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RESEARCH ARTICLE

Integrating Indigenous and scientific perspectives on environmental changes: Insights from boreal landscapes

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Abstract

1. Major environmental changes affect the health and capacity of ecosystems to sustain Indigenous people's well-being in boreal landscapes. Collaboration between Indigenous communities and researchers could help assessing and mitigating the consequences of environmental changes.
2. We used Driver Pressure State Impact (DPSI) conceptual models to compare the perspectives of Indigenous and scientific communities on environmental changes in boreal landscapes of Quebec, Canada.
3. The Indigenous DPSI model emerged from interviews with local land-use experts from two Indigenous communities. The scientific model was informed by the publication topics of expert researchers.
4. We compared the Indigenous and scientific models and exposed convergences and divergences between perspectives. Forestry was identified as a major driver of change in both models. Most issues related to mining, hydro-power and forest road development were specific to the Indigenous model. Climate change and wildfires were of greater interest in the scientific model.
5. Convergences between the perspectives of Indigenous and scientific communities are conducive to collaborative research. Divergences could be addressed through reciprocal knowledge transfer activities, which would lead to research that better aligns with the concerns and needs of Indigenous communities.

KEYWORDS
boreal landscapes, collaborative research, DPSI, environmental changes, traditional ecological knowledge

1 | INTRODUCTION

Globally, landscapes are facing unprecedented transformations under the pressures of climate change, natural resource exploitation and land-use change (IPBES, 2018; Lewis & Maslin, 2015). Environmental changes affect human well-being, especially in Indigenous contexts (Chapin et al., 2004; Fuentes et al., 2020). Indigenous people have a close and multifaceted relationship with the land, as it provides goods and services, in addition to supporting livelihood, culture and identity (Bélisle et al., 2021; Davidson-Hunt & Berkes, 2003; Saint-Arnaud et al., 2009). The consequences of environmental changes are observed first-hand by Indigenous people and interpreted through Indigenous ecological knowledge, anchored in place, time and culture (Asselin, 2015; Davidson-Hunt & O'Flaherty, 2007).

The necessity of combining scientific and Indigenous knowledge to face the challenges raised by environmental changes has been increasingly acknowledged (Ericksen & Woodley, 2005; Ford et al., 2016; Tengö et al., 2017). Collaboration between Indigenous communities and researchers contributes to better address complex environmental problems (Blackstock et al., 2007; Parsons et al., 2016). Indigenous and scientific knowledge are complementary (Fagerholm et al., 2012; Lyver et al., 2018), and when combined, they can increase the legitimacy of the resulting land management decisions to local populations (Cash & Belloy, 2020; Ericksen & Woodley, 2005; Tengö et al., 2014). Collaboration also contributes to local development and empowerment by generating knowledge and expertise that are directly relevant to the communities (Ban et al., 2018; Brook & McLachlan, 2005).

However, Indigenous and scientific knowledge belong to different knowledge systems and their weaving is an intricate an delicate exercise (Davis & Ruddle, 2010; Stefanelli et al., 2017; Tengö et al., 2014). Furthermore, in many Indigenous contexts, unethical research practices tainted by colonialism have created a feeling of mistrust towards the scientific community and still hinder harmonious and satisfactory collaborations (Smith, 2021). The extractive paradigm of scientific research has been criticized, where researchers go to Indigenous communities or territories and extract knowledge, plants or tissues, without giving back (Asselin & Basile, 2018; Kwaymullina, 2016). The implicit hierarchization of knowledge systems is another common issue that manifests when scientific data and methods are used to verify or validate Indigenous knowledge (Brook & McLachlan, 2005; The Indigenous Circle of Experts, 2018). New research approaches are necessary to foster knowledge conciliation.

Knowledge conciliation relies on the premises that any knowledge is partial and situated, and that there is no hierarchy between knowledge systems (Ericksen & Woodley, 2005; McGregor, 2018). The *two-eyed seeing* approach provides guidance for applying these principles by considering multiple perspectives on a phenomenon such as environmental changes (Abu et al., 2019; Rayne et al., 2020; Reid et al., 2021). '*Two-Eyed Seeing* is the gift of multiple perspectives treasured by many aboriginal peoples [...] it refers to learning to see from one eye with the *strengths* of Indigenous knowledges and ways of knowing, and from the other eye with the *strengths* of Western knowledges and ways of knowing, and to using both these eyes together, for the benefit of all' (Bartlett et al., 2012, p. 335). *Two-eyed seeing* is increasingly used to foster collaboration in various contexts, including river ecology (Abu et al., 2019), fisheries (Reid et al., 2021) and climate change (Galway et al., 2022).

In this research, we used a *two-eyed seeing* approach to assess and compare the perspectives of Indigenous and scientific communities on environmental changes (hereafter called Indigenous and scientific perspectives for readability). We focused on boreal landscapes of Eastern North America, where Indigenous and scientific communities are increasingly working together to address the effects of acute environmental changes. We developed conceptual models to represent the perspective of each community and compared the models. Furthermore, we assessed convergences and divergences between perspectives and discussed collaboration challenges and opportunities.

2 | STUDY AREA

The study area is located in boreal Quebec, Canada (Figure 1). This region is influenced by a subpolar subhumid continental climate, is mainly forested, and has a high density of lakes and rivers. The relief is low and is characterized by plains and rounded hills (Jobidon et al., 2015). Forests are mainly coniferous, with black spruce (*Picea mariana*, *SESEKATiK*, *iiyaahtikw*),[1] jack pine (*Pinus banksiana*, *OKiK*, *uschisk*) and balsam fir (*Abies balsamea*, *CiKOPi*, *iinaasht*) as the most common tree species. Broadleaved species, mainly trembling aspen (*Populus tremuloides*, *ASATi*, *miitus*) and paper birch (*Betula papyrifera*, *8iK8AS*, *wishkui*) are also present. Wildlife species include moose (*Alces americanus*, *MOS*, *muus*), woodland caribou (*Rangifer tarandus caribou*, *ATiK*, *atihkw*), American marten (*Martes americana*, *8APiCECi*, *Waapishtaan*), North American beaver (*Castor canadensis*, *AMiK*, *Amiskw*) and black bear (*Ursus americanus*, *MAK8A*, *mihkihtaauskw*), among others. Common fish species include northern pike (*Esox lucius*, *KiNOCE*, *chinusheu*), walleye (*Sander vitreus*, *OKAS*, *ukaash*) and lake sturgeon (*Acipenser fulvescens*, *NAME*, *nameu*).

Boreal Quebec provides fertile ground to bring together Indigenous and scientific perspectives on environmental changes (Figure 2). First, boreal landscapes are under the influence of various natural and industrial disturbances. Large and severe wildfires are recurrent in the study area (Boulanger et al., 2013), which is also influenced by climate change (Ouranos, 2015). Most areas located south of the northern limit of the commercial forest are dedicated to extensive forestry, mainly through clear-cut harvest (Ministère des Ressources naturelles du Québec, 2013). Active, abandoned and projected mines are numerous (Ministère de l'Énergie et des Ressources naturelles du Québec, 2016). Hydro-electricity dams were developed in the northern part of the study area in the 1970s and high-voltage powerlines (735 kV) transmit electricity from north to south (Hydro-Québec, 2015).

Second, boreal Quebec is part of the traditional lands of eight Indigenous peoples who are actively involved in land use, management and knowledge development. Landscape practices, including hunting, fishing, trapping and a variety of other cultural and recreational activities, are key contributors to Indigenous livelihoods, cultures and identities (Bélisle et al., 2021; Bellefleur, 2019; Saint-Arnaud et al., 2009).

Third, there have been extensive scientific research efforts in boreal Quebec in the last decades that have generated a network of dozens of active researchers on boreal environments (e.g. refer to http://www.cef-cfr.ca/). Ecosystem-based forest management was adopted by the Quebec Government in 2013 and its application relies on in-depth knowledge of forest ecology stemming from scientific research (Gauthier et al., 2023).

The research presented in this paper has emerged from a partnership between a local university (Université du Québec

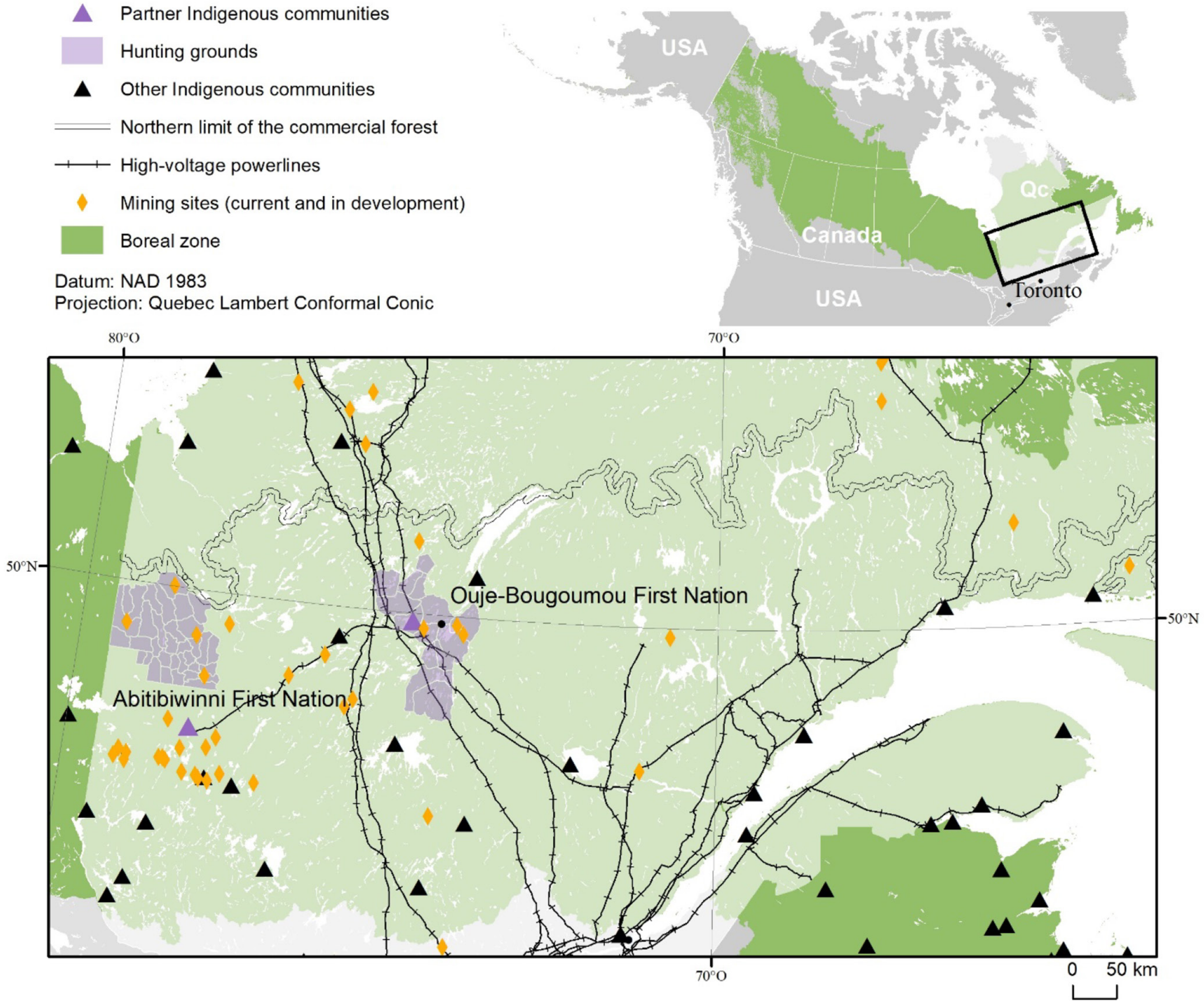

FIGURE 1 The boreal zone in Canada (Brandt, 2009) and Quebec (light green) and the hunting grounds of the Abitibiwinni and Ouje-Bougoumou first nations. Boreal landscapes are affected by forestry south of the northern limit of commercial forests (Ministère des Forêts de la Faune et des Parcs du Québec, 2018), mining (Ministère de l'Énergie et des Ressources naturelles du Québec, 2018), hydro-electric development (Hydro-Québec, 2015) and climate change (Ouranos, 2015).

en Abitibi-Témiscamingue), the Abitibiwinni First Nation (Anishnaabeg) (population of ca. 1080) and the Ouje-Bougoumou First Nation (Cree) (population of ca. 906) (Indigenous and Northern Affairs Canada, 2015). In both communities, life on the land takes place on family hunting grounds which are transferred from one generation to the next (Feit, 1985). There are 34 hunting grounds (11,430 km^2 in total) on the Abitibiwinni territory and 14 (10,560 km^2 in total) on the Ouje-Bougoumou territory, with sizes ranging between 112 and 1652 km^2. The hunting grounds are located on public lands under provincial government regulation. Activities on Eeyou Istchee, the Cree territory, are subject to the *James Bay and Northern Quebec Agreement* (1975) (a modern treaty) and *La Paix des Braves Agreement* (2002). These agreements impose guidelines for the economic development of the territory and ensure that the Cree Nation is involved in decision-making and derives benefits from it. No treaty is yet in force on the Abitibiwinni territory, hence industrial projects and their benefits and consequences for the community are negotiated on a case by case basis.

3 | METHODOLOGY

3.1 | Collaborative design and research ethics

Our research team included academic and community researchers. Community researchers were employees of the department of natural resources and environment in each Indigenous community. The whole research team met once at the beginning of the project (May 2016) and set the objectives and research design. Short group meetings were held afterwards at each step of the research (i.e. data

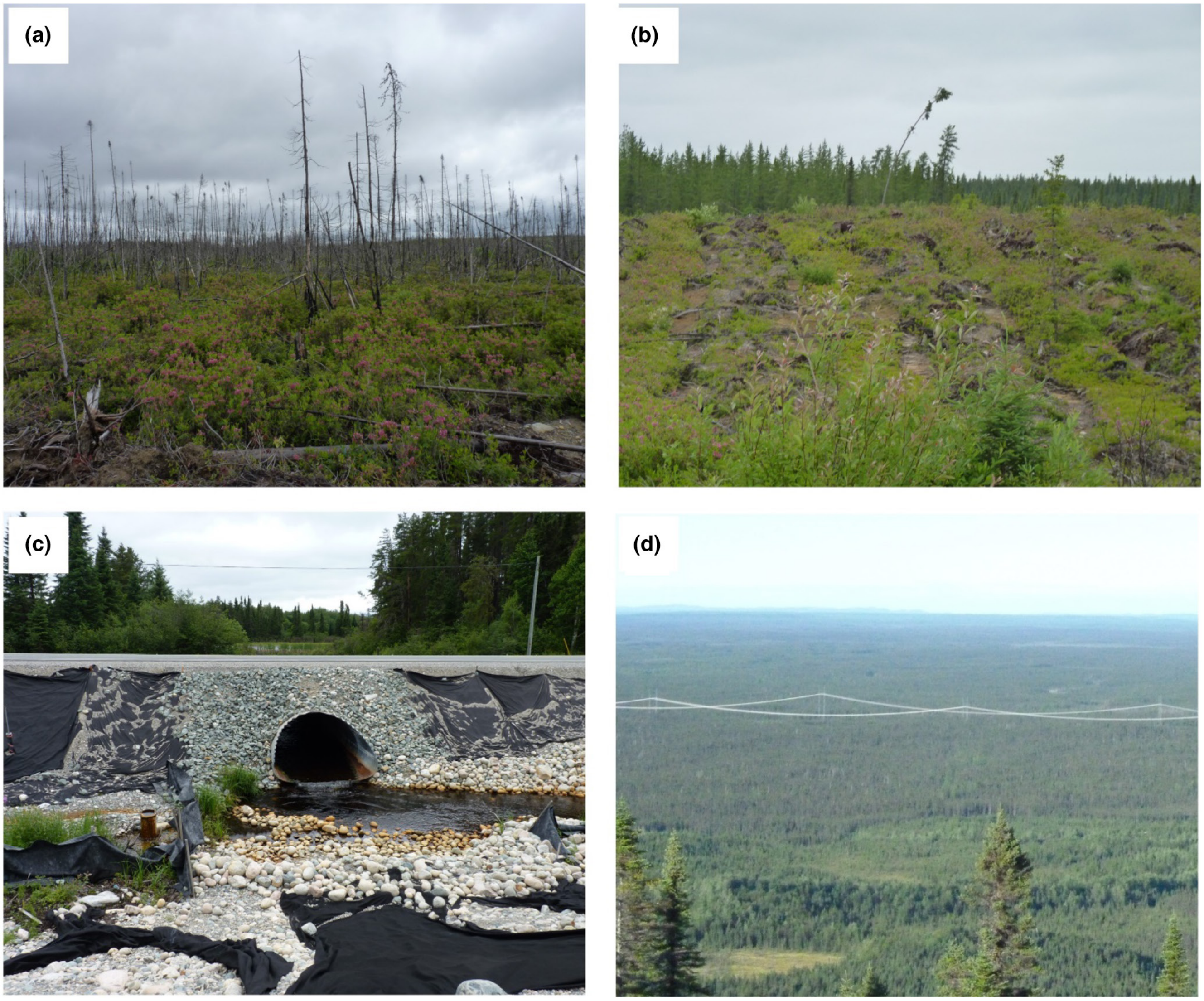

FIGURE 2 Pictures from the study area taken during field work in 2016: (a) burned forest land, (b) harvested forest, (c) main road, (d) high-voltage powerline.

collection, analysis, validation and knowledge mobilization), as explained in the next sections.

We developed the project following the research protocol of the Assembly of First Nations of Quebec and Labrador (AFNQL, 2014), based on the OCAP® principles (ownership, control, access and possession of research data). The research agreements stipulated the roles and responsibilities of the researchers and the communities, data uses, the publication process and a procedure to resolve conflicts. They were signed by representatives of the university and the two participating communities.

The project was approved by the Ethics Review Board of Université du Québec en Abitibi-Témiscamingue (certificate # 2016-04). Participants agreed to take part in the project by signing a consent form (adapted from Basile et al., 2018) with the assurance that the data would remain confidential. Members of the research team had to sign a commitment to confidentiality before they could access the data. Datasets (agglomerated for confidentiality), Scopus® outputs and R codes can be found in an open-access repository (refer to https://github.com/acbelisle/Perspectives-of-environemental-change).

3.2 | Analytical approach

We assessed and compared Indigenous and scientific perspectives on the impacts of environmental changes using conceptual models (Delgado et al., 2009) developed with similar DPSI[2] structures. DPSI models address complex environmental problems through a hierarchical causality network (Borja et al., 2006; Gregory et al., 2013; Lewison et al., 2016), identifying: Drivers (D) that are forces operating on the system (e.g. climate change, forest industry); Pressures (P) that are environmental or ecological processes (e.g. wildfire, timber harvesting); States (S) that are environmental conditions in a given time and place (e.g. biodiversity, water quality, habitat suitability);

Impacts (I) on landscape value that are the outcomes of States (Bélisle et al., 2021; Bélisle & Asselin, 2021).

We focused on ecological Driver, Pressure and State variables and did not include economic, political or social factors to the DPSI models. Although such factors influence boreal landscapes, their assessment was beyond the scope of our research and could be addressed with a dedicated research design. We approached the Impacts on landscape value with the relational lens (Klain et al., 2017; Pascual et al., 2017), whereby 'Relational values are not present in things but derivative of relationships and responsibilities to them' (Chan et al., 2016, p. 1462). The relational lens is increasingly used to assess landscape value in Indigenous contexts (e.g. Grubert, 2018; Sheremata, 2018).

We developed two DPSI models based on expert knowledge and interests, one for the Indigenous communities and one for the scientific community. We designed parallel methods for defining, selecting and identifying experts within Indigenous and scientific communities, and for the elicitation, measure and validation of Indigenous and scientific perspectives (Table 1). First, we developed the Indigenous DPSI based on interviews and participatory mapping. Second, we developed the scientific DPSI based to the number of active researchers having an interest in each component of the Indigenous DPSI. Third, we compared the relative importance of each DPSI component from the Indigenous and the scientific perspectives (Figure 3). We associated a number of experts to each relationship between DPSI variables, thus ensuring the diversity and the distribution of viewpoints within a community.

3.3 | Expert definition, identification and selection criteria

We developed the DPSI models based on the expertise held within Indigenous and scientific communities. Experience-based expertise refers to specialists' abilities (Collins & Evans, 2019), and experts stand out from novices by their process of judgement and reasoning. We used expertise criteria encompassing peer assessment, length of experience and demonstrable ability (O'Hagan et al., 2006).

3.3.1 | Indigenous communities

Experts from the Indigenous communities were experienced land users, acknowledged by their peers and having land management responsibilities. Community researchers were responsible for their identification, selection and recruitment. As part of their job, community researchers work on a regular basis with land-use experts on matters related to land management, consultation, and knowledge sharing. We took into account the diversity of exposition levels to environmental changes within and between communities by recruiting a single expert (and sometimes his/her family) per hunting ground, maximizing the number of hunting grounds.

In the Ouje-Bougoumou First Nation, all tallymen met the expertise criteria as per the requirements of their function. The Indigenous experts were active land users with several years of experience, were responsible for coordinating family activities on the hunting ground and were mandated to participate in consultations with extractive industries. Each tallyman was invited to participate by a personal letter and by at least one in-person visit or phone call.

In the Abitibiwinni First Nation, land management roles are less formal, so community researchers listed the people responsible for consultation and management for each hunting ground and identified those who met the expertise criteria. We needed additional selection criteria in the Abitibiwinni First Nation, as there are more hunting grounds than in Ouje-Bougoumou. We, thus, assessed the hunting ground disturbance level through mining, wildfire and timber harvesting, and balanced the number of experts with the environmental conditions of the territory. In both communities, family members were invited to join the interviews, adding age and gender diversity.

3.3.2 | Scientific community

Experts from the scientific community were active researchers on a given topic associated with boreal environments in Quebec, Canada. An active researcher was identified as the author or co-author of at least three scientific articles published in peer-reviewed journals between

TABLE 1 Characteristics of the experts and perspectives for Indigenous and scientific communities

	Indigenous communities	Scientific community
Experts		
Description	Tallymen (Ouje-Bougoumou), hunting ground informal managers (Abitibiwinni)	Active researchers
Identification	Researchers from the communities	Scopus® search
Selection criteria	Active land users, peer recognition, land management responsibilities	Authors or co-authors of ≥3 scientific articles (2000–2019)
Perspectives		
Elicitation	Participatory mapping and semi-guided interviews	Research topics identified through a Scopus search
Metrics	Number of experts who mentioned an association between DPSI variables	Number of experts having published research on each component of the Indigenous DPSI
Validation	Revision of coding and ambiguous quotes by the collaborative research team	Sensitivity and susceptibility analysis—adjustment of Scopus queries

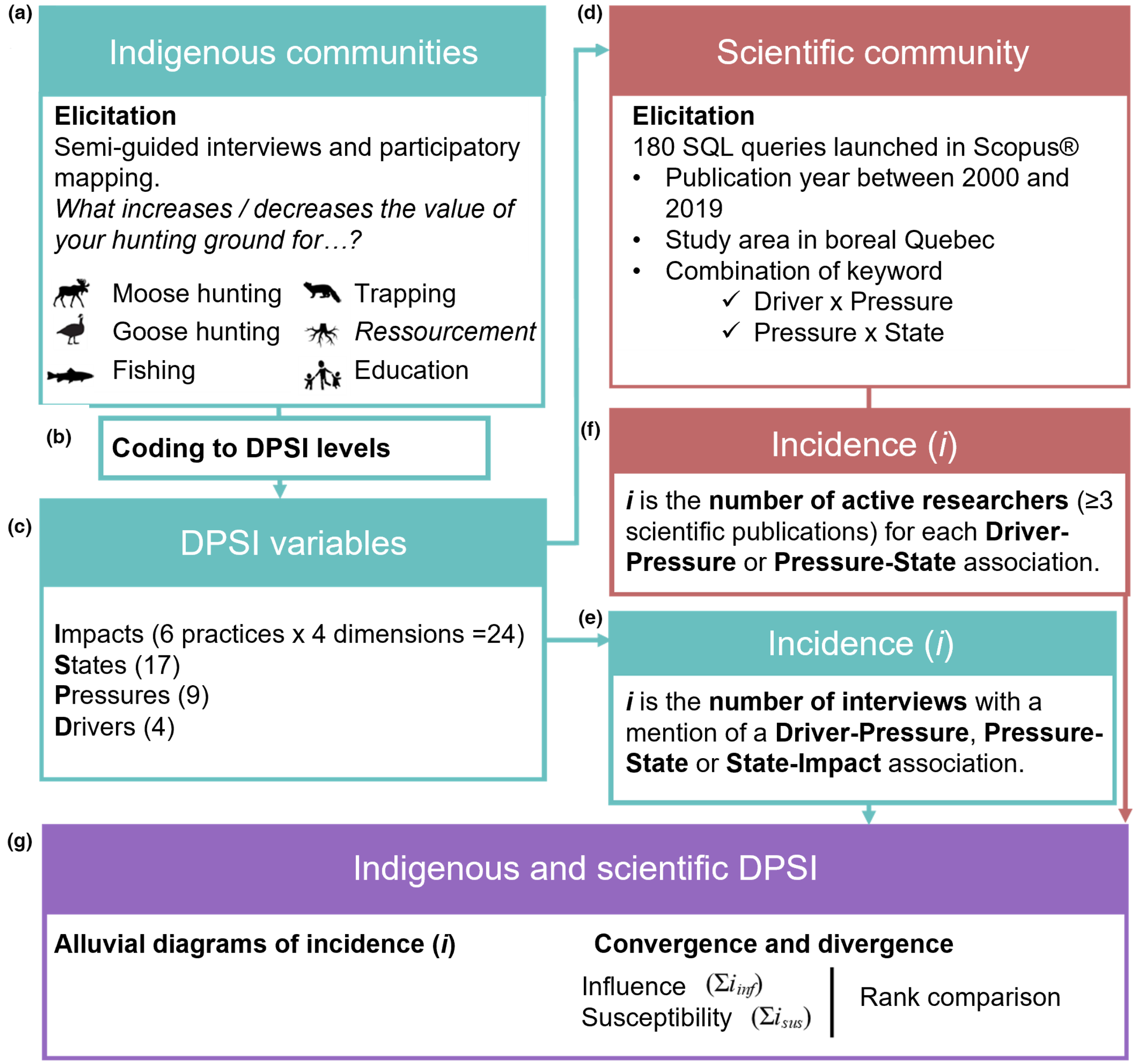

FIGURE 3 Methodology for developing the scientific and the Indigenous conceptual models and comparing perspectives on environmental changes.

2000 and 2019. We tested thresholds between one and four articles, and we found that the three-article limit was the best able to associate researchers with their research topics while excluding punctual collaborations (see Anderegg et al., 2010 for a similar methodology).

3.4 | Elicitation, metrics and validation of perspectives

3.4.1 | Indigenous communities

With the research team, we identified six landscape practices that have provisioning and cultural functions in both communities and that are affected by environmental changes. These are moose hunting, trapping, fishing, goose (*Branta canadensis*, *NiKA*, *niska*) hunting, education and *ressourcement* (see Bélisle et al., 2021 for a qualitative landscape valuation). We conducted 12 semi-structured interviews and participatory mapping exercises with Abitibiwinni experts and 11 with Ouje-Bougoumou experts (some interviews involved more than one expert) (Figure 3a). Interviews and participatory mapping took place in the communities or nearby (e.g. band office, restaurant, Chibougamau Eenou Friendship Center, participant's residence) between June and September 2016. All interviews were conducted by the first author, sometimes accompanied by co-researchers and research assistants. Ten interviews were conducted in French, 7 in English, 5 in Cree and 1 in Anishnaabemowin. A member of the research team from the community live-translated the interviews when needed. Interviews were audio-recorded and lasted between 45 min and 2 h.

Interviews started with close-ended questions dedicated to sketch the social profile of participants (gender, age, attendance on the land). We verified the participants' expertise by asking if they were active in each of the six landscape practices (yes/no). As the interview progressed, we asked participants to self-assess their expertise level on a visual scale (0–10) for each landscape practice. We further questioned participants who answered 'no' or who rated their expertise below 5/10. If low expertise was confirmed with statements such as 'I do not go trapping' or 'I do not go moose hunting', then the specific landscape practice was not investigated in the interview. Oppositely, when the reason behind a self-assessed low expertise revealed anecdotal (e.g. a bad hunting year in a lifetime), expertise was confirmed.

Participatory mapping was supported by laminated maps (1:60,000) showing hunting ground delineation, elevation lines, lakes, rivers, wetlands, powerlines, quad paths and roads (Figure S1). Landmarks were chosen as neutral as possible to avoid introducing bias. We asked Indigenous experts to locate their cabins and campsites and we validated their understanding of the map with simple orientation questions. For each landscape practice, the experts had to indicate places of high value with green chips and places of low value with red chips (Raymond et al., 2009). Experts drew the boundaries of places of high value with a green pen and the boundaries of places of low value with a red pen. Each feature drew on the map led to a discussion between the researcher and the expert.

We used the NVivo 11 software (QSR International, Melbourne) to perform a thematic analysis of the interview transcripts and develop the DPSI structure (Figure 3b). We followed an inductive and bottom-up procedure. In a first step, we analysed all excerpts with mentions of Impacts. Four dimensions of landscape value emerged, namely abundance, access, quality and experience (the full procedure is presented in Bélisle et al., 2021). We created 24 Impact themes (6 landscape practices × 4 dimensions, e.g. fishing-abundance, fishing-access, fishing-quality, fishing-experience) (Figure 3c). We coded interview excerpts to the corresponding Impact theme(s) and we coded the excerpts contained in Impact themes to one or many State themes, when appropriate (example in Figure 4). We created the State themes as they were mentioned for the first time. We coded excerpts contained in State themes to

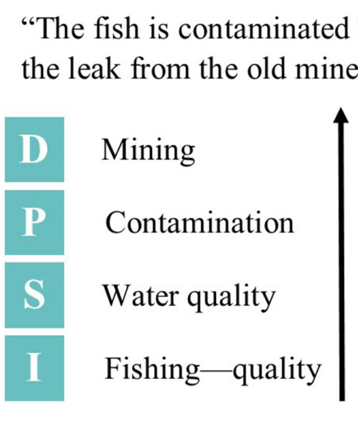

FIGURE 4 Example of the coding procedure of an interview excerpt into Impact (I), State (S), Pressure (P) and Driver (D) levels. The arrow presents the bottom-up coding sequence.

Pressure themes and Driver themes following the same procedure. We extracted the excerpts coded to each possible Driver-Pressure, Pressure-State, or State-Impact combination using NVivo queries (Figure 3d).

The first author anonymized the participants and undertook the coding prior to presenting the results to the research team. A meeting was held with each community to discuss and validate coding accuracy. We discussed the rare ambiguous statements and we paid attention to topics mentioned by only a few experts to distinguish rare, but important phenomena from anecdotal events. Although informative for interpretation, this information did not lead to the exclusion of any quote.

3.4.2 | Scientific community

We developed a set of keywords for each variable in the Indigenous conceptual model (Table S2). We searched the Scopus® database to identify the scientific articles published on each Driver-Pressure and Pressure-State association (Figure 3d). We searched article titles, abstracts and keywords with SQL queries that specified keyword combinations, publication year and geographical area. We developed the queries as follows: (1) geographic location keywords to restrict the search to the study area; (2) publication year boundaries to capture articles published between 2000 and 2019 for consistency with Indigenous experts' experience on the land. Although the interviews were conducted in 2016, we extended the search period to 2019 to consider the time lag between data collection and publication and (3) keywords associated with the query variables (a Driver and a Pressure or a Pressure and a State), separated by the Boolean operator 'AND'. We did not investigate the links between States and Impacts because too few articles were published on landscape practices. We compiled the list of authors and the associated number of publications for each query with the R 3.4.4 software. We calculated the number of active researchers for each Driver-Pressure and Pressure-State association (Figure 3e).

We verified the ability of the queries to generate an accurate list of active researchers for each topic using specificity and sensitivity analyses. The specificity analysis aimed to ensure that no article outside the intended scope of a query was selected. We inspected the list of researchers for each query to spot 'intruders' and unknown authors, and we investigated suspicious cases and clarified the queries when necessary.

The sensitivity analysis aimed to identify queries that failed to identify all the authors active in a given topic. To do so, we listed the queries that generated little or no results. Each query was inspected for grammatical or keyword errors. We also investigated whether some authors were not associated with their known research topics. In these cases, we searched articles that should have qualified, inspected the keywords and adjusted the queries. We uniformized the names of authors with spelling differences (e.g. with or without middle name initial) in the Scopus® generic reports and kept in check the authors sharing the same initials.

3.5 | Development and comparison of Driver Pressure State Impact models

We represented the Indigenous and the scientific DPS(I) models with alluvial diagrams using the web open-source platform RAWGraphs® (refer to https://rawgraphs.io/) (Figure 3g). A variable is represented by a node, and nodes are grouped into blocks (Drivers, Pressures, States, Impacts). Flows connect nodes from adjacent blocks. Flow width is proportional to flow incidence (i). For the Indigenous DPSI model, i is the number of interviews with at least one mention of the association between nodes. For the scientific DPS model, i is the number of authors who published at least three peer-reviewed articles on the association between nodes during the studied period (2000–2019). A node's length is proportional to its influence (Σi_{inf}) or susceptibility (Σi_{sus}), depending on its hierarchical position in the network. A node's influence (Σi_{inf}) is the sum of the incidences (i) going towards the right. A node's susceptibility is the sum of the incidences (i) coming from the left. We ranked the variables according to Σi_{inf} and Σi_{sus} to compare the Indigenous and scientific DPS. When $\Sigma i_{inf} = 0$ or $\Sigma i_{sus} = 0$, we attributed the latest rank.

We identified convergence and divergence between the Indigenous and the scientific perspectives visually on scatter plots. Each variable was attributed an x- (Indigenous rank) and a y- (Scientific rank) coordinate on a scatter plot. The diagonal and its surroundings (similar Indigenous and scientific ranks) corresponded to the convergence zone. The variables located over the diagonal belonged to the scientific perspective and those under the diagonal belonged to the Indigenous perspective. Variables with no active researcher associated were considered exclusive to the Indigenous perspective and were shown below the x-axis.

3.6 | Methodological limitations

This perspective assessment was based on the number of persons (either land-use expert or researcher) who reported an Impact. This metric is informative to compare the perspectives but should not be interpreted as a proxy for the ecological importance or influence of ecological phenomena. For instance, a localized but high-impact disturbance such as a mine or a spill may have tremendous local impacts but would be reported by only a few land-use experts whose hunting grounds are affected. Similarly, the scientific research orientations depend on many factors other than ecological importance (e.g. funding priorities, commercial interest, scientific trends) so the scientific perspective needs to be interpreted as the interest of researchers for an environmental phenomenon rather than its ecological importance.

Causal inference is another limitation of our research design. By its hierarchical structure, the DPSI model assumes a directional causality from the Drivers to the Impacts. It does not take into account backwards influences (i.e. the influence of States on Pressures), feedbacks or even the positive or negative effects of Responses that were omitted in this study. Associations between two variables should therefore not necessarily be interpreted as a causal relationship. Similarly, the influence of a variable is calculated according to the number of variables from the lower hierarchical level with which it is connected. This does not assume a direct causality on each connected variable. It is also worth noting that the Indigenous model represents the perspective of active Indigenous land users and that the perspective of Indigenous people who live in urban areas, or who do not go out on the land might be different (Landry et al., 2019).

4 | RESULTS

4.1 | Indigenous Driver Pressure State Impact

We conducted 23 interviews and met with 27 Indigenous experts (some interviews included two members of the same family). Twenty-five experts were men, and two were women. Most experts (17) were older than 54 years old. All experts were active land users with confirmed expertise in most of the six landscape practices. Twenty-one experts reported going on their hunting ground one to three times a month and 15 of them at least one to three times a week. Additional information on the profile of participants is available in Table S3.

4.1.1 | Drivers–Pressures

Four Drivers of environmental changes emerged from the interviews with Indigenous experts: forestry, mining, climate change and hydro-electric development (Table 2). Forestry ($\Sigma i_{inf} = 59$) was associated with five landscape Pressures (Figure 5a): timber harvesting ($i = 22$), silvicultural treatments ($i = 12$), forest road network development and maintenance ($i = 12$), contamination of terrestrial and aquatic ecosystems ($i = 9$) and changes in species distribution ranges ($i = 4$). Mining ($\Sigma i_{inf} = 19$) was associated with contaminant release ($i = 9$), mineral extraction ($i = 6$) and road network development and maintenance ($i = 4$). Climate change ($\Sigma i_{inf} = 16$) was associated with changes in species distribution ranges ($i = 9$) and weather events and season changes ($i = 7$). Hydro-electric development ($\Sigma i_{inf} = 12$), was associated with electricity transmission by high-voltage power lines ($i = 12$).

4.1.2 | Pressures–States

Ten Pressures emerged from the interviews with Indigenous land-use experts (Table 1). Timber harvesting ($\Sigma i_{sus} = 22$, $\Sigma i_{inf} = 56$) was the most susceptible and influential Pressure (Figure 5a), associated with all 10 States, with greatest incidence on forest age structure ($i = 17$) and naturalness ($i = 13$). Road network development and maintenance ($\Sigma i_{sus} = 16$, $\Sigma i_{inf} = 34$) was associated with six States, mainly affluence ($i = 12$), road network density ($i = 10$) and transportation ($i = 4$). Silvicultural treatments ($\Sigma i_{sus} = 12$, $\Sigma i_{inf} = 21$) was associated

TABLE 2 Driver–pressure–state–impact (DPSI) variables that emerged from the interviews with Indigenous experts. Definitions are based on Indigenous experts' explanations and scientific literature when available

DPSI level	Variable	Definitions
Drivers	Climate change	'A change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer' (IPCC, 2015)
	Forestry	Forestry includes landscape planning, timber harvesting methods, silvicultural practices and forest road development and maintenance (Doucet & Côté, 2009). Forest management practices are regulated by the Quebec Law on sustainable forest management (A-18.1), by wood markets and by certification agencies (e.g. Forest Stewardship Council)
	Hydro-power development	The energy sector, in the study area, includes hydroelectricity production, transportation and distribution
	Mining	Mining includes mineral prospection, extraction, transformation and transportation, waste disposal, and restoration of closed mining sites
Pressures	Contaminant release	Substance or agent released in the soil or water as a result of human activities (e.g. oil spill, phosphorous loading) (adapted from IPBES, 2018)
	Distribution changes	Shifts in species distributions (including range displacement, local extinction, or local apparition)
	Electricity transmission	Transmission of electricity from the place of production to the place of distribution by aerial or underground lines at a voltage between 44 and 765 kV (Hydro-Québec, 2015)
	Mineral extraction	'The removal of a mineral resource in or on the Earth's crust, which has appropriate form, quality and quantity to allow economic extraction' (IPBES, 2018)
	Road network development	Changes in the extent and distribution of areas accessible by the road network (including forestry roads)
	Silviculture	Intervention to direct the development of a forest stand, including its renewal, or to increase its yield, on a given area and time. Silvicultural treatments include regeneration intervention, site preparation, plantation, thinning and other treatments (adapted from Boulet and Huot (2013))
	Timber harvesting	Tree removal for industrial purposes, including partial and total harvests (Doucet et Côté, 2009)
	Weather and season changes	Anomalies in the timing of seasons and weather (temperature, precipitation, wind, extreme events)
	Wildfire	Wildfires are described by their size, duration, intensity and severity. Fire activity depends on the fire regime parameters such as burn rate (or fire cycle), seasonality, size distribution and periodicity (Vaillancourt et al., 2009)
States	Affluence	Amount of land users on the hunting ground
	Cultural places	'Particular places, for any cultural group, that are critically important to people's lifeways and identity' (Cuerrier, Turner, et al., 2015) such as graves, ancient trails and birthplaces
	Forest age structure	The age can represent the time elapsed since the last stand-replacing disturbance or a successional stage
	Forest composition	Tree species assemblage of a forest
	Goose landing areas	Suitable landing and resting areas for geese during migrations
	Ground condition	Microtopography of the soil surface (e.g. bumpiness, muddiness) and soil proprieties
	Ice conditions	State of the ice on rivers and lakes (e.g. thickness, dates of formation and break-up)
	Mine tailings	Solid wastes left after mineral processing
	Naturalness	Areas undisturbed by industrial activities
	Predators	Wildlife species feeding on species of interest for the community

(Continues)

TABLE 2 (Continued)

DPSI level	Variable	Definitions
	Road network	Density of roads providing access by car or truck to the different parts of the hunting ground
	Spawning areas	State of fish spawning areas for species valued by the community
	Technology (communication)	Availability of a cellphone, internet, or television signal
	Transportation	Passage of truckloads of minerals, timber or other material
	Water quality	Chemical, physical and biological properties of water
	Water temperature	Surface water temperature
	Wildlife diversity	Abundance and richness of wildlife species valued by the community
	Wildlife health	General health of wildlife species valued by the community (diseases, fat reserves, parasites)
Impacts on landscape practices: • Moose hunting • Goose hunting • Trapping • Fishing • *Ressourcement* • Education	Abundance	Quantity of landscape features (material or immaterial), necessary for the satisfactory achievement of a landscape practice
	Access	Ease with which a landscape feature can be reached or obtained in the course of a landscape practice
	Quality	Characteristics of a landscape feature and its capacity to satisfy a need or to fulfil a function of a landscape practice
	Experience	Emotional response, positive or negative, associated with a landscape practice

with wildlife health ($i = 5$), naturalness ($i = 4$), tree species composition ($i = 4$), water quality ($i = 3$) and ground condition ($i = 2$). Contaminant release ($\Sigma i_{sus} = 18$, $\Sigma i_{inf} = 6$), either from abandoned mining sites or from harvesting operations, was associated with wildlife health ($i = 3$) and water quality ($i = 3$). Mineral extraction ($\Sigma i_{sus} = 6$, $\Sigma i_{inf} = 4$) was associated with mine tailings ($i = 2$), naturalness ($i = 1$) and transportation ($i = 1$). Wildfires ($\Sigma i_{sus} = 0$, $\Sigma i_{inf} = 1$) can increase naturalness, as long as they are not followed by salvage logging ($i = 1$). Changes in species distribution ranges ($\Sigma i_{sus} = 13$, $\Sigma i_{inf} = 8$) was associated with wildlife health because of parasites and diseases dispersion ($i = 5$), and predator abundance ($i = 3$). Weather events and season changes ($\Sigma i_{sus} = 7$, $\Sigma i_{inf} = 1$) was associated with ice condition ($i = 1$). Electricity transportation ($\Sigma i_{sus} = 12$, $\Sigma i_{inf} = 5$) was associated with the health of wildlife that lived and fed under powerlines ($i = 3$), cultural places ($i = 1$) and goose landing areas ($i = 1$).

4.1.3 | States–Impacts

Eighteen States emerged from the interviews with the Indigenous land-use experts (Table 1). Affluence ($\Sigma i_{sus} = 20$, $\Sigma i_{inf} = 35$) was associated with all six landscape practices, especially moose hunting ($i = 7$ for abundance, $i = 6$ for experience) (Figure 6). Forest age structure ($\Sigma i_{sus} = 17$, $\Sigma i_{inf} = 31$) was associated with the abundance of moose (for moose hunting) ($i = 16$) and furbearers (for trapping) ($i = 11$). Naturalness ($\Sigma i_{sus} = 22$, $\Sigma i_{inf} = 24$) was associated with moose hunting ($i = 5$ for abundance and $i = 4$ for experience) and *ressourcement* ($i = 8$) for abundance. Road network density ($\Sigma i_{sus} = 10$, $\Sigma i_{inf} = 21$) was associated with access to moose hunting ($i = 3$), trapping ($i = 4$) and education ($i = 6$) sites. The association was perceived as positive when facilitating access to the land for short trips, but as a limitation when non-Indigenous recreational hunters used the roads to appropriate parts of the land. Wildlife health ($\Sigma i_{sus} = 13$, $\Sigma i_{inf} = 13$) was associated with fish abundance ($i = 3$) and quality ($i = 3$) (for fishing), moose abundance ($i = 3$), moose quality ($i = 4$) (for moose hunting) and beaver quality ($i = 3$) (for trapping). Wildlife diseases included excessive thinness, parasites (especially ticks), and flesh alteration (colour, texture). Water quality ($\Sigma i_{sus} = 11$, $\Sigma i_{inf} = 1$) was associated with fish abundance ($i = 3$) and quality ($i = 3$) and with educational activities ($i = 2$ for experience).

Ground condition ($\Sigma i_{sus} = 8$, $\Sigma i_{inf} = 11$) was associated with land walkability and the ability to travel with a snowmobile when the snow layer is not yet thick enough for trapping ($i = 3$) and moose hunting ($i = 2$) (Figure 6). Tree composition ($\Sigma i_{sus} = 5$, $\Sigma i_{inf} = 7$) was associated with the quality of trapped wildlife ($i = 5$). Transportation of wood and minerals by truck ($\Sigma i_{sus} = 9$, $\Sigma i_{inf} = 7$) was reported as a noisy and dangerous disturbance affecting *ressourcement* (quality) ($i = 3$). Wildlife diversity ($\Sigma i_{sus} = 5$, $\Sigma i_{inf} = 5$) was considered important for educational purposes ($i = 5$). The abundance of cultural places ($\Sigma i_{sus} = 3$, $\Sigma i_{inf} = 4$) such as old portages and graves was associated with education ($i = 3$). Predators ($\Sigma i_{sus} = 3$, $\Sigma i_{inf} = 3$) were considered competitors for beaver trapping ($i = 3$), whereas spawning areas ($\Sigma i_{sus} = 2$, $\Sigma i_{inf} = 2$) were considered necessary for maintaining fish populations, especially lake sturgeon and walleye ($i = 2$). Increased water temperature ($\Sigma i_{sus} = 2$, $\Sigma i_{inf} = 2$) caused by windthrow on shorelines was associated with lower fish abundance ($i = 2$). Ice conditions ($\Sigma i_{sus} = 1$, $\Sigma i_{inf} = 1$) and mine tailings ($\Sigma i_{sus} = 2$, $\Sigma i_{inf} = 1$) was associated with goose hunting, the first affecting the access to hunting sites ($i = 1$) and the second providing hunting sites themselves ($i = 1$). Additional explanations and interview excerpts are provided in Supplementary Material S4.

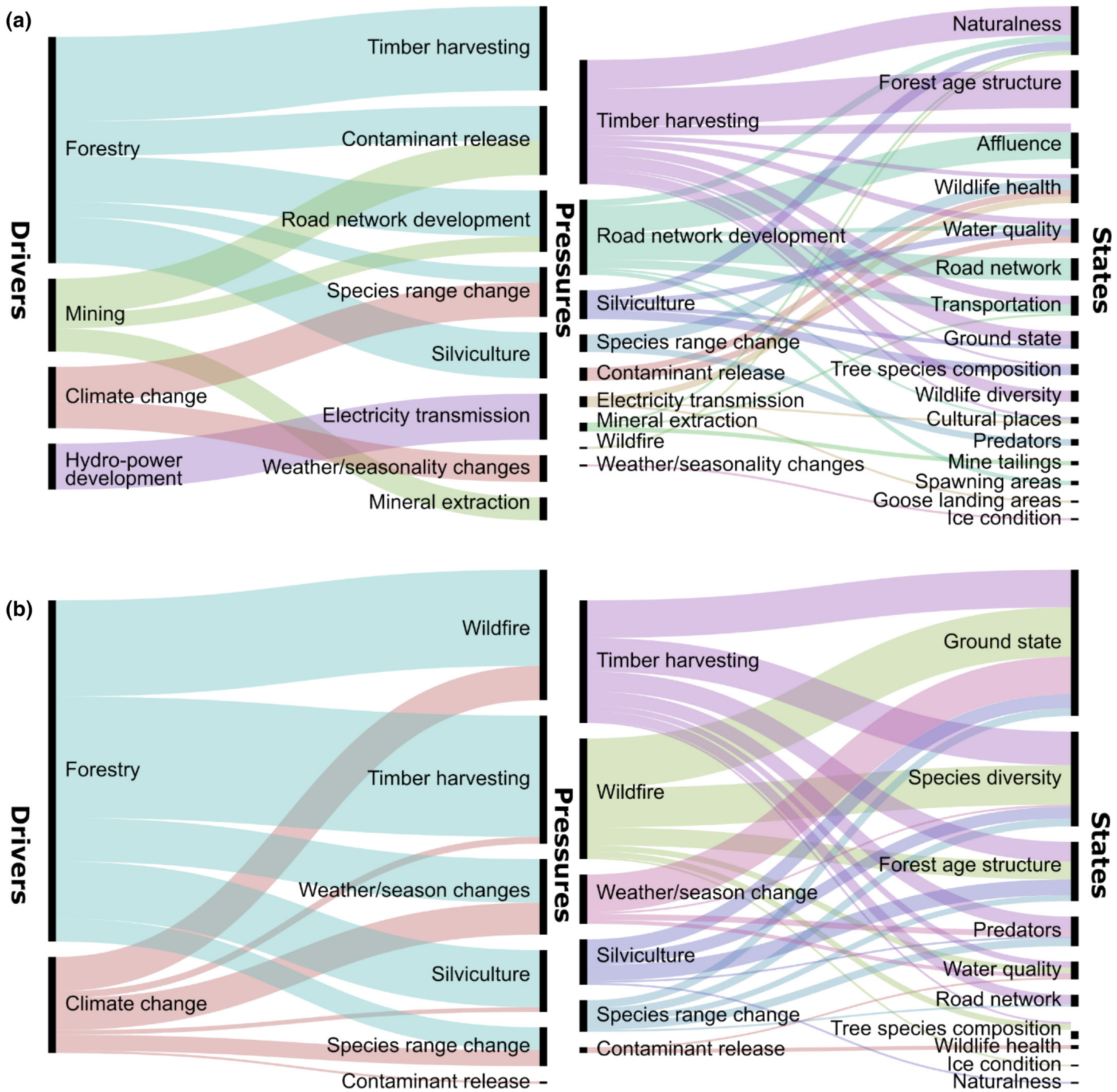

FIGURE 5 Driver–Pressure–State (DPS) conceptual models based on the perspectives of (a) the Indigenous land experts and (b) the scientific experts. Flow thickness is proportional to incidence (i). Node length (black lines) is proportional to influence (Σi_{inf}) when on the left side of the flows and to susceptibility (Σi_{sus}) when on the right side. Impacts are shown in Figure 6.

4.2 | Scientific DPS(I)

The bibliometric search led to the identification of 91 experts in at least one Driver–Pressure association, and 81 in at least one Pressure–State association.

4.2.1 | Drivers–Pressures

We identified expert scientists for two Drivers: forestry and climate change (Figure 5b). Experts associated forestry (Σi_{inf} = 149) with timber harvesting (i = 53), wildfire (i = 42), silvicultural treatments (i = 25), weather changes (i = 19) and species range changes (i = 10). Climate change (Σi_{inf} = 42) was associated with wildfire (i = 15), weather and season changes (i = 14), species range changes (i = 7), timber harvesting (i = 3), silvicultural treatments (i = 2) and contaminant release (i = 1).

4.2.2 | Pressures–States

We identified expert scientists for six Pressures (Figure 5b). Timber harvesting (Σi_{sus} = 56, Σi_{inf} = 62) had the greatest influence with associations with seven States: ground condition (i = 19), species diversity (i = 17), forest age structure (i = 10), predators (i = 7), road density (i = 5), water quality (i = 3) and tree species composition (i = 1). Wildfires (Σi_{sus} = 57, Σi_{inf} = 62) were associated with ground condition (i = 25),

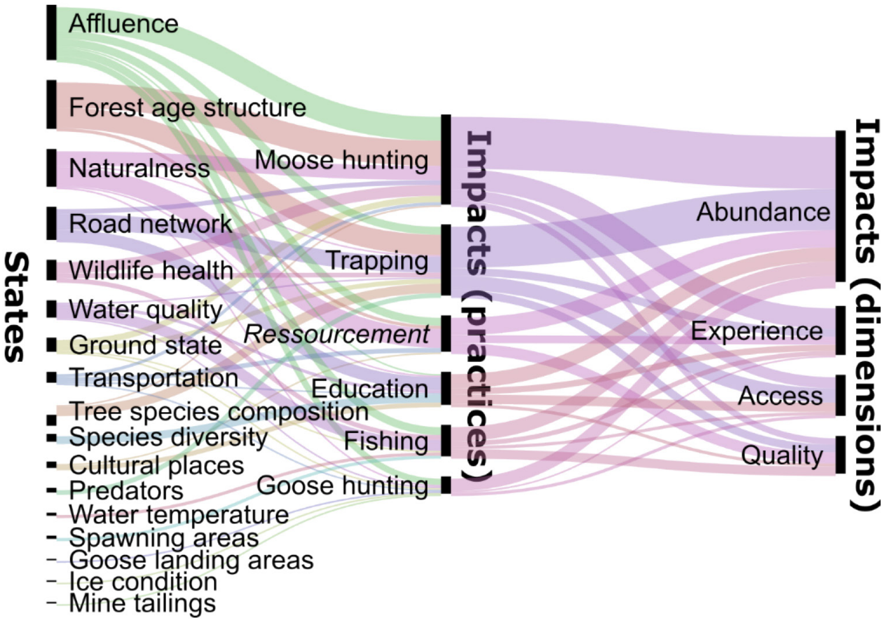

FIGURE 6 State-impact model from the Indigenous perspective. Impacts are reported for six landscape practices and four dimensions of landscape value (abundance, experience, access, quality). Flow thickness is proportional to incidence (i). Node length (black lines) is proportional to influence (Σi_{inf}) when on the left side of the flow and to susceptibility (Σi_{sus}) when on the right side.

species diversity ($i = 20$), forest age structure ($i = 9$), species composition ($i = 3$), water quality ($i = 3$) and ice conditions ($i = 1$). Weather and season changes ($\Sigma i_{sus} = 33$, $\Sigma i_{inf} = 25$) were associated with ground condition ($i = 19$), predators ($i = 7$), water quality ($i = 2$) and species diversity ($i = 1$). Silvicultural treatments ($\Sigma i_{sus} = 27$, $\Sigma i_{inf} = 23$) were associated with forest age structure ($i = 8$), ground condition ($i = 7$), species diversity ($i = 6$), naturalness ($i = 1$) and predators ($i = 1$). Species range change ($\Sigma i_{sus} = 17$, $\Sigma i_{inf} = 16$) was associated with ground condition ($i = 4$), predators ($i = 4$), species diversity ($i = 4$), forest age structure ($i = 3$) and road density ($i = 1$). Contaminant release ($\Sigma i_{sus} = 1$, $\Sigma i_{inf} = 16$) was associated with wildlife health ($i = 2$) and water quality ($i = 1$).

We identified expert scientists for 10 States (Figure 5b). Ground condition ($\Sigma i_{sus} = 74$) had the greatest susceptibility, associated with wildfire, timber harvesting, weather and season changes, silvicultural treatments and species range changes. Forest age structure ($\Sigma i_{sus} = 74$) was associated with timber harvesting, wildfire, silvicultural treatments and species range changes. Composition ($\Sigma i_{sus} = 4$) was associated with timber harvesting and wildfires. Ice condition ($\Sigma i_{sus} = 1$) was associated with wildfires. Naturalness ($\Sigma i_{sus} = 1$) was associated with silviculture. Predators ($\Sigma i_{sus} = 15$) were associated with timber harvesting, weather and season changes, silviculture and species range changes. Road density ($\Sigma i_{sus} = 6$) was associated with timber harvesting and species range changes. Species diversity ($\Sigma i_{sus} = 48$) was associated with all Pressures except contaminant release. Water quality ($\Sigma i_{sus} = 9$) was associated with timber harvesting, wildfire, weather and season changes and contaminant release. Wildlife health ($\Sigma i_{sus} = 2$) was associated with contaminant release.

4.3 | Convergence and divergence between perspectives

We compared the influence and susceptibility ranks for each Driver, Pressure and State, and we identified convergence and divergence between the Indigenous and scientific perspectives (Figure 7). We note here that references to the scientific literature, uncommon in a *Results* section, are direct outputs from the bibliometric search.

4.3.1 | Convergence

The primary influence of forestry as a Driver of boreal landscapes is common to the Indigenous and the scientific models. The influence of climate change on boreal landscapes is present in both models. From the Indigenous perspective, climate change was associated with wildlife distribution and weather. From the scientific perspective, climate change was mainly associated with wildfire activity (Flannigan et al., 2009; Terrier et al., 2013), weather and forest productivity (Grant et al., 2009; Rossi et al., 2014), and tree species distributions (Graignic et al., 2014; Housset et al., 2016).

Three Pressures had similar ranks in the Indigenous and scientific models. Timber harvesting ranked first in both the Indigenous and the scientific (equally with wildfire) models. In the Indigenous model, timber harvesting was associated with landscape practices through terrestrial and aquatic ecosystem alteration, increased affluence and timber transportation by trucks and loss of naturalness. From the scientific perspective, timber harvesting affects forest soils (e.g. Brais et al., 2013; Simard et al., 2001), species diversity of a variety of taxa (e.g. Nappi et al., 2004; Paradis & Work, 2011), and forest age structure (Bélisle et al., 2011; Cyr et al., 2009) and composition (Boucher et al., 2014; Dupuis et al., 2011).

Indigenous experts reported negative effects of silviculture. They shared concerns about ground bumpiness and the development of contaminated ponds after soil preparation for tree planting. They reported a loss of naturalness in plantations, and observed water contamination downstream. In contrast, scientific experts were interested in using silviculture to increase stand productivity (Bilodeau-Gauthier et al., 2011; Thiffault et al., 2013), enhance

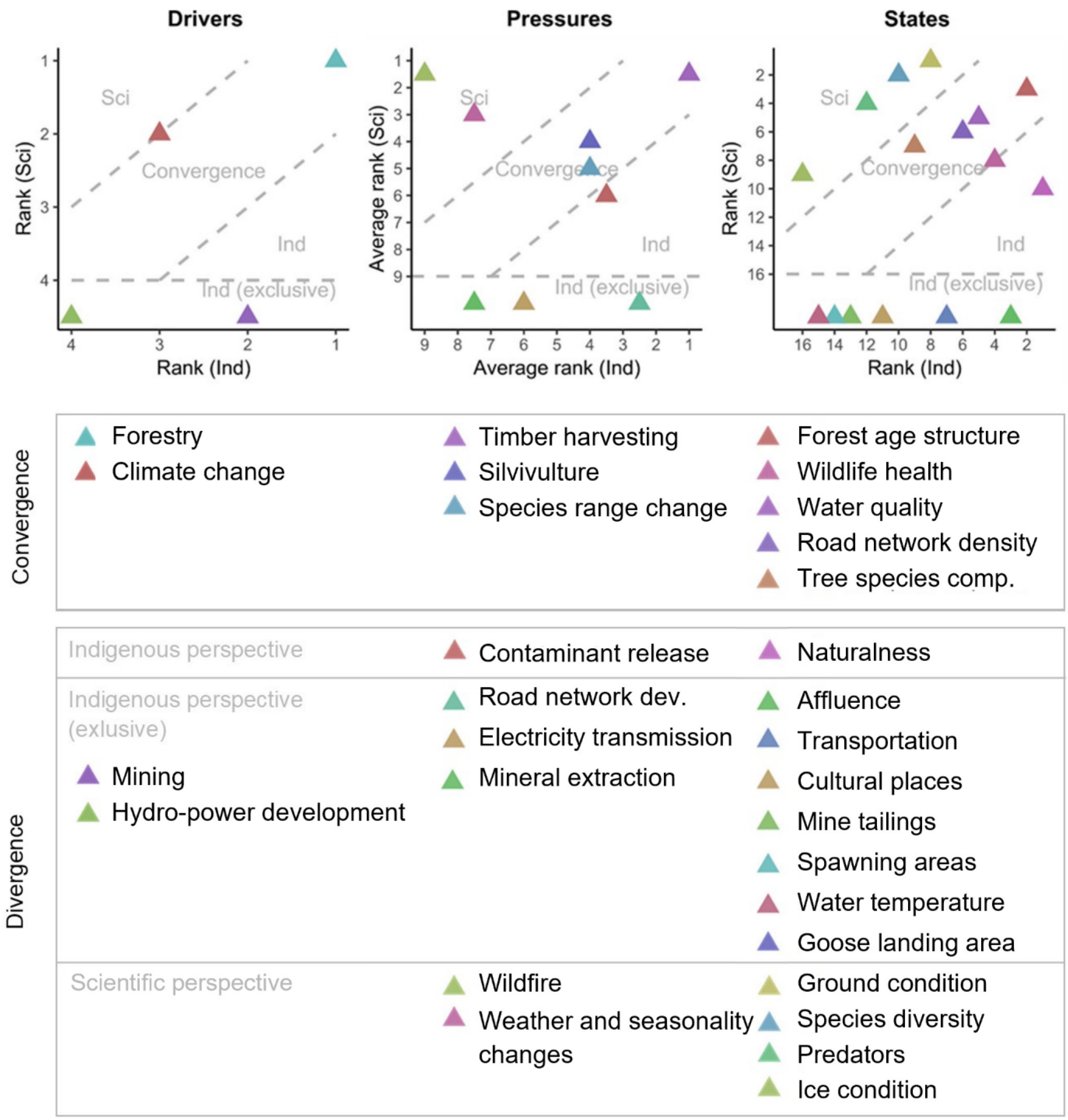

FIGURE 7 Convergence and divergence between the Indigenous (Ind) and the scientific (Sci) perspectives. Drivers are compared based on Σi_{inf} rank. Pressures are compared based on the average of Σi_{sus} and Σi_{inf} ranks. States are compared based on Σi_{inf} rank. The closer the dots are to the diagonal, the more convergence there is between the Indigenous and scientific perspectives for a given variable. Dots above the diagonal indicate greater interest from the scientific perspective and dots below the diagonal indicate greater interest from the Indigenous perspective. Variables that are absent from the scientific model are shown in the 'Ind exclusive' area at the bottom of the plots.

forest resilience and carbon sequestration (Tremblay et al., 2013; Van Bogaert et al., 2015) and restore old-growth attributes to recover diversity in managed landscapes (Fenton et al., 2009; Hodson et al., 2012).

Changes in the range of wildlife species range changes were reflected in both the Indigenous and the scientific models. Indigenous experts reported fine-scale observations of mammals, fishes and birds they encountered in unusual places. Some reported increased sightings of bald eagles (*Haliaeetus leucocephalus*, *MiKiSi*, *mikisow*). Others worried about the northward expansion of white-tailed deer (*Odocoileus virginianus*, *WAWACKECi*, *âpisimôsos*), threatening moose populations with diseases. One participant shared concerns about the loss of mice and other small wildlife habitats in harvested forests. From the scientific perspective, researchers were interested in the availability of deadwood habitat in managed forests (Aakala et al., 2008; Déchêne & Buddle, 2010) and in the sensitivity of tree species to climate change and wildfire (Bergeron et al., 2004; Pilon & Payette, 2015).

Five States had similar ranks in the Indigenous and scientific models. Forest age structure ranked high in both models. Experts from Indigenous communities reported an excess of regenerating forests due to harvesting with effects on hunting and trapping, as well as on the general experience out on the land. Scientific experts also considered the depletion of old-growth forests in managed landscapes as a threat to boreal biodiversity and resilience (Kuuluvainen & Gauthier, 2018; Tremblay et al., 2018). Indigenous experts reported changes in tree species before and after harvesting and tree planting. They also reported a takeover of forest road borders by broadleaved species (trembling aspen). From the scientific perspective, composition transition from coniferous to broad-leaved forests in managed forests was a concern as well (Danneyrolles et al., 2016; Laquerre et al., 2011).

Road network density ranked high in both models, but for different reasons. Some experts from Indigenous communities mentioned that road density threatened beaver populations and interrupted the connection with the land because of noise and affluence. They mentioned the necessary balance to be found between facilitating access while keeping in check the negative consequences of increasing road density. From the scientific perspective, most experts studied landscape fragmentation (Croke & Hairsine, 2006), and woodland caribou and wolf (*Canis lupus*, *MAiKAN*, *mahihkan*) dynamics (Lesmerises et al., 2012; St-Laurent et al., 2009). A few experts addressed the social consequences of forest roads (Asselin, 2011; Kneeshaw et al., 2010).

Water quality was a concern in both Indigenous and scientific perspectives. Some experts from Indigenous communities lived in areas contaminated by abandoned mines (Ministère de l'Environnement du Développement Durable et des Parcs du Québec, 2008). They had to buy drinking water and could not eat fish from contaminated areas. Lake eutrophication was also reported and attributed to road building and salvage logging upstream. Some experts mentioned oil leaks and stream contamination after forest harvesting. Scientific experts were interested in the effects of forest harvesting on hydrology (Tremblay et al., 2009) and lake ecology (Pinel-Alloul et al., 2002). Scientific experts also studied water and wildlife contamination by heavy metals (Montgomery et al., 2000). Wildlife health was a particular case of convergence because most of the scientific articles that came out from the bibliometric search resulted from collaborative research with Indigenous communities.

4.3.2 | Divergence–Indigenous perspective

Mining and hydroelectric development were two Drivers exclusive to the Indigenous perspective. Although the consequences of mining on the environment are widely acknowledged in the academic literature (Bridge, 2004; Dudka & Adriano, 1997) and conflicts between mining companies and Indigenous Nations are numerous (Hilson, 2002), no scientific expert of the association between mines and landscape processes was identified. The influence of hydro-electric development was also specific to the Indigenous perspective and to a few hunting grounds crossed by high-voltage powerlines.

Road development, mineral extraction and electricity transmission were Pressures exclusive to the Indigenous perspective. Land-use experts mentioned conflicts associated with increased affluence, impairment of naturalness and threats to water quality caused by erosion, bridges and culverts. Some scientific experts described the cascading effects of road development on boreal landscapes (e.g. Kneeshaw et al., 2010) but did not cumulate enough publications to be considered as experts. Mineral extraction was associated with mine tailings and with a loss of naturalness. Electricity transmission raised suspicions regarding the edibility of food growing underneath power lines, even if the usage of chemicals for vegetation control is forbidden in the region. Contaminant release ranked high in the Indigenous model but low in the scientific model. Most scientific research that came out from the bibliometric search was performed in Indigenous contexts, in collaboration with the communities (Tsuji et al., 2007; Valera et al., 2011).

Eight States were more prevalent in the Indigenous model, among which seven were absent from the scientific model. Affluence and transportation were shared concerns among land-use experts. Affluence limited the access and experience associated with landscape practices. Safety and noise problems were associated with wood transportation by trucks. Cultural places such as old portages and graves were reportedly altered or destroyed by industrial development, especially forest harvests and transmission lines. The increase in water temperature caused by windthrow in riparian areas and the state of goose landing areas were also specific to the Indigenous model.

4.3.3 | Divergence–Scientific perspective

Wildfires were more prominent in the scientific model. Fire regimes are studied to set benchmarks for ecosystem-based management aiming to maintain forest ecosystems within their natural range of variability (Bergeron et al., 2006; Vaillancourt et al., 2009). Increased fire activity is expected due to climate change (Boulanger et al., 2013), with substantial research efforts dedicated to better understand fire hazards and ecology (Portier et al., 2016; Terrier et al., 2013). Conversely, few experts from Indigenous communities reported the effects of wildfires although they are frequent in the study area. Some conceived them as forest rejuvenating processes rather than threats to landscape value. Weather and season changes also received greater attention in the scientific model. Experts were interested in the association between soil temperature and moisture and tree growth (Gewehr et al., 2014; Lupi et al., 2012) and in carbon sequestration (Miquelajauregui et al., 2019). Some experts studied the effects of weather and season changes on wildlife habitats (Beauchesne et al., 2014; Lafontaine et al., 2017), hydrology (Proulx-McInnis et al., 2013) and lake ecology (Fauteux et al., 2015).

Ground condition ranked first among all States in the scientific model. Ground and soil studies are at the intersection of various research fields. Foresters (Laamrani et al., 2014; Trottier-Picard et al., 2016), plant physiologists (Dao et al., 2015; Deslauriers & Morin, 2005), fire scientists (Portier et al., 2019; Schaffhauser et al., 2017) and pedologists (Bélanger et al., 2003; Paré et al., 2011) all take forest soils into account in their research. Species diversity is studied by community and conservation ecologists (Boudreault et al., 2018; Cadieux & Drapeau, 2017; Work et al., 2013). Experts on predators were especially interested in the conservation of woodland caribou, a vulnerable species in boreal Quebec (Boisjoly et al., 2010; Lesmerises et al., 2012).

5 | DISCUSSION

When looking critically all the findings reported in Section 4, Indigenous land-use experts and researchers seem to look at the same biophysical landscape but through different lenses. In this section, we discuss the Drivers of environmental changes in boreal landscapes according to both perspectives, we explore opportunities for collaborative research based on perspective convergence and divergence, and we formulate recommendations for future research.

5.1 | Drivers of environmental changes

Forestry had the greatest influence on boreal landscapes from both the Indigenous and the scientific perspectives. The primary influence of forestry from the Indigenous perspective is consistent with previous research in North America (Adam et al., 2012; Saint-Arnaud et al., 2009) and Fennoscandia (Sandström et al., 2016). Environmental changes which stem from forestry are extensive, affect most hunting grounds and a variety of forest values. From the scientific perspective, the primary influence of forestry is associated with research efforts dedicated to assessing the influence of forestry on ecosystems in the 1990s–2000s, along with the development of sustainable management practices (Angelstam & Kuuluvainen, 2004; Gauthier et al., 2009; Klenk & Hickey, 2009). The prevalence of climate change in the Indigenous model was lower than expected based on previous research (Cuerrier, Brunet, et al., 2015; David-Chavez & Gavin, 2018; Turner & Clifton, 2009). This can be explained by the lower latitude of our study area compared with other studies that were performed in Arctic and Subarctic environments where climate change is more acute (Ford et al., 2008; Furgal & Seguin, 2006; Royer & Herrmann, 2013). Moreover, as the Ouje-Bougoumou and Abitibiwinni hunting grounds are located inland and have a dense network of forest roads, access to the land is less vulnerable to climate change than in coastal or remote communities that rely on ice for transportation (Tremblay et al., 2006).

The absence of mining from the scientific model could be explained by the fact that studies on acid drainage (Bussière, 2010; Reid et al., 2009), forest and lake recovery near mining sites (Alpay et al., 2006; Hamilton et al., 2015; Larchevêque et al., 2014) and the effects of mining on quality of life (Fuentes et al., 2020) did not consider the effects on landscape processes and states. The influence of hydro-electric development was also absent form the scientific model. This is because most of the research effort was done in the 1970s and 1980s when dams and reservoirs were developed in James Bay (Quebec), affecting Cree populations (Feit, 1979, 1985; Niezen, 1993). Comparatively, few research projects on the impact of hydropower facilities were done since 2000 (Rood et al., 2005).

5.2 | Collaboration opportunities

Our results showed that environmental changes are a major concern from both the perspectives of Indigenous and scientific communities. Mitigation and adaptation strategies are needed to maintain the capacity of boreal landscapes to sustain Indigenous and other forest values and uses. To this end, strategies emerging from collaborative research would benefit from knowledge complementarity and find higher legitimacy within the respective communities (Wong et al., 2020).

Convergences between the Indigenous and scientific perspectives can be good starting points for new collaborations (Robinson & Wallington, 2012). Issues related to wildlife have been fertile grounds for collaborative research in the sturdy area. Studies with Cree and Anishnaabe communities improved the understanding of moose habitat quality (Jacqmain et al., 2008; Tendeng et al., 2016). The knowledge of local trappers (Indigenous and non-Indigenous) led to the formulation of research hypotheses about marten and fisher (*Pekania pennanti*, *ODCiK*, *uchaak*) habitat use (Suffice et al., 2017) that were tested in a research project based on wildlife ecology methods (Suffice et al., 2020). Wildlife monitoring by local populations has reportedly been an important source of information to address the effects of environmental changes (Ban et al., 2018), as evidenced through caribou monitoring by Cree and Naskapi communities (Herrmann et al., 2014). The consequences of environmental contamination for wildlife and human health were also the focus of many other collaborative research projects (Bordeleau et al., 2016; Larose et al., 2008; VanSpronsen et al., 2007). Other converging interests that could be further explored through collaborative research include the impacts of the forest road network (Kneeshaw et al., 2010), timber harvesting and silviculture on boreal landscapes.

Divergences between Indigenous and scientific perspectives shed light on knowledge complementarity. Our results revealed that on the one hand, Indigenous experts possess a deep ecological knowledge of topics that have not yet received much attention from the scientific community. They knew precisely where and when fish species spawn, and were able to locate seasonal moose habitat according to vegetation and topography (Jacqmain et al., 2008). They described with precision the spatial progression of a moose parasite in the region (*Dermacentor albipictus*) and located ancient trails and portages with patrimonial and historical value. On the other hand, researchers have used remote sensing and modelling to study large-scale phenomena such as the historical decrease in the proportion of old-growth forests throughout the managed boreal zone in Quebec (Cyr et al., 2009), an ecotone shift between closed boreal forest and open woodlands (Girard et al., 2008) and a risk of biome transitions due to environmental changes (Gauthier et al., 2015; Johnstone et al., 2010). The complementarity between Indigenous and scientific knowledge needs to be explored further, as shown in other regions of Canada (Abu et al., 2019; Mantyka-Pringle et al., 2017), New-Zealand (Lyver et al., 2018) and Australia (Liedloff et al., 2013). Mixed-method research designs combining qualitative and quantitative methods are especially well suited to bridge perspectives at all steps of a research project (Bélisle, 2022; Cuerrier, Brunet, et al., 2015; Cuerrier, Turner, et al., 2015; Taghipoorreyneh & de Run, 2020). Methods from ecological modelling that are designed to integrate expert knowledge such as Bayesian networks or fuzzy rule-based models also have great potential to integrate meaningfully different sources of knowledge (Bélisle et al., 2018).

5.3 | Implications and recommendations

Four recommendations to foster Indigenous and scientific knowledge conciliation arose from this research. First, our research design faced certain limitations that will need to be addressed in future collaborative research. For instance, women were underrepresented among the Indigenous experts that took part in our study. The lack of women is a chronic issue in participatory studies in environmental sciences that aim to bridge Indigenous and scientific knowledge systems (Alexander et al., 2019). Designs dedicated to elicit women perspectives such as workshops led by women from the community will be necessary to fill gaps in such research and access the 'whole story' (Basile et al., 2017; Kim et al., 2013). Our method for quantifying associations in the DPSI was based on the number of experts who mentioned (or published on) them. This provided an overview of the incidence of environmental changes but it did not address their strength. Further research would be needed to differentiate infrequent but acute changes from common but lighter environmental changes.

Second, the involvement of community co-researchers in the research design, as well as in the elicitation and interpretation of local experts' knowledge, was essential for the success of this collaborative research. Community-based research institutions and dedicated human resources in the long term are key to maintaining fruitful research partnerships (Bohensky & Maru, 2011; Reid et al., 2016; Robinson & Wallington, 2012). The *Chisasibi Eeyou Resource and Research Institute* (Cree Nation) (refer to www.cerri.ca/) and the *Bureau Ndakina* (refer to https://gcnwa.com/bureau-du-ndakina/) (Wabanaki Nation) are eloquent examples of dynamic Indigenous research agencies. Funding programs committed to increase research capacity within Indigenous communities would help multiplying such initiatives.

Third, researchers need to avoid 'disciplinary silos' by addressing simultaneously the ecological, geological, social and cultural aspects of environmental changes (Castleden et al., 2017; Termorshuizen & Opdam, 2009; Tress & Tress, 2001). The *Delta Dialogue Network* is an example of a transdisciplinary partnership that addressed environmental issues for three river deltas in Canada. The collaboration revealed fruitful in knowledge sharing and co-creation (Abu et al., 2019; Bradford & Bharadwaj, 2015; Mantyka-Pringle et al., 2017).

Fourth, addressing the underrepresentation of Indigenous researchers in universities and scientific institutions is a critical step towards knowledge conciliation (Castleden et al., 2017; Littlechild et al., 2021; McGregor, 2018). To the best of our knowledge, among all the researchers that came out of our bibliometric search, none was Indigenous. Thus, efforts would be needed to increase the cultural relevance of university curricula and to enhance the representation of Indigenous students in scientific training programs (Bartlett et al., 2012).

6 | CONCLUSION

This research proposed a framework to integrate Indigenous and scientific knowledge about environmental changes, using the boreal landscape of Quebec as a case study. Our findings showed that Indigenous and scientific communities have different perspectives on the effects of environmental changes. The Indigenous perspective was characterized by a broad and diversified scope of impacts, ecosystems and interactions, with a focus both on cultural and provisioning landscape values. Alternatively, the scientific perspective was strongly oriented towards the effects of disturbances from forestry and climate change on forest ecosystems, witnessing a research effort driven by ecosystem-based forest management. The differences between perspectives underline the crucial role of Indigenous communities in seeking the balance between the economic development of the land and the consequences on people's lives.

Although collaborative approaches such as *two-eyed seeing* are increasingly valued to bridge Indigenous and scientific knowledge systems, applied examples remain few. The method we developed based on expert knowledge and DPSI conceptual models could be applied to impact assessments and collaborative research in other social-ecological contexts where multiple and potentially conflicting perspectives on the land are both relevant and at stake.

AUTHOR CONTRIBUTIONS

Annie Claude Bélisle, Sylvie Gauthier and Hugo Asselin conceived the ideas and designed the methodology; Annie Claude Bélisle collected the data; Annie Claude Bélisle, Sylvie Gauthier and Hugo Asselin validated the bibliometric data; Annie Claude Bélisle, Sylvie Gauthier and Hugo Asselin analysed the data; Annie Claude Bélisle led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

Authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Datasets (agglomerated for confidentiality), Scopus® outputs and R codes can be found in an open-access repository (refer to https://github.com/acbelisle/Perspectives-of-environemental-change).

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ENDNOTES

[1] Species names are presented in English, Latin, Anishnaabemowin and Cree (Iyniwayamiwin) in this specific order.

[2] The DPSI is a simplified version of the Drivers-Pressures-States-Impacts-Responses framework(DPSIR). In this study we have omitted the Responses (R) level as we considered that assessing the responses to change and their feedback on Drivers would be another research project altogether. We thus focused on the DPSI components, as exemplified by Camilleri et al. (2015).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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