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Critical Review

A State-of-the-Art Review of Indigenous Peoples and Environmental Pollution

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ABSTRACT

Indigenous peoples (IPs) worldwide are confronted by the increasing threat of pollution. Based on a comprehensive review of the literature (n = 686 studies), we present the current state of knowledge on: 1) the exposure and vulnerability of IPs to pollution; 2) the environmental, health, and cultural impacts of pollution upon IPs; and 3) IPs' contributions to prevent, control, limit, and abate pollution from local to global scales. Indigenous peoples experience large burdens of environmental pollution linked to the expansion of commodity frontiers and industrial development, including agricultural, mining, and extractive industries, as well as urban growth, waste dumping, and infrastructure and energy development. Nevertheless, IPs are contributing to limit pollution in different ways, including through environmental monitoring and global policy advocacy, as well as through local resistance toward polluting activities. This work adds to growing evidence of the breadth and depth of environmental injustices faced by IPs worldwide, and we conclude by highlighting the need to increase IPs' engagement in environmental decision-making regarding pollution control. *Integr Environ Assess Manag* 2020;16:324–341. © 2019 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION

Global levels of pollution are increasing in many parts of the world, generating pernicious impacts upon both ecological and human health (Rockström et al. 2009; UNEP 2017). Exposure to environmental pollution (Landrigan et al. 2018) is the largest environmental cause of disease, responsible for >9 million premature deaths worldwide in 2015, although according to some research this number is considered an underestimate of the true health impacts of pollution (Landrigan et al. 2016; WHO 2016).

Recent international political agreements have emphasized the need to control and abate environmental pollution. For example, the theme of the 2017 United Nations Environment Assembly meeting was "Towards a Pollution-Free Planet." Similarly, the Aichi Target 20 of the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 aims to bring pollution to levels that are not detrimental to ecosystem functioning and biodiversity by 2020. Finally, the Sustainable Development Goals stress the urgency of addressing environmental pollution at the global level in several of its targets (Landrigan et al. 2018).

While environmental pollution is a global concern, its impacts are unequally distributed, with low-income and/or marginalized communities (particularly in urban and semi-urban settings) experiencing disproportionate burdens

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(Taylor 2014; Hajat et al. 2015). For instance, a meta-analysis of environmental pollution across 2083 US counties revealed that toxic releases increase as a function of the number of local minorities (Allen 2001). On a global scale, the Lancet Commission on Pollution and Health concluded that >90% of pollution-related deaths occur in low- and middle-income countries (Landrigan et al. 2018).

Among populations vulnerable to pollution, indigenous peoples (IPs) are of particular concern. Though IPs make up only around 5% of the global population, they account for >15% of the extreme poor (UNPFII 2016), lagging behind other population groups on nearly every social and economic indicator. Research suggests that this socioeconomic situation is most likely the direct consequence of colonization and historical exclusion (Morton 2007; Maru et al. 2014). For example, under colonial rule, many polluting infrastructures (e.g., mines, pipelines, waste incineration facilities) were built without the free, prior, and informed consent (FPIC) of affected communities; thus, pollution was displaced from colonial powers to colonized areas (Dokis 2015; Parfitt 2017). Moreover, the impacts of environmental pollution for IPs go beyond health impacts. For example, as a healthy ecosystem is essential for IPs' sociocultural wellbeing, the presence of pollution in wildlife or water has forced many individuals to shift away from traditional lifestyles (Hoover et al. 2012).

While the number of studies examining the impacts of environmental pollution upon IPs is growing (Brugge and Gobble 2002; Curren et al. 2015), most of this research is isolated and fragmented across disciplines and geographic regions. Few efforts have cut across disciplinary topics or regions (e.g., pollution in Arctic traditional foods [Kuhnlein and Chan 2000]; water, sanitation, and IPs [Jiménez et al. 2014]), and there is no global review that maps out the worldwide impacts of environmental pollution on IPs. Accordingly, this study aims to present the current state of knowledge on: 1) the burden that pollution imposes on IPs; 2) the environmental, health, and cultural impacts of pollution upon IPs; and 3) IPs' contributions to prevent, limit, and abate pollution.

METHODS

We conducted an extensive review of scholarly papers, books, book chapters, doctoral theses, government and technical reports, and other grey literature examining different environmental pollution impacts on IPs. Following Garnett et al. (2018), we used the International Labour Organization's definition of IPs throughout the paper (ILO 1989). We used the Lancet Commission's definition of pollution (Landrigan et al. 2018). In the context of this paper, "impacts" are understood as any noticeable effects or changes wholly or partially resulting from the spread of environmental pollution. We focus on: 1) environmental impacts, defined as any pollution-induced changes in the local environment (including land, water, and biota); 2) health impacts, or the changes in the health of a specific community resulting from continued exposure to environmental pollution; and 3) cultural impacts, or changes in a community's lifestyle, traditions, knowledge, practices, and/or beliefs, driven by the exposure to environmental pollution. Given that most of the reviewed documents did not define any specific thresholds for defining impacts, we considered that there was an impact when this was explicitly described as such in the original source.

Our methodological approach consisted of 3 sequential steps (see Supplemental Data) that resulted in a final sample of 686 different publications and 367 case studies, providing the most comprehensive review of pollution impacts on IPs at the global level. Although we do present some bibliometric analyses, our objective was not to perform a quantitative assessment of the literature but rather to situate pollution burdens on IPs in the context of growing research on global environmental justice. We take a critical approach inspired by environmental justice scholarship, responding to recent calls to expand the analytical focus of systematic reviews and better integrate qualitative insights (Sterling et al. 2017a).

RESULTS

Overview of studies

Geographic patterns. The impacts of environmental pollution have been documented among 141 different indigenous groups from all inhabited continents. Table 1 shows the 20 indigenous groups for whom there is the largest body of evidence documenting the impacts of pollution. Interestingly, 50.7% of all studies linking pollution and IPs have been conducted among only 15 different indigenous groups, with the Inuit from the circumpolar region (31 studies), and the Cree (23) and the Ojibwe (21) in North America being the groups with the most available documentation.

A large share of the documented evidence of the impacts of pollution upon IPs comes from North America (47%; 156 cases) and South America (27%; 99 cases), with strong research foci on the Arctic (Paunescu et al. 2013; Binnington et al. 2016; Krümmel and Gilman 2016) and the Amazon (da Silva Brabo et al. 2000; Rosell-Melé et al. 2018) (Figure 1). Research on pollution and IPs in Africa is relatively meager (11%; 41 cases), with most of it coming from the Niger Delta region; there is limited information for the rest of the continent. Basu et al. (2018) documented similar geographic patterns on a state-of-the-science review of Hg biomarkers.

Pollutants. In our review of 324 case studies, we were able to identify at least 21 different chemical pollutants of concern for IPs (Table 2). These pollutants largely separate into 3 main categories: heavy metals (e.g., Pb, Hg), persistent organic pollutants ([POPs] e.g., organochlorines, PAHs) and others (e.g., asbestos, endocrine disruptors). Each of the identified pollutants has been documented to be of human health concern, and here we focus on the most compelling cases that involve IPs.

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Table 1. Indigenous groups in which pollution impacts have been most extensively documented[a]

Rank	Group	Geographic area	Documented evidence		
			Number of studies	% of total	Cumulative %
1	Inuit	Canada, Greenland, USA	31	8.18%	8.18%
2	Cree	Canada, USA	23	6.07%	14.25%
3	Ojibwe	Canada, USA	21	5.54%	19.79%
4	Dene	Canada	20	5.28%	25.07%
5	Métis	Canada, USA	15	3.96%	29.02%
6	Mohawk	Canada, USA	13	3.43%	32.45%
7	Achuar	Ecuador, Peru	10	2.64%	35.09%
8	Ogoni	Nigeria	10	2.64%	37.73%
9	Quechua	Argentina, Bolivia, Chile, Colombia, Ecuador, Peru	9	2.37%	40.11%
10	Dayak	Indonesia, Malaysia	8	2.11%	42.22%
11	Saami	Finland, Norway, Rusasia, Sweden	7	1.85%	44.06%
12	Maya	Belize, El Salvador, Guatemala, Honduras, Mexico	7	1.85%	45.91%
13	Navajo	USA	7	1.85%	47.76%
14	Kichwa	Colombia, Ecuador, Peru	6	1.58%	49.34%
15	Aymara	Argentina, Bolivia, Chile, Peru	5	1.32%	50.66%
16	Mapuche	Argentina, Chile	4	1.06%	51.72%
17	Sioux	Canada, USA	4	1.06%	52.77%
18	Urarina	Peru	4	1.06%	53.83%
19	Yupik	Russia, USA	4	1.06%	54.88%
20	Wayuu	Colombia, Venezuela	4	1.06%	55.94%

[a]Both percentages refer to the total number of studies identified in the literature review.

Sources of pollution. Indigenous peoples are exposed to numerous polluting activities, most of which are linked to agriculture, extractive operations, urban growth, and industrial development.

Oil and gas extraction and development. This category includes exploration, fracking and extraction operations, and pipeline transport, and is the source of considerable amounts of pollution in many IP lands (Cepek 2002; Dana et al. 2008; Pristupa et al. 2018). Although there is no global database on the impacts of oil releases on indigenous communities, well-known cases featured in the media include the Exxon Valdez oil spill that affected Chugach hunting grounds in Alaska, resulting in a nearly 50% drop in hunting (Burger 1997; O'Rourke and Connolly 2003) or the infamous oil spills in Ogoniland (Osuagwu and Olaifa 2018). Our review of the literature indicates that there are many other documented examples of water contamination resulting from direct release on rivers of deep waters extracted during petroleum exploitation (Moquet et al. 2014; Barraza et al. 2018). In Peruvian Amazonia, downstream of several oil spills, 64% of children <10 years old showed levels of Hg higher than recommended limits (O'Callaghan-Gordo et al. 2018).

Mineral extraction. Both from large-scale industrial ore mining (Byrne et al. 2012) and local artisanal small-scale mining (Ashe 2012; Angosto-Fernández 2019), it is another major source of pollution in IP lands. Mineral extraction activities affect IPs who are participants or workers at mines (Kwaansa-Ansah et al. 2010; Basu et al. 2018), as well as in wider areas downstream from operations affected by tailings disposal, impacting indigenous water supplies (Shaw and Welford 2007; Daigle 2018). For example, the Ok Tedi mine in Papua New Guinea dumped 1 billion metric tons of tailings in local rivers used by the Yonggom (Kirsch 2007), and the Grassberg mine in Indonesian Papua has also resulted in substantial impacts upon the water resources used by the Amungme and the Kamoro peoples (Rifai-Hasan 2009). Several studies have documented pollution by Ni mining in waterways used by Kanak fishers in New Caledonia (Horowitz 2010; Lassila 2016). There is also a legacy of As deposition from mining and processing refractory Au ore at Giant Mine in Canada's Northwest Territories, which has

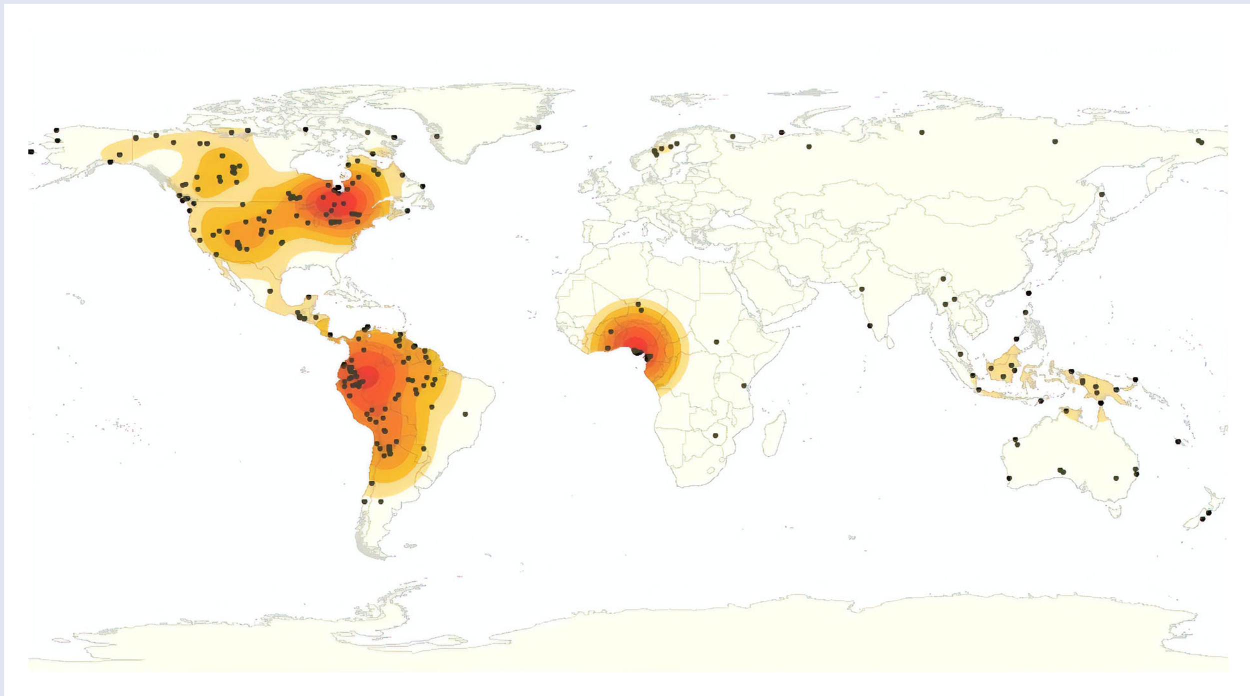

Figure 1. Distribution map of the case studies documenting pollution impacts upon indigenous peoples (n = 367) with Kernel density estimations.

had acute health impacts on the Yellowknives Dene First Nation (Keeling and Sandlos 2017).

Toxic waste dumping. Often this is done by multinational corporations or exported to developing countries (Adeola 2000). Hazardous waste siting, including incinerators and landfills, also seriously affects indigenous communities because such polluting infrastructures are often placed in their lands, either because their lands have unclear tenure status or because poverty has induced them to accept such facilities (Williams 1992; Sitkowski 1995; Gowda and Easterling 2000). Some of the most controversial nuclear waste facilities being imposed on IP lands include the cases of the Yami of Orchid Island in Taiwan (Chi 2001; Fan 2006), the Skull Valley reservation in Utah (Brook 1998), and the case of the Yucca Mountain Nuclear Waste Repository on the Western Shoshone lands (Thorpe 1996). Landfills are also an important problem in IP lands (Soliman et al. 1993; LaDuke 1999).

Industrial development. Long-distance transport of pollutants produced elsewhere through industrial processes or use has been documented in numerous IP lands (van Wendel et al. 2012). For example, long-distance air pollution is a major problem in the polar regions (AMAP 2006), as first evidenced by "Arctic haze" created by the volatilization of chemical compounds that persist due to slower decomposition times in cold weather (Ma et al. 2017). The long-range transport of pollution from Asian emissions is also an important source of atmospheric Hg to the Arctic (Kirk et al. 2012).

Agrochemical contamination. Pesticides (e.g., DDT and toxaphene) into IP lands have been documented by both freshwater and marine routes (Muir et al. 1992; Tsygankov et al. 2018). Long-range air transport of organochlorine pesticides and exposure to pesticides through bioaccumulation in animals are both common in the Arctic (Muir et al. 1992). Although the scale of pesticide pollution from agroindustrial operations in the Amazon has not yet been systematically documented (Waichman et al. 2007; Schiesari and Grillitsch 2011), there is evidence of increasing pesticide pollution in the Xingu River Basin, affecting at least 16 indigenous groups (Brando et al. 2013; Pignati et al. 2018).

Radioactive contamination. Also well documented among IPs (Haywood and Smith 1992; Williams et al. 2017), for example, the historical legacy of radionuclide exposure among IPs in the Aleutian Islands following 3 underground nuclear tests (1961–1975) has received substantial scholarly attention (Burger et al. 2007). Similarly, radioactive contamination of lichen communities, a principal winter feed for reindeer, has been documented in Saami reindeer herding areas of northern Fennoscandia, a result of the Chernobyl fallout (Beach 1990; Löfstedt and White 1990).

Polluting activities conducted by IPs. Such activities have been highlighted in the literature, particularly those activities related to the use of fire. Indoor air pollution caused by cooking fires can be a serious concern for those who are in rural areas unconnected to electricity grids (Díaz et al. 2007; Torres-Dosal et al. 2008). Exposure from vegetation

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Table 2. Pollutants to which indigenous peoples are exposed

Category		Pollutant(s)	Reported evidence
Heavy metals		As	Atkins et al. 2007; Liu et al. 2010; Bordeleau et al. 2016; Sandlos and Keeling 2016
		Cd	Orta-Martínez et al. 2007; Mapani et al. 2010; Curren et al. 2015; Bordeleau et al. 2016
		Pb	Mapani et al. 2010; Bordeleau et al. 2016; Ullah et al. 2016
		Hg	Hoover et al. 1997; Dallaire et al. 2003; Basu et al. 2018; O'Callaghan-Gordo et al. 2018
		U	Haywood and Smith 1992; Brugge and Gobble 2002; Lewis et al. 2017
Persistent organic pollutants	Organochlorines	Chlorinated benzenes (e.g., pentachlorobenzene, hexachlorobenzene)	Dallaire et al. 2003; Walker et al. 2003; Flores-Ramírez et al. 2016
		Chlorinated cyclodienes (e.g., aldrin, dieldrin, endrin, chlordane, heptachlor)	Kuhnlein et al. 1995; Johansen 2002; Dallaire et al. 2003; Curren et al. 2015
		DDT	Dallaire et al. 2003; Walker et al. 2003; Curren et al. 2015
		Hexachlorocyclohexanes (e.g., alpha-hexachlorocyclohexane, beta-hexachlorocyclohexane, lindane)	Kuhnlein and Chan 2000; Trejo-Acevedo et al. 2012
		Mirex	Chan 1996; CCU 2000; Kuhnlein and Chan 2000; AMAP 2004
		PCBs	Dewailly et al. 1994; Walker et al. 2003; Curren et al. 2015; Binnington et al. 2016
		Toxaphene	Chan et al. 1997; Wade et al. 1997; Kuhnlein and Chan 2000
	Dioxins and dioxin-like compounds	PCDDs (e.g., 2,3,7,8-TCDD)	Dewailly et al. 1994; Kuhnlein and Chan 2000; AMAP 2004; Paunescu et al. 2013
		PCDFs	Dewailly et al. 1994; Kuhnlein and Chan 2000; AMAP 2004
	PAHs and volatile organic compounds	Benzene	San Sebastián et al. 2001; Pruneda-Álvarez et al. 2012
		Toluene	Pruneda-Álvarez et al. 2012; Flores-Ramírez et al. 2016
	Organobromines	Polybrominated diphenyl ethers	de Wit et al. 2010; Carlsson et al. 2014; Byrne et al. 2018
Others		Asbestos	Myers 1981; Moerman and van der Laan 2011
		Chemicals of emerging concern (e.g., pharmaceutics, endocrine-disruptors, microplastics)	Godduhn and Duffy 2003; Jenssen 2006; Scott 2013; AMAP 2016
		Cyanide	McKinnon 2002; Leung and Lu 2016
		Radioactivity and radionuclides (e.g., radiocesium)	Beach 1990; Haywood and Smith 1992; Johnston et al. 1992; Williams et al. 2017

burning, a common agricultural practice among some indigenous groups, can also lead to negative health impacts, mostly on the respiratory system (Hanigan et al. 2008). Indigenous burning has also been partially blamed for large-scale air pollution incidents in Southeast Asia, such as widespread haze in the 1990s in which emissions of carbon dioxide, carbon monoxide, and methane exceeded regulatory levels for several months (Aiken 2004; Dennis et al. 2005). Other examples of polluting activities conducted by IPs include the intentional use of poison against carnivores and vultures across Africa (Ogada 2014; Murn and Botha 2018), or the numerous cases of reported contamination due to the use of Pb ammunition in subsistence hunting (Cartró-Sabaté et al. 2019).

Impacts of pollution on IPs

Environmental impacts. Indigenous peoples inhabit some of the most ecologically undisturbed areas of the world, often of outstanding biodiversity importance (Garnett et al. 2018). Thus, pollution in IP lands has an uneven and significant impact on critical environments, affecting large numbers of wildlife species (Basu et al. 2009; Wilson et al. 2018). While the impacts of pollution on ecosystems and biodiversity have been studied extensively (Taylor et al. 2016), particularly in aquatic systems (Desforges et al. 2018), accumulated evidence of these impacts comes primarily from industrialized nations, with a strong focus on consequences of agricultural intensification and industrialization. From this research we know that pollution has impacts at multiple levels, from altering wildlife physiology (Vernberg and Vernberg 1974) and behavior (Briffa et al. 2012), to noticeable impacts on population abundances (Gilburn et al. 2015), species richness (Stevens et al. 2004), and ecosystem functioning (Woodward et al. 2012). Although the detection of pollution impacts in remote areas, often inhabited by IPs, has so far lagged behind, remote sensing allows large-scale and real-time mapping of impacts, such as the detection of oil spills (Asner et al. 2013; Arellano et al. 2015).

Pollution-induced wildlife decline has been recorded in numerous IP lands (Cepek 2002; Young et al. 2016). For example, native pollinators, on which the food systems of IPs rely, are declining due to increased exposure to pesticides (IPBES 2016). Similarly, oil spills in the Gulf of Mexico have driven mortality of marine birds and sea turtles (Antonio et al. 2011). Reduction of pastures through industrial pollution has been also documented in tundra ecosystems (Forbes et al. 2009).

Waste from artisanal and small-scale Au mining in the Madre de Dios region, Peru, is known to be one of the most important sources of water contamination for Amazonian amphibians (Catenazzi and von May 2014), many of which are used in traditional medicine by Amazonian IPs such as the Yawanawa (Souto et al. 2013). Videos recorded with infrared camera traps have evidenced wildlife ingestion of petroleum-contaminated soils in areas situated within the hunting grounds of the Achuar in the Amazon (Orta-Martínez et al. 2018; Cartró-Sabaté et al. 2019). Polluting activities can also drive other forms of ecosystem degradation; for example, illegal Au mining has been implicated as a main cause of deforestation and habitat loss in areas inhabited by IPs in the Amazon and Myanmar (Swenson et al. 2011; Papworth et al. 2017).

Plastics are a growing source of marine pollution and a cause of marine animal mortality (Derraik 2002; Gregory 2009). It is estimated that by 2050, 99% of all seabirds will have ingested plastic during their life cycle (Wilcox et al. 2016), including many species central to IPs' diets (AMAP 1998; Gilchrist et al. 2005). Similarly, freshwater crabs and turtles of several rivers in the Amazon, which are both culturally and nutritionally important for IPs, have been impacted by widespread high Hg and Pb pollution levels (Schneider et al. 2010). Intentional poisoning of carnivores by African pastoralists have also resulted in wildlife declines (Ogada 2014; Murn and Botha 2018).

Pollutants accumulating in food chains through biomagnification have been particularly well-documented in marine mammals (Kuhnlein et al. 1995; Binnington et al. 2016), seafood (Donatuto et al. 2011), riverine fish (Ullah et al. 2016), birds (Bidleman et al. 2010), large mammals (Doyle et al. 2012), and caribou (Ostertag et al. 2009), and IPs in many areas depend heavily on these foods. Several studies have shown that global warming may increase pollution levels in fish and marine mammals by increasing rates of ecological mobilization and biomagnification (Jenssen 2006; Dudley et al. 2015).

Health impacts. Most health impacts documented among IPs are mediated through the consumption of polluted water (Huseman and Short 2012; Dudarev et al. 2013; Bradford et al. 2016) and food (Bordeleau et al. 2016), including wild foods obtained through hunting (Cartró-Sabaté et al. 2019), fishing (Marushka et al. 2017), and gathering (Strand et al. 2002). Because IPs often eat animal parts where pollutants accumulate (e.g., fatty tissues), their exposure is higher than among nonindigenous groups who discard these parts.

Exposure to POPs is associated with increased risk of diabetes among many indigenous groups, such as the Mohawk or the Kitchenuhmaykoosib Inninuwug First Nation of Ontario (Sharp 2009). Exposure to POPs has also been associated with immune system problems and increases in infections among Inuit infants (Dewailly et al. 2000; Dallaire et al. 2003), and to hypertension among Inuit adults (Valera et al. 2013). Among POPs, organochlorines such as PCB can cross the placental barrier and lead to permanent neurodevelopmental effects, as it has been the case among Arctic indigenous children (AMAP 2015).

There are also documented elevated cancer risks among IPs living near oil fields in the Ecuadorian Amazon, including high incidence of childhood leukemias (Hurtig and San Sebastián 2002, 2004). Similarly, high levels of autism, cardiovascular disease, and cancer have been reported among

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the Aamjiwnaang First Nations living near Chemical Valley in Canada (Bagelman and Wiebe 2017). Lead exposure is associated with growth and weight deficiencies, neurological impacts, and anemia among the Achuar, Quechua, and Urarina (Anticona and San Sebastian 2014). The health impacts of Hg, a known neurotoxicant, have been documented among numerous IPS (Wheatley and Wheatley 2000; Takaoka et al. 2014; Basu et al. 2018).

Exposure to pollution has been associated with increased cancer incidence and mortality among several IPs (San Sebastián et al. 2001; García-Esquinas et al. 2014). There have also been concerns regarding high rates of miscarriage and high risks of kidney disease and hypertension among Native Americans (e.g., Navajo, Lakota) living near U mining (Lewis et al. 2017). Exposure to endocrine disruptors has been associated with changes in age of menstruation and other health effects among some IPs (Godduhn and Duffy 2003; Denham et al. 2005). Inuit women have been reported to have levels of PCB in breastmilk 7 times higher than control populations in Québec (Dewailly et al. 1993; Johansen 2002). Among Mohawk women, those who ate local fish near hazardous waste sites had higher levels of contaminants in their breast milk than women in control groups (Fitzgerald et al. 1998). Numerous studies also report impacts of pollution on IPs' mental health, including psychological disorders associated with oil spills (Nriagu et al. 2016) or high levels of anxiety among the Anishinaabe, Potawatomi, and Ottawa IPs of Canada due to worries about their children's health (Hanrahan 2017).

There are indirect health impacts of pollution through IPs' food systems. For example, pollution can result in fear of consuming traditional wild foods (Turner and Turner 2008; Baker 2017), and the decline in game availability due to pollution can foster increased reliance on nutrient-poor and expensive market foods, often increasing the risk of malnutrition and chronic diseases (Young et al. 1992; Howard et al. 1999). For example, some IPs in British Columbia (Canada) have stopped gathering seaweeds in large amounts due to fears about marine pollution (Turner and Turner 2008; Turner and Clifton 2009). Loss of hunting or fishing activities can mean loss of physical activity as well, with resulting health impacts (Hoover 2013). Fear of using contaminated local sources of medicine can lead to declines in the use of traditional remedies, as documented among the Mohawk (Arquette et al. 2002). There are also reports of Inuit women choosing not to breastfeed their children because of fear of pollutants in their milk (Johansen 2002).

Cultural impacts. Environmental pollution impacts both material and nonmaterial cultural dimensions of IPs' ways of life (Pufall et al. 2011; Alonzo et al. 2016), including their knowledge systems (Boischio and Henshel 2000; Yakovleva 2011). For example, herbicide treatments by the US Forest Service have contaminated plants used by California Native American tribes for different cultural uses, including traditional basket weaving where holding reeds in the mouth is part of the process (O'Neill 2003).

Other traditional practices, such as harvesting local plants for sustenance, ceremonial, or medicinal purposes, or drinking from historical water sources can also increase exposure to pollutants (Arquette et al. 2002). Thus, recommendations to refrain from fishing or gathering plants can affect indigenous cultural traditions based on these activities (Kuhnlein and Chan 2000). Further, without access to information about sources of pollution, IPs can also inadvertently associate health conditions with other factors. For example, in Ecuador, the Cofan blamed high rates of cancer not on oil extraction but on shamanic identification of human agents, leading to cultural conflict (Cepek 2002).

Several studies have shown how pollution jeopardizes the complex web of relationality that many IPs establish with their lands (Nelson et al. 2001; Hoogeveen 2016). Because activities associated with collecting wild foods generally serve important community roles (e.g., intergenerational exchange, maintenance of language), concerns associated with pollution regarding the consumption of wild foods can also impact these practices (Berkes and Farkas 1978; ICC-AK 2015). For example, the Mohawk Nation at Akwesasne (United States and Canada) report a loss of language and culture around subsistence activities that have been largely abandoned because of fear of pollution exposure (Hoover et al. 2012).

Finally, pollution can also affect the spiritual wellbeing of IPs (Temper and Martínez-Alier 2013; McCreary and Milligan 2014). In many indigenous world views, water is a living and sentient being or a spiritual resource (e.g., the lifeblood of Mother Earth) that must be respected and kept clean from pollution (Singh 2006; Toussaint 2008). From a Western scientific perspective, drinkable water may have some level of acceptable contaminants, but in contrast, Māori in New Zealand require drinking water to be entirely free of physical contamination in order to eliminate spiritual pollution (Tipa and Teirney 2006; Sterling et al. 2017b). Another example comes from Arizona where the Snowbowl ski resort wanted to make snow from reclaimed sewage water and spread it on a mountain considered sacred by the Navajo and Hopi. In a lawsuit, the communities argued that contamination by the sewage would undermine their belief systems and the cultural practices that depend on the mountain's purity (Schlosberg and Carruthers 2010).

IPs' contributions to control pollution

Resistance to polluting activities. Worldwide, IPs are campaigning against pollution impacts on their environment and health (Evans et al. 2002; Veltmeyer and Bowles 2014). Resistance against polluting activities includes actions such as protests, cultural resistance camps, calls for policy action, occupation of resource infrastructures (e.g., pipelines, landfills), and litigation to hold polluters accountable (Martínez-Alier et al. 2010; Rudel 2018). Mainly through global citizen action; social mobilization; successful links with environmental activists, scientists, and journalists; and capitalizing on modern technologies, IPs have attracted global attention and support, helping to raise awareness of the impacts of pollution (Sikor and Newell 2014; Vásquez 2014).

These activities have in some cases prevented the installation of polluting industries upon IP lands (Nesper 2011; Temper 2018; Widener 2018). However, these campaigns are not always articulated as solely a crusade against pollution, but rather as conflicts in defense of land rights, sovereignty, and justice (Temper et al. 2015, 2018). Prominent examples include the opposition of different IPs (e.g., Inupiat, Gwich'in) across Canada and the United States to different oil drilling plans in the Arctic (Cho et al. 2018), or widespread social mobilization against pipelines such as the Dakota Access Pipeline (Donaghy and Lisenby 2018), the Enbridge Pipeline (Donaghy 2018), the Trans Mountain Pipeline (CRED 2013), or the Keystone XL Pipeline (Bradshaw 2015).

There are also many examples of these types of preventive conflicts in countries in the global South, such as the U'wa fight against oil drilling in Eastern Colombia (Arenas 2007), the Chiquitanos opposition to the Cuiabá pipeline in eastern Bolivia (Hindery 2013), resistance towards the Doba-Kibri oil pipelines across Chad and Cameroon (Nelson et al. 2001), or the fight of the Dongria Kondh against bauxite mining in their sacred homelands in India (Temper and Martínez-Alier 2013). The fact that indigenous values (e.g., sacredness, spirituality) are often harmed by the expansion of commodity frontiers is a common thread in the IPs protests (Hinzo 2018; Panikkar and Tollefson 2018). Indigenous women across the world have been particularly vocal against pollution impacts from mining, hydrocarbon exploration, and toxic waste dumping in their lands (Krauss 1993; Macleod 2016).

Several examples of successful alliances of IPs with scientists (Armstrong and Brown 2019; Caron-Beaudoin and Armstrong 2019) and non-governmental organizations exist (O'Faircheallaigh 2015). For example, the Gundjehmi Aboriginal Corporation partnered with a league of environmental activists to defeat the Jabiluka mine in Northern Australia (Hintjens 2000). These alliances extend to scientists because access to scientific information on pollution impacts has been important in spurring indigenous protests in many regions (Stetson 2012). For example, knowledge of high levels of Cd in their blood triggered a change in the resistance methods employed by the Achuar in the Corrientes River (Orta-Martínez and Finer 2010) and the Yanomami in Brazilian Amazonia (Vega et al. 2018). Based on their own experiences, some indigenous representatives have also travelled to warn others against accepting polluting industries on their lands (Kirsch 2007).

There are several documented examples of how IPs' movements have managed to limit or stop polluting activities by putting both companies and administrative authorities under pressure, for example, through strikes, financial divestment campaigns, community-organized consultations, and rallies (Wiebe 2016; Bromwich 2017). Resistance to polluting activities has also rejuvenated indigenous activism because concerns about environmental justice are extended to advocacy in other issues such as racial injustices, and strengthening of social networks has been an important outcome (Sawyer 2004; Valdivia 2007).

The arts (e.g., music, storytelling, photography) have been particularly effective at relaying IPs' fights against pollution to global audiences and inspiring social and policy action towards pollution issues affecting IP (Branagan 2005; Gillespie 2013; Horton 2017). Increasing presence of IPs on social media (Carlson et al. 2017; Nunn 2018) is also contributing to give visibility to conflicts around pollution (Örestig and Lindgren 2017). For example, contestation of resource extraction can be traced through digital media in Inuit communities (Scobie and Rodgers 2013).

Traditional management systems. The management practices conducted on many IP lands, including indigenous community conserved areas and sacred sites, contribute to pollution buffering and nutrient cycling (Ulrich et al. 2016; Hill et al. 2019). Moreover, the abandonment of these indigenous traditional management practices might result in increasing levels of pollution (Baudron et al. 2009). Examples on how IPs contribute to limit pollution include the maintenance of traditional management systems that make no use of chemical products, as well as those that include remediation techniques to restore polluted areas. For example, many IPs are limiting local levels of N pollution through the maintenance of traditional agricultural practices with minimal use of chemical pesticides or fertilizers (Wezel et al. 2014). Organic farming is an integral part of many IPs' food production systems, including the Maya of Mexico and the Wanka of Peru (Grossman 2003; Moreno-Peñaranda and Egelyng 2008; Huaman 2014), in which applying natural pest control is more congruent with traditional IPs' worldviews than the use of modern pesticides and agrotoxics (Kayahara and Armstrong 2015; Malmer and Tengö 2019).

Similarly, the multifunctional and holistic systems of IPs' water resource management, sometimes referred to as indigenous water cultures (McLean 2017), have been deemed effective at preventing pollution of freshwater environments (Hughey and Booth 2012; Shemsanga et al. 2018). This includes traditional water purification methods (Opare 2017), complex systems of river zonation (Halim et al. 2013), protection of sensitive areas (Dyck et al. 2015), and forestry-based systems of water quality protection (Kreye et al. 2014; Camacho et al. 2016). IPs' management practices also include remediation techniques (e.g., phytoremediation) to restore landscapes affected by pollution (Sistili et al. 2006). Moreover, many IPs have also initiated or engaged in efforts to restore polluted rivers (Fox et al. 2017), lakes (Coombes 2007), and wetlands (Henwood et al. 2016).

Participatory monitoring. While the number of projects that claim to conduct participatory environmental monitoring is growing (Turreira-García et al. 2018), most research reporting the impacts of environmental pollution on IPs has been conducted by scientists. For example, the Aamjiwnaang First Nations community in Ontario, Canada, requested scientists to assess level of exposure to pollutants both in their lands and bodies through a community-based participatory research project (Cryderman et al. 2016). There are, however, some pollution monitoring programs engaging IPs, such as the Arctic Monitoring and Assessment Program (AMAP 1998, 2015), the Māori Cultural Health Index for Streams (Tipa and Teirney 2006), the Northern Contaminants Program in Canada (Donaldson et al. 2013), or stakeholder-driven pollution assessments with active involvement of Aleut communities in Alaska (Burger and Gochfeld 2009). For example, since 2006, the Achuar and Quechua in the Peruvian Amazon have led a community-based monitoring program to map oil spills in their lands (Orta-Martínez et al. 2007, 2018) and to monitor their impacts (Rosell-Melé et al. 2018; Cartró-Sabaté et al. 2019). The release of this information has strengthened the role of indigenous leaders in negotiations with the oil companies and the Peruvian state agencies. In Bolivia and Peru such negotiations have resulted in sanctions to oil companies, a relative improvement of their operational standards, and economic and social compensations to IPs (Pellegrini and Arismendi 2012; Schilling-Vacaflor and Eichler 2017).

Similar community-led pollution monitoring programs have also been conducted among the Kwakoegron IPs in Suriname to monitor Hg (Peplow and Augustine 2007), and the Akwesasne Mohawk Task Force on the Environment (Canada and the United States) to monitor the health consequences of environmental contamination (Schell et al. 2005). Similarly, recent comparative research has documented Sami, Cree, and Nakaspi efforts to document pollution impacts of mineral development on reindeer habitats in Sweden and Canada (Herrmann et al. 2014). Community-led pollution monitoring programs seem to offer the potential to monitor environmental pollution through the empowering of IPs (Suk et al. 2004). However, such programs face barriers such as lack of financial support, bureaucracy, and lack of culturally appropriate indicators to monitor pollution according to community needs and priorities (Hutchings and Tipene 1998; Sterling et al. 2017b).

Policy development. Representatives for IPs are increasingly participating in international policy development to reduce pollution burdens (Godduhn and Duffy 2003; Selin and Selin 2008). The Arctic Council has played a particularly crucial role in amplifying indigenous concerns to international levels (Koivurova and Heinämäki 2006; AMAP 2015). For example, the Northern Aboriginal Peoples' Coordinating Committee on POPs helped support the Inuit Circumpolar Council's participation in negotiating the Convention on Long Range Transboundary Air Pollution Protocols on POPs and Heavy Metals (Selin and Selin 2008). The concerns of the Arctic IPs are also reflected in the Stockholm Convention, where they have been strong advocates for expanding beyond the initial 12 banned persistent chemicals, and including precautionary language (Downie and Fenge 2003; Godduhn and Duffy 2003). More recently, Inuit populations have been vocal in helping shape the Minamata Convention on Mercury (Basu 2018).

In addition to global policy advocacy, indigenous communities have also worked for policy changes to gain local control over natural resource management, which has been argued to increase IPs' abilities to address pollution more effectively (Verbrugge 2015; Dare and Daniell 2017). For example, many IPs participated in Canada's Arctic Environmental Strategy to include a Northern Contaminants Program (Selin and Selin 2008). Other examples include changes in Indonesian law to add indigenous permits for mining (Spiegel 2012), use of impact benefit agreements (Wright and White 2012); creation of IP corporations and contracts for running oil concessions (Dana et al. 2008; O'Faircheallaigh 2013), community mining consultations (Walter and Urkidi 2017), or participatory mechanisms to involve IPs in pollution assessments (Burger et al. 2009).

Indigenous peoples have also been strong advocates for strengthening right-to-know laws and the use of FPIC previous to any establishment of polluting activities in their lands (O'Rourke and Connolly 2003; Leifsen et al. 2017). In Canada, the use of environmental impact assessments with indigenous participation and monitoring has helped to reduce the possibility of pollution and to have remediation plans in place (O'Faircheallaigh 2015). Campaigns to get corporations to have FPIC policies and pollution reduction measures in their corporate social responsibility statements have also been relatively successful in some contexts such as Fennoscandia, Australia, Ecuador, and Peru (O'Faircheallaigh and Ali 2008; Finer et al. 2013; Billo 2015). However, in other regions, such as Eastern Siberia or Ghana, there is a documented absence of attention to cultural issues in environmental impact assessment for polluting activities (Appiah-Opoku 2001; Yakovleva 2011). Similarly, there are examples of co-optation of IPs (e.g., in the Philippines) in FPIC processes (Holden et al. 2011).

Litigation processes. Indigenous peoples facing pollution threats have also been savvy users of legal systems to limit or stop polluting activities in their lands and to obtain compensation or remediation after pollution events (Conde 2014; Pickerill 2018). Their claims have often emphasized that their high exposure to pollution is generally due to polluting activities that are imposed on IP lands for the benefit of others, such as resource users elsewhere (Martínez-Alier 2001, 2014). However, many IP movements have claimed that their fights go beyond monetary or material compensations (Morden 2015).

There are several high-profile lawsuits involving IPs and polluting industries. For example, IPs in Ecuador filed a suit against the pollution caused by Chevron-Texaco, which they alleged violated US laws (Kimerling 2006; Joseph 2012), and a 2011 verdict against Chevron required the payment of billions of dollars in damages, although this has yet to be realized by the IPs themselves. Moreover, this case motivated the adoption of the Rights of Nature in the Ecuadorian constitution in 2012 (Cely 2014) and state-mandated rules on corporate social responsibility (Billo 2015).

A similar case against the BHP mining company in Australian court for the pollution caused by their Ok Tedi mine in Papua New Guinea was settled for US$500 million in compensation damages to IPs and a commitment to containing the tailings from the mine (Kirsch 2007). In a related Indonesian case against Newmont, a US mining company, a nongovernmental organization representing IPs and local communities demanded corporate guidelines for remediation and compensation after a lawsuit was filed against a local Au mine subsidiary, leading to changes in corporate practices (Shaw and Welford 2007). Along these lines, the case of the Ogoniland dispute about pollution in their lands has been brought before the African Commission on Human and Peoples' Rights (Atapattu 2018).

Other IPs remain unsupported in their legal battles against polluting corporations operating in their lands (MacDonald 2015; Tsosie 2015; Shipton 2017), often due to a lack of legal recourse in states insufficiently supportive of IP rights (Holden and Ingelson 2007; Langton and Mazel 2008). This has led many to argue for an international legal framework for compensation for social and environmental damages to IPs (Nuttall 2010; Orta-Martínez and Finer 2010), given that IPs still face barriers to receiving full compensation for pollution impacts (Martínez-Alier et al. 2014; Koh et al. 2017).

DISCUSSION

The literature reviewed clearly shows that IPs are among the populations at highest risk of impact by environmental pollution of water, land, and biota through both exposure and vulnerability. Global evidence is accumulating for pollution-driven environmental degradation in many IP lands (Dudgeon 1999; AMAP 2018). Environmental pollution directly affects the health of IPs in several ways, for example, by increasing risks and burdens of disease (Gracey and King 2009; Mapani et al. 2010). While cultural impacts have often been overlooked, the literature suggests that they are substantial in extent and scope (Pufall et al. 2011).

Because IP lands tend to be sparsely populated (Garnett et al. 2018) but are often rich in resources like ores or oil and gas (Finer et al. 2008), they are often the targets of extractive operations that entail pollution risks (Dokis 2015; Álava and Calle 2017). For example, 71.76% of all oil blocks in the Ecuadorian Amazon overlap with IP lands (Codato et al. 2019), and around 60% of all areas identified in mining applications in the Philippines are within ancestral homelands of IPs (Aytin 2015). In recent years, this situation has become more acute, driven by the exhaustion of resource extraction in easy-to-reach areas and the consequent move toward more remote lands, many of which are inhabited by IPs (Gautier et al. 2009; Finer and Orta-Martínez 2010). A range of extractive frontiers are rapidly expanding upon IP lands (Muradian et al. 2012; Martínez-Alier et al. 2016).

Polluting infrastructures have often been established in IPs' lands without FPIC and without the appropriate social and environmental safeguards (Dokis 2015; Tófoli et al. 2017). In other contexts, IPs have also made the decision to accept polluting infrastructures in exchange for development, such as the Skull Valley Goshute in Utah, who agreed to host a high-level nuclear waste facility on their reservation (Gross 2001), or the Ipili of Papua New Guinea, who agreed to the opening of a large-scale Au mine in their lands (Jacka 2007; Macintyre 2007). Similarly, in the Amazon and Malaysia, IPs engage in polluting activites (e.g., artisanal mining), as other livelihood options become unavailable due environmental degradation (Papworth et al. 2017).

Indigenous peoples are particularly vulnerable to the impacts of pollution due to their high and direct dependency on local natural resources, limited access to health care, and relatively low levels of governmental support (Lewis et al. 2015; Whyte 2015). Indeed, IPs' marginalization, and physical distance to centers of power (e.g., seat of government) often decrease their ability to take advantage of protection from national pollution laws (Moerman and van der Laan 2011). Given that the levels of sanitation and water service coverage in IPs' lands are generally low, many IPs use untreated surface water for drinking (González Rivas 2012; Hanrahan 2017). Even where IPs have access to treated or piped water, this water is often of poorer quality than in other areas. For example, 20% of all drinking water advisories in Canada are in indigenous communities, who only make up 5% of the country's population (Daley et al. 2015). Overall, water contamination has resulted in greater exposure to mine wastes among Native Americans than other populations (Brugge and Gobble 2002; Harper et al. 2012). It is estimated that >600 000 Native Americans in the Western United States live within 10 km from an abandoned mine, having an increased likelihood of elevated exposures to several pollutants (Lewis et al. 2017).

Moreover, pollution risks are not homogeneous within indigenous communities, with much research documenting that, for social and cultural reasons mostly linked to gender inequality, indigenous women are more vulnerable than men to pollution impacts (White and White 2012; Hoover 2017; Horowitz 2017). There are other culture-specific situations of vulnerability, such as those of IPs living in voluntary isolation, whereby the establishment of polluting activities may bring not only pollution but also exposure to disease (Walker and Hamilton 2014; Kesler and Walker 2015). This is the case of several IPs in voluntary isolation in Ecuador (e.g., Tagaeri, Taromenane), whose lands are under increasing assault from oil extraction operations (Lu et al. 2016).

It is also important to acknowledge that IPs often have different conceptions and acceptance of pollution risks than other sectors of society (Lu et al. 2014), which might aggravate their vulnerability. For example, many members of the Aamjiwnaang First Nation in Ontario, whose lands are surrounded by the largest complex of petrochemical plants in Canada, have repeatedly asserted that they would never leave their ancestral lands, regardless of concerns for high rates of cancer and respiratory diseases in their communities (Luginaah et al. 2010). Further, in many countries there has been a trend away from risk reduction in pollution control towards risk avoidance;

for example, advisories discouraging fish and wildlife consumption among the Mohawk in the United States (Hoover 2013) or Inuit in the Arctic (Kuhnlein and Chan 2000) have focused on avoiding rather than reducing sources of risk (O'Neill 2003; Burger and Gochfeld 2011).

Further, while fish and wildlife consumption advisories might discourage the hunting or fishing of species exposed to pollutants, for some IPs the consumption of certain foods, even if impacted by pollution, may have more cultural benefits that make them willing to take certain risks (Donatuto et al. 2011). Language and cultural barriers can also pose difficulties for health practitioners to warn about pollution and contamination affecting IPs (O'Neil et al. 1997; Wheatley and Wheatley 2000). Additionally, harvesting and consuming traditional foods have many nutritional, social, and cultural health benefits that must be weighed in risk management (Kirk et al. 2012).

Part of the literature on IPs and pollution has framed pollution as a field of technical intervention, where impacts can often be curtailed or compensated, thereby relegating IPs to the status of helpless victims whose vulnerabilities should be remediated (Bagelman and Wiebe 2017; Nunn 2018). The depoliticization of pollution through the deployment of technical narratives (e.g., offering only technical solutions to problems that are fundamentally political) has rendered IPs' interests, agencies, and claims largely invisible (Cameron 2012; Liboiron et al. 2018), often overlooking the proactive role of IPs in fighting against environmental injustices. A growing scholarly body is challenging this research tradition by showing how IPs actively contribute to develop innovative strategies to limit pollution or prevent it from the outset (Capasso 2017; Wehi and Lord 2017).

In several countries, IPs have been marginalized from environmental management bodies (Weir 2009; Finn and Jackson 2011), which undermines their capacity to defend their stakes in terms of environmental pollution at subnational levels (Behrendt and Thompson 2004). With the exception of the Arctic (Hansen 2000; AMAP 2015), in most regions there is a lack of regular monitoring and impact assessments on the specific impacts of pollution on IPs (Appiah-Opoku 2001; Jollands and Harmsworth 2007). Biomonitoring informed by IPs' concerns can help to create a better understanding of IPs' exposure to pollution, ensuring also that ethical research practices are followed (Sterling et al. 2017b; Caron-Beaudoin and Armstrong 2019). Several studies have described the long-term cultural and spiritual connections of IPs to their lands as a central element of IPs' experiences of pollution (Scott 2013; Armstrong and Brown 2019). In fact, current levels of engagement of IPs in environmental management bodies at national and international levels are low (Jollands and Harmsworth 2007; Memon and Kirk 2012), underresourced (Shrubsole et al. 2017), and largely uncoordinated (Te Aho 2010; Hoverman and Ayre 2012). Furthermore, the important environmental justice issues surrounding IPs, in that they did not create much of the pollution they are exposed to, remain neglected by both national and international laws. Furthermore, the contributions of IPs to prevent, limit, and control pollution have seldom been recognized (Bagelman and Wiebe 2017; Nunn 2018). Greater engagement of IPs on environmental governance can help to incorporate IPs' social, spiritual, and customary values in environmental quality and ecosystem health (Finn and Jackson 2011; Escott et al. 2015). We argue that IPs should be part of any conversation on policy options to reduce risks of pollution to human well-being, ecosystem services, and biodiversity.

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SUPPLEMENTAL DATA

S1. Literature review strategy.

S2. Case studies documenting pollution impacts on IPs.

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