OPEN ACCESS | Review Article

Ecological restoration research in Canada: who, what, where, when, why, and how?

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Abstract

Much has been achieved by research into ecological restoration as a nature-based solution to the destruction of ecosystems, particularly in Canada. We conducted a national-level synthesis of Canadian restoration ecology research to understand strengths and gaps. This synthesis answers the following questions: Who is studying restoration? What ecosystem types are studied? Where is restoration studied? Which themes has restoration research focused on? Why is restoration happening? And how is restoration monitored and evaluated? We employed systematic searching for this review. Our results show that restoration research is conducted mainly by academics. Forest, peatland, grassland, and lake ecosystem types were the most commonly studied. There was a concentration of research in four provinces (Ontario, Quebec, Alberta, and British Columbia). Research into restoration has changed its thematic focus over time from reforestation to climate change. Legislation was the most common reason given for restoration. Restoration research frequently documented results of less than 5 years of monitoring and included one category of response variable (e.g., plant response but not animal response). Future research could investigate the outcomes of restoration prompted by legislation. At the dawn of the UN Decade on Ecosystem Restoration, this work demonstrates Canada's momentum and provides a model for synthesis in other countries.

Key words: ecological restoration, Canada, systematic scoping review, bibliometric analysis, systematic map

Introduction

The scale of ecosystem degradation is massive: more than 75% of terrestrial lands have been severely altered by human actions, and one million species are at risk of extinction (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019). Ecological restoration has emerged as a means of addressing this degradation, but the implementation lacks effectiveness (Jones et al. 2018). Knowledge synthesis is a crucial step to enhance and strategically build the effectiveness of restoration (Cooke et al. 2018). Knowledge synthesis and data sharing have the potential to help restoration practitioners engage with the available research and improve their practice based on the evidence (Ladouceur et al. 2022). Access to robust and wide-ranging knowledge supports two of the main principles—effective and efficient—of restoration (Keenleyside et al. 2012). There is an urgent need for restoration to be conducted at greater scales to meet the ambitious mission of the UN Decade on Ecosystem Restoration in addressing escalating global ecosystem degradation (Perring et al. 2018).

While the UN Decade is international in scope, ecological restoration projects tend to be executed at the national, provincial, or state levels. Restoration outcomes are sensitive to legislation, which suggests that synthesis of published research at the national and provincial scales can produce meaningful insights (Brudvig et al. 2017). Canada is a large country with diverse ecosystems, a resource-based economy with significant environmental consequences, and regulatory frameworks that require restoration (Cooke et al. 2016). Canadians developed the first national principles and guidelines for ecological restoration and the first international guidance for the World Commission on Protected Areas (Canadian Parks Council and Parks Canada 2008; Keenleyside et al. 2012); however. relatively little is known about characteristics of restoration in Canada.

Past syntheses in ecological restoration have focused on synthesizing knowledge of specific ecosystems and restoration methods (Bernhardt et al. 2005; Dhar et al. 2020; Huffman et al. 2020) or have reviewed knowledge at a global level (Wortley et al. 2013; Jones et al. 2018), but greater

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understanding at the national and provincial level can inform future research directions and aid practitioners. To that end, here we conduct an evidence mapping exercise to understand what has been studied in Canada and discover objectives for future research. This review searched for and screened articles from several databases. The authors then conducted manual tagging and extraction of data from studies (systematic mapping) and an automated analysis of keywords (bibliometric analysis) to answer the questions posed above.

Methods

A systematic scoping review approach was used to answer the questions raised above by gathering available scientific literature through systematic searching (Pham et al. 2014). This systematic scoping review employed both a systematic map and bibliometric analysis to answer questions about what is published (Nakagawa et al. 2019). Systematic mapping is a technique where categorical data, such as ecosystem type and target species, are manually extracted from studies to gain an understanding of what is studied in the published research. Bibliometric analysis is a technique that analyses a large set of metadata about published research to assess factors such as the most published authors, study areas of institutions, and citation networks (Linnenluecke et al. 2020). Using both in tandem allowed for a more detailed understanding of what is published than each method would allow for independently (Nakagawa et al. 2019).

When defining our search terms, we used the Society for Ecological Restoration's (Gann et al. 2019) definition of ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." However, we did not limit our searches to focus solely on projects that aspire to a reference ecosystem standard. We embraced the big tent conceptualization of restoration proposed by Murphy (2018) that includes remediation, reforestation, rehabilitation, rewilding and reclamation, as is reflected in our search string, which was developed in collaboration with a University of Waterloo research librarian (Table 1).

Since each database had different advanced search options, formats, and limits, we altered the search strings appropriately to fit each database's limitations. The search string for Scopus served as a model for the remaining searches (Table 1). To focus on studies that documented outcomes, we filtered search results based on their inclusion of the terms "BACI", "recover", "outcome", "success", or "failure" in the title, abstract, or keywords. Some search options in other databases were limited in maximum length or search capacity; so alterations were made accordingly. For instance, search strings used on databases housing Canadian government documents omitted filters based on location under the assumption that all literature in those databases would be related to Canadian ecosystems.

Our literature search included both academic literature databases and gray literature databases for the systematic map (Table 1). The bibliometric analysis relied solely on results from Scopus because of software limitations. See Supplement 2 for details on the bibliometric analysis search and screening strategy. The Bibliometrix R package was used to create a three-field Sankey diagram showing the evolution in keywords over time (Fig. 4). The function used to create the graph counted and visualized keyword occurrences and co-occurrences across time. The vertical sections are sized according to the occurrence in each time section, and the thickness of the horizontal bands of colour correspond to the co-occurrence of linked keywords.

The systematic map literature search returned 2357 entries after removing duplicates. Further manual screening as applied to ensure that studies focused on ecological restoration. Screening and data extraction were performed in Cadima (https://cadima.info), an online tool for systematic reviews. Screening took place in two stages: title and abstract, followed by full-text screening. We had two primary screening criteria: 1) Is the research site in Canada? (Yes/No/Unclear), and 2) does it include field research that measures outcomes of intentional ecological interventions by humans? (Yes/No/Unclear).

We performed a consistency check after the initial title and abstract screening wherein each reviewer screened the same 235 articles (10% of the dataset) and responses were compared. The level of agreement between inclusion decisions was used to calculate Cohen's Kappa, a measure of interrater reliability that factors in chance agreement (Cohen 1960). The resultant Cohen's Kappa score was 0.339, which indicated "poor" agreement. However, we disagreed on only 13% of records in such a way as the inclusion would be affected, and of those 30 disagreements, nearly half ($n = 14$) were a result of one reviewer selecting "unclear" for one of the criteria. We discussed each material disagreement to reach clarity on our application of the inclusion criteria.

The title and abstract screen yielded 677 appropriate entries for full-text screening. The same criteria were applied to the full text screening, barring the option for "unclear." The full-text screening resulted in 308 appropriate literature entries for data extraction.

We manually extracted data in 16 fields. Those fields were: first author affiliation, action taken, intervention type, coarse ecosystem type, fine ecosystem type, main species, disturbance type, reason for restoration, reference ecosystem type, research province, research city, research coordinates, time since restoration, monitoring period, outcome sentence, and response variables. Automated analysis was used to examine the keywords used in results from the most comprehensive database, Scopus. In six cases, the systematic map data produced results that were too heterogenous for meaningful analysis; so the results were grouped into categories.

Results

The first authors of the papers were primarily affiliated with academic institutions ($n = 248$). Federal government ($n = 21$) and provincial government ($n = 18$) employees were also found to have authored studies. A relatively small number of papers were authored by private organizations ($n = 15$) and NGOs ($n = 6$).

Table 1. Each database was searched independently and results were scraped into a database, which was then screened for duplicates. Search strings are included and demonstrate the syntax required by each search engine. The full search string was used where possible and only truncated if there were restrictions on the length of search string.

Database	Search string	Results
Scopus	TITLE-ABS-KEY ("recover∗" OR "BACI" OR "outcome∗" OR "success" OR "failure") AND TITLE-ABS-KEY ("restoration ecology" OR "eco∗ restoration" OR "environment∗ restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗") AND AFFILCOUNTRY ("Canada") OR TITLE-ABS-KEY ("Canada" OR "Canadian" OR "Ontario" OR "Ont." OR "Manitoba" OR {Man.} OR "Saskatchewan" OR "Sask." OR "Alberta" OR "Alta." OR "British Columbia" OR "B.C." OR "Northwest Territories" OR "N.W.T." OR "Yukon" OR "Y.T." OR "Nunavut" OR "Nvt." OR "Quebec" OR "Québec" OR "Que." OR "Newfoundland" OR "N.L." OR "Prince Edward Island" OR "P.E.I." OR "Nova Scotia" OR "N.S." OR "New Brunswick" OR "N.B.") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "bk") OR LIMIT-TO (DOCTYPE, "cr"))	990
Web of Science	(TS = ("BACI" OR "recover∗" OR "outcome∗" OR "success" OR "failure") AND TS = ("restoration ecology" OR "eco∗ restoration" OR "environment∗ restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗") AND (CU=("Canada") OR TS = ("Canad∗" OR "Ontario" OR "Ont." OR "Manitoba" OR {Man.} OR "Saskatchewan" OR "Sask." OR "Alberta" OR "Alta." OR "British Columbia" OR "B.C." OR "Northwest Territories" OR "N.W.T." OR "Yukon" OR "Y.T." OR "Nunavut" OR "Nvt." OR "Quebec" OR "Québec")	402
ScienceDirect	Title, abstract, or author-specified keywords: ("BACI" OR "recover" OR "outcome" OR "success" OR "failure") AND ("restoration ecology" OR "ecological restoration" OR "environmental restoration") AND "Canada"	11
Google Scholar	("BACI" OR "recover" OR "outcome" OR "success" OR "failure") AND ("restoration ecology" OR "ecological restoration" OR "environmental restoration") AND "Canada"	500
Ecological Management and Restoration (academic journal not indexed by major databases prior to 2015)	""BACI" OR "recover" OR "outcome" OR "success" OR "failure"" anywhere and "Canada" anywhere published in "Ecological Management and Restoration"	35
Ecological Restoration (academic journal not indexed by major databases prior to 2015)	Searching journal content for BACI recover outcome success failure (any words) in title or abstract and Canada (all words) in full text in Ecological Restoration (journal)	658
Federal Science Library (of Canada)	(((Abstract:("BACI" OR "recover" OR "outcome" OR "success" OR "failure")) AND ((Abstract:("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗")) OR (SubjectTerms:("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗")))) AND ("Canad∗" OR "Ontario" OR "Ont." OR "Manitoba" OR "Saskatchewan" OR "Sask." OR "Alberta" OR "Alta." OR "British Columbia" OR "B.C." OR "Northwest Territories" OR "N.W.T." OR "Yukon" OR "Y.T." OR "Nunavut" OR "Nvt." OR "Quebec" OR "Québec")	186
Proquest Canadian Research Index	((noft("BACI" OR "recover" OR "outcome" OR "success" OR "failure") AND noft("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗")) AND noft("Canad∗" OR "Ontario" OR "Ont." OR "Manitoba" OR "Saskatchewan" OR "Sask." OR "Alberta" OR "Alta." OR "British Columbia" OR "B.C." OR "Northwest Territories" OR "N.W.T." OR "Yukon" OR "Y.T." OR "Nunavut" OR "Nvt." OR "Quebec" OR "Québec")) AND la.exact ("English")	21
GEOSCAN	restoration; rehabilitation; reclamation; remediation; reforestation; rewild	204

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Table 1. (*concluded*).

Database	Search string	Results
Aurora	(kw:("BACI" OR "recover" OR "outcome" OR "success" OR "failure") OR su:("BACI" OR "recover" OR "outcome" OR "success" OR "failure") OR ti:("BACI" OR "recover" OR "outcome" OR "success" OR "failure")) AND (kw:("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗") OR su:("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗") OR ti:("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗"))	27
ProQuest Dissertations and Theses Global	noft("BACI" OR "recover" OR "outcome" OR "success" OR "failure") AND noft("restoration ecology" OR "ecological restoration" OR "environmental restoration" OR "habitat restoration" OR "eco∗ remediation" OR "environment∗ remediation" OR "habitat remediation" OR "eco∗ reclamation" OR "environment∗ reclamation" OR "habitat reclamation" OR "eco∗ rehabilitation" OR "environment∗ rehabilitation" OR "habitat rehabilitation" OR "rewild∗" OR "re-wild∗" OR "reforest∗" OR "re-forest∗") AND noft("Canad∗" OR "Ontario" OR "Ont." OR "Manitoba" OR {Man.} OR "Saskatchewan" OR "Sask." OR "Alberta" OR "Alta." OR "British Columbia" OR "B.C." OR "Northwest Territories" OR "N.W.T." OR "Yukon" OR "Y.T." OR "Nunavut" OR "Nvt." OR "Quebec" OR "Québec")	28
NRC Publications Archive	Any of these words: "restoration ecology", "ecological restoration", "environmental restoration", "habitat restoration", "eco∗ remediation", "environment∗ remediation", "habitat remediation", "eco∗ reclamation", "environment∗ reclamation", "habitat reclamation", "eco∗ rehabilitation", "environment∗ rehabilitation", "habitat rehabilitation", "rewild∗", "re-wild∗", "reforest∗", "re-forest∗"	8

The most commonly studied ecosystem type was forest ($n = 123$), which included boreal and temperate forests. This was followed by three ecosystem types with significant representation in the literature: peatland ($n = 52$), grasslands ($n = 47$), and lake ($n = 41$). Wetland ecosystems are also represented reasonably well ($n = 21$). Marine ($n = 6$), coastal ($n = 5$), river ($n = 4$), and tundra ($n = 4$) ecosystem types had relatively little representation in the systematic map results.

A breakdown of ecosystem type by province is presented in Fig. 1. This shows that British Columbia and Ontario have had restoration studied in a diversity of ecosystems. Lakes, forests, and wetlands are studied across the country, while tundra, river, peatland, coastal, and marine ecosystem types are limited to a few provinces (Fig. 1).

Figure 2 reveals which disturbances are being studied by the ecosystem type. Forest ecosystems are the most widely affected, with studies being conducted for nearly every disturbance type. Development as a disturbance, which includes the construction of roads and buildings, affects nearly every ecosystem type (Fig. 2).

The map of study locations (Fig. 3) shows clear clusters of research around three main locations: the Alberta oil sands; Sudbury, Ontario; and the Bois-des-Bel peatland research centre.

Our analysis also included an automated bibliometric analysis of the broader restoration literature, moving beyond the 308 studies to include other studies that were authored by a Canadian researcher but may not have documented outcomes (Supplement 1). This resulted in a Sankey diagram (Fig. 4) that shows the evolution of keywords used in restoration papers over time. The time periods were created by the software putting an equal number of papers in date range. There are three distinct themes over time: reforestation (1961–2005); restoration (2006–2012), and climate change (2013–2020).

The disturbance types in the literature set focused on extractive industries (peat extraction: 47; energy: 45; forestry: 36; mining: 23). Agriculture was the most common disturbance studied ($n = 50$). While climate change is a growing area of research, it was only cited once as a cause of disturbance, though the impacts of climate change may be seen in other disturbance types (e.g., invasive species: 19; fire: 10; biotic pressure: 8).

Of the 308 papers reviewed, 52% stated a reason why restoration had been conducted ($n = 161$), with 61% of those stating that legislation had motivated restoration ($n = 98$; e.g., Jones et al. 2018; Lazcano et al. 2018).

The response variables that were measured by each study were extracted and grouped into categories. Studies tended to rely on a single category of response variables (e.g., plant response: 181; soil properties: 51). Some studies did combine response variables (e.g., plant response; soil properties: 33),

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Fig. 1. The count of studies in each ecosystem type and province is shown in the squares of this heatmap. The horizontal axis indicates the province, while the vertical axis indicates the ecosystem type. Darker squares indicate a higher number of studies. The heatmap reveals that ecosystems falling under the forest type have the broadest geographical study range, while Ontario and British Columbia are home to the widest diversity of ecosystem types being studied.

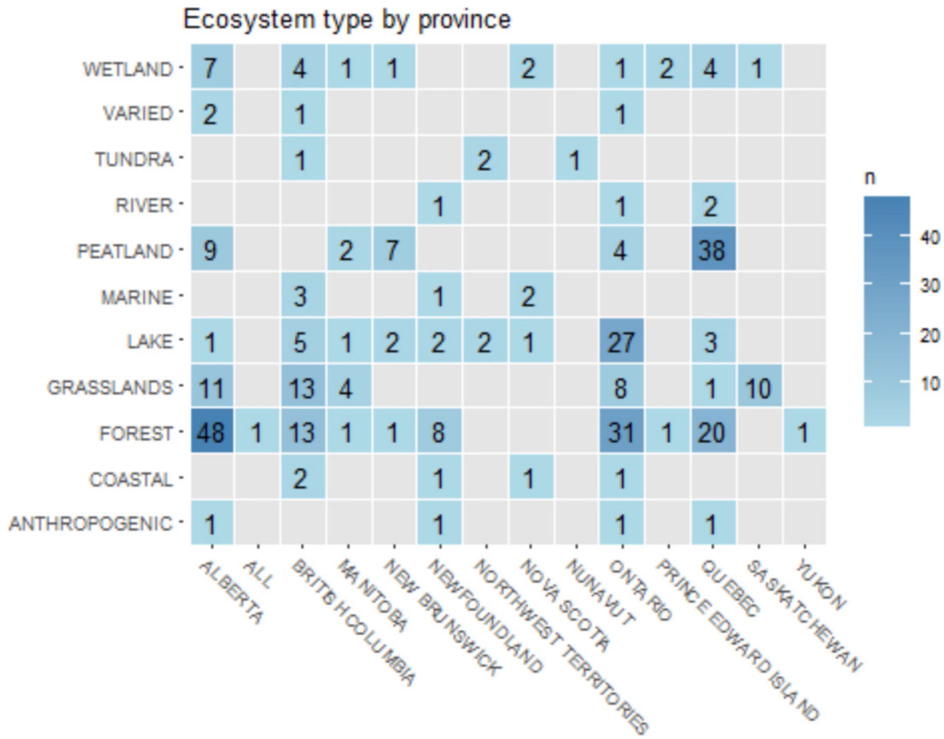
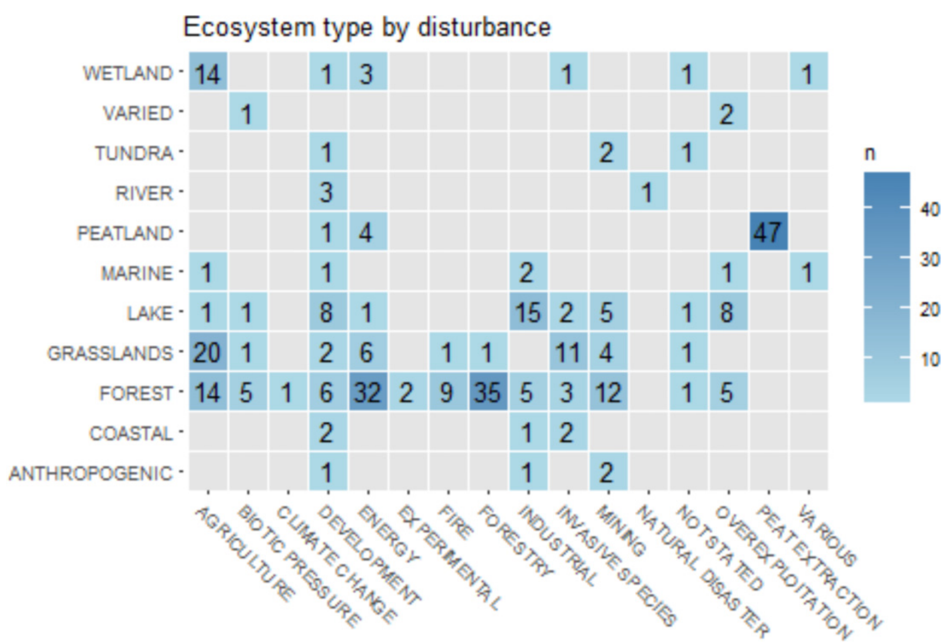


Fig. 2. The count of studies in each ecosystem type and disturbance type is shown in the squares of this heatmap. The horizontal axis contains the disturbance type and the vertical axis contains the ecosystem type. Darker squares indicate more studies. Forest ecosystems are affected by nearly every disturbance type. Development—a disturbance type that includes roads and construction—affects nearly every ecosystem type.



though far fewer studies focused on multiple response variables (Fig. 5).

The majority of ecological restoration studies reported results with less than five years of monitoring ($n = 230$; e.g., Hankin et al. 2015; Ormshaw and Duval 2020). Some studies did document long-term outcomes by examining results for more than 10 years ($n = 37$; e.g., Gonzalez et al. 2014) or between 5 and 10 years ($n = 39$; e.g., Truax et al. 2018). However,

Fig. 3. The map of Canada showing the distribution and concentration of restoration efforts identified in 308 studies. Each point is one study, and the green halo indicates multiple studies in close proximity. The projection used was Lambert Conformal Conic, and the coordinate system was NAD83. Boundary Files, 2011 Census. Statistics Canada Catalogue No. 92-160-X.

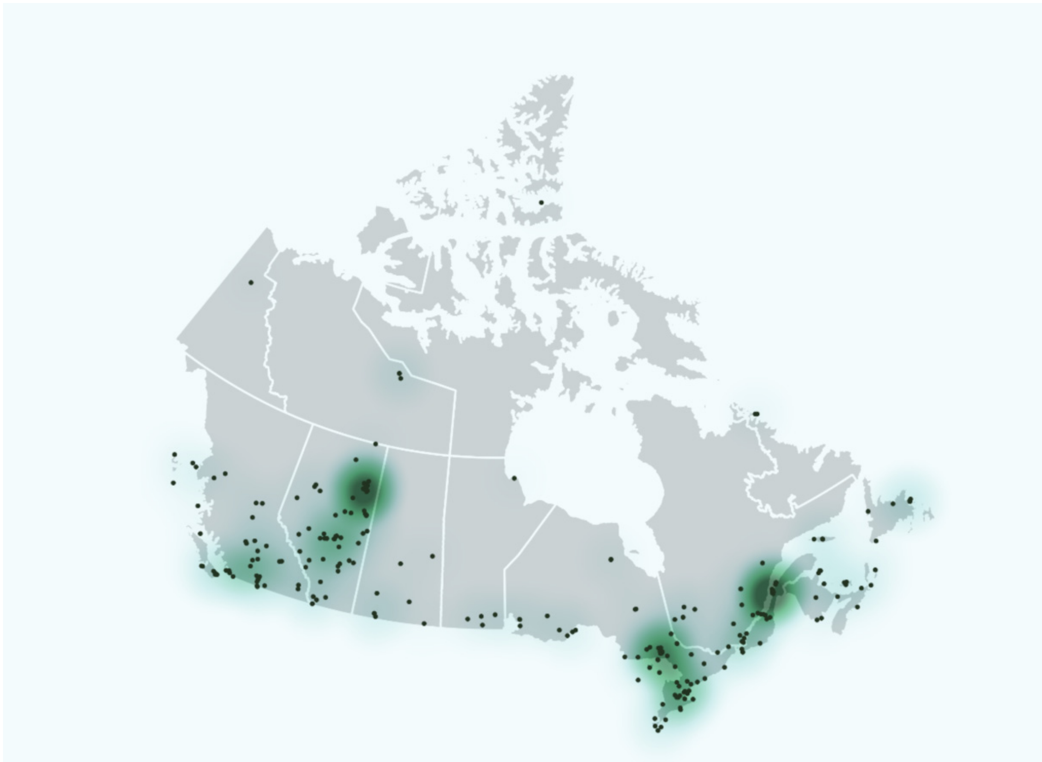


Fig. 4. The Sankey diagram showing the thematic evolution of keywords over three time periods: 1961–2005, 2006–2012, and 2013–2020. Each of the three vertical sections shows bars of heights that correspond to the number of occurrences of each keyword. The thickness of the horizontal flow lines corresponds to the number of co-occurrences between the linked keywords in the dataset. For instance, the line between forest management and climate change is thick because those two terms occur frequently together in both the 2006–2012 and 2013–2020 time series. The first time series includes a wide variety of keywords that point to specific geographic locations (e.g., British Columbia) or specific extractive industries (e.g., reforestation and fisheries). Climate change emerged as a major theme in the second time period and further increased in prominence in the third time period. Some terminology varied over time, particularly with keywords such as "ecosystem restoration," "restoration," and "ecological restoration", which may be used interchangeably.

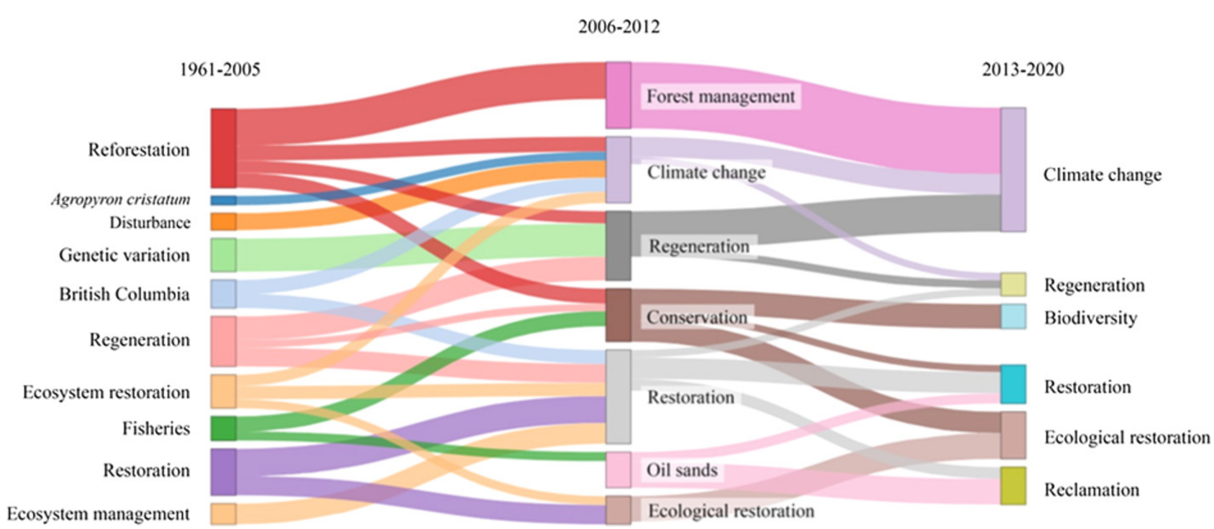


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Fig. 5. The count of studies combining response variables is shown in this heat map. Both axes contain the categories of response variables extracted by the co-authors. The numbers in the boxes indicate the number of studies that used both response variables. Darker blue squares indicate a higher number of studies.

	Plant response	Plant biodiversity	Animal response	Animal biodiversity	Soil properties	Microbial properties	Abiotic chemical properties	Hydrological properties
Plant response	181	39	6	3	33	0	6	7
Plant biodiversity	39	64	2	4	8	1	3	1
Animal response	6	2	59	8	1	1	2	0
Animal biodiversity	3	4	8	30	1	0	9	1
Soil properties	33	8	1	1	51	1	4	4
Microbial properties	0	1	1	0	1	5	1	0
Abiotic chemical properties	6	3	2	9	4	1	30	3
Hydrological properties	7	1	0	1	4	0	3	13

it is noteworthy that many studies with less than five years of monitoring were studying projects more than ten years after the initial restoration activity took place ($n = 68$; e.g., Azeria et al. 2020; Hugron et al. 2020).

Discussion

Who is studying restoration?

It came as little surprise that a review of academic literature found that academics were mostly responsible for leading the studies. However, the majority of restoration practice in Canada seems to be oriented more toward public and private sectors rather than academia (Higgs et al. 2021). This is a challenge for restoration because it suggests that there is little knowledge exchange (Djenontin and Meadow 2018), which is a hallmark of generating science that is embraced by practitioners (Laurance et al. 2012). In conservation, more broadly, there is a well-known divide between science and practice (Cook et al. 2013), which seems to be true of restoration as well (Dickens and Suding 2013).

What ecosystem types are being studied?

The most studied ecosystem types were forests, peatlands, grasslands, lakes, and wetlands. The four less commonly studied ecosystem types (marine, coastal, river, and tundra) suggest focal areas for restoration research on a national scale.

The preponderance of research into forests and other ecosystems impacted by resource extraction aligns with the economic importance of the sector to the Canadian economy—natural resources contributed \$199.6 billion to the economy in 2020, which represents 9.2% of the overall GDP (Statistics Canada 2021). The wealth of this sector has driven restoration, but it is also a sector where restoration is often legally required by provincial and federal laws. Overall industry was a frequent partner in restoration projects studied in our dataset.

In some cases, there was a focus on specific resource extraction techniques and attendant methods of restoring areas affected by them, which highlights future areas for meta-analysis. Several papers focused on the restoration of drilling pads, which are temporary structures used to explore the oil sands (e.g., Caners and Lieffers 2014; Jones et al. 2018; Azeria et al. 2020). Systematic analysis of papers focusing on a specific type of degradation like oil drilling pads would provide meaningful, actionable knowledge to practitioners and researchers (Cooke et al. 2018).

Where is restoration being studied?

The geographic spread of restoration studies follows the sources of degradation, with clusters of studies in areas where there is heavy resource extraction, such as northern Alberta, Sudbury and surrounds in Ontario, and the peatlands of Quebec. In Alberta, the oil sands area is a frequent location for restoration research due to significant degradation (e.g., Brown and Naeth 2014; Khadka et al. 2016; Stack et al. 2020). In Sudbury, nickel mining in the 20th century led to nearly complete deforestation and acidification of lakes, which was subsequently addressed through restoration (e.g., Babin-Fenske and Anand 2010; Labaj et al. 2014; Santala et al. 2016). Bois-des-Bel peatland is a large research peatland, home to many studies on peatland restoration (e.g., Andersen et al. 2010; Rochefort et al. 2013).

There is a dearth of restoration research in Canada's far north (i.e., Yukon, Northwest Territories, Nunavut), and with the exception of Alberta, in the northern reaches of most provinces. This may be related to the cost of research at those latitudes, but given the high level of resource extraction in northern ecosystems, it could form another point of focus for Canadian restoration research. This is especially urgent as climate change will shift ecosystem composition, increase wildfire prevalence in northern forest regions, and lead to range shifts of forested ecosystems into arctic ecosystems (Rees et al. 2020; Chen et al. 2021). However, the prioritization of ecosystems for restoration and conservation requires the consideration of factors beyond the scarcity of research—relative importance to global biodiversity, connectivity and the potential for areas to be refugia from climate change have been suggested as several among many factors to consider (Myers et al. 2000; Hodgson et al. 2009; Moore and Schindler 2022).

Which themes have restoration research focused on over time?

Reforestation dominated the early period of ecological restoration research (Fig. 4), which is understandable given that the practice has taken place in Canada for more than 100 years (Kuhlberg 2014). The goals of reforestation are distinct from restoration: while restoration seeks to recover ecological integrity, reforestation is more frequently concerned

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with the growth of harvestable species (e.g., Santala et al. 2019; Dumais et al. 2020). Early work in reforestation referred to "nature's wealth" (Lambert 1967) and focused on restocking the supply of a commodity depleted by extraction. While there is valuable research in forestry, its goals are fundamentally different from ecological restoration, which typically seeks to prevent any further degradation (Reid et al. 2017).

The middle period (2006–2012) is characterized by the accelerated development of ecological restoration as a major scientific field. This coincides with the release of the first-ever national guidelines on ecological restoration (Parks Canada & Canadian Parks Council 2008), and the launch of an international guiding document on restoration in protected areas with Canadian leadership (Keenleyside et al. 2012).

The most recent time period (2013–2020) is characterized by a focus on climate change which reflects a growing urgency to consider the implications of human-caused climate change on restoration efforts (Murphy 2018). While prominence of climate change in the Canadian literature is growing, it has long been a concern in ecological restoration broadly (Harris et al. 2006). Climate change emerged as both a source of degradation and a potential stressor on ecological restoration outcomes (Sebastian-Azcona et al. 2020). Restoring ecosystems degraded by climate change is distinct from industrial degradation, as the effects of climate change are not as easily mitigated as, for example, toxic effluent from a mine. Any restoration projects attempting to address impacts from climate change must also be adaptable to climate change.

Why is restoration taking place?

Not all studies reported the reason for the restoration being undertaken, but those that did cited legislation ($n = 98$). This contrasts with recent results from a survey of Canadian practitioners, who highlight political will as a major barrier to restoration (Higgs et al. 2021). The other reasons cited for conducting ecological restoration included endangered species conservation, natural resource regeneration, and restocking species for hunting. The role of legislation in promoting restoration and its potential effect on outcomes has been the subject of debate in other jurisdictions, with critics saying that current restoration science is not advanced enough to form a sound basis for standardized practices through legislation (Aronson et al. 2011). One future direction of research could closely examine Canada's federal, provincial, and regional legislative mechanisms and how those mechanisms influenced restoration effectiveness, both in terms of project success and the amount of area restored.

How is restoration monitored and evaluated?

Much of the ecological restoration literature identified in this review focused on a single category of response variable (e.g., Bakker and Wilson 2004; Desserud and Naeth 2013; St-Denis et al. 2017) (Fig. 5). In the case of forestry, for example, the focus is on seedling regeneration and less on understory vegetation, fungi, wildlife, and more. Such research is primarily focused on the growth responses of saplings to various replanting techniques and rarely considers reforestation in the context of habitat or ecosystem function. It would be beneficial for Canadian ecological restoration researchers to consider studying restoration responses beyond the plant community level and incorporating such goals into restoration plans (Fraser et al. 2015).

Despite the importance of long-term monitoring in ecological restoration, most studies monitored outcomes for less than 5 years. Long-term monitoring is important because restoration results can diminish over time. For example, plant reintroduction success has been found to decline year-over-year, leading to overreporting of success in short-term studies (Godefroid et al. 2011). Incomplete exotic species removal may initially show positive effects but can result in secondary invasion and further degradation as time goes on (Murphy et al. 2007). Without long-term monitoring, it is difficult to know whether a restoration effort will persist into the future, which is essential for realizing the benefits of the project (Reid et al. 2017).

Limitations

The most notable limitation of this analysis was the inability to efficiently search for, gather, and include a variety of unpublished or "grey" ecological restoration literature. The absence of these documents underrepresents restoration efforts that tend not to publish results in a formal academic journal. There is also a well-known file drawer effect (Wood 2020) whereby projects that are not successful are not published while those that are successful are shared via publication. This can create substantial bias in the evidence base. Valuable information regarding outcomes, methods, and engagement are therefore lost in favour of details derived from prolific industry-led published literature. The inability to reliably extract restoration motivations or outcomes from the entries examined in the systematic mapping analysis weakened our ability to examine important information relating to incentives, drivers, and methodological success in the ecological restoration domain. This was compounded by the challenges of finding indexed publications in French.

Conclusion

The who, what, where, when, why, and how of ecological restoration outline a field of study in Canada that is tightly tied with degradation from resource extraction and increasingly concerned with climate change. At the dawn of the UN Decade on Ecosystem Restoration (2021–2030), momentum in ecological restoration research has the capacity to further strengthen Canada's role internationally. The peer-reviewed literature has shortcomings in research that addresses multiple response variables and long-term monitoring of restoration projects. Future opportunities lie in developing a research agenda for holistic restoration monitoring, evaluating the effectiveness of restoration prompted by Canadian policy and legislation, and committing to long-term monitoring and evaluation of ecological restoration projects.

This analysis has reviewed the themes and ideas over more than 50 years of published ecological restoration literature, which can be used to identify the trajectory of future research and the roots of ecological restoration

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research in Canada. The detailed systematic mapping analysis component provides insights into the nature and distribution of ecological restoration research, which are important for the identification of research gaps, methodological shortcomings, and the adequacy of research representation across provinces/territories, ecosystems, and industries. Further work is required to uncover a rich source of unpublished literature that typically provides practitioner-driven insights into restoration effectiveness, efficient, and engagement. Although we focused on a single country (i.e., Canada), the findings are also relevant to other jurisdictions. We submit that the patterns observed here may be similar to issues pervasive in the broader restoration literature. Identifying disconnects between restoration research and practice and ensuring that the research that is conducted has the potential to impact practice remain high priority topics for ecological restoration.

Acknowledgements

Thanks to the University of Waterloo Research Librarian Agnes Zientarska-Kayko for assistance in developing search strings. Thanks to Kent Prior, Parks Canada, for his guidance in this work. This research was supported by the Knowledge Synthesis Program of the Social Sciences and Humanities Research Council of Canada.

Data generated or analyzed during this study are available in the Borealis repository, https://doi.org/10.5683/SP3/NOBFEW.

Article information

Editor

Fanie Pelletier

History dates

Received: 12 July 2022
Accepted: 20 February 2023
Version of record online: 15 June 2023

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Steven Cooke served as Subject Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Fanie Pelletier.

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Competing interests

The authors declare there are no competing interests.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/facets-2022-0157.

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