



Review

Status and Trends of Wetland Studies in Canada Using Remote Sensing Technology with a Focus on Wetland Classification: A Bibliographic Analysis

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Abstract: A large portion of Canada is covered by wetlands; mapping and monitoring them is of great importance for various applications. In this regard, Remote Sensing (RS) technology has been widely employed for wetland studies in Canada over the past 45 years. This study evaluates meta-data to investigate the status and trends of wetland studies in Canada using RS technology by reviewing the scientific papers published between 1976 and the end of 2020 (300 papers in total). Initially, a meta-analysis was conducted to analyze the status of RS-based wetland studies in terms of the wetland classification systems, methods, classes, RS data usage, publication details (e.g., authors, keywords, citations, and publications time), geographic information, and level of classification accuracies. The deep systematic review of 128 peer-reviewed articles illustrated the rising trend in using multi-source RS datasets along with advanced machine learning algorithms for wetland mapping in Canada. It was also observed that most of the studies were implemented over the province of Ontario. Pixel-based supervised classifiers were the most popular wetland classification algorithms. This review summarizes different RS systems and methodologies for wetland mapping in Canada to outline how RS has been utilized for the generation of wetland inventories. The results of this review paper provide the current state-of-the-art methods and datasets for wetland studies in Canada and will provide direction for future wetland mapping research.

Keywords: Canada; classification; remote sensing; wetland

1. Introduction

Wetlands are ecosystems where terrestrial and aquatic regions meet and share some characteristics. Wetlands also contain water for some periods of a year and are characterized by the presence of water, hydric soil, and specific vegetation adapted to a wet environment [1,2]. Wetlands are invaluable natural resources that provide exceptional benefits to humans and the surrounding environment [2]. Due to numerous environmental services of wetlands, including carbon sequestration [3], water purification [4], sediment filtration [5], soil conservation [6], and other critical services, wetlands have been called the “kidneys” of nature [7]. Additionally, from an economic perspective, wetlands are important due to their extensive applications for recreational activities [8], fish and shellfish aquacultures [9], flood mitigation [10], and providing diverse wildlife habitat [11,12]. Despite their numerous benefits, wetlands have been threatened by climate

change, natural catastrophic events (i.e., wildfire), and anthropogenic activities, such as intense irrigation practices, water drainage, groundwater extraction, and replacement by urban and agricultural landscapes [13]. Therefore, it is vital to obtain precise, reliable, and up-to-date information about the different characteristics of wetlands (i.e., extent, type, health, and status).

Traditionally, wetland mapping was conducted by collecting airborne photographs and in situ data through intensive field surveys [14,15]. Although these methods were very accurate, they were resource-intensive and practically infeasible for large-scale studies with frequent data collection necessities. Consequently, advanced Remote Sensing (RS) techniques were proposed for wetland mapping and monitoring [2,16–18]. RS systems provide frequent Earth Observation (EO) datasets with diverse characteristics and broad area coverage, making them attractive to map and monitor wetlands' dynamics from local to global scales through time [2,19,20]. However, it should be noted that the possibility of obtaining reliable information about wetlands using RS data does not obviate the necessity of collecting in situ data, and their incorporation shall provide more profound results.

Passive and active RS systems capture EO data in different parts of the electromagnetic spectrum. In this regard, aerial [21–23], multispectral [18,24–27], Synthetic Aperture Radar (SAR) [28–31], hyperspectral [20,32], Digital Elevation Model (DEM) [33–36], and Light Detection and Ranging (LiDAR) point cloud datasets [36–38] have been extensively used separately or in conjunctions for wetland mapping. Since each of these data sources acquire EO data in different parts of the electromagnetic spectrum, they provide diverse information about the spectral and physical characteristics of wetlands [39]. Moreover, deployment of these sensors on airborne, spaceborne, and Unmanned Aerial Vehicle (UAV) platforms allows recording EO data over wetlands with different spatial resolutions and coverages. Finally, the integration of RS data with machine learning algorithms provides an excellent opportunity to fully exploit RS data for accurate wetland mapping and monitoring tasks [40,41].

Machine learning algorithms allow extracting and interpreting RS data automatically and robustly to map wetlands and derive relevant information about the wetlands' condition. For instance, Random Forest (RF) [42–45], Support Vector Machine (SVM) [46–49], Maximum Likelihood (ML) [50–53], Classification and Regression Tree (CART) [35,36], and Deep Learning (DL) [21,27,40,54] algorithms have been implemented to produce high-quality wetland maps. In this regard, both pixel-based and object-based approaches have been applied to exploit the most delicate possible information about wetlands by integrating RS data and machine learning algorithms [55–62]. Moreover, studies [21,40,41,47,48,63] were also dedicated to assessing the performance of machine learning algorithms for accurate wetland mapping and monitoring to elucidate the path for other interested researchers all around the globe.

Global wetland extents were predicted to be from approximately 7.1 million km² to 26.6 million km² [64] and 25% of globally documented wetlands have been recorded over Canada, covering approximately 14% of the total Canadian terrestrial surface [65]. Wetlands are extended across Canada, with the greatest concentration in northern regions. The Northwest Territories (NT), Ontario (ON), and Manitoba (MB) provinces contain the highest coverage of wetlands [66]. Considering the environmental and economic benefits of wetlands, as well as the immense wetland extent in Canada, it is essential to produce precise wetland inventories for conservation and sustainable developments. Accordingly, different Canadian associations have categorized wetland types based on their morphology, hydrology, hydrochemistry, plant communities, soil and sediment characteristics, depth, productivity, and wildlife usages to establish practical guidelines to study and monitor wetlands [67]. One of these categorizations that has received much attention is the Canadian Wetland Classification System (CWCS), by which wetlands are divided into five classes: bog, fen, marsh, swamp, and shallow water [67].

Due to the importance of wetlands for the Canadian environment, many studies have been conducted to produce wetland inventories from local to national scales using different

types of EO datasets and machine learning algorithms [40,41,68–70]. For instance, the study by [23] was an early study that employed aerial imagery for wetland mapping in Canada. Later, a combination of multi-source RS datasets, including aerial, SAR, DEM, and optical satellite images, were employed in most of the Canadian provinces for wetland classification [7,71–73]. A significant effort has also been made to produce nation-wide wetland inventories using cloud computing methods. For instance, [68] created the first Canada-wide wetland inventory with 30 m spatial resolution and based on the CWCS categories. In this regard, they processed over 30,000 Landsat-8 images within the Google Earth Engine (GEE) cloud computing platform. Afterwards, two generations of Canadian wetland inventories with 10m spatial resolution were produced by combining Sentinel-1 and Sentinel-2 images within GEE [69,70]. However, they have addressed various uncertainties regarding the large-scale and wetland types mapping.

Until now, several studies have been conducted to review the wetland studies which have been conducted using RS technology. For instance, a two-part review [74,75] provided a guide on how RS data can be used to quantify boreal wetland extent and monitor drivers of change on wetland environments, along with a technical review of RS data processing and analysis techniques. The authors of [2,76] also comprehensively discussed the characteristics and importance of wetlands, as well as the advantages and disadvantages of various RS sensors and methods used in wetland research. Additionally, [18] considered the global application of SAR data for wetland mapping. Furthermore, [17] conducted a meta-analysis of wetland classification focusing on the publication trends in North America. However, there is a need for a national-scale, bibliographic analysis of efforts to map wetlands with RS data within and across Canada. Therefore, this review paper aims to provide necessary information on (1) identifying and categorizing wetland studies using RS data, (2) illustrating the geographical distribution of inventories, (3) discussing the classification techniques for wetland mapping, (4) assessing RS data applications, and (5) discussing classification accuracy through a systematic literature search and meta-analysis of studies conducted in Canada. Additionally, a comprehensive review of lead- and co-authors and their affiliated universities/institutions who have published research studies in Canada is provided. Keywords and citation surveys have also been individually analyzed.

2. Wetland Classification Systems in Canada

Multiple wetland classification systems have been proposed and utilized in Canada. The three well-known Wetland Classification Systems (WCS) are presented in Figure 1a. CWCS is the main system used across Canada. The Alberta Wetland Classification System (AWCS) is a customized form of CWCS for the Alberta province [77]. Both systems have the same wetland classes with the difference in forms and subclasses. The Enhanced Wetland Classification System (EWCS) is another system applied in Canada. This system divides the original five classes of the CWCS into 19 finer subclasses [78].

CWCS has emerged from a series of developments within the NWWG started in 1976 [79]. The second edition and final document of CWCS was released in 1997 [67], which classifies wetlands into five major classes and has additional characteristics features of form and sub-form. These forms can be further categorized regarding dominant vegetations. Each of the five classes of CWCS is briefly described below and summarized in Figure 1b. A more detailed description of each wetland class can also be found in [80,81].

Bog is a type of ombrogenous peatland, which means its major water source is precipitation [39]. Therefore, it is an acidic and low nutrient environment mostly covered with sphagnum moss, sedge, and ericaceous shrub species [82]. Bog's vegetation form may vary between open, shrubby, or treed depending on soil, hydrology, and nutrient characteristics.

Fen, another type of peatland, is similar to bog in terms of peat accumulation. However, its water source is not limited to precipitation like with bogs, but includes water surface flows and groundwater contributions to its moisture [82]. Fens are typically divided into two classes of rich fens and poor fens based on having contact with mineral-rich water and nutrient availability. The vegetation cover of poor fens is similar to bog, while

sedges, brown moss, grass, and graminoids are the dominant vegetation species in rich fens. Nevertheless, all fens have minerotrophic indicator species meaning that they only grow in the right nutrient environments [80].

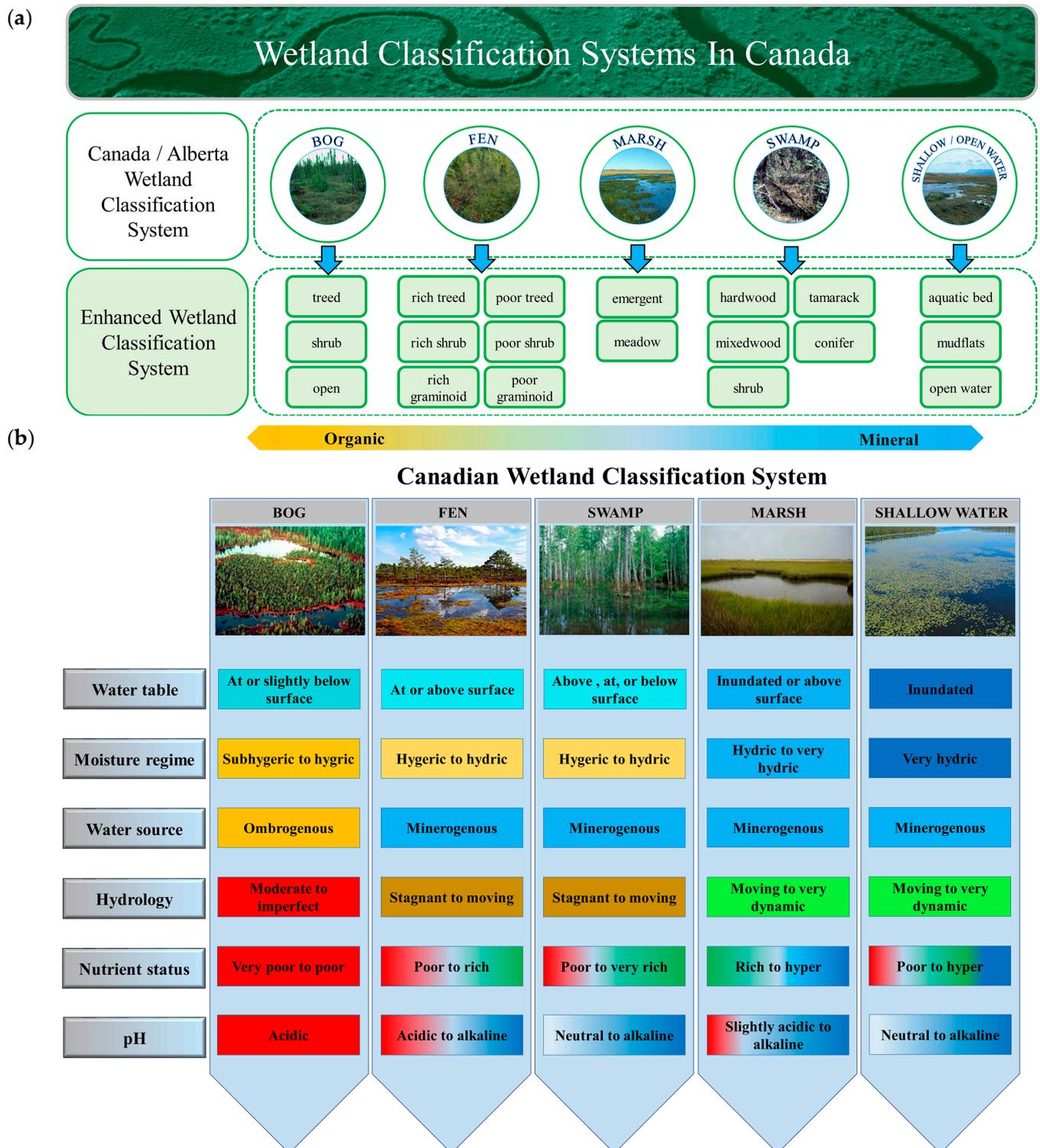


Figure 1. (a): The well-known Wetland Classification Systems used in Canada. (b): Wetland classes based on the CWCS.

Swamps exist in both mineral and peatland wetland types [80]. Swamps are often found in contact with other hydrological systems; hence they are difficult to identify. One of the distinguishing characteristics of swamps is that the woody vegetation (trees and

shrubs) dominates the swamp environment (30% up to 100%) [82]. Additionally, the peat soil in swamps is composed of well-decomposed wooded species rather than the organic sphagnum or sedge-dominated peat in bogs and fens. The water table fluctuates in swamps, and they are not permanently saturated or inundated like bogs and fens; thus, the soil layer can be well-aerated [80].

Marsh is a type of mineral wetland class that experiences a high temporally periodical (seasonal/annual) rate of inundation. The hydrology inputs are from numerous sources, such as tides, water flow, groundwater, surface runoff, precipitation, and flooding. The variety of dissolved mineral inputs and freshening ventilation lead to high productivity and a diverse range of vegetation species [80]. Marsh vegetation communities are often comprised of emergent aquatic types, such as rushes, sedges, grasses, broad-leaved emergent, floating, and submerged aquatic plants [83].

Shallow water is a semi-permanent to permanent water body with a water depth of fewer than 2 m during mid-summer [39]. However, mudflats might be exposed in occasions of water drawdown. Submerged aquatic and floating vegetation with the capability of adaptation to constant inundation are present in shallow waters [82].

3. Method of META-Analysis

Figure 2 shows the workflow of preparing the documents for content analyses in this review. The bibliographic database of the present review was attained through performing a title, abstract, and keywords systematic literature search of relevant articles in the two well-known scientific databases of Clarivate Analytics Web of Science and Elsevier Scopus. To this end, all the combinations of search words (see Table 1) were applied to select English language journal papers, conference papers, and review papers between 1975 and the end of 2020. For instance, the combination of “wetland”, “Canada”, and “remote sensing” was the first combination for the literature search. It is worth mentioning that “Canada” was separately considered to include those research papers conducted over the entire country of Canada, as well as papers in which the province name was not stated in the title, abstract, or keywords. Afterwards, the Preferred Reporting Item for Systematic Review and Meta-Analysis (PRISMA) checklist was applied to organize the collected documents [84]. First, all the results for each combination were separately examined, and then the duplicate documents were removed. Subsequently, the remaining corpus of documents was combined to generate a consolidated database that encompassed 686 papers. A title filtering was then performed to identify the duplicate documents obtained by different combinations, which led to 473 documents. Later, those documents that their source file was not found, along with irrelevant documents, were also excluded, which finally resulted in 300 remaining papers. Following this filtering step, the title, abstract, and keywords sections of the remaining papers were screened to distinguish papers associated with wetland mapping from other wetland studies. This was performed because further attributes (see Figure 2) were derived from wetland mapping-related papers as the primary focus of this review. Finally, all 300 papers were fully inspected to extract different attributes (see Table 2), such as year, study area, classification method, and data type, for further analyses (see Table A2).

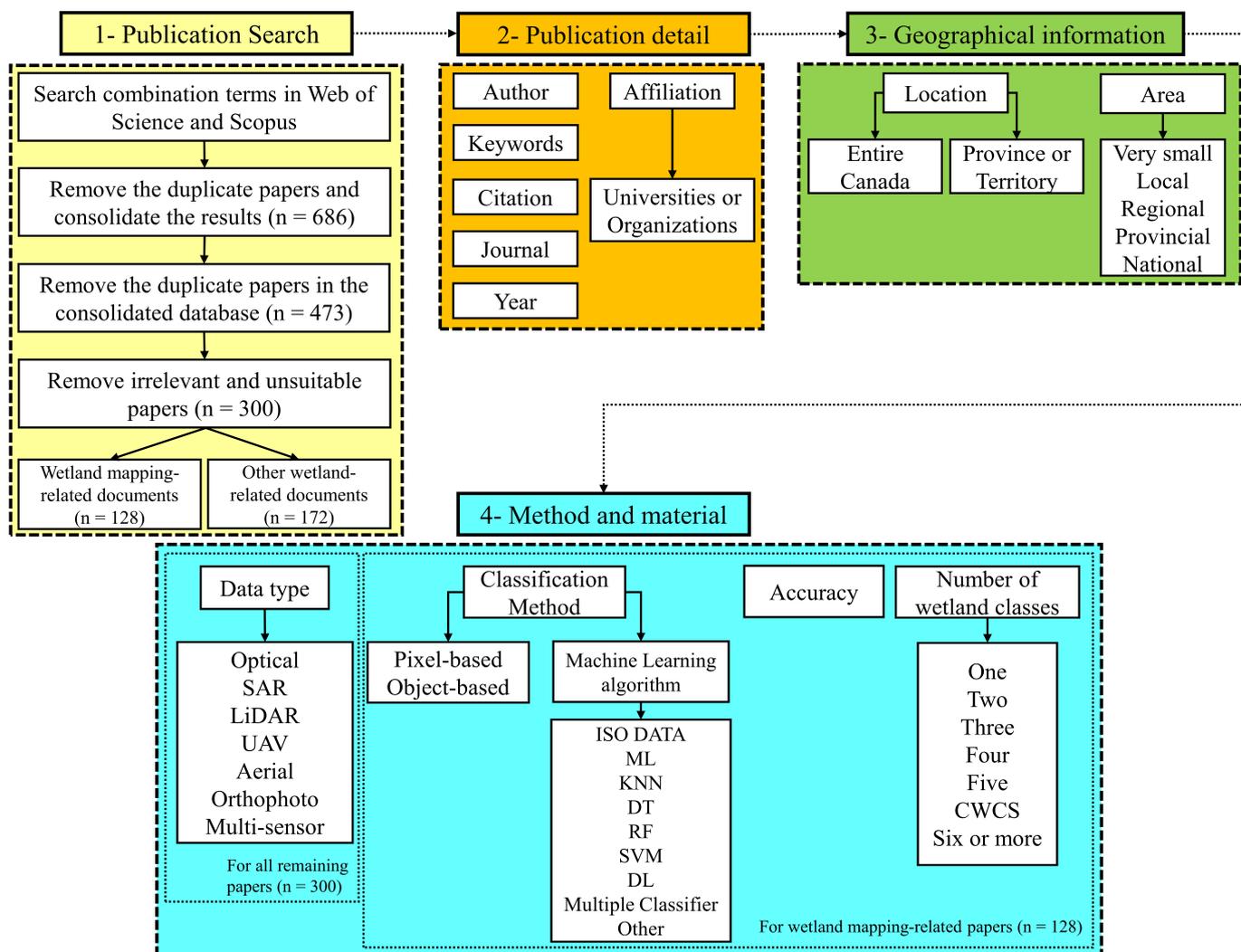


Figure 2. Workflow of preparing content analyses of this review paper.

Table 1. List of search words to prepare the procurements of this review.

First Word	Second Word	Third Word
Wetland	Canada Newfoundland and Labrador (NL) Ontario Quebec (QC) Nova Scotia (NS) New Brunswick (NB) Manitoba British Columbia (BC) Prince Edward Island (PE) Saskatchewan (SK) Alberta (AB) Northwest Territories Yukon (YT) Nunavut (NU)	Remote Sensing Radar Satellite

Table 2. The 14 attributes considered for content analysis of all 300 papers for further investigations.

	Attribute	Categories
1	First Author	Name
2	Co-authors	Name
3	Publication year	Value
4	Citation	Value
5	Paper type	Type: Journal, Conference
6	Study area	Type: 13 provinces/territories and Canada
7	Affiliation	Type: University, Organization
8	Data type	Type: Optical, SAR, LiDAR, UAV, Aerial, Orthophoto, Multi-sensor
9	Method	Type: (Supervised, Unsupervised), (Object-based, Pixel-based)
10	Number of wetland classes	Value: One, Two, Three, Four, Five, CWCS, and Six or more
11	Classifier	Type: 8 classifiers, multiple classifiers, and Other
12	Journal	Name
13	Area extent	Type: Very small, Local, Regional, Provincial, National
14	Accuracy	Value

4. Results and Discussion

Several statistical analyses were first conducted in the following subsections based on the procedure defined in the method section. In addition to demonstrating the general characteristics of 300 RS-based wetland studies in Canada (e.g., publication details, geographical information, and RS datasets), a comprehensive survey and discussion of the meta-analysis status and trends were provided to present a comprehensive overview of 128 mapping studies. Policymakers can gain advantages from this overview in wetland mapping over Canada using RS technology.

4.1. Publication Details

4.1.1. Number of Annual Publications

Figure 3 shows a schematic summary of the distribution of published articles during the time-period studied period along with the number of journal and conference papers. Figure 3 also includes those journals that have published more than one paper in each time interval. It is worth noting that for the period 2006–2020, those journals that have published more than three papers are only provided. According to Figure 3, several clear-up conclusions can be drawn and summarized as follows. Over time, the number of published papers increased. As such, the distribution of articles shows a major positive trend in publications of wetland studies in Canada. A total of 9 (3%), 14 (4.7%), 10 (3.4%), 37 (12.4%), 43 (14.4%), 62 (20.7%), and 124 (41.5%) papers were, respectively, published in 1976–1985, 1986–1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, and 2016–2020. These results show that the published articles gradually increased about 50% in the period 1976–2020.

After evaluating the time-level publication rates, we examined the number of publications for each year according to the study area. To this end, 300 articles were divided into 12 categories based on the Canadian provinces and territories, including BC, QC, SK, NU, MB, YT, NS, NL, AB, NT, NB, and ON. Figure 4 summarizes yearly trends in Canada's wetland publications according to the study area. Based on the results, there were no studies published from 1983 to 1987. It must be kept in mind that in this period, articles were presented in printed mode. Although many of them have been scanned into searchable formats and made available online, there may have been some other articles that were not scanned. Additionally, our extensive search of online resources indicates no studies published before 1987, and a small number of papers were published in early 2000 as well as in 2004. Almost 75% of the total 300 papers were published after 2004. The year 2020, with a total of 15 papers, had the most published articles since 1976. Moreover, the years 2019, 2018, and 2017, with a total of 24 published articles, were the second years with the most papers published about RS-based wetland studies in Canada.

published more than three times, are illustrated in Figure 6. *The Canadian Journal of Remote Sensing* and *Remote Sensing* (MDPI) with 46 and 40 papers were the top two journals, respectively. Moreover, *Hydrological Processes*, *Remote Sensing of Environment*, and *International Journal of Remote Sensing* with 19, 14, and 12 papers, respectively, were the other journals of interest in this field. In terms of the publisher center, most of the journal papers were published by Taylor & Francis followed by Wiley, MDPI, and Elsevier. Less than 8% of the journal papers were published by the SPIE, IEEE, and Springer. Among the conference papers, the IEEE IGARSS with 16 papers is the top conference for publishing papers on wetland studies in Canada, where the ISPRS Archive was the second one with 10 papers.

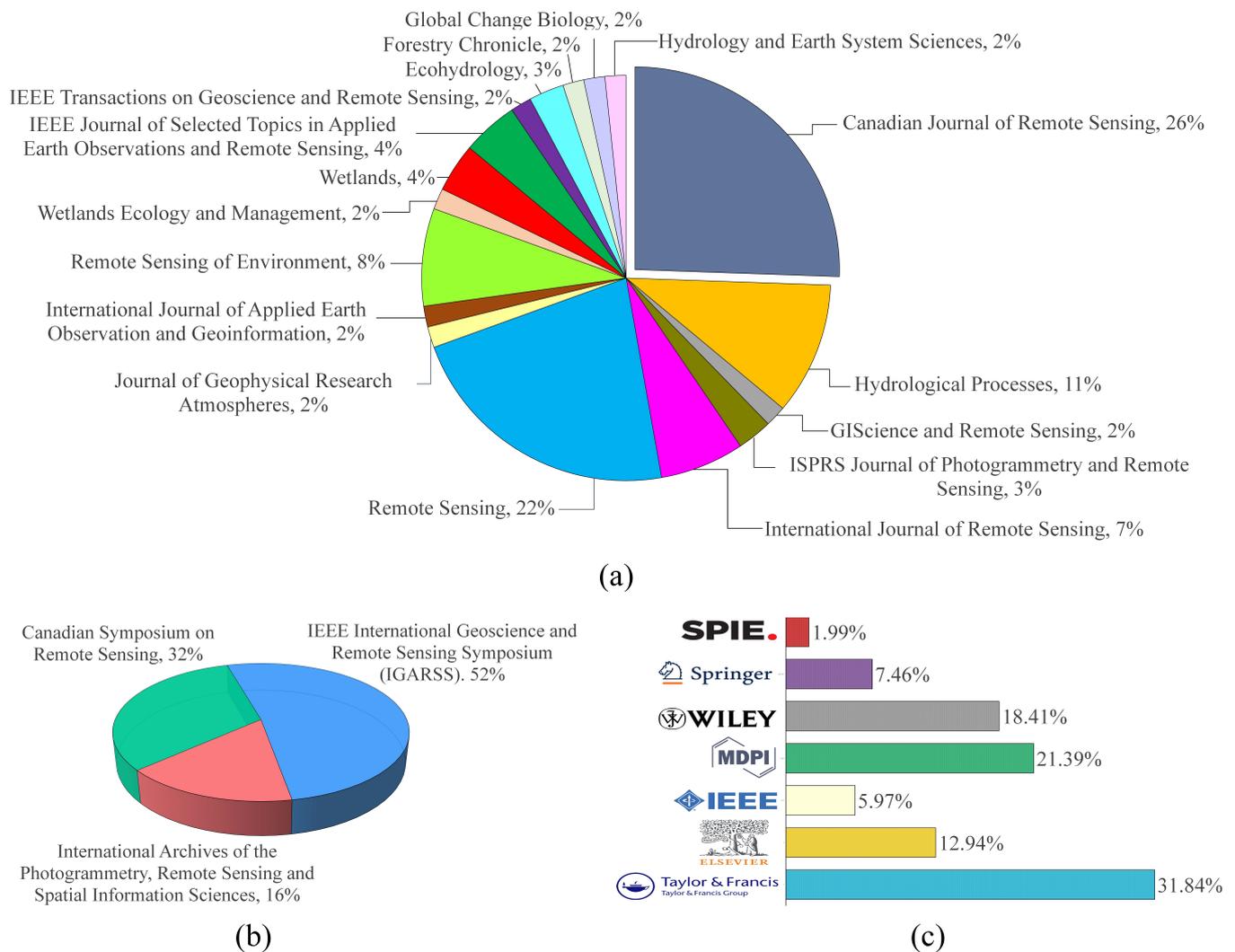


Figure 6. Percentage of published RS-based wetland studies in Canada per (a) journal, (b) international conference, and (c) publisher.

4.1.4. First and Co-Authors Analysis

This section summarizes the number of authors and co-authors in word-cloud, respectively. All the 300 papers were written by 210 unique first authors, and there were 943 co-authorships by 614 unique co-authors. Figure 7 displays all the authors who have more than three papers in their contributions, whether as author or co-author. Brisco B. is the lead author with a considerable difference from others. Additionally, Amani M. and Mahdianpari M. with 10 contributions are at the top as first authors. Brisco B. and Salehi B. with about 35 and 25 papers, also have the highest number of papers, respectively.

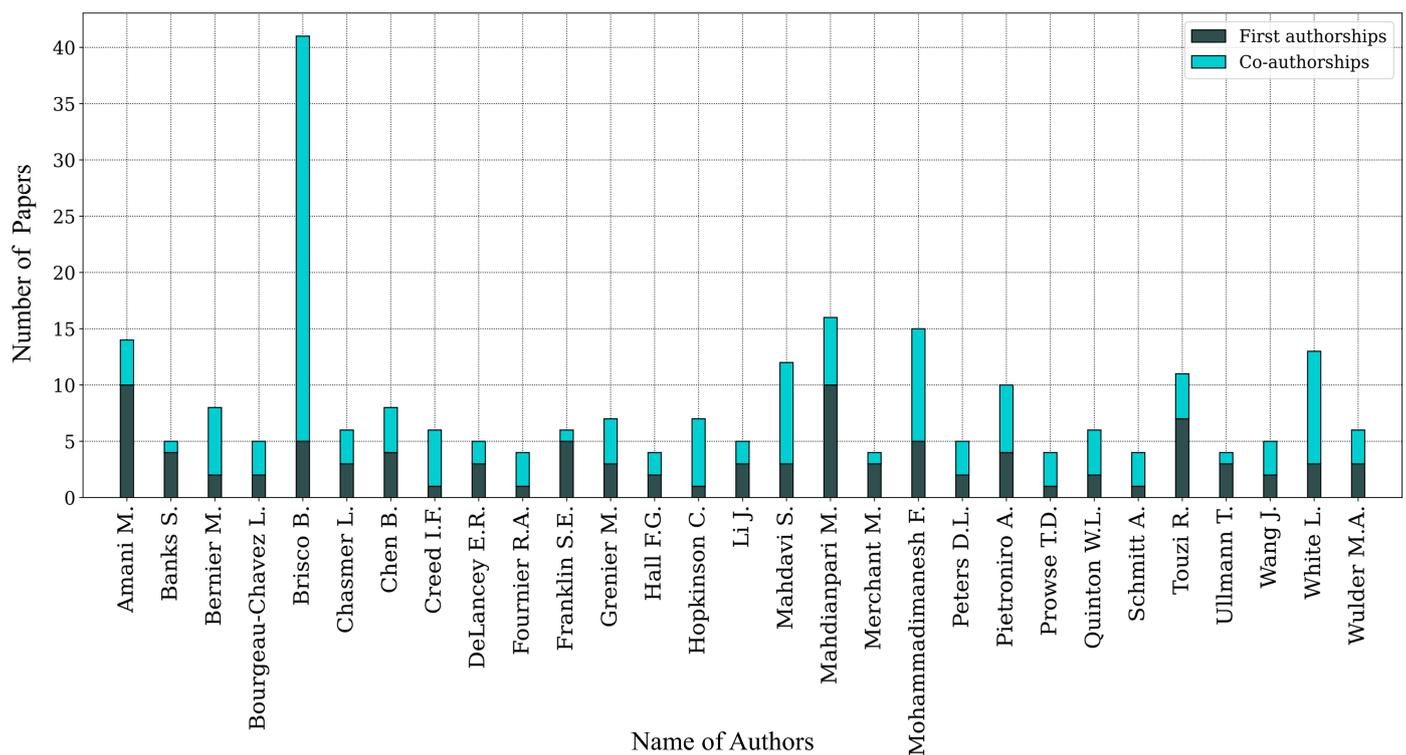


Figure 7. Authors who have contributed more than three papers as first author or co-author (alphabetically ordered).

4.1.5. Affiliation Analysis

In Table 3, the top universities and institutions and their contribution are summarized. For this analysis, only institutions with three or more publications were considered. Memorial University of Newfoundland has the highest number of publications in wetland classification. However, multiple institutions from ON (e.g., Canada Centre for Remote Sensing and National Wildlife Research Centre) also have a significant contribution with a total number of 61 papers.

Table 3. The detailed information of affiliations analysis.

Institute	Country/Province	Papers	Citation	CPP
Memorial University of Newfoundland	NL	29	787	27.14
Canada Centre for Remote Sensing	ON	15	952	63.47
INRS	QC	11	419	38.09
University of Saskatchewan	SK	10	423	42.3
Ducks Unlimited Canada	MB	9	23	2.56
University of Western Ontario	ON	9	279	31
University of Alberta	AB	9	236	26.22
Canada Center for Mapping and Earth Observation	ON	9	71	7.89
National Wildlife Research Centre	ON	8	105	13.125
Carleton University	ON	7	176	25.14
Université de Sherbrooke	QC	7	85	12.14
Canadian Wildlife Service of Environment Canada	QC	6	218	36.33
University of Toronto	ON	6	150	25
National Water Research Institute, Environment Canada	SK	6	416	69.33
McMaster University	ON	5	93	18.6
University of New Brunswick	NB	5	26	5.2
University of Calgary	AB	5	270	54
University of Victoria	BC	5	211	42.2
Wilfrid Laurier University	ON	4	270	67.5
University of Guelph	ON	4	106	26.5
University of Alaska Fairbanks	Alaska, U.S.	4	85	21.25

Table 3. Cont.

Institute	Country/Province	Papers	Citation	CPP
University of Lethbridge	AB	4	44	11
McGill University	QC	3	375	125
University of Waterloo	ON	3	102	34
Trent University	ON	3	48	16
Université Laval	QC	3	110	36.67
Environment and Climate Change Canada	QC	3	70	23.33
The University of British Columbia	BC	3	65	21.67
University of California at Los Angeles	CA, U.S.	3	39	13
Ontario Centre for Remote Sensing	ON	3	26	8.67
Wood Environment & Infrastructure Solutions	NL	3	23	7.67

In terms of citation, publications of the Canada Centre for Remote Sensing have attracted the greatest amount with a total citation of 952, followed by Memorial University of Newfoundland (787); University of Saskatchewan (423); INRS (419); National Water Research Institute, Environment Canada (416); and McGill University (375). Additionally, regarding Citation Per Paper (CPP), McGill University with a CPP of 125 is the highest. The next top institutions were the National Water Research Institute, Wilfrid Laurier University, and the Canada Centre for Remote Sensing having CPP values of 69.33, 67.5, and 63.46, respectively.

4.1.6. Citation Analysis

Citation analysis helps to ascertain prominent documents that significantly influence the corresponding field [85]. Furthermore, it also reflects the objectivity and quality of a paper by manifesting the number of attracted scholars to cite such a paper. Therefore, the citation number of all considered papers until the end of 2020 was extracted from Google Scholar to identify the high-contributing papers. It should be noted that earlier papers may have more citations than the recently published articles due to a more extended availability to the scientific community. Thus, the average citation per year was also calculated along with the total number of citations to reduce the effect of the elapsed time since publication. Table 4 presents the ten most cited papers devoted to wetland mapping in Canada. Based on Table 4, Ref. [27] was recognized as the most influential paper in the wetland studies conducted in Canada, in which the authors examined the applicability of various deep Convolutional Neural Networks (CNNs) for wetland mapping using high-resolution RS imagery.

Table 4. Highly cited papers devoted to wetland studies in Canada.

Rank	First Author	Average Number of Citations per Year	Total Citations	Publication Year	Region
1	Mahdianpari et al. [27]	44	132	2018	Part of NL
2	Mahdianpari et al. [86]	37.5	75	2019	Entire NL
3	Kokelj and Jorgenson [87]	30.37	243	2013	-
4	Mahdianpari et al. [44]	29.75	119	2017	Part of NL
5	Touzi, R. [88]	28.5	399	2006	Part of ON
6	Mahdavi et al. [2]	24	72	2018	-
7	Delancey et al. [21]	23	23	2020	Part of AB
8	Hird et al. [40]	22.5	90	2017	Part of AB
9	Connon et al. [89]	18.28	128	2014	Part of NT
10	Amani et al. [68]	17	34	2019	Entire Canada

4.1.7. Number of Wetland Classes

As mentioned, 128 out of the 300 papers were about wetland classification in Canada. These 128 papers were analyzed based on the number of wetland classes they included (see Figure 8). Almost all the papers (i.e., 114 papers) used five or fewer wetland classes. In total, 40 articles focused on five wetland classes (i.e., based on CWCS). Then, the second highest amount (29) belongs to papers covering one wetland class. The number of papers considering two, three, and four wetland classes were 14, 20, and 12, respectively. A few studies considered more than five classes. For example, four papers mapped six and seven classes, and two papers considered eight classes. There were only three papers discussing a large number of wetland classes, including 11, 12, and 17 classes.

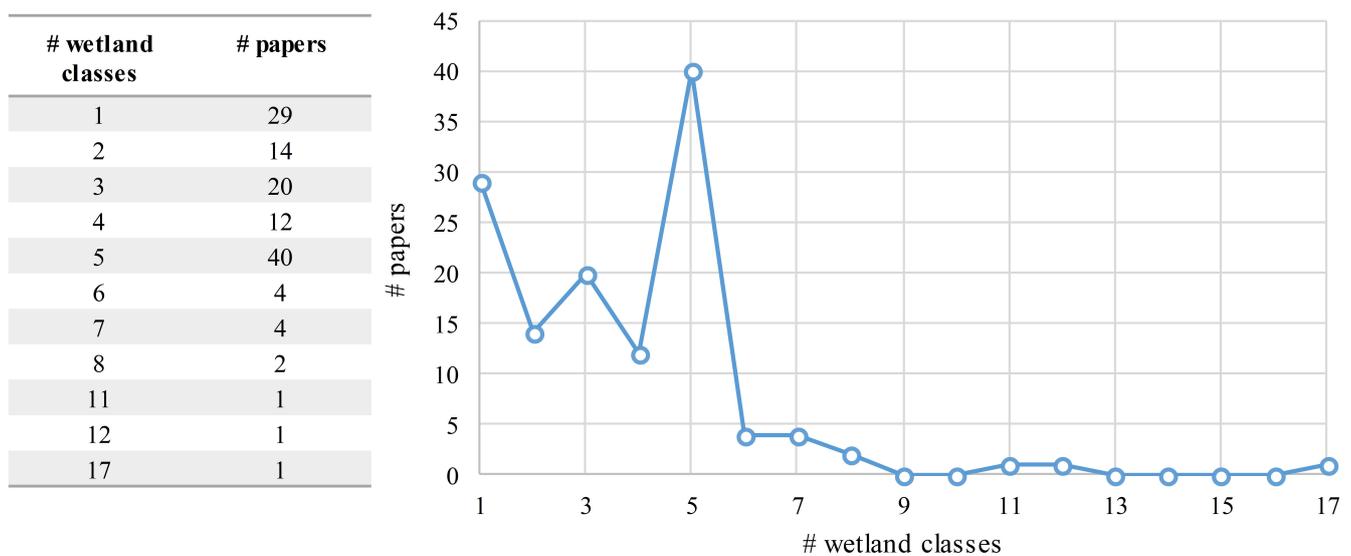


Figure 8. The number of papers based on the number of wetland classes included.

4.1.8. Province- and Territories-Based Analysis

The percentage of the papers based on the number of mapped wetland classes in each Canadian province/territory are illustrated in Figure 9. Note that articles that covered large regions and nationwide study areas were not considered in this analysis.

Since almost 90 percent of the papers considered five or fewer wetland types, the classes in Figure 9 were decided to be from one to five, and others were considered as having six or more classes. Furthermore, an extra category of CWCS was also considered to depict the percentage of papers that followed the CWCS specifications. The NL province had the highest number of published papers (86.4%) based on CWCS specifications, followed by NS, BC, and YT (~50%). ON had the highest number of papers overall (36); however, none of them used CWCS. In addition, NB and SK were not studied in any CWCS-structured paper. Finally, the only paper studying wetlands in NU considered only one wetland class.

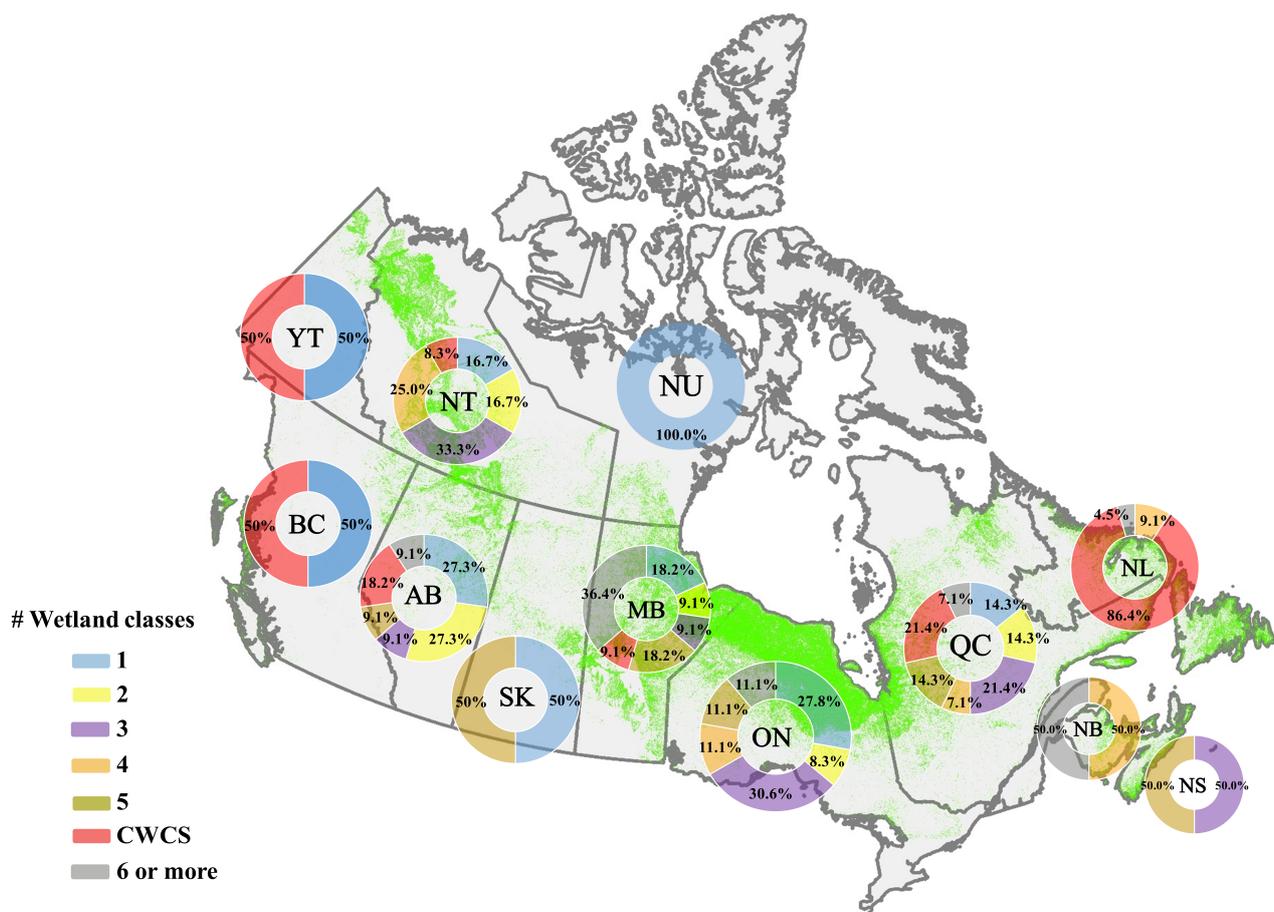


Figure 9. The province-based analysis of the number of wetland classes included in the published papers with the Canada wetland layer (Canada post-2000 wetland extent [90,91]) superimposed onto the map.

4.1.9. Geographical Distribution Based on Provinces/Territories

Figure 10 schematically illustrates a breakdown of RS-based wetland mapping studies in Canada by provinces/territories. This figure shows the spatial pattern of wetland mapping in Canada using RS data. Lighter and darker green hues indicate the lower and higher number of studies, respectively. The white hue depicts no study in the corresponding province/territory of Canada. It should be noted that some papers cover multiple study areas (i.e., multiple provinces, ecoregions, and entire Canada), and as a result, each corresponding province/territory was included in the count, separately. In Figure 10, those papers categories in Canada-wide studies contain all provinces. Based on a Figure 10, a large proportion of the studies were developed and assessed for only a few provinces, especially ON and NL. The literature search revealed that more than 40% of the individual case studies were focused on areas in ON and NL (darker green hues in Figure 10). Figure 10 also illustrates that NT with a total of 12 papers and AB and MB with 11 papers are other provinces where the wetlands were considered as the case studies. Very few published wetland research studies were identified from several provinces of Canada, including NU, YT, NB, NS, and BC. Overall, each of YT, NB, and NS accounted for two (less than 1.5% of published articles) studies.

As mentioned before, from all papers counted for all provinces in Figure 10, some papers contained multiple case studies and included several provinces. For example, ref. [92] expanded their study into more than one province, including MB and ON. On the other hand, ref. [54] applied their method on wetland mapping in AB and QC. As such, ref. [93] contained multiple case studies, including MB, NL, QC, and SK.

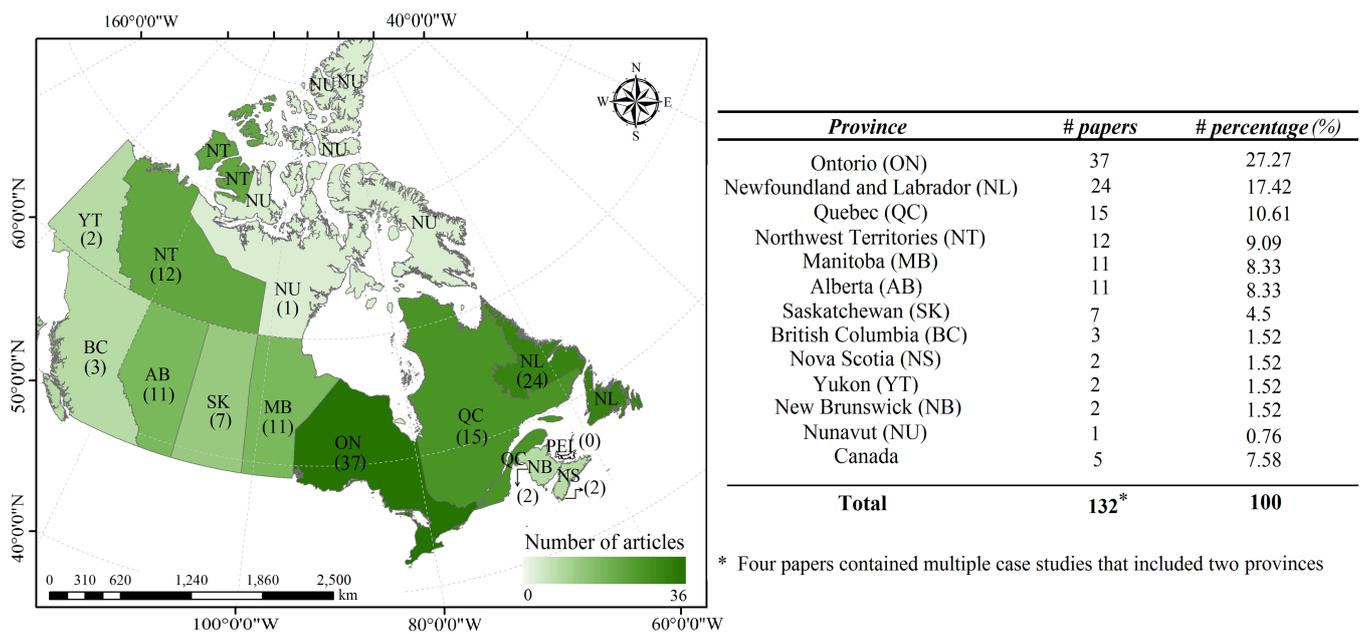


Figure 10. A choropleth map of Canada based on the number of RS-based wetland studies developed in various provinces. Lighter and darker green hues, respectively, indicate the low and high numbers of published papers.

4.1.10. Geographical Distribution Based on the Extent of the Study Area

We also examined the number of publications according to the extent of the study area (see Table 5). As such, the 128 wetland classification studies were divided into five categories based on the extent of the study area: very small (less than 100 km²), local (between 100 km² and 3000 km²), regional (more than 3000 km² and less than a provincial scale), provincial, and national (Canada-wide) scales.

Table 5. The number of publications focusing on various scales of the study area (small, local, regional, provincial, and national) in each Canadian province/territory.

Scale	ON	NL	SK	NT	NS	MB	QC	AB	YT	NU	NB	BC	Canada	Total	Percentage
Very small	8	4	1	4	2	1	5	3	—	—	2	1	—	32	25%
Local	16	10	2	3	—	3	2	1	—	—	—	1	—	36	28%
Regional	13	6	4	5	—	7	6	7	2	1	—	1	—	50	40%
Provincial	—	4	—	—	—	—	1	—	—	—	—	—	—	5	4%
National	—	—	—	—	—	—	—	—	—	—	—	—	5	5	4%

According to Table 5, the regional scale with a total of 50 papers, including 2 conference papers and 48 journal papers, had the highest number of published articles since 1976. The local and very small scales with a total of 36 and 32 publications were, respectively, the second and third scales. Each of the provincial and national study areas accounted for five (about 4% of published articles) articles.

4.2. Classification Methods

Table A1 and Figure 11 summarize the information about wetland classification methods used in Canada. Different types of unsupervised and supervised classifiers have been used for wetland mapping in Canada. In total, 16 classification methods were employed across the 128 Canadian wetland classification studies. The RF [94–96], ML [97,98], Decision Tree (DT) [38,99–102], SVM [46–48], Multiple Classifier System (MCS) [11,103], Iterative Self-Organizing Data Analysis Technique (ISODATA) [104,105], CNN [21,27,54], k-Nearest Neighbors (k-NN) [106,107], and Artificial Neural Network (ANN) [30,108–110] were the most commonly used algorithms. The Linear Discriminant Analysis (LDA) [83,111,112], Fuzzy Rule-Based Classification Systems (FRBCSs) [11,19], Markov Random Fields (MRF)-

based method [113,114], k-means, and classification methods based on polarization target decomposition [115,116] were used once or less than three times and, here, were categorized as the “Other” group.

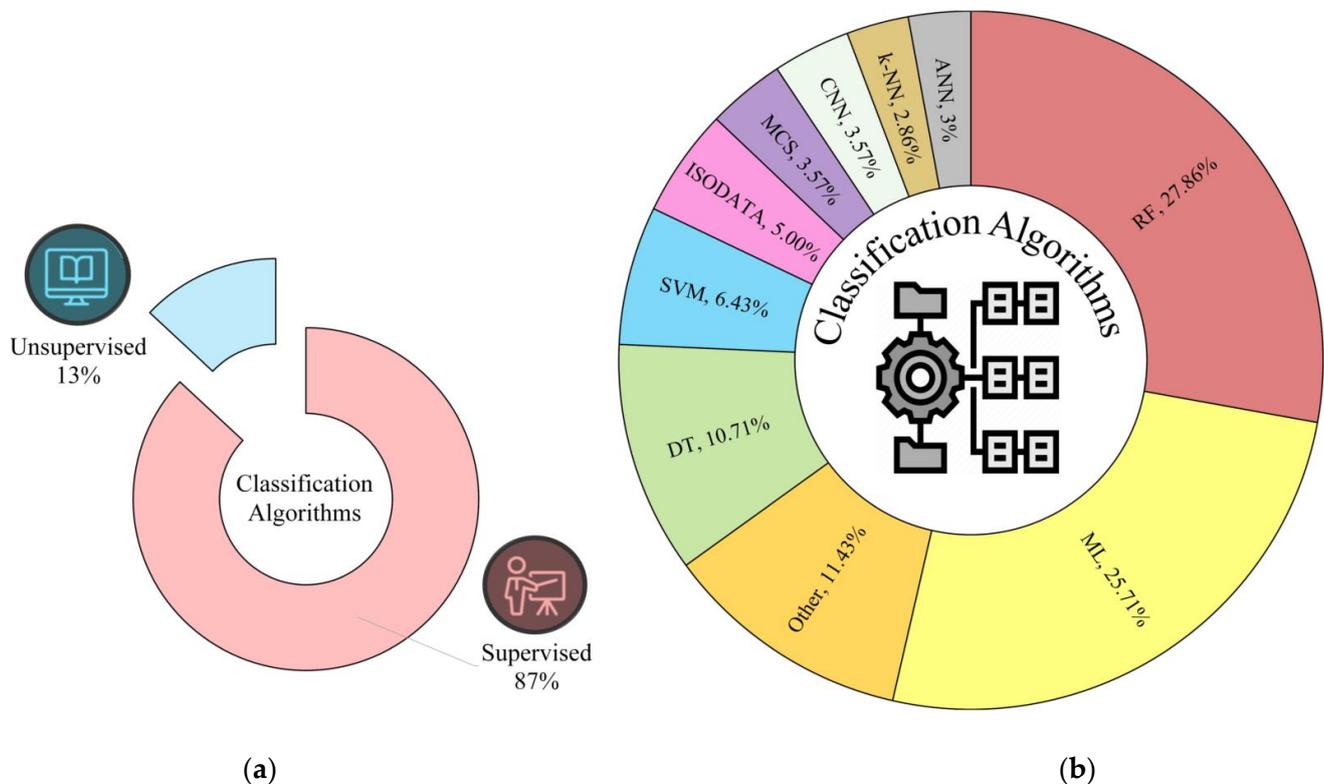


Figure 11. Percentage of the used machine learning (a) supervised and unsupervised classification approaches and (b) classifiers in wetland classification studies in Canada.

Figure 11 shows that researchers have tended to use supervised methods (87%) in studies related to wetland classification in Canada rather than unsupervised approaches (13%). This is mainly because the unsupervised methods typically deal with the untagged data, which require further analysis for mapping classes, and they usually have lower accuracies than supervised methods. Moreover, the RF classifier (27.86%) was the most widely used algorithm, followed by ML (25.71%) and DT (10.34%) classifiers. The ANN (2.86%), k-NN (2.86%), CNN (3.57%), and MCS (3.57%) were rarely employed in the studies. SVM and ISODATA were also used in more than five studies. Finally, 11.43% of the studies used other classifiers for Canadian wetland mapping.

The performance of the machine learning algorithms depends on several factors, including the complexity of the study area, type of RS data, quality of training samples, input features, classification algorithm, and tuning parameter settings [2]. Several metrics like overall accuracy, Kappa coefficient, producer’s accuracy, and user’s accuracy are typically used for classification performance evaluation. The wetland classification review studies rarely reported a complete confusion matrix to express wetland map errors (omission and commission errors), whereas they commonly stated the overall accuracy. Accordingly, the overall accuracy is here considered as a metric for comparing the accuracy of wetland mapping from different points of view.

The boxplots of the overall accuracy obtained from different algorithms are displayed in Figure 12 to evaluate their performance in wetland mapping in Canada. As shown in Figure 12 all classifiers had more than 80% median overall accuracy, except the “Other” group with the lowest median overall accuracy by 76%. Among them, RF (88%), CNN (86.6%), and MCS (85.75%) had higher median overall accuracies than the others. As expected, the “Other” group had the greatest range of overall accuracy results this group

included dissimilar classification methods with different performances. ML, SVM, k-NN, DT, NN, and ISODATA with the median overall accuracies between 83% and 85% were the mid-range classifiers. The best (97.67%) and worst (62.40%) overall accuracies were achieved by RF [117] and Other [118] classifiers, respectively.

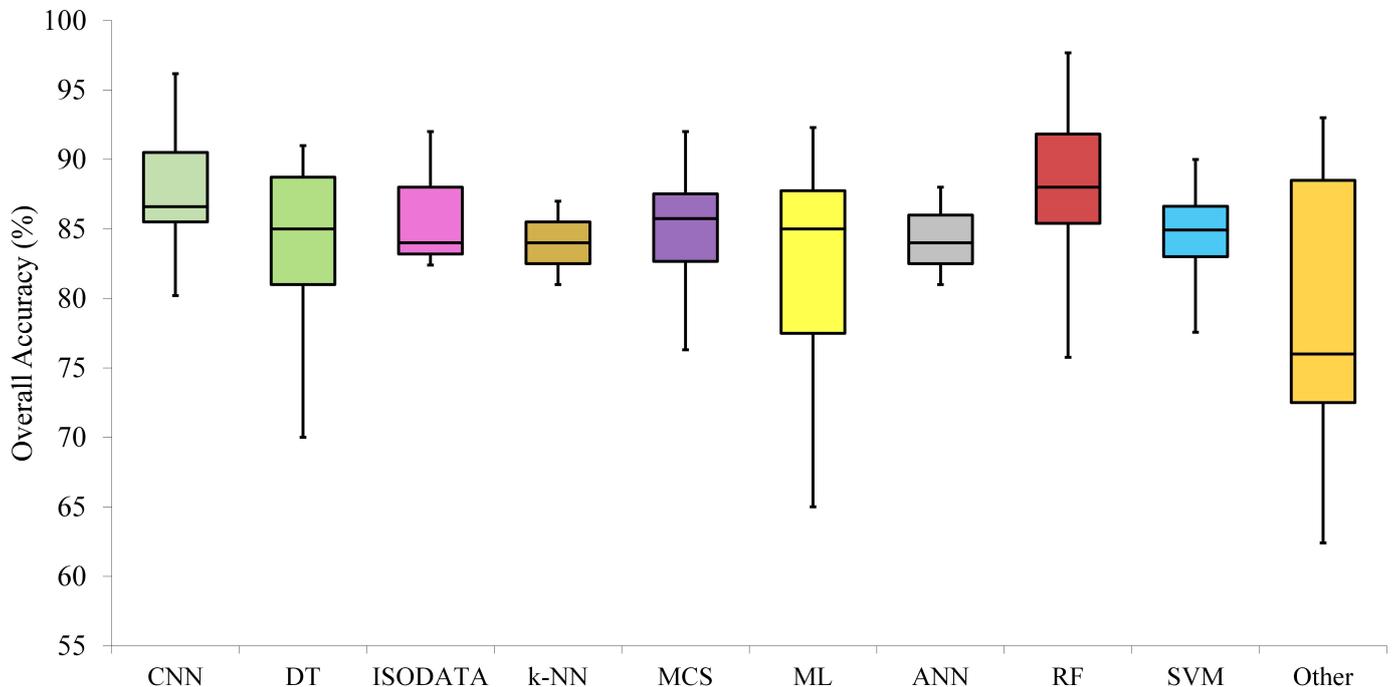


Figure 12. Boxplot distributions of the overall accuracies obtained by different classifiers used for wetland classification in Canada.

There are different wetland classification strategies. For instance, analysis of pixel information (i.e., pixel-based methods) has been emphasized in some studies. However, recent studies have frequently argued the higher potential of object-based methods for accurate wetland mapping [2]. The pixel-based methods utilize the spectral information of individual image pixels for classification [2,119]. In contrast, homogeneous information (e.g., geometrical or textural information) in images is considered through object-based methods [17,119]. The pixel-based classification methods were preferred to the object-based approaches in most of the wetland classification studies of Canada. This could be mainly due to the simplicity and comprehensibility of the pixel-based methods compared to object-based approaches. However, our investigations showed that object-based methods had been extensively utilized in recent wetland mapping studies [7,68,73,103,120] due to their higher performance than pixel-based methods. The highest median overall accuracy (87.2%) was achieved by the object-based methods indicating their higher potential in generating accurate wetland maps in Canada. Finally, the pixel-based methods involved a wider range of overall accuracies and had the lowest overall accuracy.

4.3. RS Data Used in Wetland Studies of Canada

RS datasets with diverse characteristics (e.g., different spatial, spectral, temporal, and radiometric resolutions) have been widely used for wetland mapping in Canada. In situ data and aerial imagery were the main data resources for wetland mapping in Canada before advancing spaceborne RS systems in the last four decades. Spaceborne RS systems provide a wide variety of datasets with different sensors and, these are great resources for wetland studies at different scales. Additionally, much of the spaceborne RS data is free [121], leading to high utilization in wetland studies. Moreover, with the advent of UAV technology in recent years, images with very high spatial and temporal resolutions have been provided for wetland studies. In general, with the availability of RS datasets acquired

by diverse spaceborne/airborne sensors, researchers have more options to produce highly accurate wetland maps. For example, multi-spectral passive optical satellite/aerial images have been frequently employed for wetland studies due to their straightforward interpretation and rich spectral information. However, such datasets are susceptible to clouds, resulting in their inefficiency in the cloudy regions [2,121]. Moreover, due to their short wavelength, optical signals cannot penetrate into the vegetation canopy [18]. In contrast, SAR signals are less affected by climate conditions (e.g., clouds and rain) [2,121,122]. SAR signals also have a high capability to penetrate into vegetation canopies, making them more beneficial than optical sensors to obtain information about wetland characteristics like structure, surface roughness, and moisture content [2,18]. Furthermore, modern SAR missions (e.g., RADARSAT-2, RADARSAT Constellation Mission (RCM)) acquire data in any combination of linear (horizontal and vertical) or circular (right or left) polarizations, which are very helpful for mapping treed and herbaceous wetlands [18,123].

Many wetland studies have combined optical and SAR data to achieve more accurate results. Additionally, a combination of optical, SAR, and elevation data has been extensively used for wetland studies in Canada (see Figure 13) and has usually provided the highest classification accuracies. As shown in Figure 13, single optical data (95 studies) is the most common data for wetland studies in Canada. Moreover, SAR data (57 studies) or dual combinations of SAR and optical data (53 studies) were often used. Single elevation data type (22 studies) was mostly employed to produce different topographic features, which can be accommodated for 3D analysis of wetland species and wetland mapping. Dual combinations of optical and elevation data (19 studies), and triple combination of optical, SAR, and elevation data (24 studies) were moderately considered as input data for wetland studies in Canada. The combination of elevation data with SAR data were the least utilized data types (only six studies). A total of 12 studies employed other data types, such as data derived from satellite telemetry, radiometers, satellite transmitters and ground penetrating radar for wetland studies in Canada.

The studies typically conducted on RS data acquired by different platforms, such as airborne, spaceborne or a combination of them. Most of the studies (~67%) were based on the spaceborne RS systems. This is probably due to the high capability and cost-effectiveness of spaceborne RS datasets for wetland mapping and monitoring over large areas in Canada. The airborne RS datasets were used in 13% of studies, where its combination with spaceborne RS datasets has been utilized in 20% of wetland studies. Recently, the use of Unmanned Aerial Vehicles (UAVs) equipped with RS sensors has become popular in wetland studies. In fact, the provided drone datasets could be a paradigm shift as they can be easily customized according to wetland studies specifications in contrast to spaceborne and piloted airborne RS datasets.

Figure 14 provides the frequently used optical and SAR sensors in wetland studies in Canada. Landsat, Sentinel-2, and RapidEye were the most common medium resolution spaceborne optical systems, while IKONOS and WorldView-2 were the most widely used high-resolution spaceborne optical sensors in wetland studies in Canada. Among them, Landsat 4/5 images were often employed in studies due to their affordable spatial/temporal resolutions and rich archive datasets. Moreover, ERS-1 and -2, Sentinel 1, and RADARSAT-1 and -2 are the most popular C-band SAR systems, where ALOS-1 and -2 and TRASAR-X were widely used L-band and X-band SAR system in RS-based wetland studies in Canada. RADARSAT-2 images were frequently employed for wetland studies among SAR sensors because it is a Canadian SAR system, and it provides full/dual-polarization data with suitable azimuth and slant range resolutions. Finally, Compact Airborne Spectrographic Imager (CASI) hyperspectral system was the most popular sensor among airborne sensors.

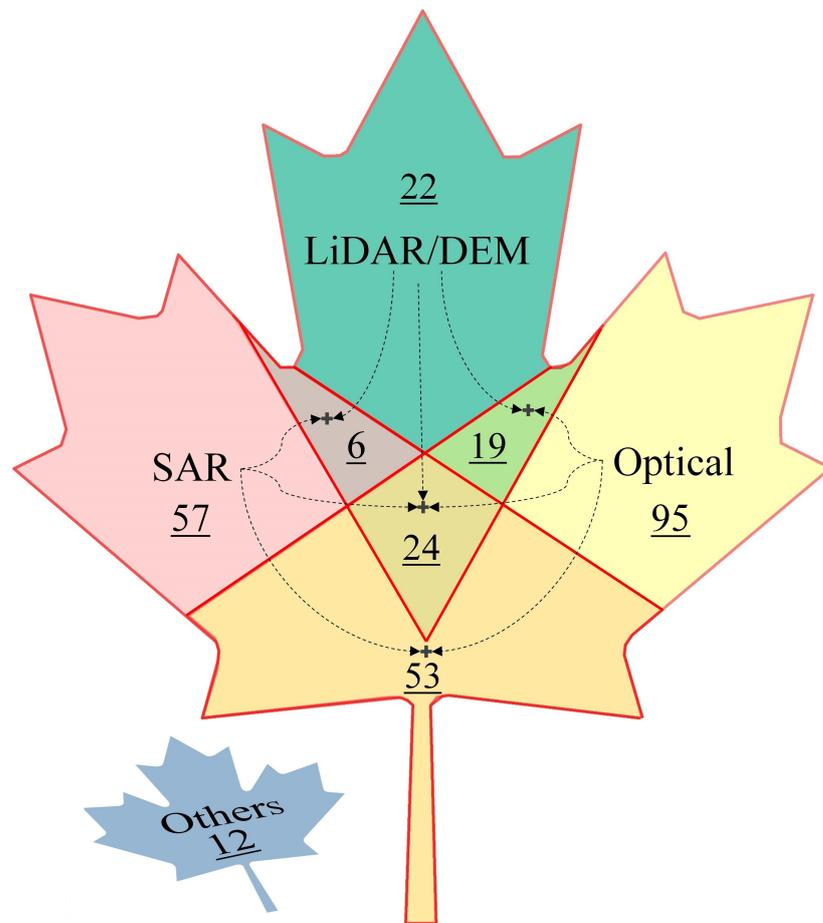


Figure 13. Data type(s) used in wetland studies in Canada.

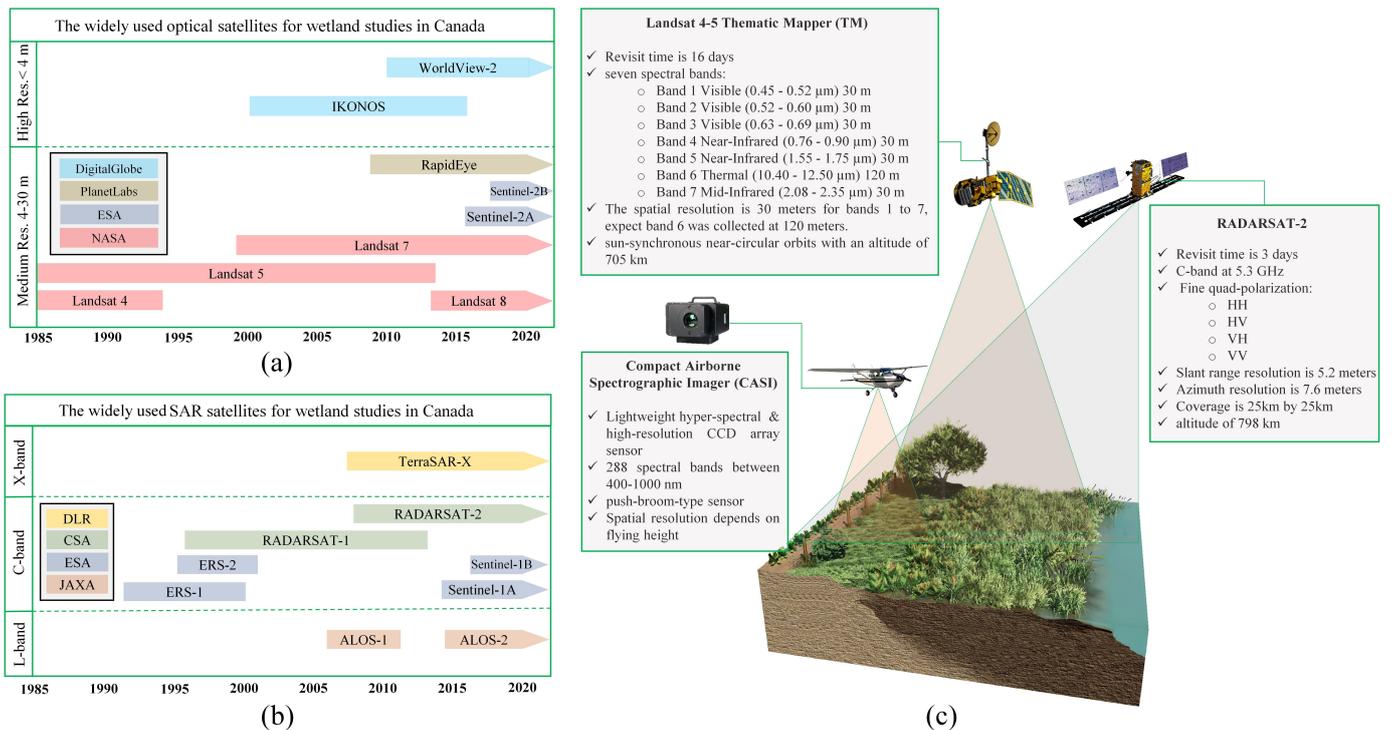


Figure 14. The frequently used (a) optical and (b) SAR satellites in wetland mapping in Canada and (c) the description of the most widely used RS systems.

For a closer look, the overall accuracy reported in wetland classification studies for various data types is shown in Figure 15a. Based on Figure 15a, the median overall accuracy of the various data types and their combinations is more than 80%. LiDAR/DEM data obtained the highest median overall accuracy (92%), resulted from only 3 papers out of 22 LiDAR/DEM papers that reported accuracy. The lowest median overall accuracy (82.4%) was achieved based on the SAR data type. However, a combination of SAR by another data type (e.g., optical or DEM) resulted in a better median overall accuracy. The median overall accuracy obtained by the optical data improved by combining with LiDAR/DEM data. Given the large number of studies conducted based on optical data, a wide range of overall accuracy (between 62.40% and 96.17%) was observed by this data, which was. Finally, the best overall accuracy (97.6%) was achieved by a triple combination of SAR, optical, and elevation data.

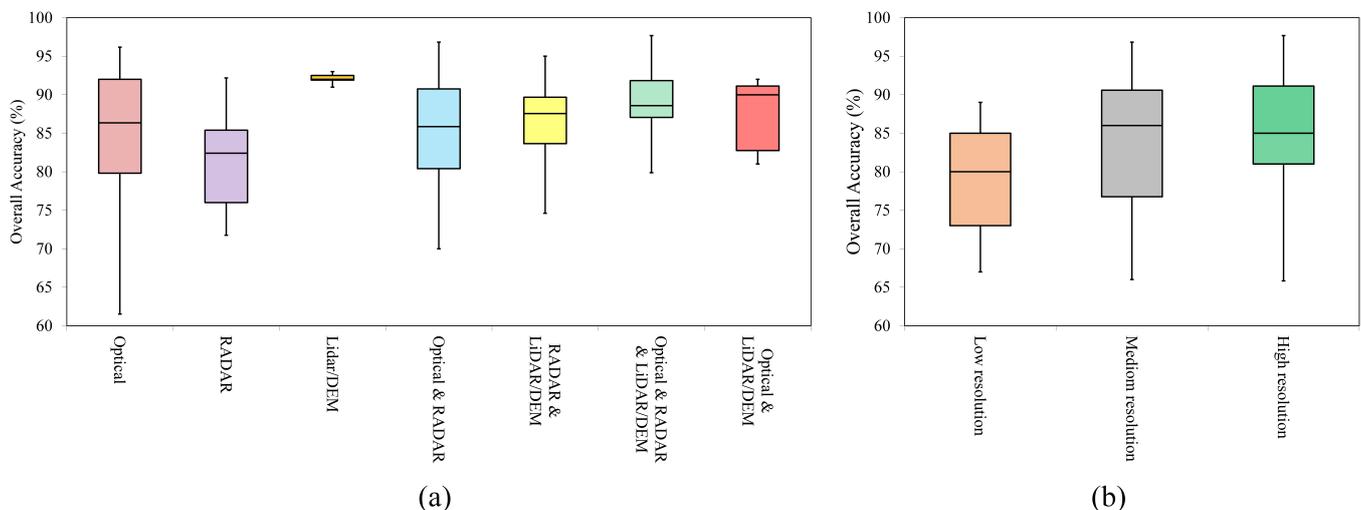


Figure 15. The overall accuracies reported in RS-based wetland classification studies in Canada (a) based on the different data types employed, and (b) based on the spatial resolution of the imagery.

Depending on the selected spatial resolution, wetland classification studies in Canada can also be categorized into three groups of high-resolution (<4 m), medium-resolution (4–30 m), and low-resolution (>30 m). Accordingly, the median overall accuracy achieved by reviewed papers using high, medium, and low spatial resolutions are illustrated in Figure 15b. The median of overall accuracy for all the spatial resolutions was more than 80%. The best median overall accuracy was achieved for studies that used medium-resolution datasets for wetland mapping, closely followed by the high-resolution datasets. Moreover, a great range of overall accuracies was reported in various studies using medium resolution images. As expected, the weakest results belonged to studies that used low spatial resolution data. The highest (97.67%) and lowest (62.40%) overall accuracies were obtained using a high-resolution and medium resolution data, respectively.

The results showed that 18 types of RS systems were used more than three times in 128 wetland classification studies, which are depicted in Figure 16. Airborne platforms, followed by RADARSAT-2 and Landsat 4-5, were the most frequently utilized sensors in Canada for wetland mapping using RS data. Among the Landsat series, Landsat 7 was less used, which was probably due to the failure of the Scan Line Corrector (SLC) on its board. Sentinel-1/2, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Quickbird, ERS-1 and -2, and ALOS-2 were also among the sensors which were used in combination with other sensors. However, Quickbird, ASTER, GeoEye, and ERS-1 and -2 were the least common sensors with five or less uses.

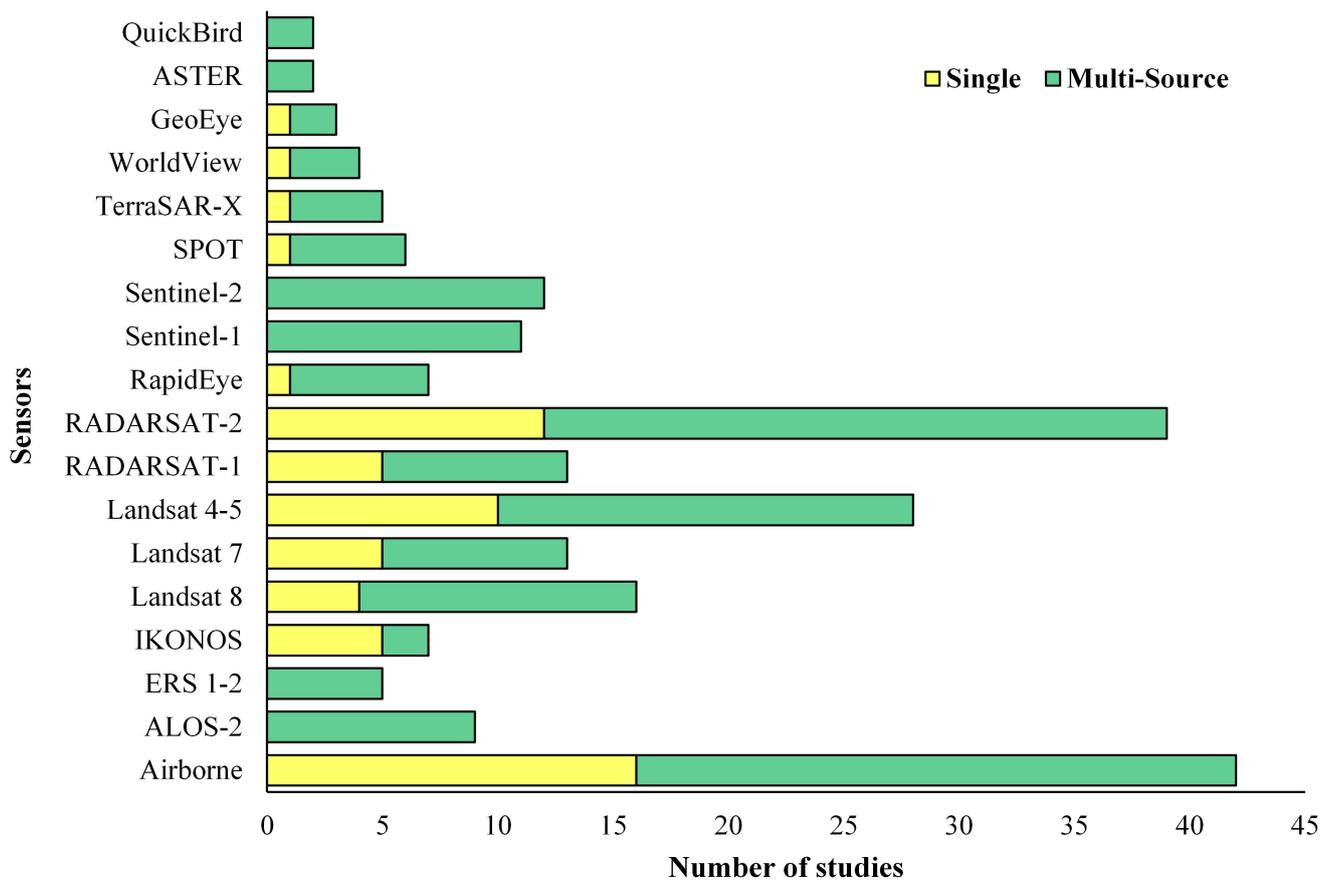


Figure 16. Frequency of different sensors used in RS-based wetland classification studies in Canada. Blue and red bars indicate if a single or multi-source data are used.

4.4. Level of Classification Accuracy

For a comprehensive investigation of the RS-based Canadian wetland studies, the reported overall accuracies were assessed and compared with various parameters, including the year of publication, the extent of the study area, and the number of classes considered in the classification method (see Figure 17). Figure 17a presents the histogram of the overall classification accuracies reported in 128 papers. Note that a wide range of studies (39 papers) did not report the overall accuracy of their classification methods (black column in Figure 17a). According to Figure 17a, almost 80% (46 papers) of the studies have an overall accuracy between 84% and 93%; while only 33 papers have an overall accuracy of less than 84% (between 62% and 83%).

Based on Figure 17b, there is not a clear relationship between the overall classification accuracy and the year of publication. Two articles that were published in 1976–1995 have close overall accuracy to each other and the medium overall accuracy of 86%. Two articles that were published in 1996–2000 have achieved different accuracies. The medium overall accuracy of those articles is 71%. In another time-interval, there is a greater number of publications that have a wide range of overall accuracies between 63% and 96%.

Based on Figure 17c, wetland classification methods applied to the provincial scales have the highest median overall accuracies, followed by very small and local study areas. On the other hand, the papers on national scales have the lowest median overall accuracies. Based on Figure 17d, more than 90% of the investigated articles used a few classes (between two and six). In these papers, the overall accuracies vary between 62% and 96%. However, the median overall accuracies of these papers are 87% for 1–3 classes and 86% for 4–6 classes. In the case of 7–9 classes, the total number of papers decreases to four papers. The median overall accuracy of these four papers is 89%. Moreover, those articles that considered a

greater number of classes have higher median overall accuracies. We also found two papers that considered 10–18 classes for classifying wetlands and achieved the median overall accuracies of 94%. As seen, a higher number of classes seem to be more accurate for the wetland classification method. We expect higher accuracies for a lower number of classes. Therefore, due to the significant discrepancy in the number of papers, it is impossible to provide a solid conclusion about the relationship between the overall accuracy of classification method and the number of classes.

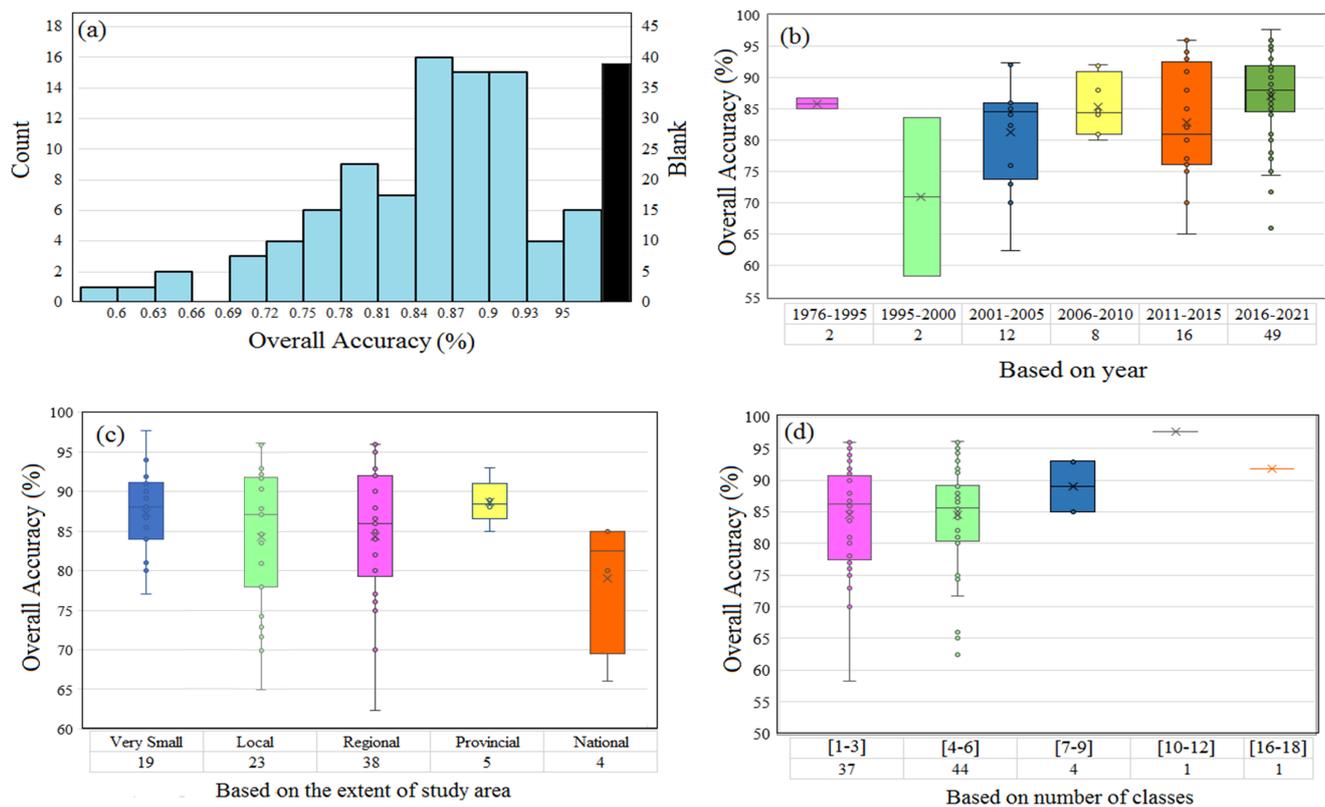


Figure 17. Overall accuracies reported in in RS-based wetland classification studies in Canada based on (a) the number of papers, (b) the year of publications, (c) the extent of study area, and (d) the number of classes considered in the classification method.

5. Conclusions

This review paper demonstrated the trends of RS-based wetlands studies in Canada by investigating 300 articles published from 1976 to 2020. In total, twelve subfields were summarized, including classification methods and their overall accuracies, RS datasets, journals, number of wetland classes, authors/co-authors contributions and affiliations, publications per year, geographical distributions, scale of the study areas, citation, and keywords. Eventually, a deeper meta-analysis was carried out to discuss the utilization of RS systems in these subfields over Canada particularly, which differentiates our survey from previous reviews. Consequently, this paper addresses the status of wetland studies in Canada using RS data and highlights opportunities and limitations for generating and updating Canadian wetland inventories, as well as classification protocols improvements. In summary, the meta-analysis of 300 wetland studies, 128 of which were related to wetland classification, presented the following outcomes:

- RS datasets have been increasingly used in the last four years, especially in NL. However, the largest number of studies has been conducted in ON over the past 40 years.
- Around half of the research studies have been implemented over the three provinces of ON, NL, and QC, indicating the requirement for more efforts of wetlands mapping

in other Canadian provinces to have a highly accurate and consistent country-wide wetland inventory.

- A total of 40% of the studies have been conducted over regional scales, and only five research papers have been published on a country scale. Although small-scale analysis can result in a classification with relatively higher accuracy, country-based classification can provide valuable details on the status and extent of wetlands for national and local administrative decision-makers.
- Novel deep learning methods and MCSs achieved more accurate maps in comparison to traditional techniques. RF, CNN, and MCS techniques provided the highest median overall accuracies.
- Pixel-based and supervised classification methods were the most popular techniques to map wetlands in Canada due to the simplicity and higher accuracies of these strategies compared to the object-based and unsupervised approaches, respectively. However, the median accuracy of object-based methods was more than pixel-based techniques and, therefore, they have been more frequently used in recent studies.
- Optical imagery and the combinations of optical and SAR datasets have been the most commonly used RS datasets to map wetlands in Canada. Availability, fulfilled archive, the high capability, and cost-effectiveness of optical and SAR imageries have attracted numerous focuses to utilize them. LiDAR/DEM data also resulted in the highest classification accuracies over small regions.
- Most (but not all) of the reviewed studies did not present the full confusion matrix and only reported the overall accuracy to evaluate the results which were easily affected by the stratification of samples between dry and wet classes. Additionally, accuracy statistics often depend on the different factors, such as the geographic extent of the study area, type of RS data, the degrees of wetland species, the quality of training and tests samples, and classification algorithm and its tuning parameter settings. Therefore, it would be required to increase the number of wetland studies that try to actually quantify wetland classification errors in different aspects.
- Approximately 30% of the studies considered the five CWCS wetland classes, and around 54% provides wetland maps using a lower number of classes.
- Frequencies of “SAR” and “RADARSAT (1/2)” displayed the importance of SAR data for wetland mapping in Canada because of the capability of SAR data to acquire images in any weather conditions considering the dominant cloudy and snowy climate of Canada.

This review paper highlights the efficiency of RS technology for accurate and continuous mapping of wetlands in Canada. The results can effectively help in selecting the optimum RS data and method for future wetland studies in Canada. In summary, implementation an object-based RF method along with a combination of optical and SAR images can be the optimum workflow to achieve a reasonable accuracy for wetland mapping at various scales in Canada.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Characteristics of the mostly used classifiers for wetland classification in Canada using RS data.

Classifier	Description	Type
ISODATA	It is a modified version of <i>k</i> -means clustering in which <i>k</i> is allowed to range over an interval. It includes the merging and splitting of clusters during the iterative process.	Unsupervised
ML	It is a parametric algorithm based on Bayesian theory, assuming data of each class follow the normal distribution. Accordingly, a pixel with the maximum probability is assigned to the corresponding class.	Supervised/Unsupervised
<i>k</i> -NN	It is a non-parametric algorithm that classifies a pixel by a variety vote of its neighbors, with the pixel being allocated to the class most common among its <i>k</i> nearest neighbors.	Supervised
SVM	It is a type of non-parametric algorithm that defines a hyperplane/set of hyperplanes in feature spaces used for maximizing the distance between training samples of classes space and classify other pixels.	Supervised
DT	It is a non-parametric algorithm belonging to the category of classification and regression trees (CART). It employs a tree structure model of decisions for assigning a label to each pixel.	Supervised
RF	It is an improved version of DT, which includes an ensemble of decision trees, in which each tree is formed by a subset of training samples with replacements.	Supervised
ANN	It is a multi-stage classifier that typically includes the neurons arranged in the input, hidden, and output layers. It is able to learn a non-linear/linear function approximator for the classification scheme.	Supervised
CNN	It is a class of multilayered neural networks/deep neural networks, with a remarkable architecture to detect and classify complex features in an image.	Supervised
MCS	It advantages from performances of dissimilar classifiers on a specific LULC to achieve accurate classification of the image.	Supervised

Table A2. List of 300 studies and main characteristics.

No.	First Author	Year	Region	Classification Method	Data
1	Jeglum J. K. et al. [124]	1975	ON	–	Aerial
2	Boissonneau A. N. et al. [125]	1976	ON	PB */Supervised/Other	Optical + Aerial
3	Wedler E. et al. [126]	1981	ON	–	Radar
4	Hughes F. M. et al. [127]	1981	AB	–	–
5	Neraasen T. G. et al. [128]	1981	Canada	–	Optical
6	Watson E. K. et al. [129]	1981	BC	–	Aerial
7	Tomlins G. F. et al. [130]	1981	BC	–	–
8	Pala S. et al. [131]	1982	ON	–	Aerial
9	Lafrance P. et al. [132]	1987	QC	–	Optical
10	Lafrance P. et al. [133]	1988	QC	–	Optical
11	Peddle D. R. et al. [134]	1989	Canada	PB/Supervised/ML	Optical
12	Kneppeck I.D. et al. [135]	1989	AB	–	–
13	Drieman J. A. et al. [136]	1989	ON	–	Radar
14	Konrad S. R. et al. [137]	1990	Canada	PB/Unsupervised/ML	Optical + Aerial
15	Franklin S. E. et al. [138]	1990	NL	–	Optical
16	Matthews S. B. et al. [139]	1991	NT	–	Optical
17	McNairn H. E. et al. [23]	1993	ON	PB/Supervised/ML	Aerial
18	Franklin S. E. et al. [140]	1994	NL	–	Aerial + Optical
19	Cihlar J. et al. [141]	1994	MB	–	Optical
20	Franklin S. E. et al. [142]	1994	NL	–	Aerial
21	Yatabe S. M. et al. [50]	1995	ON	PB/Supervised/ML	Radar + Optical
22	Strong L. L. [12]	1995	SK	–	Other = Aerial Video
23	Bubier J. L. [143]	1995	MB	–	Optical
24	Pietroniro A. et al. [144]	1996	NT	PB/Supervised + Unsupervised/Other	Optical + Aerial

Table A2. Cont.

No.	First Author	Year	Region	Classification Method	Data
25	Hall F. G. et al. [145]	1996	Canada	–	Optical + Radar + Aerial
26	Halsey L. [22]	1997	MB	–	Aerial
27	Steyaert L. T. [93]	1997	MB, SK	PB/Unsupervised/ML + Other = ISOCCLASS	Optical + Aerial
28	Hall F. G. et al. [106]	1997	SK	PB/Supervised/KNN	Optical
29	Franklin S. E. et al. [146]	1997	NL	–	Aerial
30	Collins N. et al. [147]	1997	NS	–	Aerial
31	Wang J. et al. [25]	1998	ON	PB/Supervised/ML	Optical + Radar + Aerial
32	Pietroniro A. et al. [148]	1999	AB	–	Optical + LiDAR/DEM
33	Ghedira H. et al. [30]	2000	QC	PB/Supervised/DL = NN	Radar
34	McLaren B. E. et al. [71]	2001	NL	PB/Supervised/Other	Radar + Optical + Aerial
35	Baghdadi N. et al. [101]	2001	ON	PB/Supervised/DT	Radar
36	Rapalee G. et al. [149]	2001	Canada	PB/Supervised/Other	Optical + Aerial + LiDAR/DEM
37	Murphy M. A. [29]	2001	ON	PB/Supervised/ISODATA + Other	Radar
38	Pietroniro A. et al. [150]	2001	AB	–	Optical + Radar
39	Hall-Atkinson C et al. [151]	2001	NT	–	Radar + Optical + Aerial
40	Sokol J. et al. [152]	2001	NL	–	Radar
41	Dechka J. A. et al. [111]	2002	SK	PB/Supervised + Unsupervised/ISODATA + Other	Optical + Aerial
42	Gadallah F.L et al. [105]	2002	MB	PB/Supervised/ISODATA	Optical + Radar + Aerial
43	Arzandeh S. et al. [97]	2002	ON	PB/Supervised/ML	Optical + Radar + Aerial
44	Deslandes S. et al. [100]	2002	QC	PB/Supervised/DT	Optical + Radar + Aerial
45	Jollineau M. et al. [153]	2002	ON	PB/Supervised + Unsupervised/ML + K-Means	Optical
46	Töyrä J. et al. [154]	2002	Canada	–	Optical + Radar
47	Pietroniro A. et al. [155]	2002	AB	–	Optical + RADAR + LiDAR
48	Poulin M. et al. [156]	2002	QC	–	Optical + Aerial
49	Quinton W. L. et al. [157]	2003	NT	PB/Supervised/ML	Optical + Aerial
50	Bernier M. et al. [158]	2003	QC	PB/Supervised/ML + DL = NN	Radar
51	Thomas V. et al. [118]	2003	MB	PB/Supervised/ML	Other
52	Jobin B. et al. [51]	2003	QC	PB/Supervised/ML	Optical + Aerial
53	Arzandeh S. et al. [159]	2003	ON	PB/Supervised/ML	Optical + Radar + Aerial
54	Havholm K. G. et al. [160]	2003	MB	–	Other
55	Wessels J. et al. [161]	2003	Canada	–	Optical + Radar
56	Bernier M. et al. [110]	2003	QC	–	Radar
57	Racine M. J. et al. [162]	2004	QC	PB/Supervised/ML	Radar
58	Rosenqvist A. et al. [163]	2004	Canada	–	Radar
59	Sokol J. et al. [164]	2004	Canada	–	Radar
60	Li J. et al. [33]	2005	Canada	PB/Supervised/Other	Optical + Radar + LiDAR
61	Tedford B. et al. [165]	2005	SK	–	Optical + Radar
62	Grenier M. et al. [166]	2005	QC	–	Optical + Radar
63	Cheng W. F. et al. [167]	2005	NL	–	-
64	Ju W. et al. [168]	2005	Canada	–	LiDAR/DEM
65	Hudon C. et al. [169]	2005	QC	–	Optical + Aerial
66	Niemann K.O. [170]	2005	Canada	–	Optical + Radar
67	Smith K. B. et al. [171]	2005	Canada	–	Optical + Radar
68	Li J. et al. [172]	2005	ON	–	Radar
69	Töyrä J. et al. [173]	2005	AB	–	Optical + Radar + LiDAR/DEM + Aerial
70	Mialon A. et al. [174]	2005	Canada	–	Optical + Radar
71	Brown L. et al. [175]	2006	NU	–	Optical + Radar + Aerial
72	Prowse T. D. et al. [176]	2006	AB, BC, SK	–	Optical + Radar + Aerial

Table A2. Cont.

No.	First Author	Year	Region	Classification Method	Data
73	Peters D. L. et al. [177]	2006	AB, NT	–	LiDAR/DEM
74	Dillabaugh K. et al. [178]	2006	ON	–	Optical
75	Grenier M. et al. [3]	2007	QC	OB*/Supervised/Other	Optical + Radar
76	Hogg A. R. et al. [35]	2007	ON	PB/Supervised/CART	LiDAR/DEM
77	Li J. et al. [179]	2007	ON	PB/Supervised/ML	Optical + Radar
78	Stevens C. E. et al. [180]	2007	AB	–	LiDAR/DEM
79	Smith C. et al. [80]	2007	Canada	–	-
80	Touzi R. et al. [88]	2007	ON	–	Radar
81	Fournier R. A. et al. [181]	2007	Canada	–	Optical + Radar + LiDAR + Aerial
82	Touzi R. et al. [182]	2007	ON	–	Radar
83	Gillanders S. N. et al. [104]	2008	AB	PB/Supervised/ISODATA	Optical
84	Jollineau M. et al. [154]	2008	ON	PB/Supervised/ML + Other	Optical
85	Jollineau M. Y. et al. [32]	2008	ON	PB/Supervised/ML + Other	Optical
86	Grenier M. et al. [3]	2008	QC	OB/Supervised/Other	Optical + Radar
87	Dillabaugh K. A. et al. [109]	2008	ON	PB/Supervised/ML + DL = NN	Optical
88	Hogg A. R. et al. [183]	2008	ON	–	Aerial + LiDAR/DEM
89	Sass G. Z. et al. [184]	2008	AB	–	Radar
90	Liu Y. et al. [185]	2008	ON	–	LiDAR/DEM
91	Creed I. F. et al. [186]	2008	AB	–	Radar
92	Touzi R. et al. [187]	2008	ON	–	Radar
93	Kaheil Y. H. et al. [49]	2009	AB	PB/Supervised/SVM + Other	Radar + Optical + LiDAR + LiDAR/DEM
94	Richardson M. C. et al. [36]	2009	ON	PB/Supervised/CART	LiDAR/DEM
95	Dissanska M. et al. [108]	2009	QC	OB/Supervised/DL = NN + Other	Optical + Aerial + DEM
96	Harris A. et al. [188]	2009	ON	–	Aerial + Optical + Radar
97	Rosa E. et al. [189]	2009	QC	–	Radar
98	Raynolds M. K. et al. [190]	2009	NT	–	Optical + Other
99	Pirie L. D. et al. [191]	2009	NT	–	Optical
100	Spooner I. et al. [192]	2009	NS	–	Other
101	Clark R. B. et al. [193]	2009	AB	–	Radar
102	Fang X. et al. [194]	2009	SK	–	Aerial + LiDAR/DEM
103	Touzi R. et al. [195]	2009	ON	–	Radar
104	Touzi R. et al. [196]	2009	ON	–	Radar
105	Collin A. et al. [37]	2010	QC	PB/Supervised/ML	LiDAR
106	Andrea J. M. et al. [197]	2010	ON	–	Optical
107	Soverel N.O. et al. [198]	2010	Canada	–	Optical
108	Levrel G. et al. [199]	2010	QC	–	Radar
109	Sannel A. B. K. et al. [200]	2010	Canada	–	Optical + Aerial
110	Neta T. et al. T. [201]	2010	MB, ON	–	Optical
111	Midwood J. D. et al. [202]	2010	ON	–	Optical
112	Touzi R. et al. [203]	2010	QC	–	Radar
113	Fang X. et al. [204]	2010	SK	–	Optical + Lidar/DEM
114	Brisco B. et al. [205]	2011	MB	PB/Supervised/ML + Other	Radar + LiDAR/DEM
115	Crowell N. et al. [206]	2011	NS	–	LiDAR/DEM
116	Quinton W. L. et al. [207]	2011	NT	PB/Supervised/Other	Optical + Aerial + LiDAR/DEM
117	Rokitnicki-Wojcik D. et al. [208]	2011	ON	OB/Supervised/Other + DT	Optical
118	Muskett R. R. et al. [209]	2011	YT	–	Optical + Other
119	Chen B. et al. [210]	2011	Canada	–	Optical
120	Neta T. et al. [211]	2011	ON, MB	–	Optical + Aerial
121	Hogan D. et al. [212]	2011	AB, BC, YT	–	Optical + Aerial
122	Shook K. R. et al. [213]	2011	SK	–	LiDAR/DEM
123	Watchorn K. E. et al. [92]	2012	MB, ON	–	
124	Fraser S. et al. [214]	2012	MB	–	Optical + Other

Table A2. Cont.

No.	First Author	Year	Region	Classification Method	Data
125	Guo X. et al. [215]	2012	SK	PB + OB/Supervised/ML + KNN	Radar
126	Allard M. et al. [11]	2012	QC	OB/Supervised/Multiple classifier	Optical
127	Dribault Y. et al. [19]	2012	QC	OB/Supervised/Other	Optical + Aerial
128	Barker R. et al. [216]	2012	QC	–	Aerial
129	Kaya S. et al. [217]	2012	Canada	–	Radar
130	Pivot F. C [218]	2012	MB	–	Radar
131	Midwood J. D. et al. [219]	2012	ON	–	Optical
132	Gala T. S. et al. [220]	2012	SK	–	Optical + Radar + LiDAR/DEM
133	Brisco B. et al. [48]	2013	MB	PB/Supervised/SVM + ML	Radar + Aerial
134	Chen W. et al. [221]	2013	MB	PB/Supervised/Other	Optical + Radar + LiDAR/DEM
135	Lantz N. J. et al. [63]	2013	ON	OB + PB/Supervised/NN + ML	Optical
136	Millard K. et al. [42]	2013	ON	PB/Supervised/RF	Radar + LiDAR
137	Kokelj, S. V. et al. [87]	2013	YT, NT	–	LiDAR
138	Doiron M. et al. [222]	2013	NU	–	Optical
139	McClymont A. F et al. [223]	2013	NT	–	Other
140	Lapointe J. et al. [224]	2013	QC	–	Other
141	Huschle G. et al. [225]	2013	SK, MB, ON	–	Other
142	Mattar K. E. [226]	2013	ON	–	Radar
143	Jacome A. et al. [227]	2013	QC	–	Radar
144	Chasmer L. et al. [102]	2014	NT	PB/Supervised/DT + Other	Optical + LiDAR/DEM
145	Banks S. N. et al. [228]	2014	NT	PB/Supervised + Unsupervised/ML	Optical + Radar + UAV
146	Banks S. N. et al. [229]	2014	NT	PB/Supervised + Unsupervised/Other	Radar + UAV
147	Touzi R. et al. [115]	2014	AB	PB/Supervised/Other	Radar
148	Pastick N. J. et al. [99]	2014	YT	PB/Supervised/DT	Optical
149	Sutherland G. et al. [38]	2014	AB	PB/Supervised/DT	LiDAR + LiDAR/DEM
150	Ullmann T. et al. [52]	2014	NT	PB/Supervised + Unsupervised/ML	Optical + Radar
151	Dech J. P. et al. [95]	2014	ON	–	LiDAR/DEM
152	Gosselin G. et al. [116]	2014	QC	OB/Supervised/ML + Other	Optical + Radar
153	Ahern F. J. et al. [230]	2014	ON	PB/Supervised/Other	Radar
154	Armenakis C. et al. [231]	2014	BC, NS	–	-
155	Connon R. F. et al. [89]	2014	NT	–	Optical + Aerial
156	Ely C. R. et al. [232]	2014	Canada	–	Radar
157	Chabot D. et al. [233]	2014	QC	–	UAS
158	Cable J. W. et al. [234]	2014	ON	–	Radar
159	Nelson T. A. et al. [235]	2014	Canada	–	Optical
160	Clare S. et al. [236]	2014	AB	–	-
161	Mui A. et al. [107]	2015	Canada	OB/Supervised/KNN	Optical + LiDAR/DEM
162	Dabboor M. et al. [16]	2015	MB	PB/Unsupervised/Other	Radar
163	Bourgeau-Chavez L. et al. [237]	2015	ON	PB + OB/Supervised/ML + Other	Optical + Radar + Aerial
164	Sizo A. et al. [114]	2015	SK	PB/Unsupervised/Other	Optical
165	Umbanhowar Jr C. E et al. [238]	2015	MB	PB/Unsupervised/ISODATA	Optical + Aerial + LiDAR/DEM
166	Sagin J. et al. [239]	2015	SK	–	Optical
167	Dingle R. L. et al. [240]	2015	ON	–	Optical
168	Kalacska M. et al. [241]	2015	ON	PB/Supervised/Other	Other
169	Kotchi S. O. et al. [242]	2015	QC	–	Optical + Radar
170	Tougas-Tellier M. A. et al. [243]	2015	QC	–	Optical + Aerial
171	Messmer D. J. et al. [244]	2015	ON	–	Optical + UAV + Aerial

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No.	First Author	Year	Region	Classification Method	Data
172	Brisco B. et al. [245]	2015	ON	–	Radar
173	Muster S. et al. [246]	2015	NU	–	Optical
174	Jiao X. et al. [247]	2015	AB	–	Radar
175	Li-Chee-Ming J. et al. [248]	2015	AB	–	Radar + UAV
176	Thompson S. D. et al. [249]	2016	BC	PB/Unsupervised/Other	Optical + LiDAR + Aerial
177	Braverman M. et al. [34]	2016	NT	-	LiDAR/DED
178	Marcaccio J. V. et al. [250]	2016	ON	OB/Supervised/ML + Other	Optical + Radar + Aerial + UAV
179	Ou C. et al. [56]	2016	ON	PB/Supervised/RF	Optical + Radar + LiDAR/DEM
180	Lara M. J. et al. [98]	2016	NT	PB/Supervised/ML	Optical + Radar + Aerial
181	Mohammadimanesh F. et al. [112]	2016	NL	PB/Supervised/Other	Radar
182	Chasmer L. et al. [251]	2016	AB	–	LiDAR + Aerial
183	Spence C. et al. [252]	2016	SK	–	Optical + UAV + LiDAR/DEM
184	Shinneman A. L. C. et al. [253]	2016	MB	–	Optical
185	Finger T. A. et al. [254]	2016	ON	–	Other
186	Miller S. M. et al. [255]	2016	Canada	–	Optical + Aerial
187	Kross A. et al. [256]	2016	ON, AB	–	Optical
188	Shodimu O. et al. [257]	2016	NB	–	Optical
189	Schmitt A. et al. [258]	2016	Canada	–	Radar
190	Emmerton C. A. et al. [259]	2016	NU	–	Optical
191	Serran J. N. et al. [260]	2016	AB	–	Aerial + LiDAR/DEM
192	Bolanos S. et al. [261]	2016	AB, SK	–	Optical + Radar
193	Morsy S. et al. [262]	2016	ON	–	LiDAR
194	van der Kamp G. et al. [263]	2016	Canada	–	-
195	Sizo A. et al. [264]	2016	SK	–	Optical
196	Ullmann T. et al. [265]	2016	NT	–	Radar
197	Mahdianpari M. et al. [43]	2017	NL	OB/Supervised/RF	Radar
198	Banks S. et al. [58]	2017	NU	PB/Supervised/RF	Radar + Optical + LiDAR/DEM + UAV
199	Merchant M.A. et al. [47]	2017	NT	PB/Supervised/SVM	Radar
200	Amani M. et al. [266]	2017	NL	OB/Supervised/RF	Optical
201	Hird J. N. et al. [40]	2017	AB	PB/Supervised/ML	Optical + Radar + Aerial + LiDAR/DEM
202	Chen Z. et al. [57]	2017	NT	PB + OB/Supervised/RF + ML	Optical
203	Bourgeau-Chavez L. L. et al. [55]	2017	AB	PB + OB/Supervised/RF	Optical + Radar
204	White L. et al. [60]	2017	ON	PB/Supervised/RF	Optical + Radar + LiDAR/DEM
205	Mahdavi S. et al. [72]	2017	NL	PB + OB/Supervised/RF	Optical + Radar + Aerial
206	Franklin S. E. et al. [61]	2017	ON	OB/Supervised/RF	Optical + Radar + Aerial + LiDAR/DEM
207	Mahdianpari M. et al. [44]	2017	NL	OB/Supervised/RF + Other	Optical + Radar
208	Amani M. et al. [39]	2017	NL	OB/Supervised/RF	Optical + Radar
209	Mahdianpari M. et al. [267]	2017	NL	PB/Supervised/RF	Radar + Aerial
210	Amani M. et al. [7]	2017	NL	OB/Supervised/RF	Optical + Radar + Aerial
211	Amani M. et al. [73]	2017	NL	PB + OB/Supervised/KNN + ML + SVM + CART + RF	Optical + Aerial
212	Lovitt J. et al. [268]	2017	AB	–	UAV + LiDAR
213	Kim S. et al. [269]	2017	Canada	–	Optical + Radar
214	Mohammadimanesh F. et al. [270]	2017	NL	–	Radar + LiDAR/DEM
215	Daboor M. et al. [271]	2017	ON	–	Radar
216	Chabot D. et al. [272]	2017	ON	–	UAS
217	Perreault N. et al. [273]	2017	NU	–	Optical

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No.	First Author	Year	Region	Classification Method	Data
218	Ullmann T. et al. [274]	2017	NT	–	Radar
219	Brisco et al. [275]	2017	Canada	–	-
220	Mahdavi S. et al. [2]	2018	Canada	–	-
221	Amani M. et al. [103]	2018	NL	OB/Supervised/Other	Optical + Radar
222	Wulder, M. A. et al. [90]	2018	Canada	PB/Supervised/RF + Other	Optical
223	Mohammadimanesh F. et al. [276]	2018	NL	OB/Supervised/RF + SVM	Radar
224	Chabot D. et al. [53]	2018	ON	OB/Supervised/ML	UAV
225	Paul S. S. et al. [113]	2018	Canada	OB/Supervised/ML + Other	Optical
226	D’Acunha B. et al. [277]	2018	BC	–	Optical
227	Arroyo-Mora J. P. et al. [20]	2018	ON	–	Optical + Other
228	Mahdianpari M. et al. [83]	2018	NL	PB/Supervised/RF	Radar
229	Ahern F. et al. [278]	2018	ON	PB/Supervised/Other	Radar
230	Jahncke R. et al. [94]	2018	NS	PB/Supervised/RF	Optical + Radar + LiDAR + Aerial
231	Mohammadimanesh F. et al. [96]	2018	NL	OB/Supervised/RF	Radar
232	Amani M. et al. [39]	2018	NL	OB/Supervised/RF	Optical
233	Mahdianpari M. et al. [27]	2018	NL	PB /Supervised/DL + SVM + RF	Optical
234	Franklin S. E. et al. [62]	2018	ON	PB + OB/Supervised/ML + RF	Optical + Radar
235	Whitley M. A. et al. [279]	2018	YT	–	Optical + LiDAR + LiDAR/DEM
236	Jorgenson M. T. et al. [280]	2018	YT	–	Optical + Aerial + LiDAR/DEM
237	Ward E. M. et al. [281]	2018	AB	–	Optical
238	Potter C. [282]	2018	YT	–	Optical
239	Campbell T. K. F. et al. [283]	2018	NT	–	Optical + Aerial
240	Blanchette M. et al. [284]	2018	QC	–	Optical + Aerial + LiDAR/DEM
241	Warren R. K. et al. [285]	2018	NT	–	Optical
242	DeLancey E. R. et al. [286]	2018	AB	–	Radar + LiDAR/DEM
243	Chasmer L. E. et al. [287]	2018	AB	–	Optical
244	Montgomery J. S. et al. [288]	2018	AB	–	Optical + Radar + LiDAR/DEM
245	Mahdavi S. et al. [82]	2019	NL	OB/Supervised/RF	Optical + Radar
246	Merchant M. A. et al. [289]	2019	YT	OB/Supervised/KNN + SVM + RF	Optical + Radar + LiDAR/DEM
247	Pouliot D. et al. [54]	2019	AB, QC	PB/Supervised/DL = CNN	Optical
248	Amani M. et al. [68]	2019	Canada	PB/Supervised/RF	Optical
249	Dabboor M. et al. [31]	2019	ON	–	Optical + Radar
250	Mohammadimanesh F. et al. [28]	2019	NL	OB/Supervised/RF	Radar
251	Rupasinghe P. A. et al. [46]	2019	ON	PB/Supervised/SVM	Optical + UAV
252	DeLancey E. R. et al. [41]	2019	AB	PB/Supervised/DL	Optical + Radar + LiDAR
253	Mahdianpari M. et al. [86]	2019	NL	PB + OB/Supervised/RF	Optical + Radar
254	Judah A. et al. [290]	2019	ON	PB/Supervised/KNN + SVM + RF + Other	Optical + Radar
255	Banks S. et al. [45]	2019	ON	PB/Supervised/RF	Radar + DSM/DEM
256	Pitcher L. H. et al. [291]	2019	YT	–	Radar
257	Gonsamo A. et al. [292]	2019	ON	–	Optical
258	Westwood A. et al. [293]	2019	NB, NS	–	Aerial
259	Brisco B. et al. [294]	2019	AB	–	Radar + UAV + LiDAR + LiDAR/DEM
260	Jensen D. et al. [295]	2019	AB	–	Optical
261	Palumbo M. D. et al. [296]	2019	ON	–	Other
262	Montgomery J. et al. [297]	2019	AB	–	Optical + Radar + LiDAR

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No.	First Author	Year	Region	Classification Method	Data
263	Amani M. et al. [78]	2019	NL	–	Radar
264	Lane D. et al. [298]	2019	ON	–	LiDAR/DEM
265	Mahdianpari M. et al. [299]	2020	NL	PB/Supervised/RF + CART + Other	Optical + DEM
266	Mahdianpari M. et al. [69]	2020	Canada	OB/Supervised/RF	Optical + Radar
267	Chen Z. et al. [300]	2020	ON	–	Radar + Optical + UAV
268	DeLancey E. R. et al. [21]	2020	AB	PB/Supervised/DL = CNN	Radar + Optical + Aerial
269	Merchant M. et al. [301]	2020	NT	OB/Supervised/RF	Optical + Radar + DEM
270	Siles G. et al. [302]	2020	AB	OB/Supervised/ML + Other	Optical + Radar + LiDAR/DEM
271	White L. et al. [303]	2020	QC	PB/Supervised/Other	Radar + UAV
272	Valenti V. L. et al. [59]	2020	ON	PB/Supervised/RF	Optical + Radar
273	Hawkes V. C. et al. [304]	2020	AB	Visual Analysis/Other	Optical + Aerial + LiDAR/DEM
274	Brisco B. et al. [305]	2020	Canada	-	Radar
275	Amani M. et al. [120]	2020	NL	OB + PB/Supervised/RF	Optical + Radar + LiDAR
276	Mahdianpari M. et al. [70]	2020	Canada	OB/Supervised/RF	Optical + Radar
277	LaRocque A. et al. [306]	2020	NB	PB/Supervised/RF	Optical + Radar
278	LaRocque A. et al. [117]	2020	NB	PB/Supervised/RF	Optical + Radar + DEM
279	Ahmed, M. I. et al. [307]	2020	SK	–	DEM
280	Bahrami A. et al. [308]	2020	QC	–	Radar + Other
281	Bergeron J. et al. [309]	2020	AB	–	Optical + LiDAR + LiDAR/DEM
282	Mahoney C. et al. [310]	2020	AB	–	Radar
283	Wulder M. A. et al. [311]	2020	Canada	–	Optical + LiDAR
284	Janardanan R. et al. [312]	2020	Canada	–	Optical + UAV
285	O’Sullivan A. M. et al. [313]	2020	NB	–	LiDAR/DEM
286	Olthof I. et al. [314]	2020	QC, ON	–	Radar
287	Wadsworth E. et al. [315]	2020	Canada	–	LiDAR/DEM + Other
288	Amani M. et al. [316]	2020	Canada	–	Optical
289	Omari K. et al. [317]	2020	QC	–	Radar
290	Sewell P. D. et al. [318]	2020	AB	–	LiDAR
291	Peters D. L. et al. [319]	2020	AB	–	Optical + LiDAR
292	Zakharov I. et al. [320]	2020	AB	–	Radar
293	Wulder M. A. et al. [321]	2020	Canada	–	Optical
294	Wang L. et al. [322]	2020	QC	–	Radar
295	White L. et al. [323]	2020	ON	–	-
296	Wu J. et al. [324]	2020	NL	–	-
297	Haynes K. M. et al. [325]	2020	NT	–	LiDAR
298	Hopkinson C. et al. [326]	2020	BC	–	Optical + Radar + LiDAR/DEM
299	Adeli S. et al. [18]	2020	Canada	–	-
300	Mahdianpari M. et al. [327]	2020	NL	OB/Supervised/RF	Optical + LiDAR/DEM

* PB and OB stand for Pixel-Based and Object-Based, respectively.

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