha (%))	Min. (Mha (%))	Min. Year	Max. (Mha (%))	Max. Year
	Atlantic Maritime	3.82 ± 0.57 (18.71 ± 2.81)	3.10 (15.15)	2015	4.63 (22.68)	1986
	Boreal Cordillera	0.30 ± 0.03 (0.68 ± 0.07)	0.26 (0.59)	2002	0.38 (0.86)	2016
	Boreal Plains	11.51 ± 0.44 (16.15 ± 0.62)	10.96 (15.38)	2015	12.20 (17.12)	1991
	Boreal Shield East	16.16 ± 0.38 (15.04 ± 0.35)	15.62 (14.54)	2014	16.79 (15.63)	1992
	Boreal Shield West	17.35 ± 0.38 (21.22 ± 0.46)	16.76 (20.49)	2000	18.00 (22.01)	1986
	Hudson Plains	29.85 ± 0.07 (81.99 ± 0.20)	29.71 (81.61)	1998	29.99 (82.38)	2012
	Montane Cordillera	0.13 ± 0.01 (0.27 ± 0.03)	0.10 (0.21)	2000	0.15 (0.31)	2016
	Pacific Maritime	0.93 ± 0.02 (4.64 ± 0.11)	0.89 (4.40)	2000	0.95 (4.74)	1986
	Taiga Cordillera	1.02 ± 0.06 (4.06 ± 0.24)	0.90 (3.60)	1984	1.18 (4.68)	2016
	Taiga Plains	19.28 ± 0.51 (31.10 ± 0.82)	18.47 (29.80)	1995	20.21 (32.60)	2013
	Taiga Shield East	10.14 ± 1.19 (13.90 ± 1.63)	8.89 (12.18)	1990	12.67 (17.36)	2016
	Taiga Shield West	9.04 ± 0.30 (15.11 ± 0.50)	8.54 (14.28)	1994	9.51 (15.90)	2012
	Total	119.55 ± 1.83 (18.40 ± 0.28)	116.02 (17.86)	1999	121.98 (18.78)	2016

[1] SD as standard deviation.

At present, there is no national wetland monitoring system for Canada. Consequently, current national statistics for wetlands come from many different sources (federal, provincial, territorial government as well as non-profit organizations) and represent wetland condition interspersed from the late 1990s to 2014. Using these data, wetlands are reported to occupy approximately 13% (1.29 million km^2) of Canada's terrestrial land base. This notable national area of wetlands represents approximately 25% of global wetland area [8]. Wetland extent varies among regions of Canada in relation to regional climate and local terrain. Mountainous and hilly regions of British Columbia, Ontario, and Quebec, as well as drier regions of the country (e.g., interior British Columbia), cannot support extensive wetlands, and in these areas wetlands are confined to low slope positions and shallow depressions where water gathers permanently or for part of the year [32]. In regions of high precipitation, like coastal British Columbia, wetlands, such as blanket bogs, can occupy gently sloping terrain [6]. Wetlands are most extensive in the Mackenzie River Basin of northwestern Canada, south of Hudson's Bay, and in central Labrador, where cool, moist climates intersect expanses of flat terrain. In addition to regional climate and local terrain, water chemistry (e.g., tidal vs. freshwater) and hydrological regimes (e.g., ground water inflow vs. riparian or tidal water fluctuations), as well as peat accumulation or permafrost presence, yield the array of wetland types or wetland complexes defined for Canada. As noted above, the Canadian Wetland Classification System [6] identifies five major wetland classes: Bogs, fens, swamps, marshes, and shallow water. Bogs are treed or treeless landforms characterized as *Sphagnum* peat moss accumulations and ericaceous shrubs.

Fens are distinguished from bogs by fluctuating water tables and accumulations of peat formed from decomposed graminoids. Swamps are typically treed areas where the water table is at or near the soil surface and peat accumulations are wood-rich whereas marshes are wetlands with shallow waters that fluctuate daily, seasonally, or annually from tides, flooding, or groundwater changes and are dominated by emergent aquatic vegetation. Shallow water wetlands are transitional to deep, open water and have vegetation that tolerates permanent flooding. This paper focuses on freshwater wetlands of Canada's forest-dominated ecozones. We also aggregate the five major wetland classes into treed wetlands (e.g., swamps) and non-treed wetlands (bogs, fens, marshes, and shallow water) to better align with the resolving capacity of current remote sensing-based methods [9].

2.2. Data

This project utilized a 33-year time series of annual land cover classifications generated for the forested area of Canada using annual gap-free Landsat imagery composites (following Hermosilla et al. [26]). White et al. [33] describe the rationale and methods for generating best available pixel (BAP) composites that led to the production of Landsat image composites that are free of atmospheric perturbations (e.g., cloud, shadow, haze) and represent similar seasonality conditions (i.e., proximity to a mid-summer (August 1) target date). The methods for producing gap-free annual time series of surface reflectance composites from the above BAP composites are presented in Hermosilla et al. [34]. Furthermore, as an element of the generation of gap-free surface reflectance composites, changes from time series of imagery are utilized to provide additional evidence to populate pixels where there are no images available according to the compositing rules. As a result, changes are detected and attributed from the time series, providing a means to detect the presence of biases in trends (often indicative of haze or smoke) or higher magnitude changes related to disturbance. The entire image compositing and change detection approach (Composite-to-Change or C2C) [35] provides both the spectral reflectance information and disturbance information that can, in turn, be subject to image classification. As described in Hermosilla et al. [26], information regarding the type, timing, and location of change are used to inform the generation of a 33-year land cover cube with an annual time step. The mapping procedure is termed the Virtual Land Cover Engine (VLCE), as the highly automated approach allows for different land cover outcomes based upon alteration of the training data. Inputs to the process include surface reflectance information and vegetation indices, elevation derivatives, including slope and polar-transformed aspect (based upon ASTER Global Digital Elevation Map II) [36], and the forest disturbance information relating disturbance type and timing. A machine learning Random Forest (RF) algorithm first generates preliminary annual land cover maps using the inputs described above. The RF model produces yearly class probability maps for each of the 12 classes of relevance to the forested ecosystems of Canada [9]. These classes include water, exposed land, rock and rubble, snow and ice, conifer forest, broadleaf forest, mixed wood forest, wetlands (non-treed), treed wetlands, shrubs, herbs, and bryoids. Informed by land cover change timing and types from the C2C, these time series of initial yearly class probabilities are further processed in a Hidden Markov Model (HMM; after Abercrombie and Friedl [37]) to produce the refined class allocations for each pixel for each year (as required) throughout the time series. The harmonized annual land cover maps represent the most likely classes according to the post-HMM class probabilities for a given year with a reduction in spurious land cover changes (e.g., ambiguous pixels with classes of similar probabilities from RF classification for a given year are adjusted based upon the pixel-level time-series of classes and their probabilities) [26]. These harmonized annual land cover maps formulate the basis for this current investigation, providing the spatial extents and temporal trends of the presence of wetlands (non-treed and treed) for the period of 1984 through 2016. The overall accuracy of the land cover classification in a representative year (2005) of the VLCE product (Figure 1) is $70.3 \pm 2.5\%$ [26]. For the categories of interest, wetland non-treed and wetland treed, producer's accuracies of $64 \pm 8\%$ and $57 \pm 10\%$, and user's accuracies of $64 \pm 8\%$, and $58 \pm 9\%$, respectively, are reported. After combining both non-treed and treed wetlands, the land cover map has an overall accuracy of 70.5 ± 2.5%, with the producer's accuracy of the combined wetland class as 60 ± 6.0% and the user's accuracy as 60 ± 6.1%. Note that the confusion matrix reported in Hermosilla et al. [26] was generated following the approach recommended by Olofsson et al. [38]. Thus, the confusion matrix was based on estimated class area proportions, with overall producer's and user's accuracies, and associated error bounds (i.e., 95% confidence interval), were calculated to assess errors of omission and commission for each land cover class.

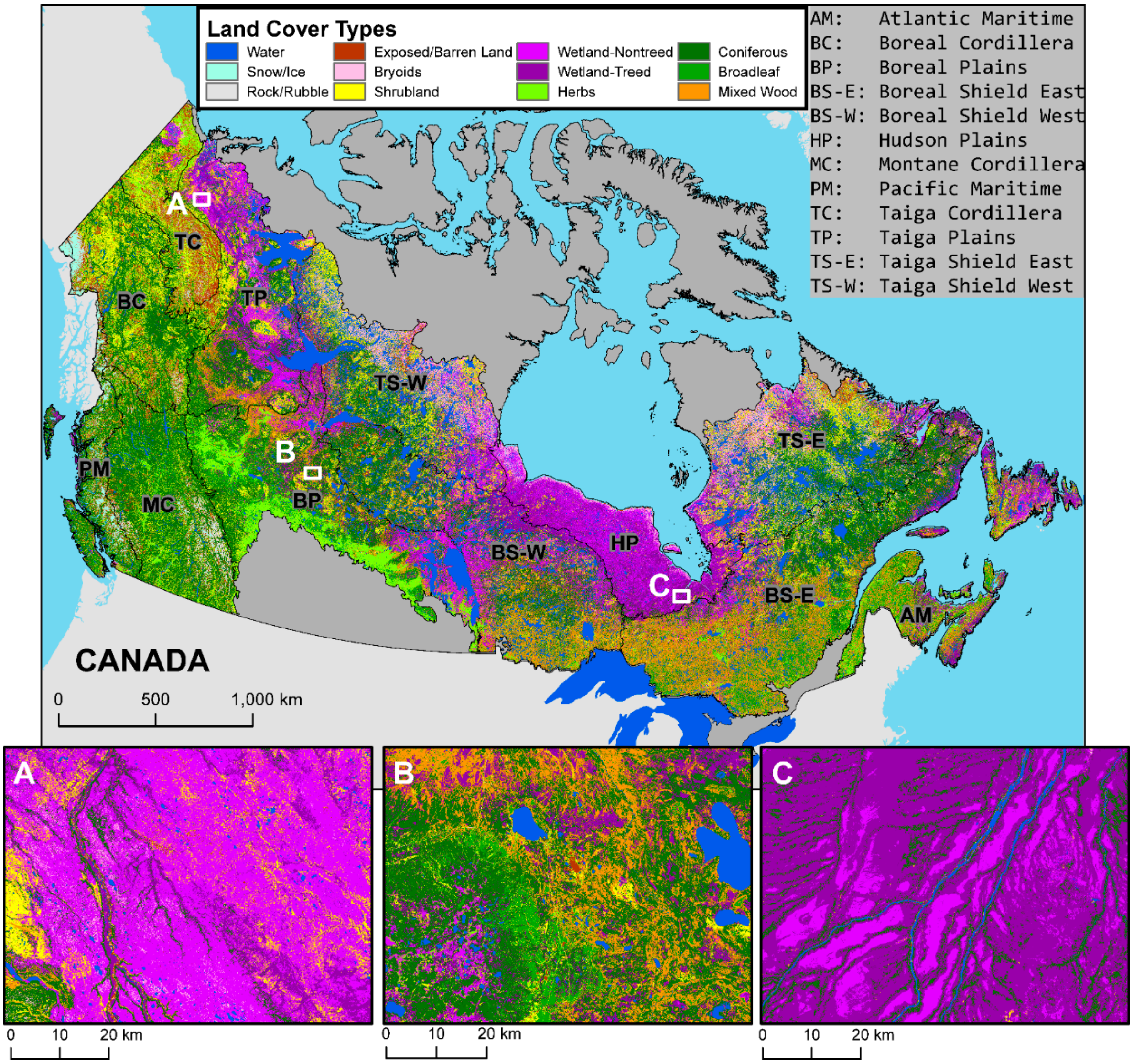

Figure 1. Land cover types within forest-dominated ecozones of Canada. The map was generated using the Virtual Land Cover Engine (VLCE) approach and validated for 2005 conditions (Hermosilla et al., 2018). Selected examples represent a landscape dominated by non-treed wetlands (**A**); a landscape mosaic of upland forest and wetlands (**B**); and a landscape complex of treed and non-treed wetlands (**C**).

2.3. Analysis

The VLCE classification outputs were used to identify pixels as wetland (both treed and non-treed; Figure 1). From these mapped data, the total annual area for treed and non-treed wetland classes were calculated, and the area of these two classes were combined to calculate the total annual wetland extent. These wetland areas were then aggregated and reported for each ecozone in our study area by year to determine ecozonal trends in wetland area. Information on the wetland status of each pixel allows tabulations and summaries over both space and time. At the ecozone level, we calculated the average wetland area, maximum area and year, minimum area and year, the range of area values, and the standard deviation of the area values. We also assessed the temporal trends of wetland areas over the 33-year periods as increasing, decreasing, or stable (i.e., no significant increasing/decreasing trend), and quantified the annual increasing/decreasing rate using the Theil-Sen slope estimator [39]. The statistical significance of the temporal trend was examined with the Man-Kendall test [40,41].

To further explore changes in wetland presence and extent across space, we examined the wetland persistence over the 33 years by calculating the numbers of years being wetland-treed, wetland-non-treed, and non-wetland per pixel. We then categorized each pixel-series by wetland frequency (flagged as wetland at least once in the 33 years; hereafter noted as wetland-occurring pixels) into different temporal wetland states according to the following procedure. We divided our 33-year temporal window into two distinct temporal epochs—one from 1984 to 1999 and the other from 2000 to 2016. For a pixel to be considered functionally as a wetland in either epoch, it must be classified as wetland in more than 80% of the years in that epoch (i.e., at least 13 years). Based upon the temporal distinctions overall and with reference to the two epochs, five temporal wetland states were defined: *Always* (a pixel was wetland during both epochs), *Is Now* (a pixel was not wetland before 2000, but has been since 2000), *Used-to-Be* (a pixel is no longer a wetland, but was before 2000), *Sometimes* (a pixel not in the previous three categories that was classified as a wetland for at least 13 years over the entire 33 years), and *Rarely* (a pixel that was classified as a wetland at least once, but for less than 13 years). To indicate the amount of current wetland extent, we combined the total areas of *Always* and *Is Now* wetland states. The area in each of the five temporal wetland states was calculated and reported upon for each forested ecozone.

3. Results

3.1. Time Series of Wetland Extent

Between 1984 and 2016, wetlands covered an average of about 18% of Canada's forest-dominated ecozones, which was equivalent to an annual mean area of nearly 120 million ha (Table 1, Figure 2). While 10–12% of the study area was covered with treed wetlands, about 6–8% was covered by non-treed wetlands (Figure 2). The total area covered by wetlands was stable from 1984 to 2016 (Figure 2), as indicated by the non-significant trend (darkest purple dotted line in Figure 2). The total area covered by treed wetlands increased over the time period considered (0.43% or 0.209 Mha per year), while the non-treed wetland area decreased (−0.32% or −0.237 Mha per year) (Figure 2). However, temporal trends in treed and non-treed wetland areas should be interpreted with caution as land cover classification confusion was largely between the two wetland classes [26].

The mean annual percentage of total ecozone area covered by wetlands varied by ecozone (Table 1; Figure 3). Wetland extent was greatest in the Hudson Plains, covering more than 80% of the total area, and least in the mountainous ecozones, Montane Cordillera and Boreal Cordillera, Taiga Cordillera, and the Pacific Maritime (<5% of total ecozone area). Mean annual wetland area percentages ranged from 14 to 31% in the Boreal, Taiga, and Atlantic Maritime ecozones.

The year, 2000, was the most frequent year of minimum wetland extent, pertaining to three ecozones: Montane Cordillera, Pacific Maritime, and Boreal Shield-West (Table 1). The most frequent years of maximum wetland extent were 1986 (Atlantic Maritime, Boreal Shield West, and Pacific Maritime ecozones) and 2016 (Boreal Cordillera, Montane Cordillera, Taiga Cordillera, and Taiga Shield East ecozones) (Table 1, Figure 3).

The Theil-Sen slope estimator and Mann-Kendall test revealed some statistically significant long-term trends in total wetland extent within ecozones (Table 2). The greatest long-term increasing trend in wetland extent occurred in the Taiga Shield East, with annual increases in wetland extent of just over 1% (Table 2 and Figure 3). The greatest long-term decreasing trend occurred in the Atlantic

Maritime at −1.31% per year (Table 2 and Figure 3). Other southern ecozones (e.g., Boreal Plains, Boreal Shield East, and Boreal Shield West) also had decreasing trends in wetlands extent.

Figure 2. Wetland area (bars, left axis), the wetland percentage (dots, right axis) of the whole forest-dominated ecozones of Canada, and their trends (lines). Increasing/decreasing rates in wetland coverage (numbers beside trend lines at the two sides of the graph, with the left being area per year and the right being percentage per year) are given for statistically significant trends in treed and non-treed wetlands, as determined by the Theil-Sen slope estimator.

Table 2. Temporal trends in wetland extent identified from the Theil-Sen slope estimator and Mann-Kendall test.

	Ecozone	Theil-Sen Slope [1] (ha/year)	Relative Theil-Sen Slope [2] (%/year)	Mann-Kendall Trend Test *p*-Value [3]	
	Atlantic Maritime	−56,363.30	−1.31%	2.42×10^{-15}	*
	Boreal Cordillera	838.41	0.27%	2.09×10^{-1}	
	Boreal Plains	−37,098.08	−0.31%	7.54×10^{-6}	*
	Boreal Shield East	−29,865.78	−0.18%	4.03×10^{-5}	*
	Boreal Shield West	−22,322.25	−0.13%	5.04×10^{-3}	*
	Hudson Plains	3838.50	0.01%	3.41×10^{-3}	*
	Montane Cordillera	32.13	0.02%	4.66×10^{-1}	
	Pacific Maritime	−215.60	−0.02%	1.33×10^{-1}	
	Taiga Cordillera	5321.58	0.56%	3.49×10^{-10}	*
	Taiga Plains	35,887.51	0.19%	6.16×10^{-4}	*
	Taiga Shield East	118,971.28	1.29%	4.55×10^{-11}	*
	Taiga Shield West	16,324.87	0.18%	4.15×10^{-3}	*
	Total	23,151.04	0.02%	3.29×10^{-1}	

[1] The Theil-Sen slope indicates the annual change of wetland areas in the long-term trend; [2] the relative Theil-Sen slope indicates the percentage of annual change in wetland areas in the long-term trend; [3] the symbol (*) indicates significant trend at $p = 0.05$ level, otherwise non-significant.

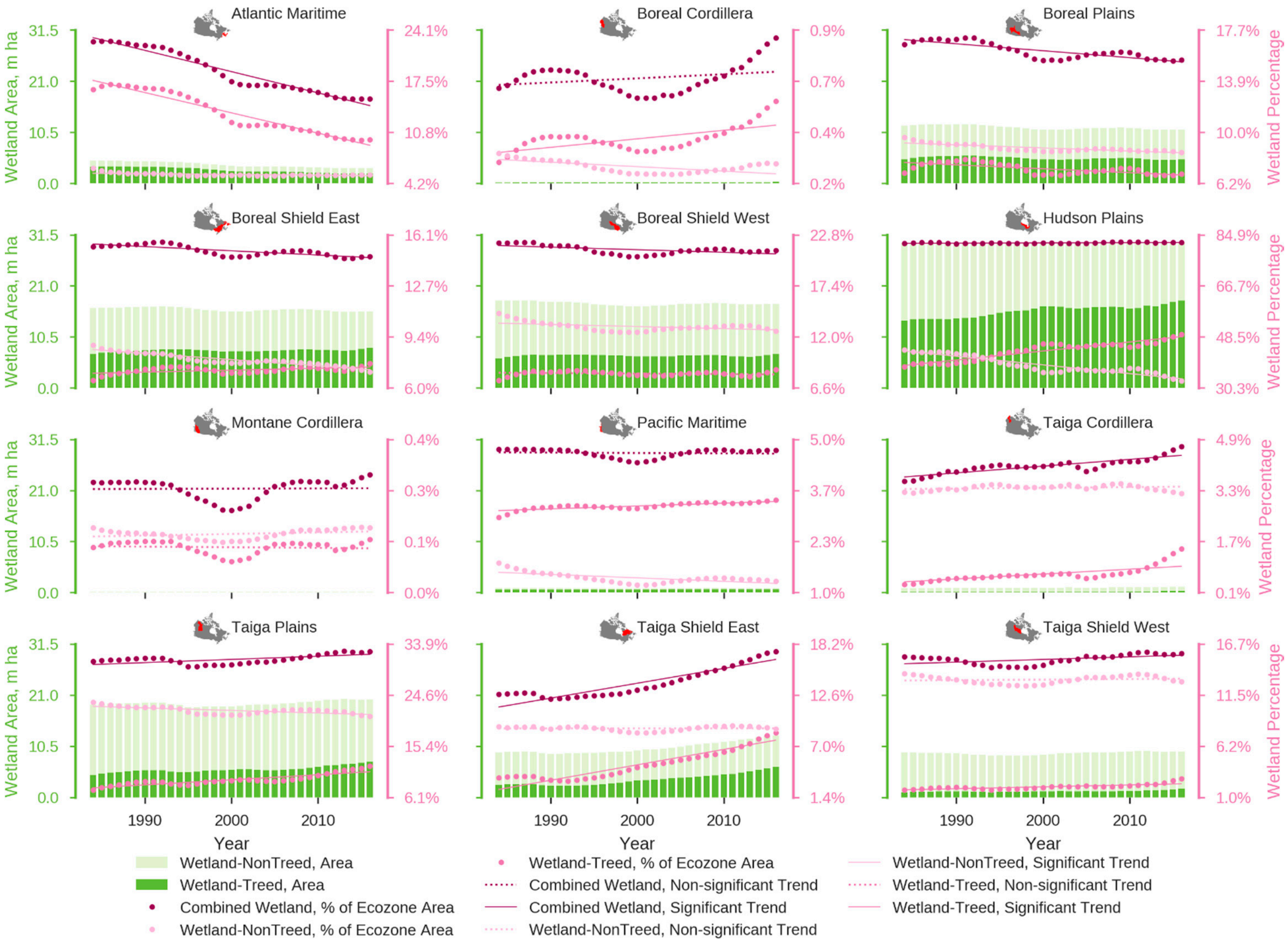

Figure 3. Wetland area (bars, left axis), the percentage (dots, right axis) of each forest-dominated ecozone, and their temporal trends (lines), in Canada.

3.2. Spatial Patterns of Wetland Change

By mapping the number of years each pixel was classed as a wetland between 1984 and 2016, we characterized geographic patterns in wetland persistence (Figure 4). The most extensive region of persistent wetlands occurs in the Hudson Plains ecozone (Figure 4C). Other major wetland ecozones (e.g., Taiga Plains, Boreal Plains, and Atlantic Maritime) contained a mix of persistent wetlands with occasional wetlands (i.e., areas of pixels classified as wetlands notably less than 33 years) (Figure 4A,B).

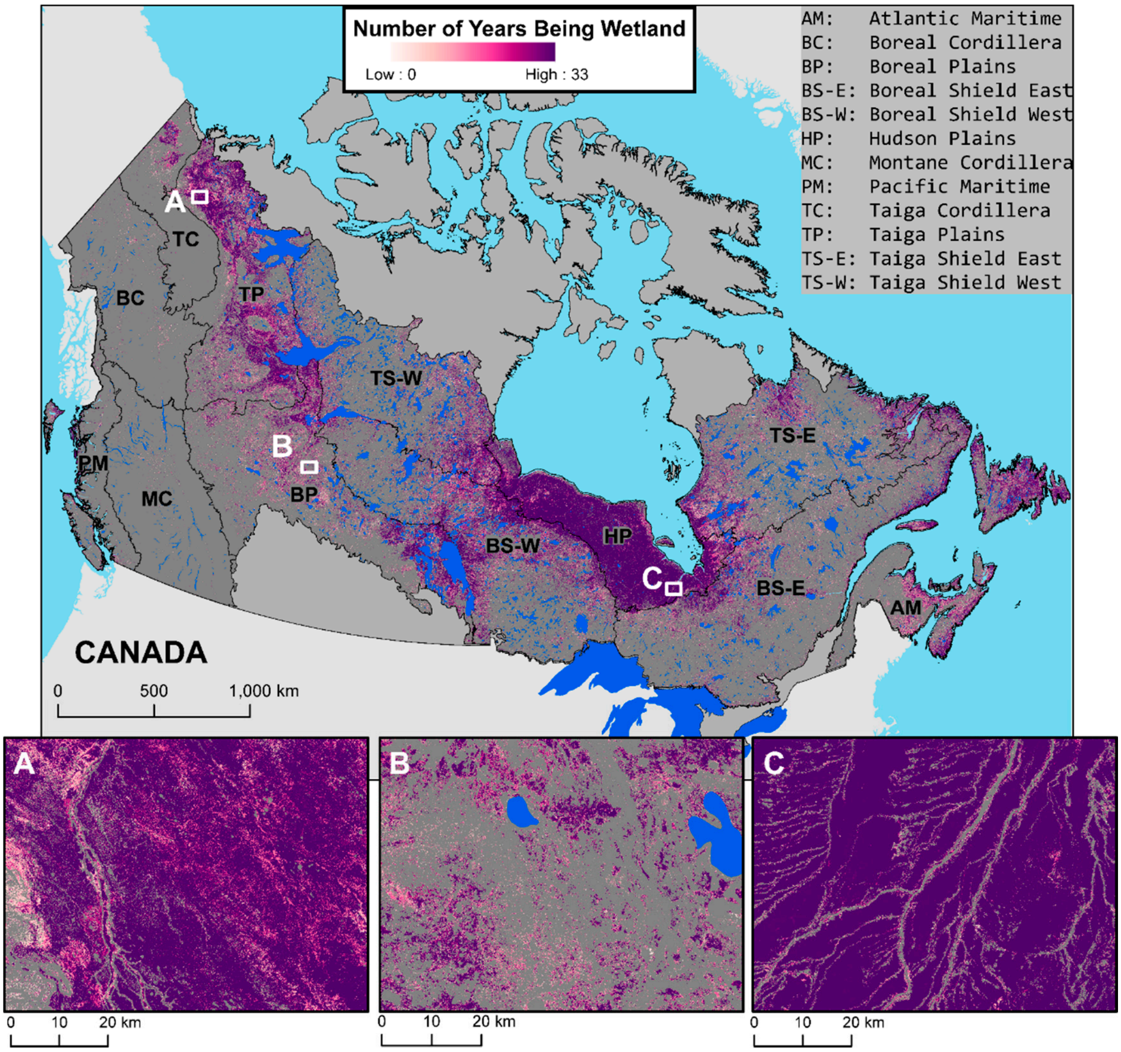

Figure 4. Number of years (maximum 33) that a given pixel was classified as a wetland (treed or non-treed). Grey represents non-wetland. Waterbodies are shown in blue for context.

We also examined the persistence of treed and non-treed wetlands by rendering the percentage of years in the two wetland types and the non-wetlands with a color triangle (Figure 5). Note that with this color composition, cyan areas represent pixels often classified as treed wetland; yellow areas represent pixels often classified as non-treed wetland; green areas represent a mix of treed and non-treed wetlands; pink shades were rarely classified as wetland of either type; and orange or purple shades were occasionally classified as wetland (i.e., a mix of non-treed or treed wetland or non-wetlands). Throughout the study area, pixels classified as wetlands remained stable within either treed or non-treed categories most of the time, as represented by shades indicating high frequency of occurrence at the bottom of the ternary legend (Figure 5A). Absence of pink shades indicates wetland stability, i.e., a majority of wetlands persisted through most of the 33 years, with areas mapped as occasional wetlands occurring on the fringes of the more persistent wetland areas.

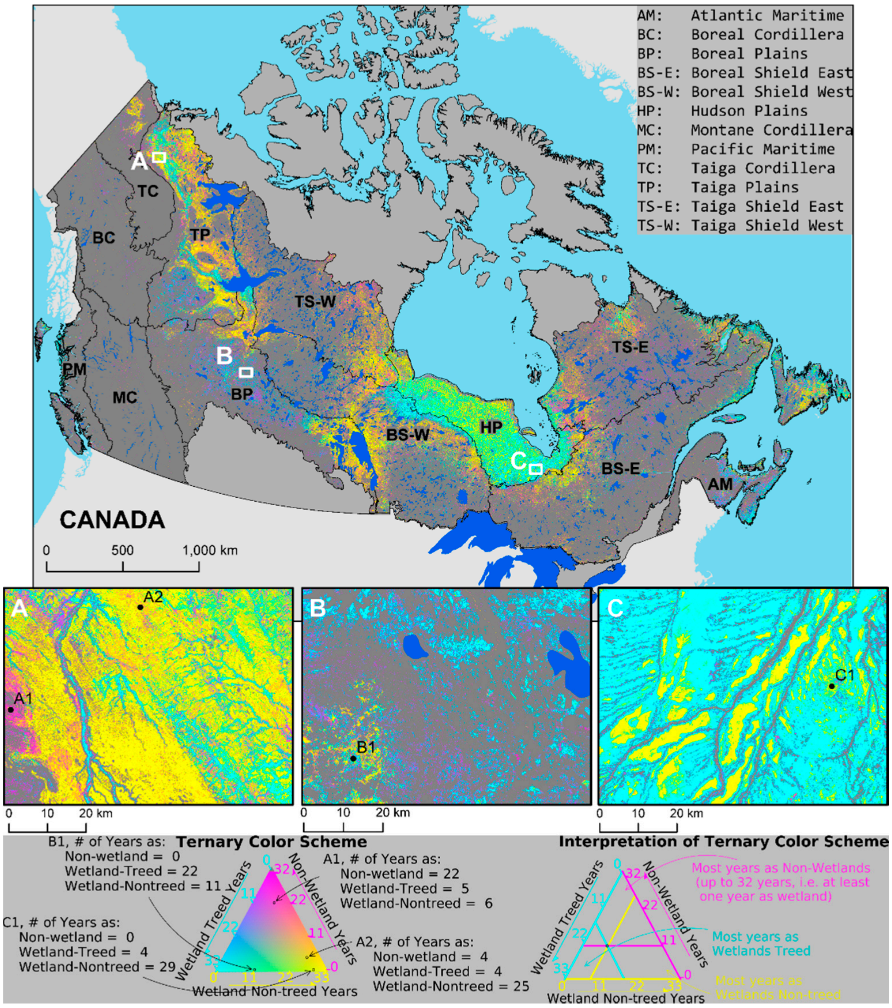

Figure 5. Number of years that a given wetland-occurring pixel (i.e., flagged as wetlands at least once in the 33 years) was classified as a wetland (treed or non-treed). Each pixel is rendered according to the ternary color legend at the bottom, with the pink hue relating to the number of years classified as non-wetland, the cyan color by the number of years classified as treed wetland, and the yellow color by the number of years classified as non-treed wetland. See bottom inset for an interpretative guide. Grey represents non-wetland. Waterbodies are shown in blue for context.

Comparisons of wetland temporal states during both epochs (1984–1999 and 2000–2016) provided more detailed insight into wetland dynamics (Table 3, Figure 6). Of the entirety of the forested ecozones, the current wetland extent, represented by the sum of *Always* and *Is Now* states, covered a larger area, ~110 Mha, than any other wetland state (Table 3, Figure 6). The majority of these wetlands were classed as *Always*, ~95 Mha or ~62% of all the wetland-occurring pixels, which characterizes the widespread stability of wetlands between 1984 and 2016. Whereas more than half of the wetland-occurring pixels across the study area were classified as *Always*, with the largest concentration of these stable wetlands being in the Hudson Plains (Table 3, Figure 6), another ~59 Mha (38% of all the wetland-occurring pixels) changed from one state to another (i.e., collectively classed as *Is Now*, *Used-to-Be*, *Sometimes*, and *Rarely*), indicating substantial flux between a wetland and non-wetland condition. Over the entire study area, 13 Mha of wetlands were lost (*Used-to-Be*) between the first and the second epochs, but were mostly compensated by a 15 Mha gain in wetlands (*Is Now*) in other areas (Table 3). Both within and among landscape composition of wetlands states varied. For example, whereas the Hudson Plains ecozone was dominated by the *Always* wetland state (Figure 6C), landscapes in the Taiga Plains (Figure 6A) and Boreal Plains (Figure 6B) were more variable, with wetland landscape mosaics containing representation of all wetland states (Table 3). While seven of the ecozones were dominated by the *Always* wetland state, in the other five other ecozones (Atlantic Maritime, Boreal Cordillera, Montane Cordillera, Taiga Cordillera, and the Taiga Shield East), wetland landscapes were more dynamic, with the wetland states, *Is Now*, *Used-to-Be*, *Sometimes*, and *Rarely*, being collectively more extensive than the *Always* wetland state. The greatest extent (2.05–2.19 Mha) of wetland loss (*Used-to-Be* wetland state) from the first epoch to the next occurred in the southern region of the boreal forest encompassed by the Boreal Shield East, Boreal Shield West, and Boreal Plains ecozones, but this loss was offset by commensurate wetland gains (*Is Now*) in other parts of these ecozones. About half as much (1.06–1.79 Mha) wetland-occurring area was no longer present (*Used-to-Be*) from the first epoch to the next in the more northern regions of the boreal forest, the Taiga ecozones (Taiga Plains, Taiga Shield). However, nearly double the lost area was gained in other parts of these ecozones. Although wetlands of the Atlantic Maritime ecozone constituted a small portion of the wetland area (~4 of 120 Mha mean annual wetland area, Table 1), the wetlands in this ecozone had the highest percentage of wetland loss (*Used-to-be*) between the first and second epochs; only about a third of these losses were compensated by gains in other parts of the ecozone. Areas that were *Sometimes* wetlands occurred in every ecozone and covered less than 5% of the wetland-occurring areas in all ecozones.

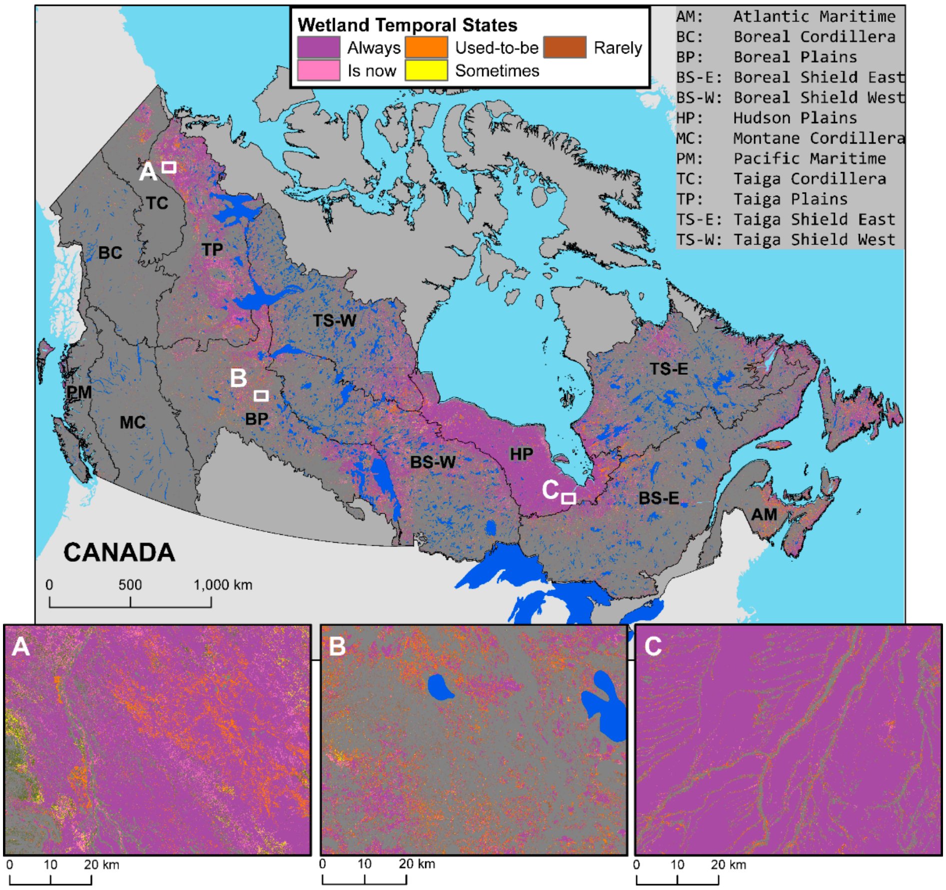

Figure 6. Wetland temporal states for the period, 1984–2016. *Always* (classified as wetland for $\geq$13 years both before and after 2000), *Is Now* (classified as wetland for <13 years before 2000 and for $\geq$13 years after 2000), *Used-to-Be* (was classified as wetland for $\geq$13 years before 2000 and for <13 years after 2000), *Sometimes* (an area not in the previous three categories, but that was classified as wetland for $\geq$13 years over the entire 33 years), and *Rarely* (an area that was classified as wetland for <13 years, but at least once over the entire 33 years). Grey represents non-wetland. Waterbodies are shown in blue for context.

Table 3. Summary of wetland temporal state (in millions of hectares, MHa) over the period, 1984–2016. Numbers in parentheses are the percentages of all the wetland-occurring area per ecozone in each temporal state.

	Ecozone	Total Ecozone Area (Mha)	All Wetland-Occurring Area [1] (Mha)	*Always*[2] (Mha (%))	*Is Now*[3] (Mha (%))	*Used-to-Be*[4] (Mha (%))	*Sometimes*[5] (Mha (%))	*Rarely*[6] (Mha (%))
	Atlantic Maritime	20.44	5.74	2.43 (42.28)	0.42 (7.27)	1.27 (22.04)	0.17 (2.90)	1.47 (25.52)
	Boreal Cordillera	44.47	0.68	0.11 (16.99)	0.09 (13.03)	0.10 (14.72)	0.03 (3.93)	0.35 (51.34)
	Boreal Plains	71.32	16.25	8.21 (50.49)	1.59 (9.81)	2.05 (12.62)	0.48 (2.93)	3.93 (24.16)
	Boreal Shield East	107.71	22.02	12.03 (54.62)	2.16 (9.79)	2.63 (11.92)	0.54 (2.45)	4.67 (21.22)
	Boreal Shield West	81.82	22.41	13.46 (60.07)	2.31 (10.31)	2.19 (9.77)	0.56 (2.49)	3.89 (17.35)
	Hudson Plains	36.41	31.46	28.46 (90.47)	0.99 (3.16)	0.82 (2.62)	0.19 (0.60)	0.99 (3.16)
	Montane Cordillera	47.79	0.32	0.04 (12.44)	0.05 (14.18)	0.04 (13.26)	0.01 (4.05)	0.18 (56.08)
	Pacific Maritime	20.13	1.30	0.72 (55.73)	0.12 (9.33)	0.10 (7.74)	0.03 (2.17)	0.33 (25.03)
	Taiga Cordillera	25.12	1.56	0.67 (43.26)	0.23 (14.57)	0.17 (11.01)	0.04 (2.47)	0.45 (28.69)
	Taiga Plains	61.99	24.66	15.35 (62.27)	2.75 (11.16)	1.79 (7.25)	0.48 (1.93)	4.28 (17.38)
	Taiga Shield East	72.98	15.48	6.97 (45.03)	2.62 (16.94)	1.03 (6.67)	0.31 (2.02)	4.54 (29.33)
	Taiga Shield West	59.81	12.72	6.70 (52.68)	1.67 (13.12)	1.06 (8.31)	0.27 (2.15)	3.02 (23.74)
	Total	649.98	154.59	95.16 (61.56)	15.00 (9.70)	13.25 (8.57)	3.10 (2.00)	28.09 (18.17)

[1] All Wetland-Occurring Area: Area of pixels that were classified as wetland at least once over the entire 33 years, i.e., sum of all the five temporal states; [2] *Always*: Area that was classified as wetland for ≥13 years in both epochs (before and after 2000); [3] *Is Now*: Area that was classified as wetland for <13 years in the 1st epoch (before 2000) and ≥13 years in the 2nd epoch (after 2000); [4] *Used-to-Be*: Area that was classified as wetland for ≥13 years in the 1st epoch (before 2000) and for <13 years in the 2nd epoch (after 2000); [5] *Sometimes*: Area that was not in the previous three temporal states, but was classified as wetland for ≥13 years throughout the two epochs; [6] *Rarely*: Area that was classified as wetland for <13 years, but at least once during the entire 33 years.

4. Discussion

Conservation or restoration of the ecosystem services provided by wetlands requires accurate up-to-date maps of wetland location and extent, and changes in location and extent of wetlands over time. Landsat imagery provides opportunities for detailed mapping of wetlands over large spatial scales [42] and automated land cover classification methods enable consistent identification of wetlands [26]. Digital remote sensing methods produce wetland maps that are typically more consistent and cover larger areas than those obtained through traditional methods relying on aerial photo interpretation and maps of soils and vegetation [14]. Satellite remote sensing can provide multi-decadal data at an annual time-step that can be used to characterize variability in wetland conditions and to detect longer-term trajectories of wetland change. However, most remote sensing applications have been used to produce maps for specific wetland systems (e.g., [43]) or for wetlands over small regions [44], with the use of long time series data uncommon [45]. We demonstrated the use of multi-decadal, annual 30-m national-scale land cover maps [26] to explore wetland change in forest-dominated ecozones of Canada from 1984 to 2016. We also examined how wetland changes varied among ecozones, which has important implications for ecosystem services that vary from region to region. This work aims to improve upon limited historical snapshot maps of Canadian wetlands [32] and complements a more recent national-scale wetland map product that is a compilation of various data sources and represents circa 2000 conditions from contributing data sources spanning from the late 1990s to 2014 [8].

Our results offer insights into trends regarding wetlands over the forested ecosystems of Canada. The wetland maps we generated embody the challenges of mapping a land condition as a feature, but offer provisional maps developed in a consistent manner over multiple decades at the national scale, which can spatially and temporally guide further investigations and modeling. The Landsat archive for Canada [46] is rich in both spatial and temporal distributions of images through the historical record [24]. Even so, much of Canada does not have sufficient images in the Landsat record to enable seasonal targeting of image composites (i.e., to capture within-year variation) over multiple decades in the past [33]. Following the initiation of a Long Term Acquisition Plan (LTAP) [47] coinciding with Landsat-7 ETM+ collections, opportunities for increased seasonal targeting of BAP composites is possible, especially at present, with both Landsat-8 OLI and Landsat-7 ETM+ data being acquired. Within-year time series could possibly be targeted to capture surface conditions in the spring that is of value to wetland mapping in boreal environments. Complementary optical data sources, such as Sentinel-2, may further increase the potential of capturing intra-annual variability in wetland extents. In addition, future research needs also include refining spatial and categorical detail (e.g., aiming to label bogs, fens, marshes, and swamps) in mapping wetlands, potentially with analysis-heavy, though costlier, approaches, such as employing higher spatial resolution imagery and/or lidar data. Alternate data sources with higher spatial resolution or different electromagnetic wavelengths (e.g., microwave bands from synthetic aperture radar [48]) can be useful for mapping wetlands, but to date, have not offered the ability to map large areas in a cost effective fashion. Similarly, airborne lidar surveys can provide detailed surface elevation data that are informative of drainage conditions and overall landscape structure to improve wetland mapping, but systematically-acquired, wall-to-wall lidar data do not exist for the forested ecosystems of Canada at this time. Targeted studies using these different data sources and imaging modes are encouraged and may form the basis for future national wetland mapping activities.

Wetlands are naturally dynamic systems with the amount of land area occupied by wetlands changing on seasonal, annual, decadal, or longer time-scales, depending on fluctuating water inputs from rain, snowmelt, thawing permafrost, changing groundwater flows, and water courses, among others [49–51]. Major droughts affecting much of the southern part of our study area occurred in 2000, 2001, and 2015 [52], and correspond with the years in which we found the minimum wetland extent in the majority of ecozones. Other studies have likewise reported reductions in wetland coverage during extreme drought years, especially in dry regions [4]; and an understanding of how extreme drought years have historically affected wetland extent provides valuable insight to the potential effects of future climate change. Our finding that maximum wetland extent occurred from 2012 to 2016 in all northern and mountainous ecozones, but not the southern parts of the study area or the maritime zones, implies melting ice, snow, and permafrost are contributing to increased water and wetland expansion in recent years.

Although our remotely-sensed data identified well-known areas of extensive and stable wetlands, they also indicated that around 38% of the areas that have been classified as wetlands from 1984 to 2016 in Canada's forest-dominated ecozones, were not persistently wetlands, i.e., non-persistent or occasional wetlands (temporal state other than *Always*, Figure 6 and Table 3). The landscapes of the Hudson Plains were dominated by persistent wetlands (high number of years being wetland in Figure 4 and temporal state of *Always* in Figure 6). In contrast, non-persistent and more isolated wetlands occurred in the southern regions of the boreal forest, especially the Boreal Plains ecozone. While this spatially-explicit wetland persistence does not directly point to the state of wetland water levels (i.e., temporary as holding water for a few weeks, seasonal as holding water for two to three months, and semi-permanent as holding water throughout the growing season for most years, [53,54]), less permanent wetlands are probably more likely to experience more frequent dried out basins, and, thus, be captured as non-wetland in the land cover classification. Therefore, the wetland persistence over multiple decades offers an indirect clue on the water permanence of wetlands across space. Such contributing information on the water permanence of wetlands is particularly important as semi-permanent wetlands are sensitive to small changes in the hydrological cycle and vulnerable to changes in climatic conditions [55,56].

The total area of wetland coverage in the forest-dominated ecozones of Canada remained relatively stable from 1984 to 2016. However, we found significant directional changes in the amount of wetland area in many ecozones, and losses of wetlands in some ecozones over the two epochs were offset by gains in wetland in other ecozones. This information is useful as it considers not only the current extent of wetlands, but also regional changes in wetland extent over time. The baseline information provided by the Landsat time series is a useful context for assessing future changes in wetland extent and can be helpful for establishing monitoring indicators, or for understanding the implications for regional changes to ecosystem goods and services, such as flood mitigation and carbon cycling, under climate change [1,2].

One of the substantial changes in national wetland extent was the decrease in wetland extent in the southern boreal forest, especially in the Boreal Plains ecozone (−0.31% per year). Wetland losses in the Boreal Plains ecozone were not compensated by gains in other parts of this ecozone. The trend in wetland loss (both treed and non-treed wetlands) observed in the Boreal Plains is consistent with increased changing patterns of surface water extent and drought severity associated with a changing climate [57–60]. The other notable change is the increases in wetland extent in the northern boreal forest, particularly in the Taiga Plains and Taiga Shield East ecozone (+0.19% and +1.2% per year, respectively). This increasing trend in wetland extent in the northern boreal forests is consistent with reports of widespread permafrost thaw and wetland expansion [61–64]. Wetlands in the Atlantic Maritime ecozone comprise a small percentage of the total wetland area of Canada's forested ecosystems, but this ecozone had the largest relative decline in wetland extent in the analyzed period, with a 1.3% decrease in area per year. The reason for this steep decline is unclear; the combined effects of drought and urban expansion might be contributing to the higher rates of decline in this ecozone than in others [49,65,66], but the ecozone may also be very sensitive to mapping errors given the relatively small extent of wetlands compared with the national wetland coverage. Wetlands in mountainous ecozones (Montane, Boreal, and Taiga Cordillera) also comprised a small portion of total wetland area, but exhibited increases in wetland extent that may be related to increased snowmelt [67,68]. As discussed above, some trends in wetland extents (e.g., Boreal Plains, Taiga Plains, and Taiga Shield East) appeared to be corroborated by other studies for possible explanations of climatic and hydrologic causes, whereas explanations for other trends (e.g., Atlantic Maritime) are unclear. Such spatially explicit, regional trends in wetland extents that are consistently obtained from multi-decadal, 30-m earth observational images can facilitate further investigations into the drivers and causes of wetland changes, as well as our understanding of the mechanisms behind wetland dynamics.

5. Conclusions

There is a national interest in monitoring wetland status and trends over time. Ideally, it will become increasingly operational to track over large geographic extents wetland type and area, as well as influences including and beyond fluctuations linked to variability in hydrological processes. Of particular interest are changes related to anthropogenic influences causing permanent wetland loss, such as those related to drainage or filling. Despite the importance of wetlands, no comprehensive systematic nation-wide monitoring of wetlands exists [8,21], largely due to the difficulties in mapping the heterogeneous and complex combinations of conditions associated with wetlands across very large spatial extents. We demonstrated that Landsat time series data provide a national, consistent source for characterizing trends in wetland dynamics in Canada's forested ecosystems. There are challenges to compiling national data sets for wetlands that are consistent across space and time (i.e., derived from single or multiple compatible data sources with a spatial resolution that is adequate for capturing requisite details that can be captured at a national level and that represents an annual time step, rather than a broad range of disparate years). The wetland information presented herein can augment these other data sources on wetlands, including ground observations. The Landsat time series is a valuable source of information for producing annual maps of wetland extent, but, more importantly, for monitoring and understanding wetland dynamics over time. For the period, 1984 to 2016, we found the extent of wetlands in Canada's forested ecosystems to be stable, with some regional variability, often resulting from offsetting decreases and increases within a given ecozone. We also revealed regional variations in wetland persistence over 33 years across Canada. Climate change has been implicated in recent changes in the location and persistence of surface water [59]; with a disappearance of previously permanent water in some regions and an increase in others. Wetlands are expected to see related effects, but have not previously been subject to similar, spatiotemporally extensive and spatially explicit investigation. Understanding the spatial and temporal patterns of wetland extent as well as trajectories of change in wetland extents will help with understanding the dynamic nature of ecosystem services provided by wetlands and also aid in identifying regions undergoing wetland changes, with implications to community safety under the changing climate.

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