2021

The Food-Energy-Water Nexus, Embodied Injustices, And Transboundary Sustainability

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Recommended Citation
Ahamed, Sonya, "The Food-Energy-Water Nexus, Embodied Injustices, And Transboundary Sustainability" (2021). *Graduate College Dissertations and Theses*. 1332.
https://scholarworks.uvm.edu/graddis/1332

THE FOOD-ENERGY-WATER NEXUS, EMBODIED INJUSTICES, AND TRANSBOUNDARY SUSTAINABILITY

A Dissertation Presented

by

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to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
Specializing in Natural Resources

January, 2021

Defense Date: November 13, 2020
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ABSTRACT

Intersections of food, energy, and water systems (the FEW nexus) pose many sustainability and governance challenges, including risks to ecosystems, inequitable distribution of benefits and harms across populations, and reliance on distant sources for food, energy, and water. Nexus-based approaches can offer more holistic pathways for societal transitions to FEW systems that are just and sustainable, but tend to focus narrowly on inputs (*e.g.* water 'for' energy) in ways that do little to address the historical roots and structural underpinnings of current system inadequacies, thus risking their perpetuation.

This dissertation widens the FEW nexus in two contexts in which the nexus extends well beyond inputs, and uses network analysis to characterize the rapidly-shifting global energy system at the core of extractive activities in both cases. Chapter 2 provides an integrated assessment of the trans-boundary FEW nexus in the Denver region, considering impacts of extensive hydraulic fracturing of the Niobrara shale on both agricultural activity and water resources.

Chapter 3 extends the FEW nexus to incorporate materials and directly address embodied injustices and transboundary sustainability, and illustrates this expanded framing by linking the northward expansion of the 'forest frontier' to the James Bay hydroelectric megaproject in Eeyou Istchee/ Jamesie, Quebec. We estimate the region's interlinked forest disturbances from hydropower, mining, clearcutting, fire, and roads since 1975 to be about 106,000 km^2, an area four times the size of Vermont, which receives about one-third of its electricity from Hydro-Quebec.

Finally, Chapter 4 employs network analysis to examine global oil and gas extraction from 2014 to 2018, highlighting cooperation ('collusion') among global investor-owned, hybrid, and national oil and gas companies in the face of existential threats to the industry that crystallized around the US election of 2016. At a system level, the interdependence, global reach, and combined power of the major extractors point to the necessity of a supply-side approach to the reduction of global carbon emissions.

CITATIONS

Material from this dissertation has been published in the following form:

Ahamed S., Sperling J., Galford G.L., Stephens J.C., Arent D.. Jan 2019. The food-energy-water nexus, regional sustainability, and hydraulic fracturing: An integrated assessment of the Denver Region in the United States. Case Studies in the Environment. https://doi.org/10.1525/cse.2018.001735.

ACKNOWLEDGEMENTS

I would like to extend heartfelt thanks to my advisors, Gillian Galford and Jennie Stephens, for their generous support and wise counsel through this process. I’m also very grateful to my dissertation committee members: Bindu Panikkar, David Massell and Donna Rizzo, for their sharing wisdom, insights and encouragement on numerous occasions, and to Paul Hines for graciously agreeing to serve on my exam committee. To the wider community at the Rubenstein School of Environment and Natural Resources, Gund Institute, IGERT, and College of Engineering and Mathematical Sciences, including my wonderful fellow graduate students and many professors: you’ve been a constant source of inspiration, even when circumstances dictated that conversation and collaboration be socially distant, virtual, and altogether different from what we expected. And to my incredible family: this tremendous experience, challenge, and (at times) respite from the wider world that has been my most recent venture into graduate school would never have been possible without your continuing love and support.

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CHAPTER 1: INTRODUCTION

Nexus-based approaches to the study of food, energy, and water systems (FEWS) are centered on the premise that these systems are fundamentally interdependent and therefore need to be examined in relation to one another in order to ensure resilience and sustainability. A key corollary is that FEW systems, framed as the basic underpinnings of modern life, are also profoundly inequitable. It has been estimated that 800 million people are hungry and 2 billion experience moderate or severe food insecurity (FAO et al., 2019), 1.2 billion live in water-scarce regions (Bigas et al., 2013), 1.2 billion do not have access to electricity, more than 2.7 billion rely on traditional biomass for cooking (WEO, 2016), and 700 million live on less than $1.90 per day (World Bank, 2015). Recent calls for research on the interdependencies between food, energy, and water systems (Belmont Forum, Urban Europe, and European Commission, 2016; National Science Foundation, 2016) highlight the critical and often-overlooked linkages among these systems, emphasizing that solutions focused on one often have unintended consequences for the other two.

The food-energy-water (FEW) nexus approach offers new ways to identify regional vulnerabilities and opportunities to transition to more just and sustainable uses of FEWS. For example, large, unmonitored surface water withdrawals for thermoelectric power plant cooling across the United States (Averyt et al., 2011; Bazilian et al., 2011) are of particular concern in the arid southwestern US. Such research has prompted the design of more water efficient electricity generation and provided additional impetus for the shift in arid regions to wind and solar power, renewable energy alternatives which require very little water input. The FEW approach can also be used to identify the dependencies of mega-cities on other regions for both real and ‘embodied’ water required for food and energy production (Anu Ramaswami et al., 2017), also referred to as virtual water (Hoeckstra et al). The closely related ‘resource nexus,’ identifies five interrelated nodes, encompassing materials and land as well as food, energy, and water (Andrews-Speed et al., 2012; Bleischwitz, Hoff, et al., 2018; Bleischwitz, Spataru, et al., 2018).

FEW / resource nexus approaches are especially relevant as the global energy system is undergoing a disjointed and politically contested sociotechnical transition away from fossil fuels to alternative forms of energy and as global grassroots efforts intensify to transition to more sustainable systems. In this context, interdependencies can be quantified in terms of embodied energy and water *inputs* to FEWS (*e.g.* water for thermoelectric power generation or energy for food transport). The *impacts* among these essential and entangled systems (*e.g* energy extraction on water and food systems) and *who* disproportionately bears the burden of these impacts, along with the historical conditions, political factors, and systemic inequities that have led to current unsustainable and inequitable transboundary patterns of extraction, production, and consumption, are less often the focus of inquiry (although a small subset of FEWS research does address these topics (*e.g*. Allouche et al., 2014; Foran, 2015; Middleton et al., 2015)). Such a focus is needed to more firmly link FEW nexus inquiry to research and action that supports both a just and sustainable transition.

In this dissertation I widen the aspects of the nexus to examine not just FEW inputs, but also impacts on FEW systems and the surrounding environment, as well as *access* to and *control* over FEW systems and material resources. I ask, what are the embodied FEW injustices and transboundary unsustainabilities that are intertwined with present FEW systems? I use two case studies and a network analysis to illustrate these conceptual framings: 1) the Denver Region in the United States, a key producer of both food and energy, 2) the contested territory of Eeyou Istchee/Jamesie, Quebec, the site of the largest hydropower complex in the Western Hemisphere, and 3) a multiplex analysis of the global oil and gas production network from 2014-2018. In this brief introduction, I will review a number of recent critiques of the nexus approach, providing context and justification for these proposed extensions to the FEW /resource nexus, before elaborating briefly on these extensions as they are implemented through the three chapters comprising this dissertation.

1.1 FEW Nexus Critiques

A number of authors point out that the FEW nexus is not a new idea: it builds on other earlier integrative approaches, most notably the Integrated Water Resource Management (IWRM) (Wichelns 2017; Cairns and Krzywoszynska 2016). Cai et al. (2018) argue that in contrast to IWRM, the FEW nexus approach has a clearer scope, explicitly setting the sectoral bounds (i.e., food, energy, and water resources) of integration, whereas IWRM attempts to integrate all resources and objectives related to water, and is often subject to institutional barriers (Cai et al 2018: 260). The fluidity of the FEW nexus concept has been well articulated; nexus investigations take on different manifestations depending on context, scale and geography (Matthews & Motta, 2015). It has also been noted that the

FEW nexus approach may miss trade-offs and conflicts with other excluded sectors (Leck et al 2015, Pittock et al. 2013).

The nexus has also been characterized as a “buzzword:” a powerful term that combines “ambiguity of meaning and strong normative resonance,” delineating power struggles over competing narratives and “nodes around which ideological battles are fought” (Cairns and Krzywoszynska 2016: 4, Stubbs, 2001: 188 cited in Mautner, 2005)). As a corollary to the integrative imaginary, the nexus is seen as a multidisciplinary problem requiring multi-disciplinary approaches (Leck et al; Albrecht et al 2018), and can be “understood as a problem that is impossible to grasp, or respond to adequately, from within the partial framings of individual academic disciplines” (Cairns and Krzywoszynska 2016: 8).

Stakeholders use the term nexus in multiple and heterogeneous ways, and there is not yet a singular ‘nexus discourse’ (Cairns & Krzywoszynska, 2016: 2). Endo et al. observe that there is no clear definition of the nexus, but in the international context it has been interpreted as a process to link different stakeholders under different sectors and spatial scales to achieve sustainable development” (2017: 21). Leck et al. characterize the FEW nexus as an “intellectually appealing” concept that faces significant conceptual and practical challenges, including “lack of clarity about what a ‘successful’ nexus approach looks like in practice and how it can be achieved” (2015: 446,454).

Another key critique of the FEW nexus approach is that, like other integrative practices that have failed to deliver in practice, the nexus concept inadequately addresses political economy, defined as “the role of power and vested interests in resource allocation, linkages to markets and equitable approaches for negotiating inter-temporal trade-offs" (Leck 2015: 453; Peronne and Hornberger 2014; Rees 2013). This shortcoming is seen as significant: Allouche et al contend that "if the nexus is to be a useful framework for exploring alternative pathways rather than a narrative that legitimizes existing dominant pathways, the political economy of the nexus must be more explicitly addressed" through bottom-up rather than "top-down ways of knowing the relationship between water, food and energy" (2014: 23). Cairns and Krzywoszynska argue that attending to such questions of power is a "crucial but often underplayed aspect of proposed integration" (2016: 11). Williams et al note that "by its very conception, 'the nexus' betokens political terrain," stating that the "contested relationships, processes and technologies through which energy and water become enrolled in nexus interactions – the political production of the nexus – are drastically overlooked in existing scholarship" and that there is "a striking absence of theoretically informed spatial and political analysis of the nexus" (2014: 4).

At the core of the nexus are *control* 'over' and *access* 'to' food, energy, water, but the deep linkages between access and the key societal structures enabling, permitting, and denying such access are often overlooked. As Leck et al (2015: 53) write:

> Access to and utilization of water, energy and food are closely linked with structural issues such as political processes, poverty and entitlements; the prevailing development and political-economic environment will therefore strongly influence both the way in which nexus approaches are implemented and their outcomes (Allouche et al. 2014; Dupar and Oates 2012; Pittock et al. 2013; Rees 2013). However, political economic considerations are largely under-represented in nexus research with analyses often completely neglecting political contexts or overlooking underlying existing unsustainable activities… *Identifying*

> *winners and losers in WEF nexus decision-making and giving explicit attention to justice and equity concerns are central for nexus agendas to be socially progressive* (Dupar and Oates 2012; Stringer et al. 2014)."

In addition to these critiques, a number of suggestions have been offered for future nexus research. Many researchers call for more critical, theoretically informed perspectives. Leck et al. propose the use of *analytical eclecticism*, defined by Sil and Katzenstein as "an intellectual stance that supports efforts to complement, engage and selectively utilize theoretical constructs embedded in contending research traditions to build complex arguments that bear on substantive problems" (Sil and Katzenstein 2010: 411). This potentially effective lens could guide nexus research in navigating the boundaries among disciplines and is unique in specifying how "elements of different causal factors might coexist as part of a more complex argument that bears on problems of interest to both scholars and practitioners." This lens also facilitates dialogue across disciplines through utilizing rather than "replacing critical research efforts by adherents of specific traditions" (Leck et al 2015: 451-452).

In following chapters, I consciously apply the lens of 'analytical eclecticism' and explore the embodied inequities that are associated with the FEW / resource nexus. In Chapter 2, I undertake an integrated assessment of the food-energy-water nexus in the ten-county Denver region, finding that the *impacts* of energy production 'on' regional water systems are as critical to assessing the FEW nexus as quantifying the *inputs* of water 'to' those systems. In Chapter 3, I extend the FEW nexus to include Materials, Embodied iNjustices and Transboundary Sustainability (FEW+M+EN+TS), addressing issues of *impacts* 'on' as well as *access* 'to' and *control* 'over' FEW+M systems. In so doing, these chapters directly address major challenges for the nexus concept and trace different causal factors that coexist as part of a more complex argument. In Chapter 3 specifically, the integration of historical and political economic considerations, and the need to give explicit attention to justice and equity concerns, is addressed through the concept of embodied injustices and illustrated by a case study of intensifying resource extraction and infrastructure development by outside entities in a contested landscape for the benefit of distant consumers over a 40-year period. Chapter 4 focuses on the fossil energy system, examining the spatial dimensions of global oil and gas production network in the critical 5-year period before, during, and after the 2016 US presidential election (2014-2018). Like Chapters 2 and 3, Chapter 4 focuses on the political economy in which the energy system operates. Across the three chapters, transdisciplinary approaches are utilized, spanning the fields of remote sensing, geographic information systems, network analysis, critical geography, forestry, history, policy studies, and ecology. Additionally, I seek to offer a framing that is flexible enough to accommodate local contexts and still be generalizable.

The following three subsections provide additional background on each of these extensions: ‘materials,’ with an emphasis on mining, embodied FEW injustices and transboundary sustainability.

1.2 The Resource Nexus: FEW + Materials

A number of nexus approaches include “materials” as part of a broader “resource nexus” (e.g. Bleischwitz et al. 2017; Bleischwitz et al. 2018; Andrews-Speed et al. 2012), and while some studies use the food-energy-water and "resource nexus" interchangeably (Foran 2015) others do not. Liu et al. 2017 distinguish between "the water, energy and food *security* nexus, and the concept of *resource* nexus [which] can also be found in the literature – water, energy, land and minerals" (Liu et al., 2017: 1716). A 2012 report on the "Global Resource Nexus" written from the perspective of "transatlantic actors and interests" (that is, the EU, the United States, and Canada) includes a security perspective, identifying three realms of the resource nexus: markets, state interests and interstate relations, and local human security (Andrews-Speed et al 2012: 5). The Routledge handbook on the resource nexus defines it "as a set of context-specific critical interlinkages between two or more natural resources used as *inputs* into systems providing essential services to humans, such as water, energy, and food," and outlines "a clearly defined five-node nexus for the systems of water, energy, food, land, and materials that seeks to provide consistency, focus, and adaptability to the respective scope and context of analysis and application" (Bleischwitz et al 2017:4; italics added).

Bleischwitz et al further subdivide *materials* (defined as "non-energy abiotic resources") into metals and critical minerals, construction minerals, industrial minerals, and mineral fertilizers. Materials are essential for housing and shelter and account for up to 50% of natural resource use. Moreover, base metals, critical minerals, and construction minerals have important implications for energy production, storage, and distribution, water provision and re-use, and urbanization. Mineral fertilizers are also key inputs for food production: mining is the source of potassium and phosphates, two key plant nutrients in mineral fertilizers. Moreover, the environmental impacts, including land and water resource degradation and GHG emissions of base metals and nutrients are considerable (paragraph, Bleischwitz et al 2018: 8; Hertwich et al., 2010). Mining additionally provides the materials needed to build the machinery and information and computing technologies critical to current FEW systems.

Humphreys (in Bleischwitz et al 2017: 266) points out the linkages between mining and the resource nexus, including land, water, energy, and food production. Mining requires land for the exploitation of ores as well as for the disposal of the substantial waste generated; an estimated 60 billion tons of material are removed from the earth each year (Humphreys 2017; Ericsson, 2016). Mining also requires considerable amounts of water to wash and process minerals: “It is estimated on average to take around 172 tons (thousand litres) of water to produce one ton of copper and 107 tons to produce one ton of nickel. Some 600–700 tons of water are required to produce 1 kilogram of gold” (Humphreys 2017: 270). Moreover, “mining has enormous impacts on the quality, quantity, and flow patterns of water, but as it flows, seeps, and drains, water also remakes mining landscapes physically and politically” (Marston 2017). Similarly, large quantities of energy are needed to recover, smelt, and refine minerals: Energy represents a approximately “one quarter of the total cost of producing the major metals. Associated with this use of energy, the industry is responsible for significant emissions of greenhouses gases to the atmosphere” (Humphreys 2017: 271). Moreover, linkages between other resource systems and mining have become more important as the pressure on these other resource systems increases, and may turn out to be more critical in constraining mining development than the physical availability of mineral ores (Humphreys 2017: 266).

1.3 'Embodiment' and embodied injustices at the resource nexus

The FEW / resource nexus literature generally envisions the interdependencies among these systems in terms of the *inputs* to one system from by another (e.g. water inputs for food). The concepts of embodied ('virtual') water and energy are widely used in FEW nexus studies to quantify the water and energy needed for food and energy production and for obtaining water supply; *e.g* the water inputs for electricity generation and agricultural crops (Ramaswami et al 2017; Konar et al 2011; Hoekstra and Mekonnen 2011), the energy impacts of high-volume hydraulic fracturing (HVHF) and horizontal drilling on water resources and farming systems (Ahamed et al. 2017); and the environmental and social impacts of hydropower (Rosenberg et al 1995; Nilsson and Berggren 2000).

Although the water inputs to high-volume hydraulic fracturing (HVFH, or 'fracking') are relatively small compared to water withdrawals for thermoelectric power and crop irrigation, the water footprint of fracking continues to intensify in the United States alongside its escalating oil and gas extraction, and fracking in combination with horizontal drilling have potentially far-reaching impacts on water, food systems, and helth. Hydropower, by contrast, can be viewed as a quintessentially 'entangled' water and energy system, wherein all the water of a dammed river serves as input to energy generation and is embodied in the resulting electricity. The embodied impacts of the energy system reverberate through the hydrological (water) system, which in turn impact the wider social-ecological systems that it supports. Considering hydropower projects to be global assemblages (Ogden et al. 2013), Gutteriez et al (2019) draw attention to the multiple scales, locations, and contingent relationships entangled with hydropower development. Dam mega-projects are seen as a vital tool for state building, with three political elements characterizing global hydropower assemblages: 1) large hydropower as a symbol for national development; 2) hydropower as a "locus of resistance" for transnational political activism; and 3) the "ongoing alteration of river systems organized according to the purported logic of renewable energy transitions" (Gutteriez et al 2019: 102).

Drawing on ideas of embodiment as well as the fields of environmental and energy justice, Healy et al. introduce the concept of "embodied energy injustice," which "explicitly integrates previously unrecognized social-environmental harms and injustices," exposing the "disproportionate distribution of such harms on vulnerable peoples situated along energy supply chains" (2019: 219, 221) focusing primarily on fossil fuels. They observe that conceptualizations of embodied energy injustices can: 1) help situate chains of energy injustices and place-based energy struggles within wider national and regional energy politics and 2) address regulatory gaps in energy governance by expanding the scope of energy decisions and processes, providing a framework to situate and understand place-based injustices as part of an unjust global order (Healy et al. 2019).

In the same way, and with equal urgency, conceptualizing embodied food, energy, water, and material (FEWM) injustices can situate chains of interacting FEWM injustices and place-based struggles within wider politics, decisions, and processes across multiple interacting lifecycles and supply chains. As with embodied energy injustice, this multi-system perspective reveals deep inequities within and among nations and generations. In conceptualizing embodied FEWM injustices on vulnerable and disenfranchised local populations along the transboundary supply chain, *control* 'over,' *access* 'to,' and *impacts* 'on' food, water, energy, materials, and land should also be understood as critical dimensions of the FEW/resource nexus. In this context, embodied FEW injustices at the nexus occur when: 1) *control* over land, water, and energy resources systematically disenfranchises vulnerable populations; 2) the environmental and health *impacts* of interdependent FEWM systems disproportionately affect these groups; 3) *access* to food, energy, water, land and material well-being of generally local vulnerable communities are systematically hampered, jeopardized or denied to benefit generally distant consumers.

In the first chapter, I describe the FEW nexus in the Denver Region, where possible quantifying inputs from each system to the other two, and examining the types of ecosystem risks associated with FEW system intersections. I also examine the distribution of these risks across the Denver Region, how they are changing over time, and consider what type of indicators are needed to address these questions, as well as the limitations of such metrics. In the second chapter, I extend the FEW / resource nexus to include embodied injustices and transboundary sustainability (FEW+M+EN+TS) and apply this extended lens to a northern “resource frontier” first opened to development 45 years ago by the James Bay hydropower megaproject, where extractive efforts, given concrete expression in Quebec’s 2011 Plan Nord, are now accelerating at the same time that hydropower is being re-branded as clean energy. In each of these cases, flows of food, energy, and water across political and administrative boundaries from sites of production (sources) to sites of consumption (sinks) are central to questions of both equity and sustainability.

1.4 Transboundary sustainability: Linking Production and Consumption Through Infrastructure

The notion of transboundary sustainability (TS) is vital to integrated, coherent efforts to increase sustainability at local, regional, national and international levels. Urban areas are responsible for much of the global demand for food, energy, water, and materials, and cities seeking to improve their overall sustainability and health are increasingly adopting a FEW nexus perspective (Ramaswami et al., 2016; Ramaswami et al., 2017; Zhang et al., 2011). Transportation, energy, and water infrastructure are key support sectors for and components of FEW systems, serving as connective tissue linking many components of FEW supply and demand across large distances. While food distribution systems and mining depend on road networks, energy and water systems have their own dedicated complex infrastructures of grids and pipes for transport across long distances. These infrastructures are highly interdependent; transportation enables the building of energy and water distribution networks and is necessary for material extraction and removal, as well as food distribution.

Embodied FEW+M injustices are also closely interlinked with teleconnected, multiscalar supply chains that span multiple regions, administrative units, and provincial, state and national boundaries. Environmental impacts and embodied injustices affect vulnerable communities along supply chains of varying complexity. Fossil fuel supply chains, for example, typically include hundreds of small and large-scale public and private corporations in numerous locations around the world, while hydropower megaprojects such as the James Bay Project may involve a single utility company, making it ostensibly easier to expose social and environmental impacts and injustices. As the James Bay case demonstrates, however, even when the actors are known, successfully opposing and defeating such projects is fraught with difficulty.

CHAPTER 2: THE FOOD-ENERGY-WATER NEXUS, REGIONAL SUSTAINABILITY, AND HYDRAULIC FRACTURING: AN INTEGRATED ASSESSMENT OF THE DENVER REGION

Abstract

Intersections of food, energy, and water systems (also termed the FEW nexus) pose many sustainability and governance challenges for urban areas, including risks to ecosystems, inequitable distribution of benefits and harms across populations, and reliance on distant sources for food, energy, and water. This case study provides an integrated assessment of the FEW nexus at the city and regional scale in ten contiguous counties encompassing the rapidly growing Denver region in the United States. Spatial patterns in FEW consumption, production, trans-boundary flows, embodied FEW inputs, and impacts on FEW systems were assessed using an urban systems framework for the trans-boundary food-energy-water nexus. The Denver region is an instructive case study of the FEW nexus for multiple reasons: it is rapidly growing, is semi-arid, faces a large projected water shortfall, and is a major fossil fuel and agricultural producer. The rapid uptake of high-volume hydraulic fracturing (HVHF) combined with horizontal drilling in populated areas poses ongoing risks to regional water quality. Through this case study, fracking is identified as a major topic for FEW nexus inquiry, with intensifying impacts on water quantity and quality that reflect nationwide trends. Key data gaps are also identified, including energy for water use and food preparation. This case study is relevant to water and sustainability planners, energy regulators, communities impacted by hydraulic fracturing, and consumers of energy and food produced in the Denver region. It is applicable beyond Denver to dry areas with growing populations, agricultural activity, and the potential for shale development.

Key Message

Readers of this case study will be able to define the food-energy-water nexus and describe emerging conceptual frameworks for examining the FEW nexus at local and regional scales. Readers will become familiar with both challenges in applying such frameworks and insights the FEW nexus approach can offer into complex issues surrounding sustainability.

Key substantive content: An integrated spatial assessment of the food-energy-water (FEW) nexus, focusing on: a) production, b) consumption, c) trans-boundary flows, d) embodied water and energy inputs, e) and embodied impacts (e.g. the impact of energy systems on regional water supplies).

Key message: As the water footprint of hydraulic fracturing continues to intensify in the United States alongside the country's escalating oil and gas extraction, fracking poses particular risks to water and food systems in regions where energy and food production are co-located. Given its role in expanding fossil fuel production and potential impacts on water and food systems, hydraulic fracturing is an important subject for emerging trans-disciplinary FEW nexus inquiry.

2.1 Introduction

Global food, energy and water (FEW) systems are profoundly interconnected: 70% of global freshwater withdrawals are for agricultural production (1); 8% of total global energy is used for water pumping, treatment, and distribution (2); and in the U.S. the amount of water withdrawn for electricity generation rivals that used by the agricultural sector (3). Solutions focused on just one of these systems, or on one geographic region, often have unintended consequences for other systems and regions. Interconnected FEW systems also have profound impacts on the overall environment, reshaping and profoundly altering land and ecosystems at large scales.

The FEW nexus has been broadly defined as the intersections among food, energy, and water systems that have major impacts on: a) natural resources, particularly water, energy, nutrients b) pollution and greenhouse gas emissions, and c) “the security of FEW supplies essential to the well-being of the world’s population” (4). The FEW nexus approach is seen as a promising way to identify and quantify the potential synergies in food, energy, and water security, while also reducing trade-offs, increasing efficiency, improving governance, and working to protect ecosystems (5). Integrated nexus assessments often focus on understanding the linkages between domains, such as water to generate thermoelectric power (6,7). Central to these assessments are attempted quantifications of the embodied, or virtual, water and energy required across different segments of FEW life cycles, but there are major gaps in the data and methodological approaches needed for such efforts (4).

High-volume hydraulic fracturing (HVHF) – “fracking” – combined with horizontal drilling is a timely, important, and contentious example of the interconnection between water and energy systems: it is a water-intensive process that uses high-pressure water to create cracks in underground shale formations to extract previously inaccessible gas and petroleum (8). It has been described as a “wicked” problem: one involving complex and opaque science and policymaking, overlapping areas of policy jurisdiction, requiring coordinated action among divided stakeholders, and resulting in limited solutions with complex consequences (9,10).

Fracking and drilling have potentially far-reaching impacts on water systems (11–13); recent research also maps the linkages between fracking and food systems (14). These impacts are unevenly distributed both in space (15,16) and across populations (17–19), with the potential to compromise water quality if not carefully managed (20,21). In the United States vast shale reserves extend from the Appalachian Mountains to the Northern Plains to the Gulf Coast (22). These processes have become widely used in the span of less than a decade (22), and have propelled the United States to become the top global producer of petroleum and gas in the world, surpassing Russia in natural gas in 2009 and Saudi Arabia in petroleum in 2013 (23), with output set to increase even further in the coming years.

It has been widely noted that the water inputs for high volume hydraulic fracturing are small compared to the requirements of agriculture and other industry (24,25) and the growing FEW nexus literature generally has not considered fracking to be a subject of inquiry. In this case study, however, the FEW nexus approach led to the identification of hydraulic fracturing as a key issue at the intersection of regional food, energy and water systems. Systematic consideration of both *inputs to* as well as *impacts on* FEW systems are vital to a full picture of the challenges posed by hydraulic fracturing for regional communities, that is, both the *quantity* of water inputs needed for fracking and the observed and potential impact of fracking on regional water *quality*.

However, as with FEW nexus data in general, water quality data related to hydraulic fracturing are limited, diverse, and often difficult to access (9). In 2014 one review called the physical science literature on fracking “remarkably inconclusive” (26), and much is unknown about current and potential impacts of HVHF and drilling on water quality. At the same, understanding how frequently these operations impact groundwater quality is essential to assessing drinking water safety and risk in regions around the country where these practices are common (27), particularly as nationwide oil and gas production continues to increase.

2.2 Case Examination

The Denver region has several characteristics that make it an instructive case study of the trans-boundary FEW nexus: it is rapidly growing, semi-arid, has diminishing groundwater reserves, and is a principal fossil fuel exporter and major agricultural producer. The ten counties included in this study had an estimated total population of 3,375,000 in 2015, grew by 20% in the preceding ten years, and are projected to gain an additional 1.2 million residents by 2035 (28,29). Eight of the ten counties in the region sit at least partially atop the Niobrara, a major shale formation that has among the highest oil and gas outputs in the country (30).

The Denver region receives between 6 and 16 inches of precipitation annually and sits atop the Denver Basin Aquifer, a largely non-renewable and extensively drilled groundwater reserve (Figure 2-1). Regional agriculture and Denver area municipalities already rely on major diversions of water from the Western slope of the Rocky Mountains over the Continental Divide to the Eastern Slope. As human settlements encroach on land previously used for agriculture, growing municipalities are permanently buying water rights from farmers, a policy known as ‘buy and dry.’ The state is facing an anticipated 163 billion gallon (500,000 acre-feet) water shortfall by 2050, twice the amount currently used by Denver Water’s 1.3 million residents (29,31).

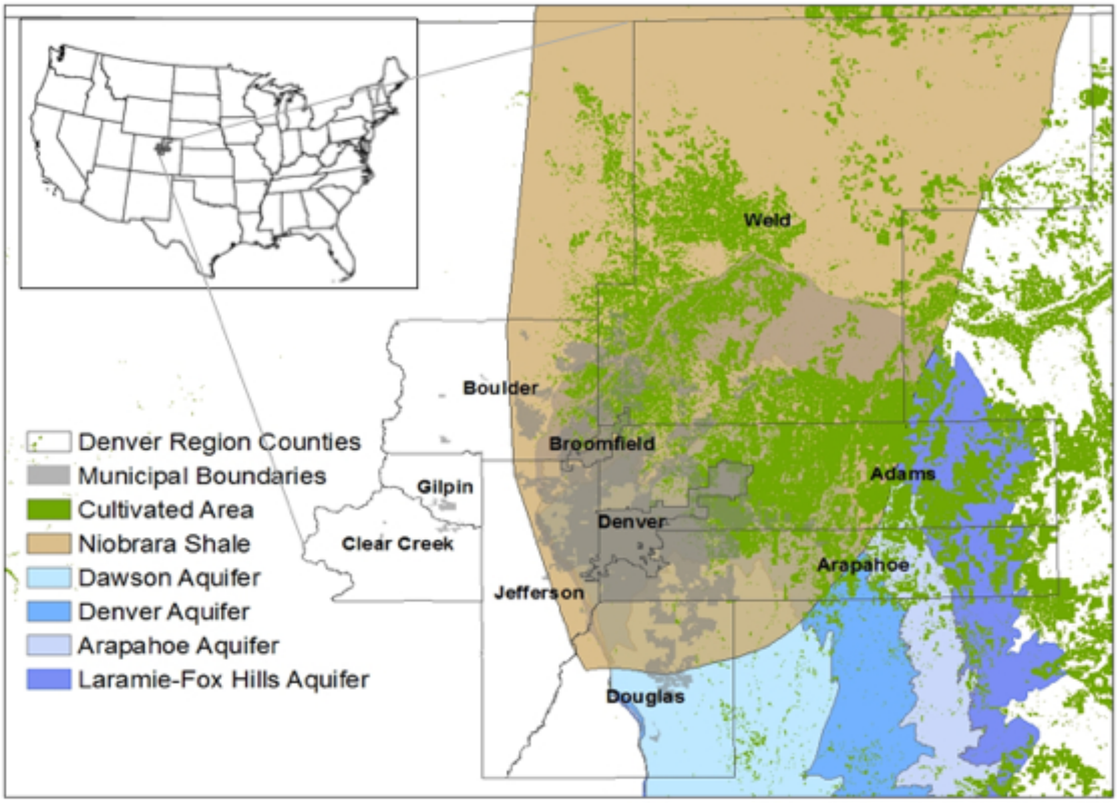


Figure 2-1. The ten-county study area. *Cultivated land, the Denver Basin aquifer system, and the Niobrara Shale Formation are overlaid with municipal extents. The inset depicts the location of the Denver region within the southwestern United States. Data sources: USDA Cropland Data Layer, Denver Region Council of Governments, US Geological Survey, US Energy Information Administration.*

Similar to rapidly-growing counties located above the rich gas reserves of the Barnett shale in Texas, Weld, Boulder, Broomfield and Adams Counties in the Denver region are in the midst of a “perfect storm” where expanding surface development meets mineral extraction (32). In Colorado this ‘split-estate’ system creates conflict between surface owners and those who own the mineral rights located below the surface (21). Responsibility for well and land reclamation in the case of abandoned wells is also a major concern under this system (34).

The following research questions, relevant to identifying more sustainable system interconnections at multiple spatial scales, are addressed:

1. To what extent can the FEW nexus in the region be described and quantified?
2. What types of ecosystem risks are associated with these activities?
3. How are risks distributed across the landscape and how are they changing over time?
4. What available and emerging indicators are needed to address these questions? In what ways are such metrics limited?

2.2.1 Methods

Extending an existing urban system framework: One way to assess FEW system intersections is through the concept of embodied water and energy. Embodied energy refers to the energy needed for food and water-related activities across the life cycle, including energy for pumping, distribution, and wastewater treatment. Similarly, embodied water refers to the water needed for energy and food related activities across the life cycle (Figure 2-2**Error! Reference source not found.**a). This case study builds o n the urban systems framework to assess the trans-boundary FEW nexus first proposed in 2017 by Ramaswami *et al.* that they used to quantify direct and embodied flows of food, energy, and water for the city of Delhi, India (4). Not considered in that case were intra-city differences, changes over time, and in-boundary FEW production.

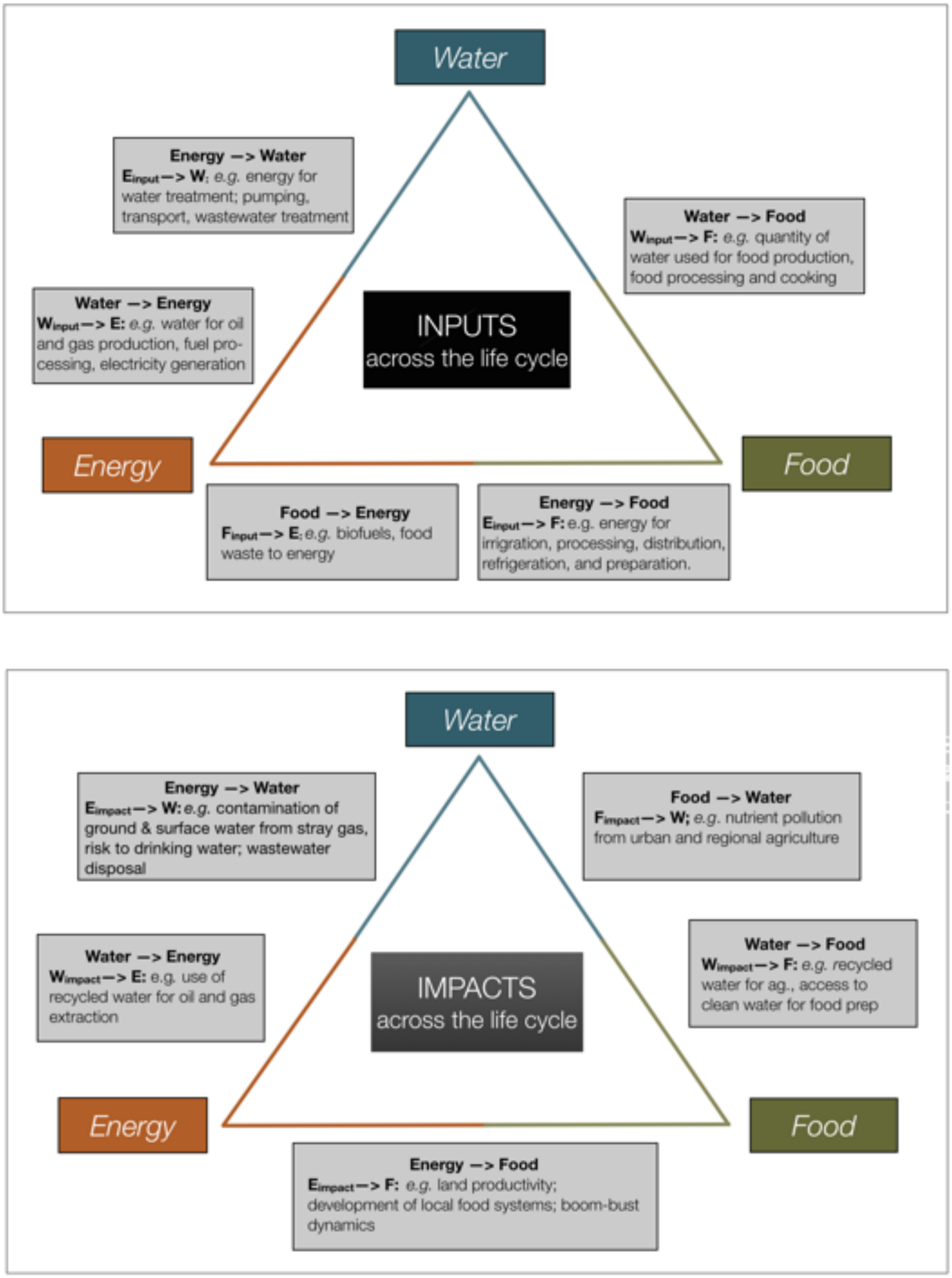


Figure 2-2a and b. *Illustration of the pairwise relations in the FEW Nexus framework for developing spatially explicit indicators at the urban-regional scale, considering (a) inputs to and (b) impacts on food, energy and water systems.*

The current study extends that framework by including data from ten counties and more than forty municipalities. Also included is an assessment of in-boundary energy and food production for export, as well as changes to FEW systems over the past decade. Embodied *impacts on* FEW systems situated within broader ecosystems as well as embodied *inputs to* FEW systems are also systematically considered (Table 2-1 and Figure 2-2b).

Table 2-1. *FEW relations, focusing on impacts, including examples specific to hydraulic fracturing and a category for impacts on overall ecosystems.*

	Pairwise Relation	**Examples (*specific to hydraulic fracturing)**
W_{impact} → E	Impact of water quality across the energy life cycle	*Use of recycled water for oil and gas extraction.
W_{impact} → F	Impact of water quality across the food life cycle	Recycled water for agriculture; access to clean water for food preparation; *Impacts from decline in water quality on soil, land, and ecosystem productivity (crops/animal health);
E_{impact} → W	Energy-related risks to/impacts on water systems	*Aquifer contamination through gas leakage from improper construction or failing wells; water resource contamination through spills, leaks, and waste management; accumulation of metals and radioactive elements in aquatic sediments at disposal and spill sites (13,20)
E_{impact} → F	Energy-related impacts on food systems	*[Second order] impacts from decline in water quality on soil, land, and ecosystem productivity (crops/animal health); effects of fracking-related air pollution on pollinators; effects on development of local, alternative food systems; fracking-related boom-bust dynamics (14). Extent of interactions among frac fluid and wastewater constituents is not well-understood (61).
E_{impact} → Ecosystems	Energy-related impacts on social-ecological system as a whole	*Total environmental study paradigm for the impacts of fracking, including the anthroposphere , atmosphere, hydrosphere, lithosphere, and biosphere (62)

F_{impact} →W	Food-related impacts on water systems	Nutrient pollution of lakes, rivers and streams from agricultural runoff (4)

This characterization focuses on: a) FEW production, b) FEW consumption, c) trans-boundary flows of food, energy, and water d) embodied FEW inputs e) and embodied FEW impacts. Where such data was not already available in GIS format, geo-referenced maps based on state, county, and regional boundary files were created. Additional detail about data sources, processing steps, and calculations are included in Supplementary Materials.

Co-production of supply and demand metrics with regional FEW experts was also undertaken. Analysts from regional utilities, regional data providers, infrastructure consultants, and city sustainability coordinators were consulted to gain additional perspectives on regionally important FEW nexus topics. During June-August 2016, semi-structured interviews were conducted with representatives from several organizations involved in FEW nexus governance, service provision, and research. These organizations included the Denver Region Council of Governments (DRCOG), Xcel Energy, Denver Water, the National Center for Atmospheric Research, and the National Renewable Energy Laboratory. The goal of these interviews was to obtain feedback on our initial research questions, identify relevant data sources, and build working relationships.

2.3 Food, energy, and water demand in the Denver region

Per day, the Denver region consumes an estimated 68.9 GWh of electricity; 378,000 MCF of natural gas for residential and industrial heating; and 1403 M gallons of water (35,36).

Approximately 114,000 tons of coal, crude petroleum, transport fuels, and natural gas; and 46,000 tons of food and agricultural products are imported into the region per day. Energy imports totaled $9.67 billion and food-related imports totaled $17.6 billion in 2015, including food and energy products that are produced within the region (37).

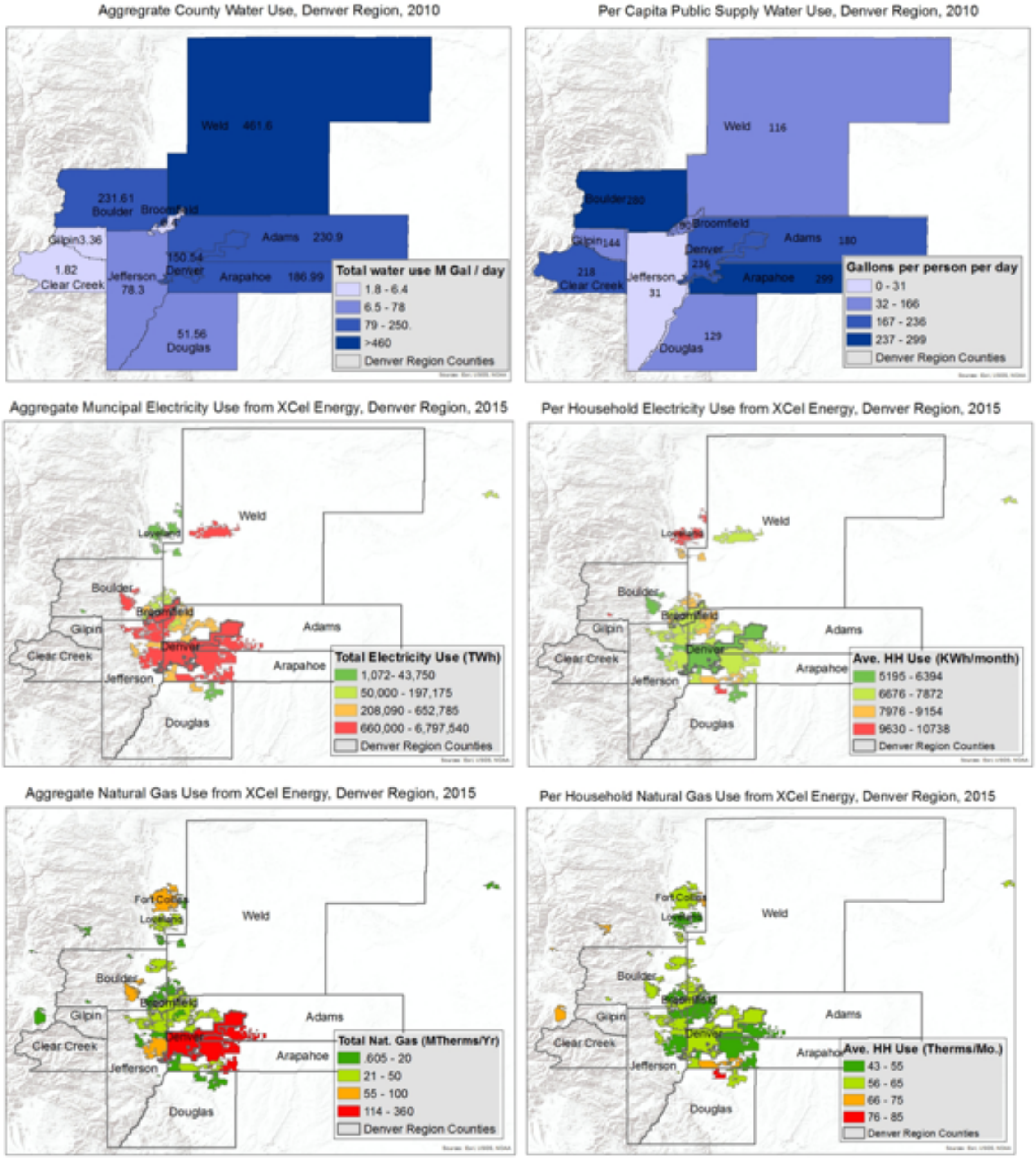
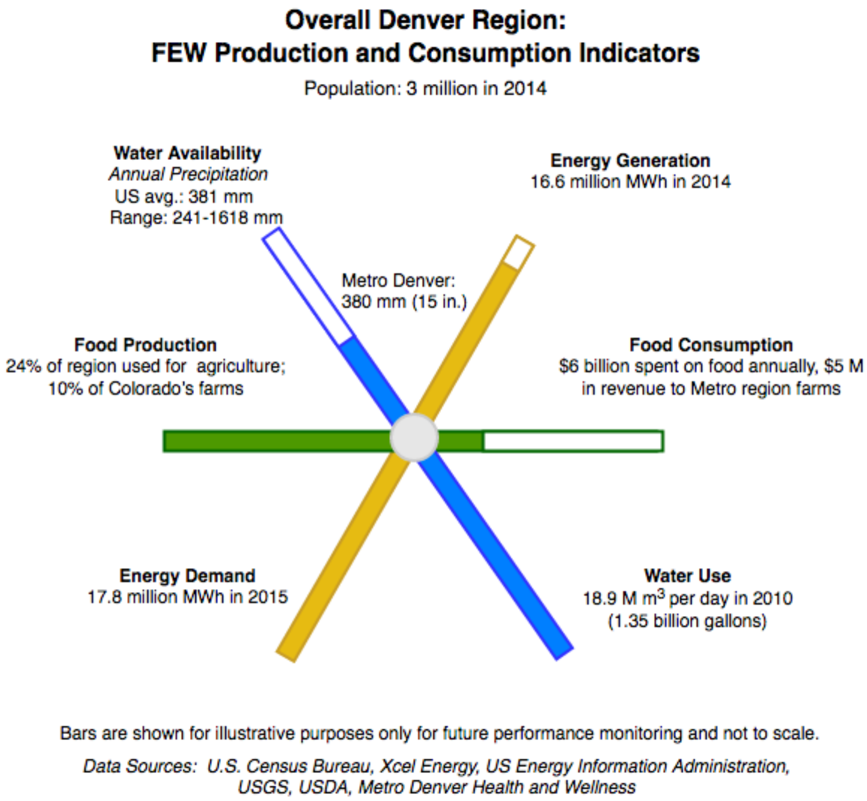


Figure 2-3. *Region-wide and per household water, electricity and natural gas consumption. Data sources: USGS and Xcel Energy.*

City-wide and per capita FEW consumption within the region varies widely

(Figure 2-3). Aggregate energy demand is greater within more densely populated cities and towns, but per household demand in these areas tends to be lower. Denver and Boulder, for example, consume the most electricity and natural gas in aggregate but have the lowest energy consumption per household (Figure 2-4; see Supplementary Materials for additional details and calculations.*]*


Overall Denver Region:
FEW Production and Consumption Indicators
Population: 3 million in 2014

Bars are shown for illustrative purposes only for future performance monitoring and not to scale.

Data Sources: U.S. Census Bureau, Xcel Energy, US Energy Information Administration, USGS, USDA, Metro Denver Health and Wellness

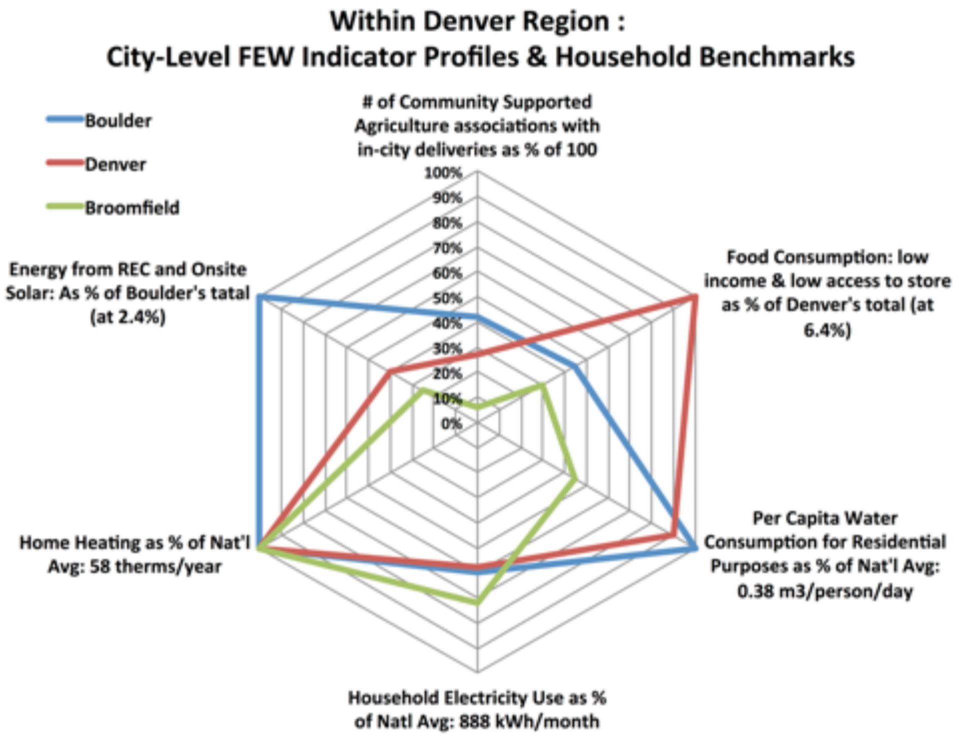
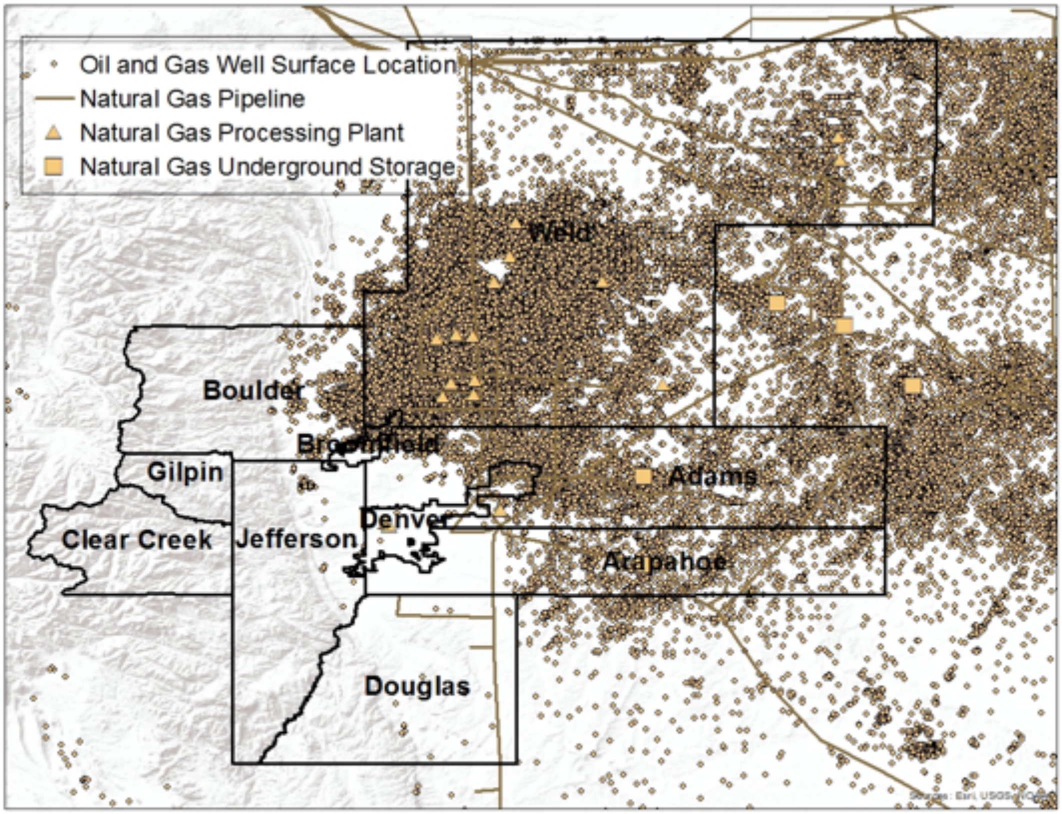


Figure 2-4. FEW Multi-Metric Visual Tools. *(Top): The three axes display regional production and consumption of food (green), water (blue), and energy (orange). (Bottom): City-level FEW sustainability metrics for selected muncipalities in the region.*

2.4 Food, energy, and water supply in the Denver region

Per day, approximately 186,000 tons of coal, crude petroleum, transport fuels, and natural gas and 39,000 tons of food and agricultural products are exported from the region. Fossil fuel extraction and food production are major activities: 44,000 oil and gas wells yielded 120 million barrels of oil and 686 million MCF in 2017 (38). Twenty-four percent of the land area was categorized as cultivated in 2015 (39). Energy exports totaled $19.7 billion, while food-related exports totaled $13.8 billion in 2015, including goods consumed within the region (37). Notably, much of this fossil fuel extraction and food production is occurring in the same place: 68% of the region's 44,000 oil and gas wells are located on farmland (**Error! Reference source not found.**), directly impacting land and water r esources used for regional food production.

Intraregional differences in food and energy production are significant. Energy and agricultural activities are concentrated in Weld County, which has 81% of the region's oil and gas wells (38). Agriculture sales (80% livestock and 20% crops) are consistently in the top ten nationwide; in 2012 sales amounted to $1.86 billion, a 21% increase from 2007 (40). Annual oil output in Weld County rose nine-fold to 118 million barrels and natural gas output more than tripled to 678 million MCF between 2006 and 2016. In neighboring Boulder County, by contrast, annual oil output fell from 27% to 97,000 barrels and natural gas output fell from 38% to 1.5 MCF during the same period (38), due to a county-wide moratorium on fracking from 2012-2017, renewed for another two years in 2018 (41). *[See Supplementary Materials for additional details and calculations.]*


Oil and Gas Well Surface Location
Natural Gas Pipeline
Natural Gas Processing Plant
Natural Gas Underground Storage
Weld
Boulder
Broomfield
Gilpin
Adams
Denver
Clear Creek
Jefferson
Arapahoe
Douglas

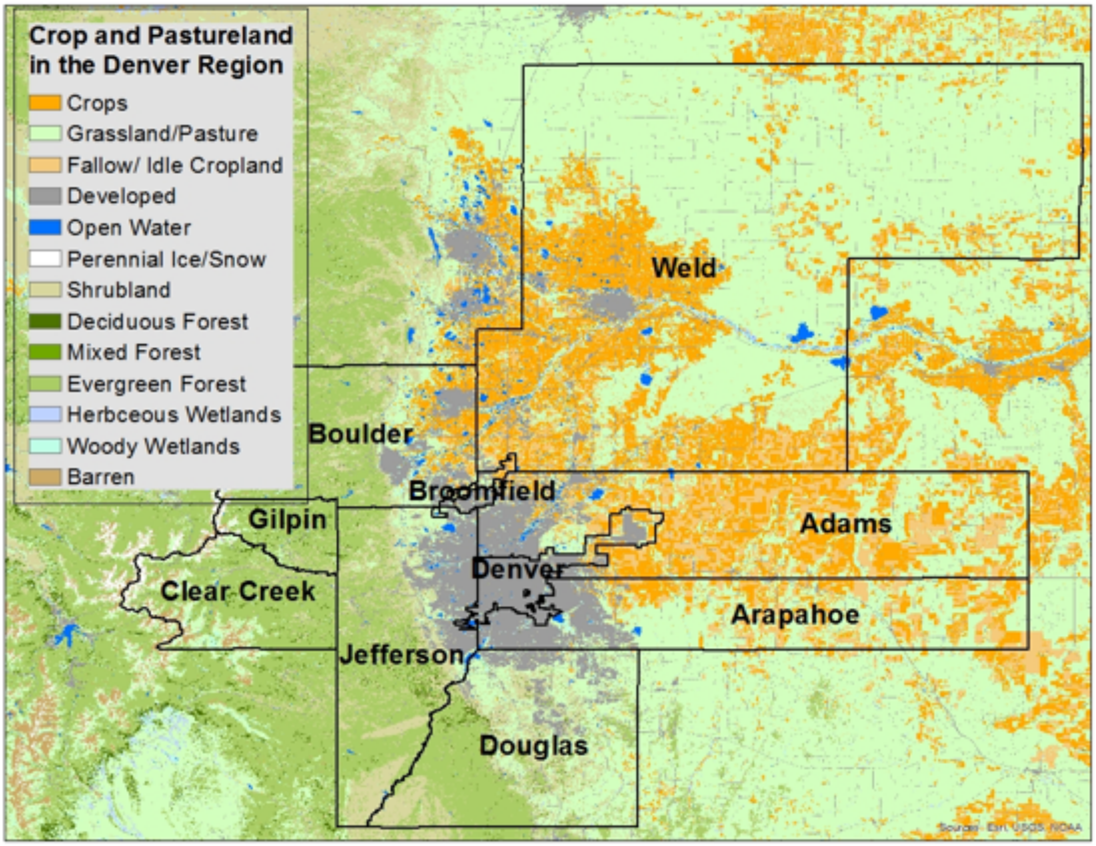


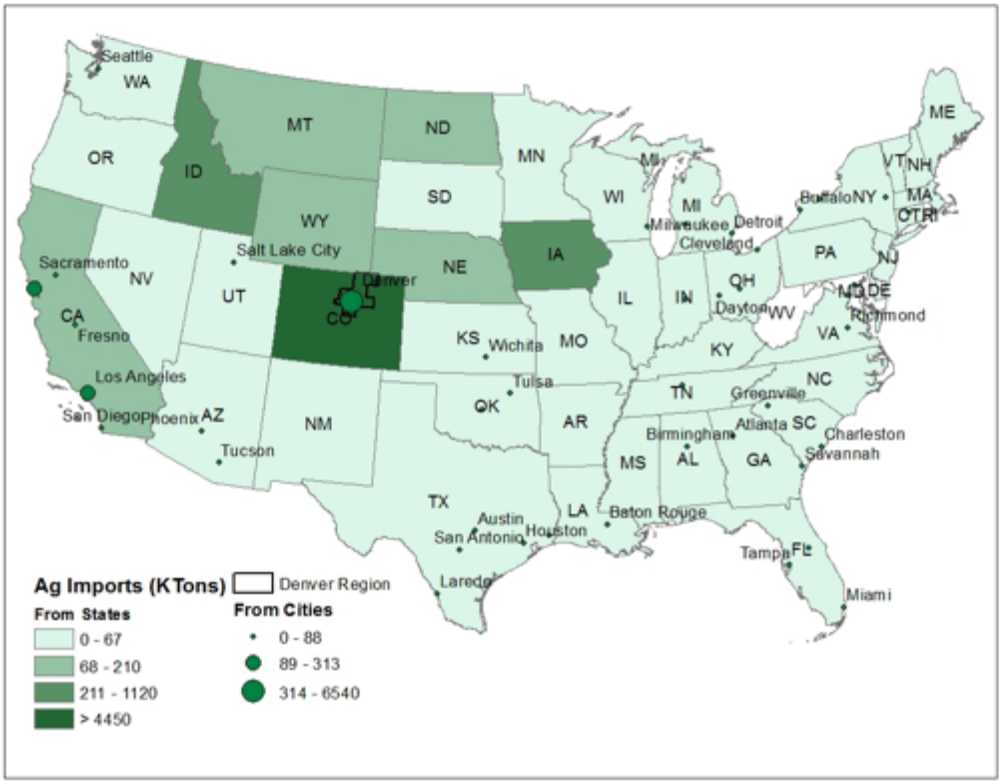
Figure 2-5. Energy and food production in the Denver Region. *(a) Surface locations of oil and gas wells: As of Jan 2018, the region has a total of approximately 44,000 oil and gas wells. Data sources: COGCC and EIA. (b) Extent of the Denver region's crop and pastureland. Human settlement is encroaching onto land previously used for irrigated agriculture. Data sources: USDA and DRCOG.*

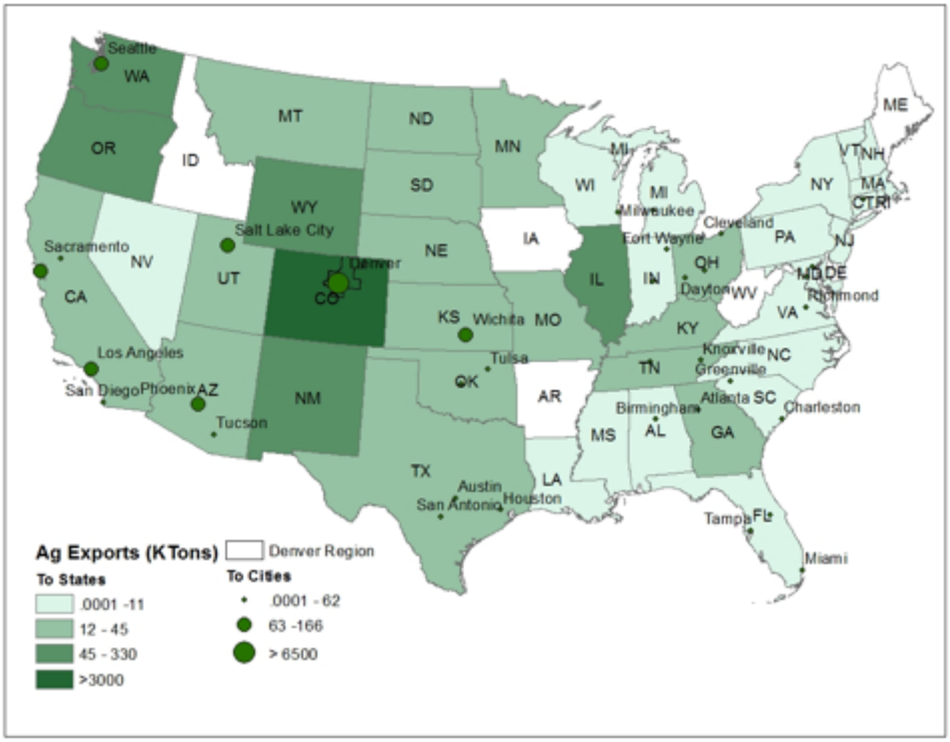
2.5 Transboundary Flows

According to freight data, in 2015 the region exported 14 megatons of food and agricultural products, generating $13.8 billion in revenue, and 67 megatons of energy-related products, generating $19.7 billion (Figure 6). Per megaton, the value of food produced in the region was about $1 billion, while per megaton of fossil fuels the value is $295,000 (37).

Food: The region is a net food importer. In 2015, 10 megatons of food-related commodities were imported into the Denver region. By contrast, 7.6 megatons were exported to destinations around the country. An additional 6.5 megatons produced in the region were also consumed in the region.

Energy: The region is a net energy exporter. In 2015, 37 megatons of energy-related commodities were imported into the Denver region. By contrast, 63 megatons were exported to destinations around the country. An additional 4.7 megatons produced in the region were consumed in the region.




Ag Exports (KTons)
Denver Region
To States
.0001 -11
12 - 45
45 - 330
>3000
To Cities
.0001 - 62
63 -166
> 6500
Seattle
WA
OR
ID
MT
ND
SD
MN
WY
Salt Lake City
NE
IA
WI
MI
Milwaukee
Cleveland
PA
NY
ME
VT
NH
MA
CT
RI
NJ
MD
DE
Sacramento
NV
UT
Denver
CO
IL
IN
Fort Wayne
OH
Dayton
WV
Richmond
VA
CA
KS
Wichita
MO
KY
Los Angeles
Tulsa
Knoxville
NC
Greenville
San Diego
Phoenix
AZ
OK
TN
NM
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SC
Charleston
Birmingham
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MS
AL
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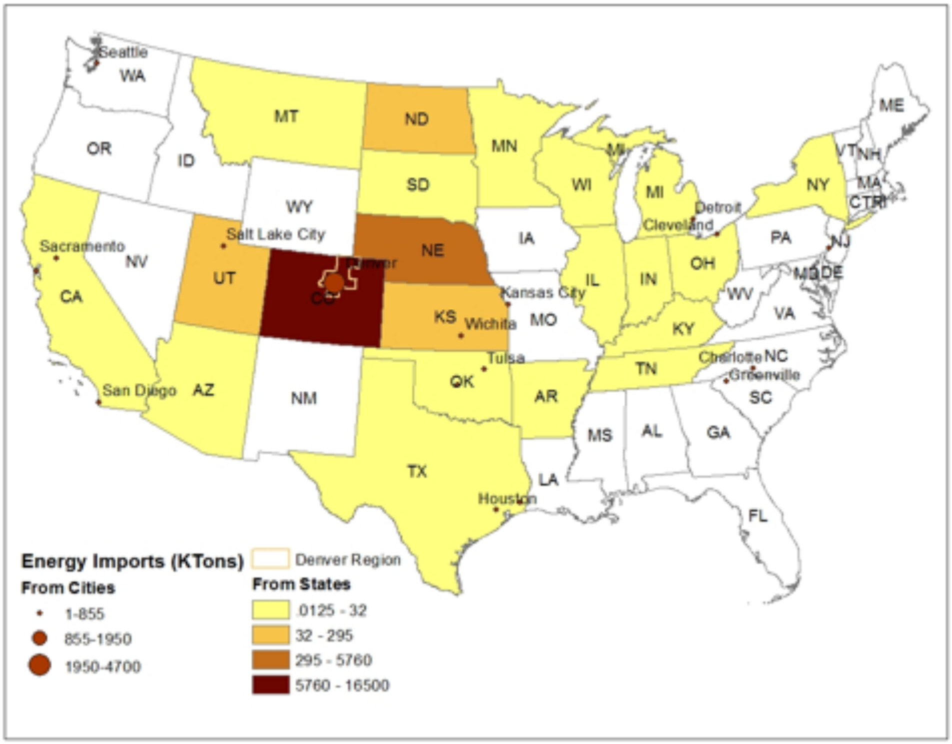
TX
Austin
San Antonio
Houston
LA
Tampa
FL
Miami


Energy Imports (KTons)
Denver Region
From Cities
1-855
855-1950
1950-4700
From States
.0125 - 32
32 - 295
295 - 5760
5760 - 16500
Seattle
WA
MT
ND
MN
ME
OR
ID
SD
WI
MI
VT
NH
NY
MA
CT
RI
WY
Detroit
Cleveland
Salt Lake City
Sacramento
NV
IA
PA
NJ
NE
Denver
UT
CA
CO
IL
IN
OH
MD
DE
Kansas City
WV
KS
Wichita
MO
VA
KY
Tulsa
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Greenville
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Houston
FL

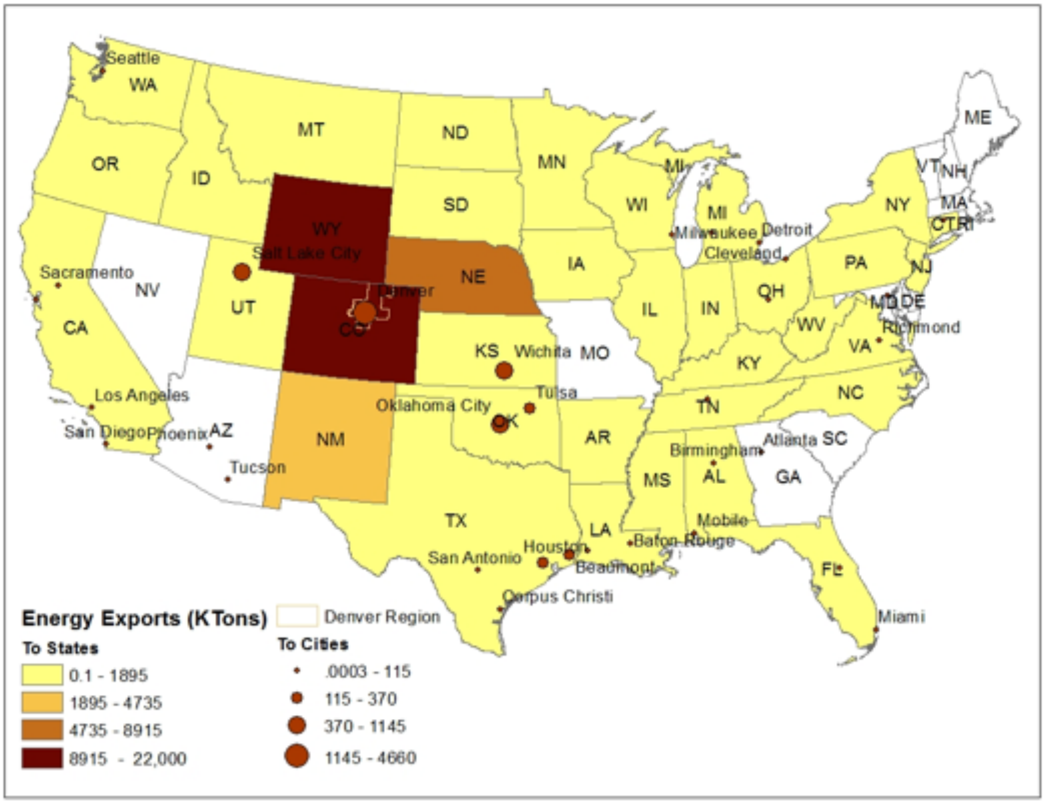


Figure 2-6 (panel; 4 maps). Food and energy imports and exports from the Denver Region. *Food and agricultural imports and exports from the Denver Region in 2015. Energy imports and exports from the Denver Region in 2015. Data source: Center for Transportation Analysis.*

Water: Seventy to 80% of Colorado's precipitation falls west of the Continental Divide and 80-90% of the state's population lives east of the Divide. The Colorado-Big Thompson Project (C-BT), built between 1938 and 1956, supplies water to more than 2.6 Gm^2 of irrigated farmland and approximately 880,000 people in northeastern Colorado in eight counties, including Boulder, Broomfield and Weld (8).

2.6 Embodied food, energy, and water: Inputs

Embodied water: inputs

Export-based agriculture and energy production consume a significant portion of the region's limited water resources. While much of the water used for agriculture percolates through the soil (to become recycled groundwater), the water used for hydraulic fracturing cannot be re-used for other purposes because of the toxic chemical additives needed for the fracking process.

$W_{inputs} \rightarrow F$: Water inputs to food systems

Irrigation in the Denver Region is the major water use. In 2010 almost one billion gallons per day were used for irrigation/agriculture (35).

$W_{inputs} \rightarrow E$: Water inputs to energy systems

Water input for hydraulic fracturing**:** Water input for hydraulic fracturing poses risks to the regional *quantity* of water supplies. As identified in a technical report issued by the National Renewable Energy Laboratory, these risks include: a) the number of wells drilled, b) the amount of water used per well, c) the amount of recycling of fluids used to offset freshwater requirements, and d) local water availability (20).

a) Number of wells drilled: There are approximately 44,000 oil and gas wells in the region. Since 2010, 9060 were reported to have used hydraulic fracturing (38,42; Figure 7).

b) Amount of water used per well: Reflecting national trends, the reported average water use per well has steadily increased over time, from 2.43 MG in 2013 to 8.8

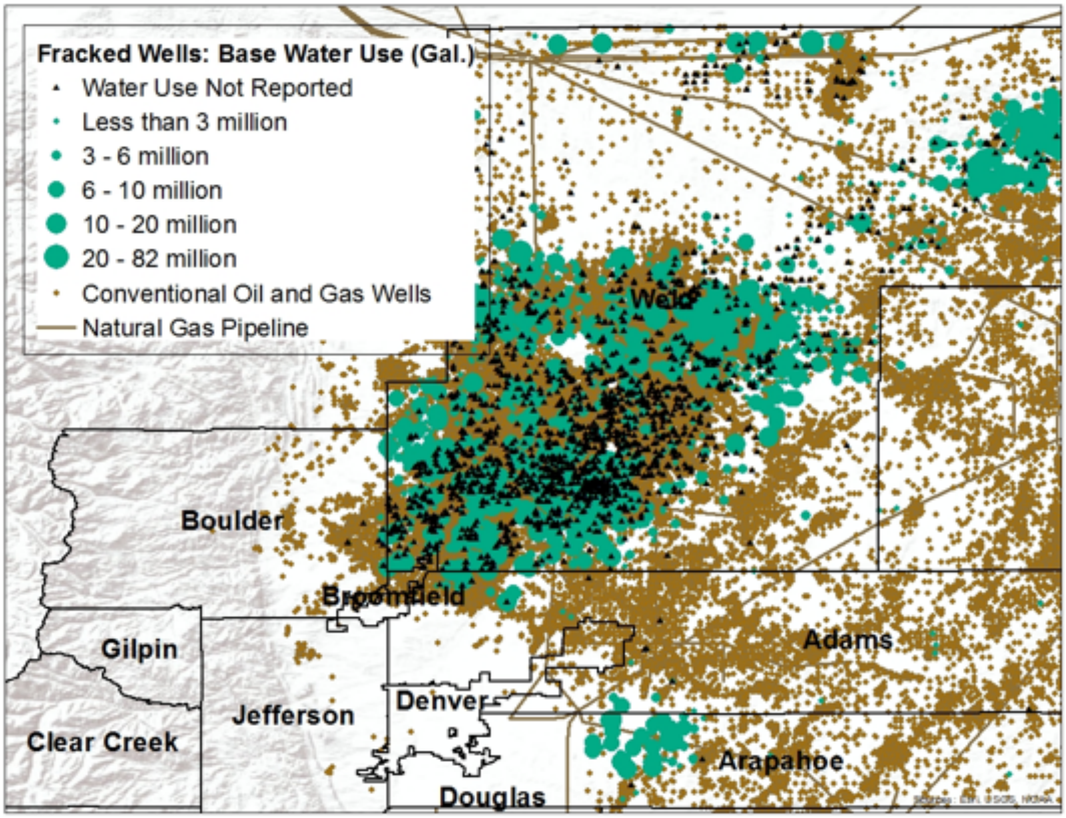
MG in 2017 (Table 2).

c) Amount of recycling of fluids used to offset freshwater requirements: In Colorado the amount of produced water reused is not tracked and the reuse of produced water is not mandatory (8,20,43) .

d) Local water availability: Reflecting national trends, the total base water volume for hydraulic fracturing has steadily increased over time, doubling from one-half billion gallons in 2016 to almost one trillion in 2017 (42). (Water source not included in the dataset.)

Table 2-2. Industry-reported water use for hydraulic fracturing on the Niobrara Shale.
Data derived from the FracFocusRegistry database (fracfocus.org).

Year	Total Base Water Volume (Mgal)	#Frack Jobs Started	Average Water Use (Mgal)
2013	3160	1300	2.44
2014	5750	1450	3.97
2015	5450	1120	4.88
2016	4920	721	6.32
2017	9770	1111	8.80


Fracked Wells: Base Water Use (Gal.)
▲ Water Use Not Reported
● Less than 3 million
● 3 - 6 million
● 6 - 10 million
● 10 - 20 million
● 20 - 82 million
◆ Conventional Oil and Gas Wells
— Natural Gas Pipeline
Weld
Boulder
Broomfield
Gilpin
Adams
Jefferson
Denver
Clear Creek
Arapahoe
Douglas
Sources: Esri, USGS, NOAA

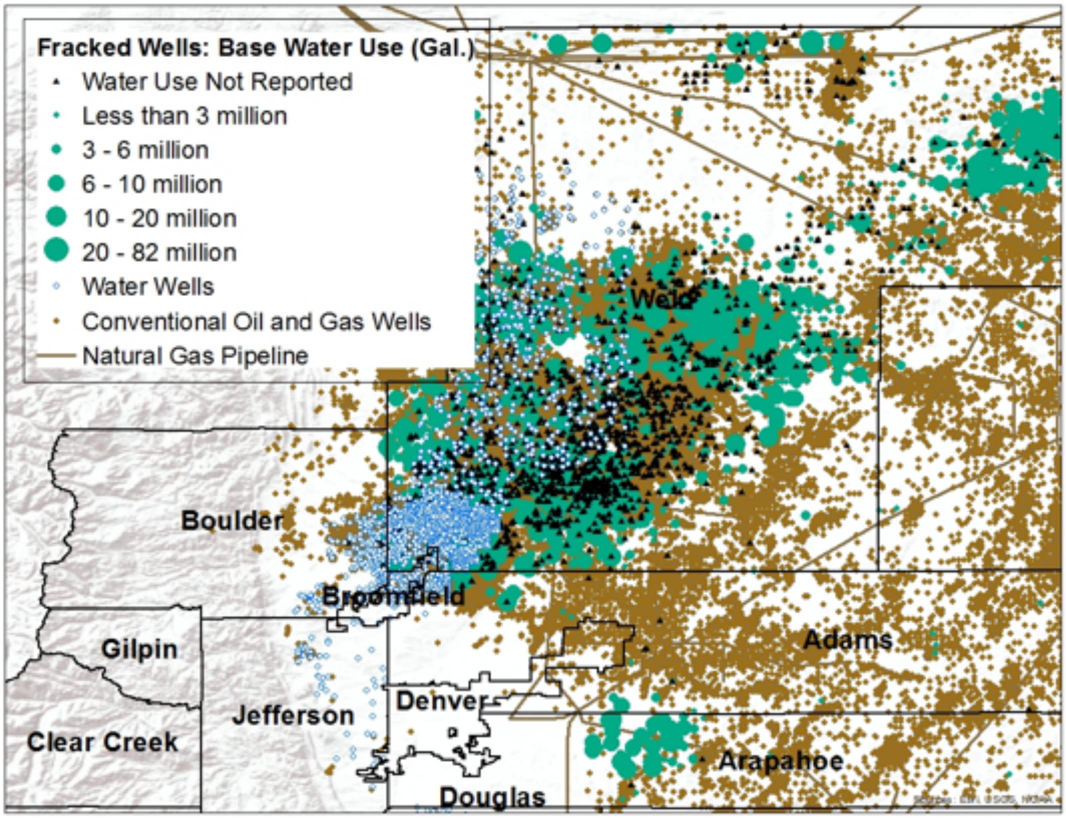


Figure 2-7a and 7b. Water inputs for hydraulic fracturing. *(a) The locations of conventional oil and gas wells and hydraulic fracturing wells along with total base water use for each well, if reported; b) Locations of water wells overlaid with oil and gas wells. Data sources: COGCC, fracfocus.org, USGS, and DRCOG.*

2.7 Shale development impacts on regional water and food systems

2.7.1 Impacts on water across the life cycle

Water quality risks posed by unconventional shale oil and gas development arise from: a) seismic exploration and discovery, b) onsite road and well pad construction techniques, c) drilling and onsite chemical management practices, d) wastewater management practices and e) interim and final reclamation (20,44). Publicly available data on impacts to water quality resulting from oil and gas development are confined to violations issued by state regulators, reported spills, accidental releases, groundwater impacts, and uncontained berms (Table 2-3).

Table 2-3. Energy impacts on water, food, and ecosystems in the Denver region.

Pairwise Relation	**Systems Analysis: Type of Impact and Relevant Indicators**
E_{impact}→W: Energy-related impacts on water systems (Figures 9,10) *Data sources: COGCC Daily Activity Dashboard (DAD); Fracfocus.org*	Aquifer contamination through gas leakage from improper construction or failing wells. Violations Issued: **In 2017: 18 (50% decrease from 2016)** Water resource contamination through spills, leaks, and waste management. Spills/Accidental releases: **Between 2014-2017: 1537. In 2017 in Weld County: 399 (36% increase from 2016)** Accumulation of metals and radioactive elements in aquatic sediments at disposal and spill sites: Between 2014-2017: • **Reported groundwater impacts at 314 sites and surface water impacts at 10 sites** • **160 uncontained berms holding produced and frac flowback water** Consumption of valuable freshwater in arid regions/ overexploitation of diminished water resources: **Water use in 2017 to 1 trillion gallons (100% increase from 2016); 8.8 million gallons per well**
E_{impact}→F: Energy-related impacts on food systems (Figures 11, 12) *Data sources: COGCC DAD; USDA 2016*	Second order impacts from decline in water quality on soil, land, and ecosystem productivity, including crops/animal health (Pothukuchi *et al*. 2017). **30,000 wells on farmland in the region: 12,000 wells on pastures/ grassland; 12,000 on active cropland; 6,000 on fallow/idle cropland**
W_{impact}→E: Impact of water quality across the energy life cycle	Use of recycled water for oil and gas extraction. **Data on the amount of water recycled not available; re-use by industry is not mandatory in Colorado.**
E_{impact}→ Social-ecological system as a whole (Figure 10)	Disposal of waste (produced) water: **About 50% is disposed by underground injection.** Most produced water not injected is disposed in evaporation and percolation pits or discharged under the Colorado Discharge Permit

Data sources: COGCC DAD; COGCC Annual Report, 2017; Fractracker.org	System**. Data on how much water is discharged and where these releases occur are not available.** Seismic activity caused by injection wells for wastewater **34 Class II injection wells** **Public complaints: Nearly six-fold increase from 190 in 2016 to 1124 in 2017** Home explosion in the town of Firestone caused by abandoned gasline from existing well

<u>Onsite practices</u>: One indicator of risk to water quality is the number of spills associated with the drilling process. There were 451 spills in the Denver Region from operations in 2014 (Figure 8). This number dropped to 366 in 2015 and 293 in 2016, but rose again in 2017. Another indicator of the risk to water quality from unsafe onsite chemical management practices is the number of violations issued by regulators to well operators. In 2017, 18 violations were issued, a 50% decrease from 2016, while public complaints increased almost six-fold during the same period, from 190 in 2016 to 1124 in 2017 (38; Figure 9).

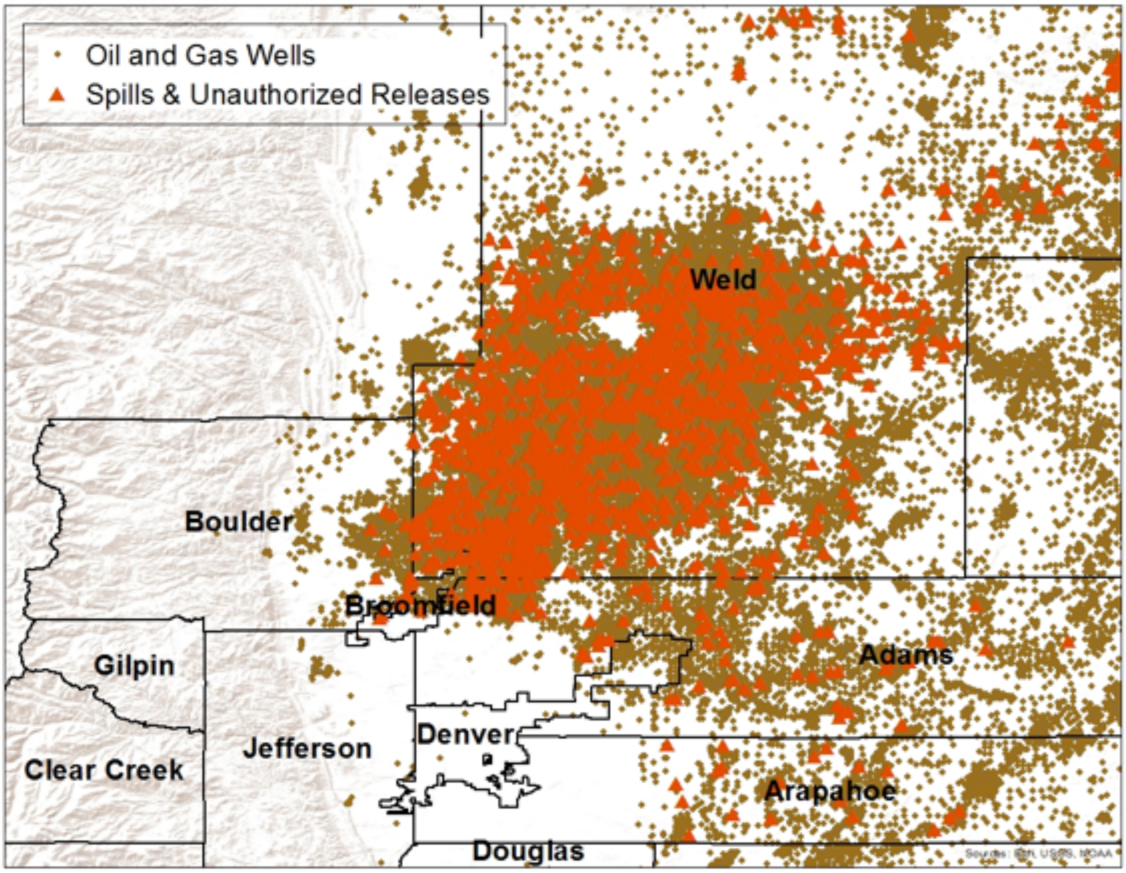


Figure 2-8. Spills and unauthorized releases. *The oil and gas extraction industry reported 1537 occurrences from 2014 to January 2018. The white spot in the middle of Weld County is the town of Greeley. Data Source: COGCC.*

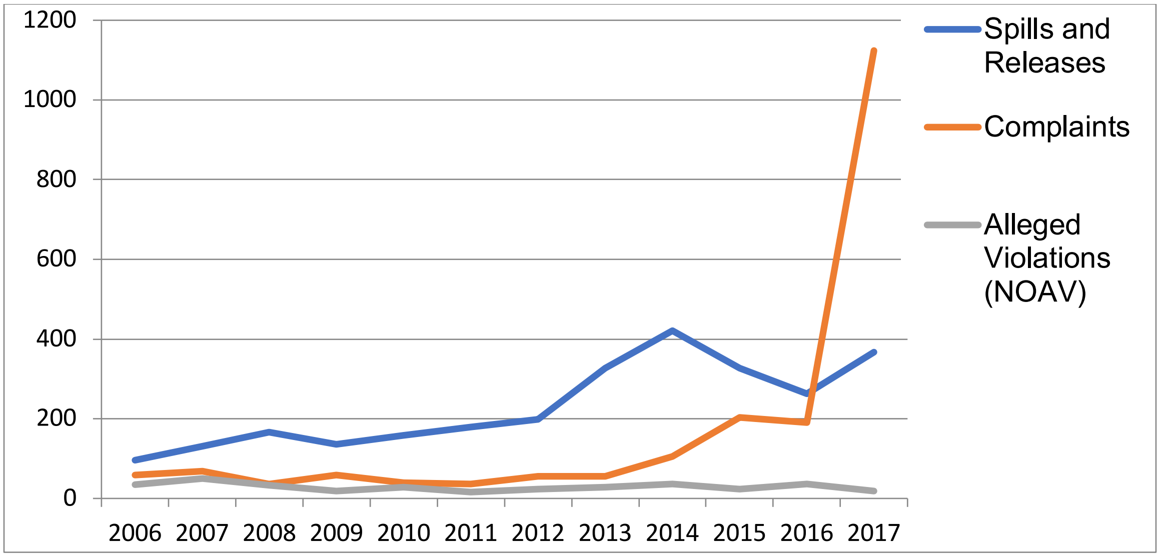
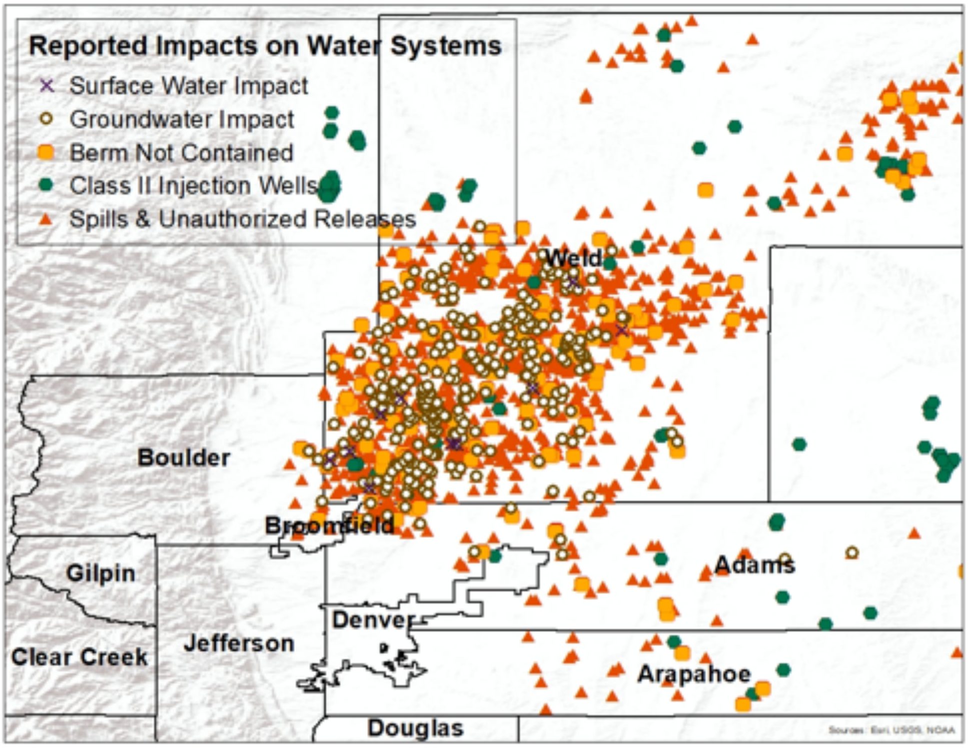


Figure 2-9. Spills and releases, public complaints, and alleged violations in Weld County from 2011 to 2017*. Data sources: COGCC Daily Activity Dashboard and the Colorado Oil and Gas Information System*

<u>Wastewater management</u>: Wastewater (also referred to as produced water) found in hydrocarbon formations, is a major by-product of the fracking and drilling process. High in salt and naturally-occurring groundwater contaminants, it returns to the surface along with chemical-laced frac-flowback water. In Colorado, a majority of wastewater is injected into the ground or taken to evaporation ponds (8). Metals and radioactive elements accumulate in aquatic sediments at disposal and spill sites (13; Figure 2-10). The Denver region's oil and gas drilling activities generated more than 35 million barrels of wastewater in 2016, compared to 8.4 million barrels in 2006 quadrupling in ten years (38).


Reported Impacts on Water Systems
× Surface Water Impact
○ Groundwater Impact
Berm Not Contained
Class II Injection Wells
Spills & Unauthorized Releases
Weld
Boulder
Broomfield
Gilpin
Adams
Denver
Jefferson
Clear Creek
Arapahoe
Douglas
Sources: Esri, USGS, NOAA

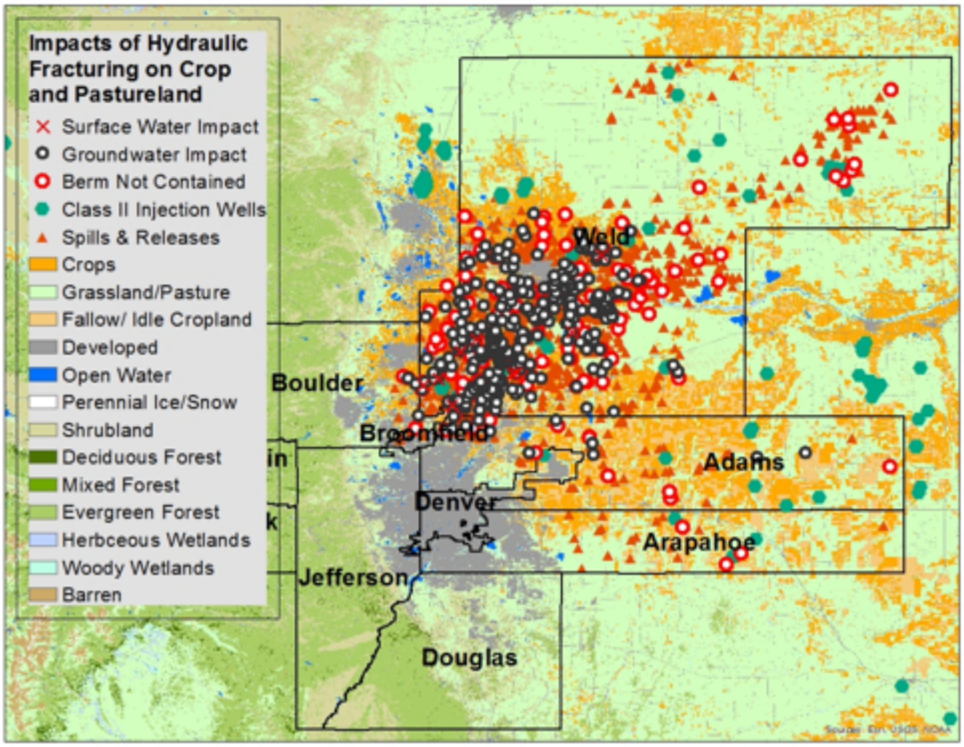


Figure 2-10a and 10b. Class II injection wells, uncontained berms, groundwater and surface water impacts. *(a) Locations where ground and surface water impacts, and uncontained berms were reported between Jan 2014 to Jan. 2018 and (b) overlaid with human settlement, cropland and pastureland Data sources: COGCC Daily Activity Dashboard, fractracker.org.*

2.7.2 Impacts on food across the life cycle

$E_{impact} \rightarrow F_{system}$ Second order impacts of hydraulic fracturing on food systems result from declining water quality on soil, land, and ecosystem productivity, including crops/animal health (14). The surface locations of 30,000 of the region's 44,000 oil and gas wells are on farmland: about 12,000 on pastures/ grassland, another 12,000 on active cropland, and 6,000 on fallow/ idle cropland (39).

2.8 Discussion

2.8.1 Framework Implementation

Building on an urban systems framework developed by Ramaswami *et al.* for FEW nexus analysis (4), the regional-level results above are synthesized within an expanded regional framework (Figure 2-11). Where data is available, quantifiable flows of food, energy, and water into and out of the region are depicted. The embodied water and energy associated with these activities are also shown (*e.g.* the water used for irrigation, electricity generation, and fracking). This approach highlights the additional vulnerabilities of water-intensive production of food and energy in the populated, semi-arid Denver region. The original framework is also extended in an initial attempt to incorporate the risk posed to the region's scarce water supplies and arable land from hydraulic fracturing to meet fossil fuel demand from outside the region.

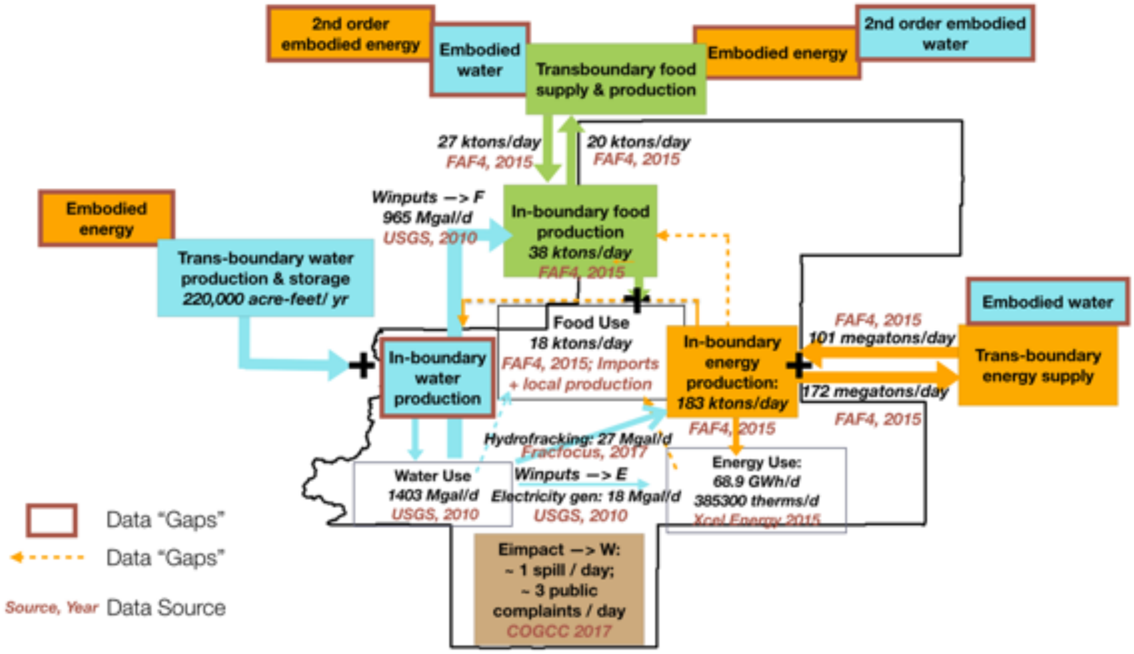


Figure 2-11. *Implementation of the trans-boundary urban systems framework for the*

FEW nexus. Flows of food, energy and water to, from, and within the Denver region are depicted. Data gaps, data sources, and time periods for numerical estimates are included. This representation focuses on inputs, with some attempt to incorporate impacts.

2.8.2 Data Availability and Gaps: Informed by Diverse Institutions, Agendas and Contexts

The implementation of this urban systems framework for the Denver region also illustrates the many gaps in data availability surrounding the interdependency of regional food, energy, and water systems (dashed lines and red boxes, Figure 2-11). The total amount of water pumped from the Denver Basin aquifer is not monitored (46) and gaps and discrepancies in federal data on water usage by thermoelectric power plants are well-known (6). Other key data gaps include energy for water use and food preparation. We also include sources and dates for available data, adding an additional layer of transparency to reflect the constructed nature of publicly available information for city/regional indicators (45) as they pertain to the FEW nexus. For example, according to self-reported industry data 28 Mgal/day of water were used in fracking jobs on the Niobrara shale that had a start date in 2017 (42), while 18 Mgal/day were used for electricity generation in 2010, according to the USGS (35).

2.8.2.1 Fracking Data

Because oil and gas industry data is proprietary, with rights to privacy protected by law, such data is not accessible to citizens and researchers working in the public interest. Local political activity has prompted public access to information on drilling operations in the state of Colorado since 2012, including disclosure of the chemicals used in the fracking process and the amount of water used per frack job (47). In the wake of a house explosion in the town of Firestone in 2017 caused by a stray gas line, Denver-area communities have demanded public maps of the state's 120,000 flow-lines (48).

Data on the impacts of hydraulic fracturing on water quality in particular are sparse and contested. Underground injection of oil and gas wastewater, for example, has not yet been researched as a source of systemic groundwater contamination on the state or national level (49) and there are no regulations requiring detailed data disclosure that could allow scientists in academia and industry to develop best practices (9). Citizens groups have stepped in to fill knowledge gaps through surface and groundwater monitoring projects (50–52). Distrust of the ability of industry and government regulators to produce valid, unbiased water quality data is common among these groups (9).

2.8.3 Hydraulic fracturing and the FEW nexus

This case study illustrates that hydraulic fracturing can be viewed as a defining issue at the intersection of food, energy and water systems. It has been emphasized in the literature that water use and produced water intensity for fracking is lower than other energy extraction methods, and represents only a fraction of total industrial water use nationwide (24). While this may be true at a large scale, this narrative misses several crucial points that are clearly illustrated in the Denver case:

With respect to water quantity:

1) Fracking poses unique risks in semi-arid, agricultural, and rapidly growing areas. In the Denver region fracking water use not only competes with municipal demand and agriculture, it is occurring within municipal boundaries and on the region's farmland.
2) Water use for hydraulic fracturing has intensified in the region over the past five years, as it has in rest of the United States; the water footprint of both inputs and wastewater are increasing.

With respect to water quality:

1) The Niobrara shale and Denver Basin Aquifer are co-located (Figure 2-1), with both drilling and wastewater injection posing risks to groundwater, a concern even in non-water scarce areas. Globally, 59% of world's shale deposits are in the footprint of major freshwater aquifers (25).
2) In Colorado, the majority of Class II injection wells and aquifer exemptions are located in regions with higher quality water, including the Denver Region, potentially jeopardizing those resources (49).

With respect to regulation and governance:

1) Water quality impact depends on construction, drilling, onsite chemical management practices, and wastewater handling, and is thus greatly impacted by regulation, monitoring, and enforcement.
2) Federal power to regulate shale gas development is limited due to fracking exemptions from the Safe Drinking Water Act and the Clean Water Act, as well as

drilling exemptions from the National Emission Standards, Hazardous Air Pollutants and other federal environmental statutes (32,53).

3) Colorado's air emissions and water-testing regulations have been called the most rigorous in the country by state officials (54); however the COGCC employs approximately 23 inspectors to monitor the 52,000 wells around the state (55), leading some stakeholders to question their effectiveness (33).
4) Regional intensification of the water footprint of hydraulic fracturing shows signs of increasing even further since Jan 2017, the start of a new presidential administration, which favors less federal regulation of the energy industry and less environmental regulation in general.
5) At the same time, inadequate enforcement may be intensifying: 2017 also saw a 36% increase in spills/releases; a 600% increase in public complaints in Weld County, and a 50% drop in Notice of Alleged Violations compared to 2016 (38).

With respect to justice, equity, and the right to ban

A nuanced grasp of '*how* energy, water, and food have been produced, historically, under particular social formations' (56) is vital to developing a full picture of the complex social, political and environmental dimensions of FEW nexus issues in general, and hydraulic fracturing in particular. Such perspectives address the power relations that underpin a given resource nexus, termed the 'critical social science' of the FEW nexus (56), and are especially relevant to the governance of fracking, distributional and environmental justice, and greater regional and global sustainability.

The lack of centralized authority over oil and gas drilling in the U.S. has left decision-making in the hands of states and local authorities. While the U.S. mandates environmental impact assessment of development projects, there is no required equivalent assessment of the social impacts of these projects on affected communities. Municipalities and communities are therefore burdened with the responsibility of addressing the costs and benefits of energy development. This can further reinforce existing inequities, as wealthier and less marginalized communities are better able to marshal the resources necessary to do this effectively.

Within this context, the potential for multiple, unknown, or contested risks related to oil and natural gas extraction has led to increased community activism across Colorado (55). The Colorado Supreme Court has struck down several local bans on hydraulic fracturing (*City of Longmont v. Colo. Oil and Gas Association; City* of *Fort Collins v. Colo. Oil and Gas Association*), based on lawsuits filed by the oil and gas industry against Denver-area cities Broomfield and Longmont, as well as nearby Fort Collins. In November 2018, Proposition 112, which would have required the setback distance for fracking from schools, homes and water sources be increased from 500 to 2500 feet, was defeated in statewide elections. The oil and gas industry spent $41 million in a campaign to reject the proposition (57); 57% voted ultimately against it.

This makes state enforcement of existing environmental, health, and safety regulations the only immediate recourse for local residents seeking to limit tracking impacts on their communities. The fracking moratorium in Boulder County has not yet been contested by industry, emphasizing the lack of consistency in *de facto* protection for residents across the region. Additionally municipal land area comprises a mere 11% of the Denver region; even if local bans were upheld, large areas would remain open to shale development.

2.8.3.1 Sustainability transitions: Teleconnections, nexus tradeoffs, and energy alternatives

The Denver region exports 93% of the energy and 54% of the food it produces to cities and states around the country, particularly the mid- and south-western U.S. The trans-boundary FEW nexus approach allows ecosystem and health risks to the Denver region's 3.2 million inhabitants to be linked indirectly to fossil fuel consumption across the country. More directly, these risks can be linked to a patchwork of local, state, and federal regulation and court rulings on hydraulic fracturing. While the region's water-intensive agricultural sector nearly rivals the energy sector in economic value, it involves fewer material flows and less groundwater risk. Co-location of renewable energy infrastructure with farming is another model for regional energy-food production that poses reduced risk to water supplies (58).

2.9 Conclusion

This case study illustrates the potential for the FEW nexus approach to identify interconnections between demand and supply networks, incorporating embodied FEW as well as ecosystem impacts and risks at multiple spatial scales. Consideration of *impacts on* as well as *inputs to* FEW systems in the Denver region places hydraulic fracturing firmly within the FEW nexus scope. This is important because FEW nexus research is the target of major funding efforts (59,60) and directly relevant to the intensifying water footprint of fracking in the United States (24), particularly when it is co-located with agriculture. FEW nexus research is also well-poised to articulate the need for more and better data on system and trans-boundary interconnections that are vital to assessing the impact of fracking on regional water quality and soil fertility that so far have not been systematically undertaken (9,61). In addition, this emerging trans-disciplinary effort has the potential to offer key insights into so-called ‘wicked problems’ that fracking exemplifies.

2.10 Case Study Questions

On describing and quantifying the FEW nexus

- What is the ‘data gap’ in FEW nexus based research?
- What other types of knowledge might be needed to assess nexus interconnections and identify sustainable solutions at multiple spatial scales and across food, energy and water systems?
- What historical factors have contributed to the current FEW systems in place in the Denver region? Why is this important?

On hydraulic fracturing

- What is the role of public policy in improving scientific understanding of the impacts of hydraulic fracturing on water quality?
- What monitoring systems, industry regulations, and environmental protections are needed to ensure that regional water supplies are not impacted by hydraulic fracturing?
- Should municipalities be allowed to ban hydraulic fracturing within their boundaries? Why or why not?

On local sustainability, regional interdependence, and distributional equity

- What are the links between local solutions to meet the food, energy, and water needs of a community, and sustainable solutions? In what cases might local production of food or energy be unsustainable?

- Why is it important that sustainable solutions also be equitable ones? Provide some examples to support your reasoning.

Investigating the FEW nexus

- Consider your hometown or other geographic area of interest. What indictors would you need to describe the interconnections between energy, water and food systems in this region? From what sources would you obtain this data?
- What important issues related to food, energy and water sustainability might such indicators overlook?
- What historical factors have contributed to the current FEW systems in place in your area of interest? Why is this important?

Envisioning sustainable, interconnected systems

- What might sustainable and equitable food, water and energy systems look like for your area of interest? How would these systems depend on each other?
- In what ways would your region depend on other regions? How would its FEW-related activities impact other regions?

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CHAPTER 3: THE FOOD-ENERGY-WATER-MATERIAL NEXUS AND EMBODIED INJUSTICES: THE ROLE OF HYDROPOWER IN DEFORESTATION IN EEYOU ISTCHEE/NORTHERN QUEBEC

Abstract

Injustices within political and economic systems profoundly influence Food, Energy, and Water (FEW) systems, yet the interdependent inequities stemming from these systems are rarely considered in nexus analyses. In this study we widen the FEW nexus to include Materials (FEWM) and examine Embodied iNjustices and Transboundary unSustainability (FEWM+ENTS) resulting from FEWM systems. We introduce a four-part monitoring framework, including 1) FEWM *inputs;* 2) the social-ecological *impacts* of these systems; 3) *access* to FEWM and 4) *control* over FEW systems and material extraction. We apply this approach to the contested region of Eeyou Istchee/Jamésie, Quebec, where the 40-year construction of the largest hydropower complex in the Western Hemisphere has enabled large-scale extraction of timber, minerals, and electricity from a relatively intact boreal ecosystem. Using remote sensing analysis and supplementary datasets, we document ecosystem disturbances by year and type since 1975, when the Cree Nations of Eeyou Istchee, the Inuit, and the Quebec and Canadian governments signed the first modern Aboriginal land claims agreement. We identify cumulative impacts and interdependencies among hydropower, roads, logging, wildfire and mining, finding that roughly 106,000 km^2 have been deforested due to these disturbances since 1975, comprising 29% of the region, an area equivalent to more than four times the state of Vermont, which receives about one-third of its electricity from Hydro-Quebec. These extensive environmental degradations undermine claims that electricity and material exports from the region are 'clean' and 'sustainable.' Instead, these disturbances illustrate the unsustainability of current interlinked transboundary FEWM supply chains and demonstrate steadily intensifying non-Native control over and extraction of the region's resources, reflecting larger patterns of embodied injustices that have recently culminated in sweeping new development initiatives and stand to further reinforce these historical trajectories.

3.1 Introduction

Nexus-based approaches to the study of food, energy, and water systems (FEWS) are centered around the premise that these systems are both fundamentally interconnected and increasingly unsustainable. Incorporating materials into food-energy-water (FEW) nexus framings is not new: a number of approaches include materials as part of a broader “resource nexus,” envisioned as “a clearly defined five-node nexus for the systems of water, energy, food, land, and materials,” whereby the “nexus” refers specifically to a set of “context-specific interlinkages between two or more natural resources used as *inputs* into systems providing essential services to humans” (Bleischwitz, Hoff, et al., 2018: 4, italics added; Andrews-Speed et al., 2012; Bleischwitz, Spataru, et al., 2018). Materials, which Bleischwitz et al. define as “non-energy abiotic resources,” include base metals, critical minerals, and construction minerals, and account for up to 50% of natural resource use, making their overall environmental impacts and GHG emissions considerable (2018: 8). As pressure on FEW systems increase, linkages among FEW systems and water- and energy-intensive mining practices have become more important (Humphreys, 2017).

The FEW/resource nexus has the potential to offer new insights in the midst of increasing global water scarcity and the deepening climate crisis, as the need to move away from fossil fuels gains urgency, bottom-up efforts to transition to sustainable FEWS intensify, and entrenched energy interests exert widespread influence on global political processes. Nexus-based approaches are useful in elucidating regional vulnerabilities, such as the dependence of mega-cities on other areas for direct water supply and for ‘embodied’ water inputs to food and energy production (Ramaswami et al., 2017; Hoekstra & Mekonnen, 2012). Nexus interdependencies are often quantified in terms of embodied inputs; for example, the amount of water needed for agricultural crop irrigation, or the energy required for groundwater pumping. Nexus analysis that focuses on embodied inputs, while important in clarifying patterns of FEW supply and demand, generally does not provide an understanding of the socio-political factors, historical conditions, and systemic inequities that have contributed to transboundary patterns of FEW production and consumption that are both inequitable and unsustainable (Allouche et al., 2014; Foran, 2015; Leck et al., 2015).

FEWS also have significant impacts upon each other; examples include the impact of hydraulic fracturing on water resources and food production (Ahamed et al., 2019); the impact of fertilizer on aquatic ecosystems; and the social and environmental impacts of hydropower (Nilsson & Berggren, 2000; Rosenberg et al., 1995). FEW nexus research exploring the interdependent relationship between *inputs* and *impacts* across social-ecological systems is necessary to provide an applied problem-solving lens to find solutions that are sustainable and just. Equally important is awareness of the historical and ongoing inequities that shape current systems. In this paper we introduce a four-part monitoring framework for FEW/resource nexus analysis, addressing 1) Food, Energy, Water, and Material (FEWM) *inputs,* 2) the social-ecological *impacts* of these interdependent systems, 3) equitable *access* to FEWM, and 4) *control* over FEWS and material extraction. We implement this framework through a case study of the contested region of Eeyou Istchee/Jamesie (EI/J), Quebec[1], which was opened by the James Bay hydropower project in the early 1970s to industrial development, and where extractive

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[1] The combined extent of the overlapping boundaries of the Cree Nations of Eeyou Istchee (translated as 'the People's Land') and the 'Territory Equivalent' (TE) of Jamésie, Quebec are used for this analysis (Figure 3-1), hereafter referred to as Eeyou Istchee / Jamésie (EI/J). See the Cree Vision of the Plan Nord for a summary of regional governance up to 2011 and the website of the Eeyou Istchee James Bay Regional Government for the governance structure in place since July 24, 2012 (https://www.greibj.ca/en/), including nine integrated Land and Resource Management Panels (https://www.greibj.ca/en/territory/tgirt) in the forestry zone within EI/J (Figure 3-4).

efforts have gained renewed traction in the past decade. [Departing from the resource nexus definition, 'materials' will be used throughout this paper to include both the biotic resource of timber as well as abiotic metals and minerals.] Reliant on the power supplied by the James Bay hydropower complex and the road infrastructure needed to construct it, logging and mining have played a central role in ongoing and *de facto* control of these resource-rich areas by outside extractive interests, working alongside non-Native state-building and territorial expansion. At the same time, the hydropower obtained from the region is billed as 'clean' energy to neighboring US markets.

We structure this analysis around the deforestation occurring in the region since the James Bay Project began in the early 1970s, focusing on embodied inputs, impacts, and injustices as they are manifested in boreal forest losses, as well as the overarching issue of control over the region's resources. Forests provide a compelling example of the FEW/resource nexus (Tidwell, 2016): they are governed for "multiple and often conflicting goals" including biodiversity protection, water resources, timber production, and community livelihoods (Bleischwitz et al., 2017: 8). Hydropower projects in forest ecosystems can also provide a guise to access lucrative resources such as timber (Matthews & Motta, 2015). Boreal forests in particular are of global ecological significance, containing 25% of the world's remaining primary forests. The 270 million hectares of boreal forest in Canada hold 306 billion tons of carbon, or 12% of the world's land-based carbon stock, almost twice as much as the world's combined oil reserves (NRDC, 2019; Swift, 2016). Large scale clearcutting, as well as ongoing overall degradation of Canada's boreal forest has prompted mounting concern regarding biodiversity, the global climate, and damages from commercial logging (NRDC, 2018; Swift, 2019). In developing forest resources, Canadian provinces have historically disregarded and ignored First Nations (Ross et al., 2002; Supplementary Information (SI) Section 1). In the following section we briefly outline recent nexus critiques, providing the theoretical context for including Embodied Injustices and Transboundary unSustainability (ENTS) in nexus analysis. We then introduce the FEWM+ENTS monitoring framework and outline our research objectives in implementing this framework in EI/J.

3.1.1 FEW Nexus: Recent Critiques

The fluidity of the FEW nexus concept has been well articulated: nexus investigations take on different manifestations depending on context, scale and geography (Matthews & Motta, 2015). Cairns and Krzywoszynska characterize the nexus as a ‘buzzword:’ a powerful term that combines “ambiguity of meaning and strong normative resonance,” delineating power struggles over competing narratives (2016: 4). Several authors note that the FEW nexus is not a new construct; rather it builds on other earlier integrative approaches, particularly Integrated Water Resource Management (Cai et al., 2018; Cairns & Krzywoszynska, 2016; Wichelns, 2017). The ‘integrative imaginary’ implies that efficient integration at multiple scales is in fact achievable and can result in managerial benefits and sustainable development, while at the same time underplaying aspects of power. As a corollary to the integrative imaginary, the nexus is seen as a multidisciplinary problem requiring multidisciplinary approaches (Leck et al; Albrecht et al 2018), which are “impossible to grasp … within the partial framings of individual academic disciplines” (Cairns and Krzywoszynska 2016: 8).

A fundamental critique of the FEW/resource nexus is that vital linkages between FEW access and key societal structures enabling, permitting, and denying such access are often overlooked. Leck et al. note that “access to and utilization of water, energy and food are closely linked with structural issues such as political processes, poverty and entitlements” and that “identifying winners and losers in WEF nexus decision-making and giving explicit attention to justice and equity concerns are central for nexus agendas to be socially progressive” (Leck et al., 2015: 453; Dupar & Oates, 2012; Stringer et al., 2012). A number of suggestions have been offered for future nexus research in response to these critiques. Many researchers call for more critical, theoretically informed perspectives. Allouche et al. contend that “if the nexus is to be a useful framework for exploring alternative pathways rather than a narrative that legitimizes existing dominant pathways, the political economy of the nexus must be more explicitly addressed” through bottom-up rather than “top-down ways of knowing the relationship between water, food and energy” (Allouche et al., 2014: 23). In widening the FEW nexus to include material extraction and explicitly consider embodied injustices and transboundary unsustainability (FEWM+ENTS), we address these challenges for the nexus concept, tracing different factors that coexist as part of a complex argument (Leck et al., 2015; Sil & Katzenstein, 2010).

3.1.2 Embodied iNjustices and Transboundary unSustainability within FEWMs – A framework

The concepts of embodied (or 'virtual') water and energy have been used to quantify water and energy inputs to FEWS at the city scale (Ramaswami et al. 2017) and to quantify water inputs to food production and the water embodied in the global food trade (Konar et al 2011; Hoekstra and Mekonnen 2011). Drawing on ideas of embodiment as well as environmental and energy justice, Healy et al. introduce the concept of "embodied energy injustice," which "integrates previously unrecognized social-environmental harms and injustices" and exposes the "disproportionate distribution of such harms on vulnerable peoples situated along energy supply chains" (2019: 219,221).

As with embodied energy injustices, conceptualizing embodied food, energy, water, and material (FEWM) injustices can help situate chains of interacting FEWM injustices and place-based struggles within wider politics, decisions, and processes across multiple interacting lifecycles, revealing profound inequities within and among nations and generations. We propose the concept of embodied injustices be extended to intertwined FEWM supply chains, and to the cumulative impacts on surrounding ecosystems that disproportionately affect disenfranchised populations. In conceptualizing embodied FEWM injustices on local populations along transboundary supply chains, we propose that *access* 'to' and *control* 'over' food, water, energy, materials, and land be understood as critical dimensions of the FEW/resource nexus. In this context, embodied FEWM injustices at the nexus occur when: 1) environmental and health *impacts* of interdependent FEWS disproportionately affect vulnerable populations; 2) *access* to food, energy, water, land and material well-being of generally local communities are systematically hampered, jeopardized or denied to benefit generally distant consumers; 3) *control* over land, water, energy resources systematically disenfranchises these groups.

Embodied FEWM injustices are also closely interlinked with teleconnected, multiscalar supply chains spanning multiple regions and international boundaries. Embodied injustices affect vulnerable communities along supply chains of varying complexity, with impacts often deliberately hidden from distant consumers. Hence, *we define embodied injustices as social, environmental, and health harms stemming from inputs, access, control, and impacts of the interdependent FEW/resource nexus landscape and its multiscalar transboundary supply chains that disproportionately affect disenfranchised populations.*

Table 3-1. *FEWM nexus interactions and embodied injustices and transboundary unsustainability (FEWM+ENTS) framework. (See SI for extended version.)*

Inputs: x 'for' y	**Impacts: x 'on' y**
Definition: The FEWM inputs to FEWS and materials across the life cycle *Examples:* o Water 'for' energy: hydropower; surface water withdrawals for thermoelectric power generation o Water and energy 'for' food: volume of water for crop irrigation, energy used for water pumping o Energy 'for' mining	*Definition (two-fold)*: 1) Disproportionate environmental and health *impacts* at the FEWM nexus on disenfranchised communities; 2) Impact of FEW/ resource nodes on each other and the wider ecosystem across FEWM life cycles *Examples*: o Food/Land 'on' Water: Impact of fertilizer on aquatic ecosystems o Impact of Barrick Gold Corporation's planned Pascua–Lama project on glaciers and water supporting indigenous agriculture in the Huasco Valley, Chile (Urkidi & Walter, 2011)

Access ‘to’: *Definition*: Equitable access to FEWM and to land; lack of access to x is correlated with lack of access to y *Examples:* Lack of FEWM access at the global scale: o 800 million people are hungry and 2 billion experience moderate or severe food insecurity (FAO et al., 2019) o 1.2 billion live in water-scarce regions (Bigas et al., 2013) o 1.2 billion do not have access to electricity o More than 2.7 billion rely on traditional biomass for cooking (WEO, 2016)	**Control ‘over’** *Definition*: Structural issues of how FEWS and material supply chains have been developed, how they interact, and how benefits and harms are distributed across populations *Examples:* o Institutions controlling regulatory processes disproportionately allow siting of toxic facilities near communities of color in the U.S. o Provincial control of industrial development in forests in Canada, systematically excluding Aboriginal Peoples from forest resource management (encompassing food, water, and o livelihoods)

Because transboundary sustainability and justice, like FEWM, are inextricably linked, nexus research should illuminate and address existing, hidden injustices and unsustainability inherent in current FEWS[2] and material supply chains. Localized sustainability initiatives often fail to account for complex, interlinked transboundary FEWM supply chains, sometimes leading to policies that may be sustainable in one region but have environmentally damaging and/or unjust impacts on another, such as the procurement of raw materials required to build low-carbon energy devices and infrastructure (Sovacool et al., 2020). The notion of sustainability that transcends

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[2] Following Barry (2012), we focus on “actually existing unsustainability” rather than the aspiration of sustainability.

administrative and political boundaries is central to the integration of such initiatives across complex global supply chains and FEWM life cycles.

3.1.3 'FEWM+ENTS:' Study design and implementation

The FEWM+ENTS framing is not only relevant to cities as centers for global demand of food, energy, water and materials, but also to remote areas targeted for new multi-sector extractive efforts. These regions are often characterized as 'frontiers,' fueling increasing global resource consumption as more accessible supplies become exhausted (Klare, 2012). To illustrate the FEWM+ENTS approach, we consider FEWM interdependencies as encapsulated by a historical case study of a near-Arctic 'frontier' region at the center of the indigenous sovereignty movement in North America before, during, and after the 40-year construction of the James Bay Hydroelectric Complex in EI/J, Quebec. We address embodied injustices across transboundary FEWM supply chains and the amplification of impacts and harms among these multiple systems. FEWM nexus interactions and embodied injustices involving food are represented through hunting, fishing, and trapping that have sustained the Crees for millennia; these pursuits, and Cree sovereignty, are compromised and undermined by ongoing deforestation due to multiple drivers. Specifically, we ask: *Using the FEWM+ENTS lens, how can we identify, assess, and monitor spatio-temporal disturbances in EI/J since the James Bay Project began? What embodied injustices and unsustainable transboundary patterns of extraction, production, and consumption can be traced to the FEWM nexus?*

The objectives of this study are to:

- Assess disturbances to the boreal forest in EI/J since the James Bay Hydroelectric Project began.
- Map ecosystem disturbances to determine both year and type of forest disturbance using remote sensing and ground-based data.
- Identify interdependencies among five key disturbance types (hydropower, roads, logging, wildfire, and mining) and their cumulative social-ecological impacts and consequences.
- Link embodied food, energy, water, and material injustices with transboundary resource consumption and resource control.

Using remote sensing and supplementary datasets, we document disturbances to the boreal forest in EI/J related to hydropower, mining, logging, roads, fire, transboundary supply chains, and their interconnected impacts. These collective activities, and the infrastructure built to facilitate non-Native control over and settlement of the region have cumulative impacts on indigenous efforts to maintain traditional livelihoods and sovereignty that are greater than the sum of their parts and illustrative of a much longer historical trajectory in North America. We consider embodied injustices spanning these sectors in terms of *impacts* 'on,' *access* 'to,' and *control* 'over' FEWM, drawing on transdisciplinary literature and data spanning the fields of remote sensing, critical geography, forestry, history, policy, and ecology to identify embodied FEWM injustices. In the following sections we review our data and methods, present the results of our analysis, discuss forest disturbance patterns and causes, and finally we consider implications for future development and governance in the region.

3.2 Data and Methods

3.2.1 Study Area and Historical Context

Mapping political boundaries and natural resources raises profound questions of resource identification, use, access, control, and governance. Highlighting the contested boundaries and sovereignty questions at the center of this study, the combined extent of the overlapping boundaries of the Cree Nations of Eeyou Istchee and the 'Territory Equivalent' (TE) of Jamésie, Quebec are used (Figure 3-1). Two legislative Acts passed by the Parliament of Canada in 1898 and 1912 tripled the territory of Quebec to its current boundaries, encompassing lands inhabited by Aboriginal Cree, Innu, Naskapi, and Inuit, and spanning more distance north to south than any other province. Hydro-Quebec planners first inventoried the region's rivers in the late 1950s (*SI, Section II*). Quebec's effort to develop the EI/J began in 1971 with the stated goal of promoting the "exploitation of natural resources" (James Bay Region Development Act, 1971). The Crees were not initially informed about the James Bay Project (JBP); once its scope became clear, they mounted a forceful campaign against it, joined by the Inuit to the north. The multi-pronged effort "mobilized on several fronts: the media, the international community, public awareness, and the courts" (Moses in von Rosen, 2013) and ultimately resulted in the historic 1975 James Bay and Northern Quebec Agreement (JBNQA), permitting the JBP to continue in exchange for Cree and Inuit self-government, along with $225 Cd million from the governments of Quebec and Canada to be distributed to 22 Indigenous communities over twenty years. The JBNQA is widely regarded as the first modern Aboriginal land claims treaty and “the first clear definition of Indian rights in Canada” (Chief Diamond in von Rosen, 2012).

A crucial feature of the JBNQA was its delineation of three distinct land categories:

- *Category 1:* Lands surrounding Cree settlements, set aside for exclusive use by Cree, Inuit and Naskapi: 14,348 km^2 (1.3% of the territory);
- *Category 2:* Public lands; hunting, fishing and trapping exclusive to Native people: 159,880 km^2 (14.8% of the territory; 70,000 km^2 in EI/J);
- *Category 3:* Public lands; rights reserved to Native people for hunting, fishing and trapping without a permit, without limit and at all times: 907,772 km^2 (83.9% of the territory; 275,000 km^2 in EI/J).

While small-scale forestry and mining by non-Natives in the southern portion of EI/J pre-dated the JBP, construction of James Bay hydropower complex would open the floodgates of development on an industrial scale previously unseen in the region. Of the 430,000 km^2 in EI/J (including waterbodies), 95,700 km^2, or 24% of the region, is located within the provincially-determined logging zone, that is, south of the northern limit for commercial forestry (Figure 3-3). In 2012, after decades of Cree protest that Quebec continually relegated Cree sovereignty over land management to the minimal extent of Category 1 lands (Figure 3-1), the regional governing body Eeyou Istchee Baie James (*GREIBJ-EIJBRG*) was established to jointly manage regional affairs on Category 2 and 3 lands.

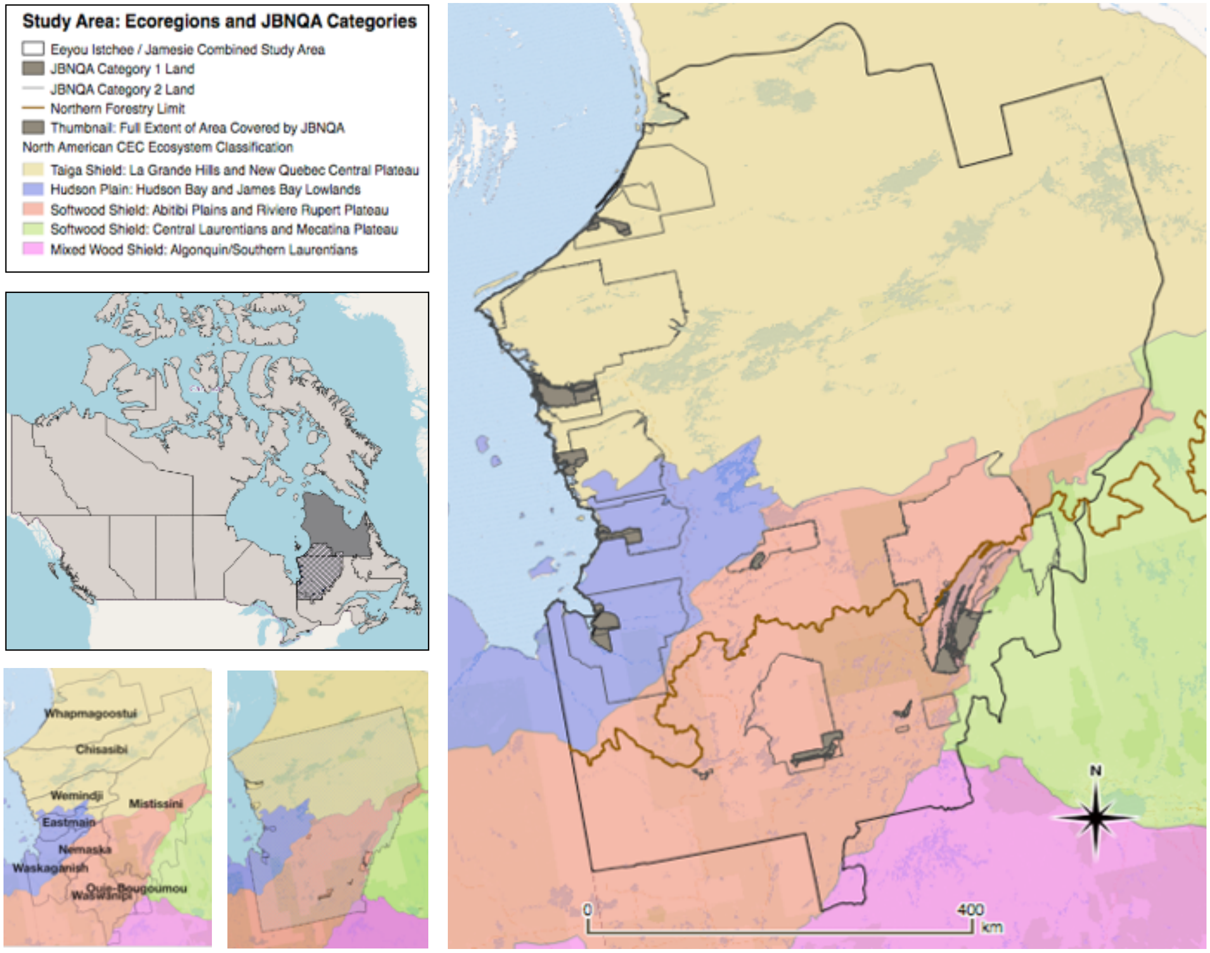

Figure 3-1 Eeyou Istchee / Jamésie (EI/J) Study Area: Ecoregions and JBNQA land categories. *Combined extent of Eeyou Istchee and Jamésie. Category 1 (gray) and Category 2 lands (gray outline). Thumbnail: Additional JBQNA territory (dark gray); and study area (crosshatch). Left, bottom row: Eeyou Istchee, including nine member Cree Nations (left). The Quebec Territory Equivalent (TE) of Jamésie (right), excludes Category 1 lands but includes Categories 2 and 3 (crosshatched). Data sources: (Wiken et al., 2011) https://www.eeyouconservation.com/protected-areas-process/*

3.2.2 Forest Change Detection Using Remote Sensing

The Landsat-based Detection of Trends in Disturbance and Recovery (Landtrendr) algorithm is a well-known method to detect forest change from moderate resolution (30m) satellite imagery that can be performed on the Google Earth Engine platform (Kennedy et al., 2018), utilizing the Landsat Data Archive (Woodcock et al., 2008; Wulder et al., 2016; Zhu, 2017). Landtrendr has been used in northern forests with high accuracy (Kennedy et al., 2010, 2012) and is designed to detect both abrupt events and gradual trends, including ecological change and degradation from annual Landsat time series data. Landtrendr's segmentation method uses medium frequency and univariate metrics, focusing on the Normalized Burn Ratio (NBR) (Zhu, 2017), derived from the Near Infrared (NIR) and Shortwave Infrared (SWIR) Bands [NBR = (NIR -SWIR)/(NIR +SWIR)]. The EI/J study area is comprised of 31 individual Landsat scenes, spanning paths 13-20 and rows 20-26 (Appendix B, Figure B-1). The Landtrendr algorithm was run using NBR on the full region for the years 1984 to 2018.

3.2.3 Disturbance Type Identification

There are a number of methods to determine the type of land cover / land use change associated with change detection. Schroeder et al. (2011) found reflectance in the short-wave infrared wavelength (Landsat Band 5) effectively separated forest fires from clearcut harvests. It is sometimes possible to infer the type of change by deduction from 'before' and 'after' land cover classes (Kennedy et al., 2015; Helmer et al., 2010). Here, we identified the types of forest change using external geospatial datasets depicting specific types of forest disturbances (Appendix B, Figure B-14). These datasets were also used to validate the Landtrendr results, which show year of forest disturbance for each pixel in the study area. In the case of hydropower, fire and mining, supplementary datasets also depict the year of disturbance, making direct comparison with the Landtrendr results possible. Although geospatial data depicting changes over time are not available for roads, two static datasets are presented. [Also see (Smith & Cheng, 2016) for a time series analysis of deforestation in the Broadback River watershed of EI/J, including roads.]

Geospatial time series data were also not available for logging disturbances in EI/J, although Environment Canada's 2010 Boreal Ecosystem Anthropogenic Disturbance (BEAD) dataset offers a snapshot of disturbances as of 2010 (Pasher et al., 2013). We constructed a time series of logging activity by overlaying Landtrendr year of disturbance pixels falling within the forestry zone with disturbances identified as cutblocks in the BEAD dataset and extended the time series based on non-fire pixels with year of disturbances from 2011 to 2018 in the logging zone (Section 3.2.3 and SI, Figure S3-20). Together, remote sensing and supplementary data provide a more complete picture of forest disturbances and ecosystem impacts than either source alone. For example, the Canadian National Fire Data Base (CNFDB) consists of polygons outlining a rough extent of forest fires containing unburned forest patches and waterbodies, but contains valuable information including ignition source, start date, and suppression efforts. Landsat-derived estimates, by contrast, more precisely identify disturbed patches, but do not as accurately gauge the number of fires, which can appear to be a series of disconnected areas (Coops et al., 2018).

3.2.3.1 Data Sources: Disturbance Type

The datasets used to provide a comprehensive picture of boreal disturbance type occurring in EI/J after 1970 include the Canadian National Fire Data Base (CNFDB) (Canadian Forest Service, 2019) and Environment Canada's 2010 BEAD dataset (Pasher et al., 2013) (SI, Table S3-3 contains the complete list of datasets used for this study). Spatial analysis was conducted in QGIS, GRASS, and ArcGIS; statistical analysis in R.

3.2.4 Embodied Injustices

To identify embodied FEW+M injustices manifested in deforestation arising from the James Bay Project, we undertook a meta-analysis of available sources, including Cree Nation and Hydro-Quebec publications, provincial and federal documents, media coverage, and the academic literature.

3.3 Results

In this section, we show forest disturbances due to hydropower, roads, logging, and mining, and fire in EI/J as depicted in external geospatial datasets (Section 3.1). We then present Landtrendr results for EI/J (Section 3.2) and disaggregate these results according to deforestation type (Section 3.3) by overlaying them with the external datasets from Section 3.1. Following this, we focus on FEWM nexus interactions among these disturbances (Section 3.4), emphasizing their cumulative impacts. Injustices arising from the *impacts* of energy systems and extractive activities *on, control over,* and resulting *access to* FEWM (Section 3.5) are pervasive.

3.1 Forest Disturbances by Type

In the following subsections, hydropower, logging, mining, and fire since 1970 are outlined. (See SI Figures xxx for map panels showing deforestation over time due to each of these disturbances).

3.1.1 Hydropower

<u>Reservoirs, Cumulative disturbance:</u> Hydropower reservoirs account for ~12,600 km^2 of flooded forest in EI/J (SI, Figure S3-15). Main stem construction began on the La Grande River, about 1000 km north of Montreal, in the early 1970s. Between 1975 and 2000, flows of adjacent rivers were diverted into the La Grande, effectively doubling its catchment area (Déry et al., 2018; Roy & Messier, 1989). During Phase 1 (1972-1986), the Eastmain, Opinaca, and Caniapiscau Rivers were diverted into the La Grande, increasing average flow from 1,700 to 3,300 m^3/s. Four dams were constructed along the La-Grande, with five reservoirs covering 11,300 km^2, contributing to an installed generating capacity of 10,800 MW, producing about 65 TWh / year. During Phase 2 (1987-1996), five secondary power plants on the La Grande and its tributaries were constructed, adding 5200 MW, with three new reservoirs flooding 1600 km^2. Phase 2 power plants generate an additional 19 TWh/year operating between 60-70% of maximum capacity.

High-Voltage Transmission Lines: An estimated **4400** km of powerlines run east to west along the La Grande Complex and north to south in EI/J (Figure 3-2).

Cumulative Disturbance: The total length of roads in the region according to the government of Canada dataset is **4065 km,** while BEAD dataset (Pasher et al., 2013) includes **21,830 km** of roads (Figure 3-2), including the network of secondary and tertiary roads built for logging occurring within the logging zone. These **17,800 km** of roads, comprising 81.5% of all roads in the region, are not included in the official roads database.

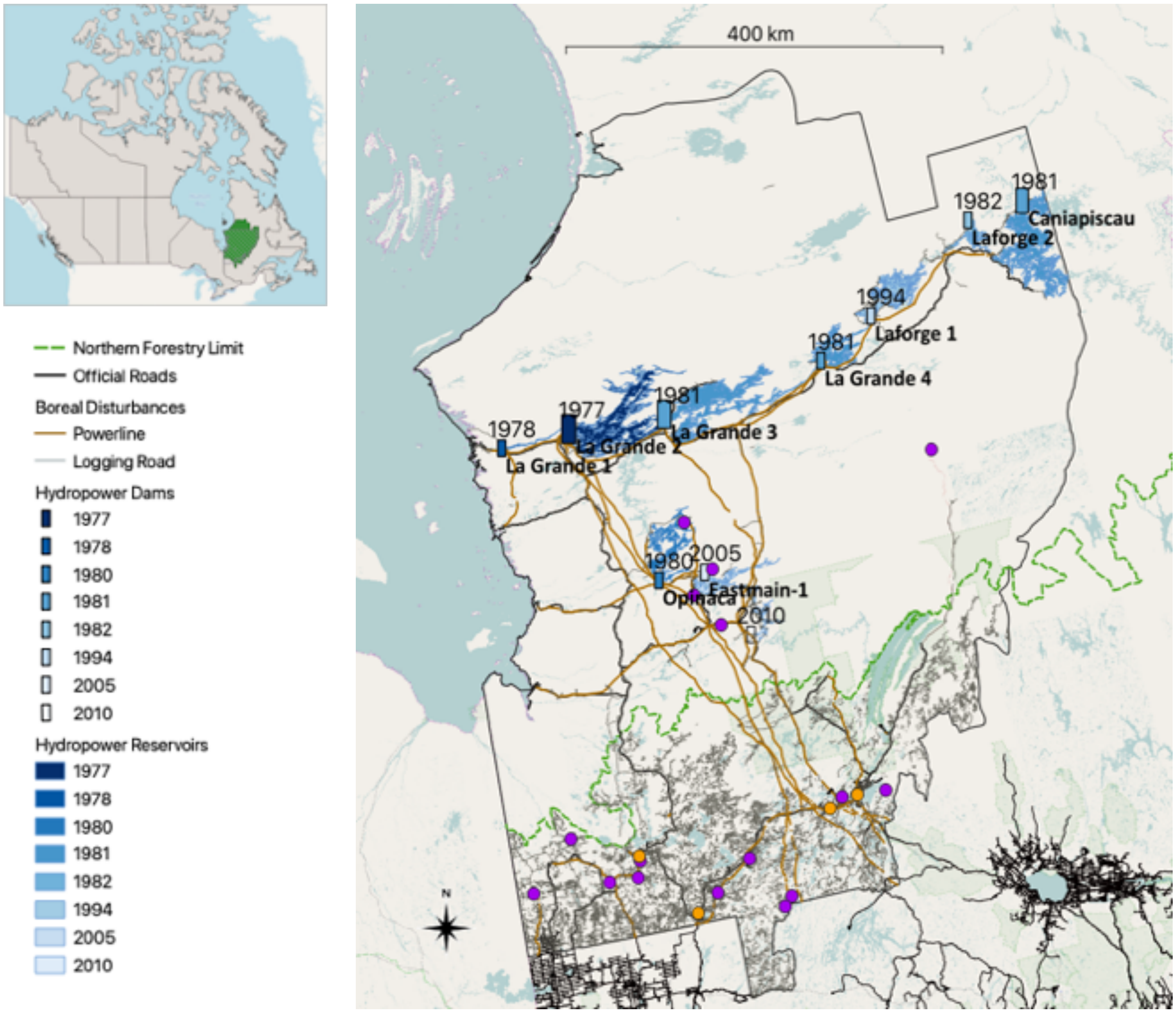

Figure 3-2. *Roads and powerlines. The official provincial road network (black) and secondary and tertiary roads for logging (gray; shown within study area) below the northern forestry limit. Data Sources: Road Network File 2019 and BEAD dataset (Pasher et al., 2013).*

3.1.3 Logging and Forestry Tenures

<u>Cumulative Disturbance:</u> The area in Eeyou Istchee that falls south of the provincially-determined northern limit for commercial forestry accounts for 95,700 km^2 of land within the 430,000 km^2 region, including waterbodies (Figure 3-3). [Excluding waterbodies, the total land area in the logging zone is 86,300, or 24% of the region's total land area of

363,000 km^2.] As of 2010, **19,100 km^2** were identified in the BEAD dataset (Pasher et al., 2013) as cutblocks, or a full 20% percent of the land area in the logging zone, not including an estimated 17,800 km of logging roads up to 2010.

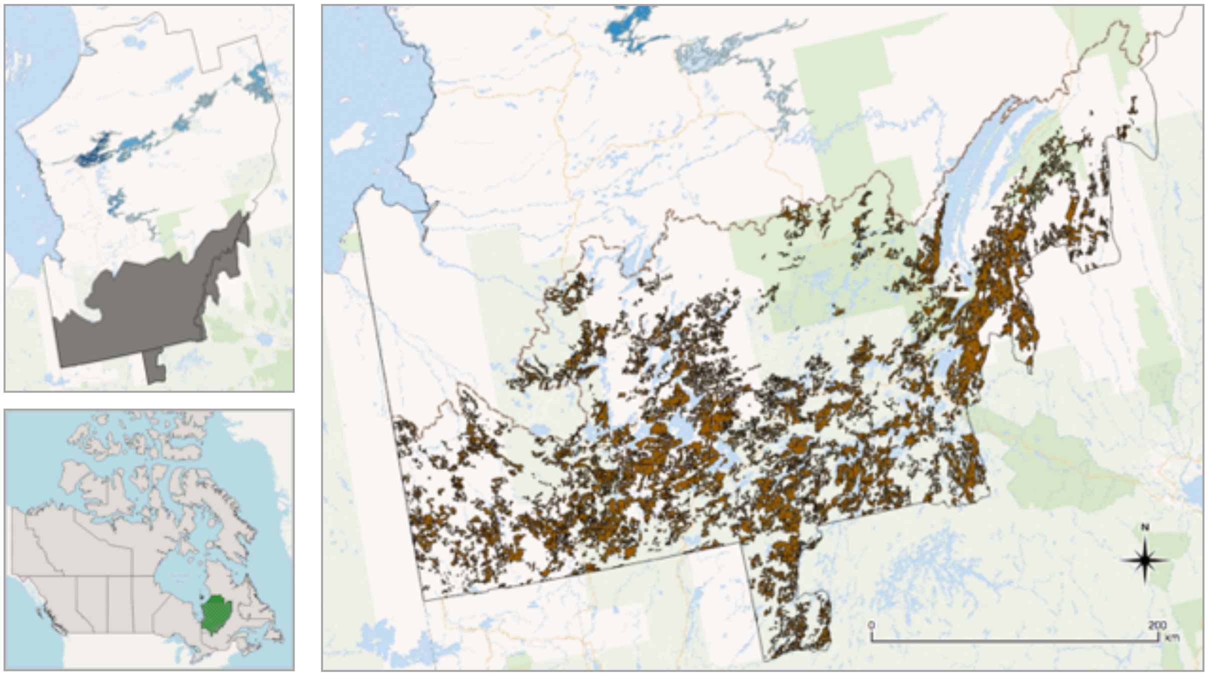

Figure 3-3. *The area in EI/J within the northern limit for commercial forestry (thumbnail, grey) and deforested areas due to logging (brown). Data source: BEAD dataset (Pasher et al., 2013).*

3.1.4 Mining

<u>Current Mining Activity</u>: There are six active mines (3 gold, 2 zinc and one diamond), eight more in the appraisal stage, one in exploration, and one in development (Quebec Système d'Information Géominière (SIGEOM) 2019) according to provincial data. There are 13 agreements between Indigenous groups and mining companies in EI/J (Natural Resources Canada, 2020), with three in production and nine in the exploration phase (Figure 3-4; SI, Table S3-4), according to national data.

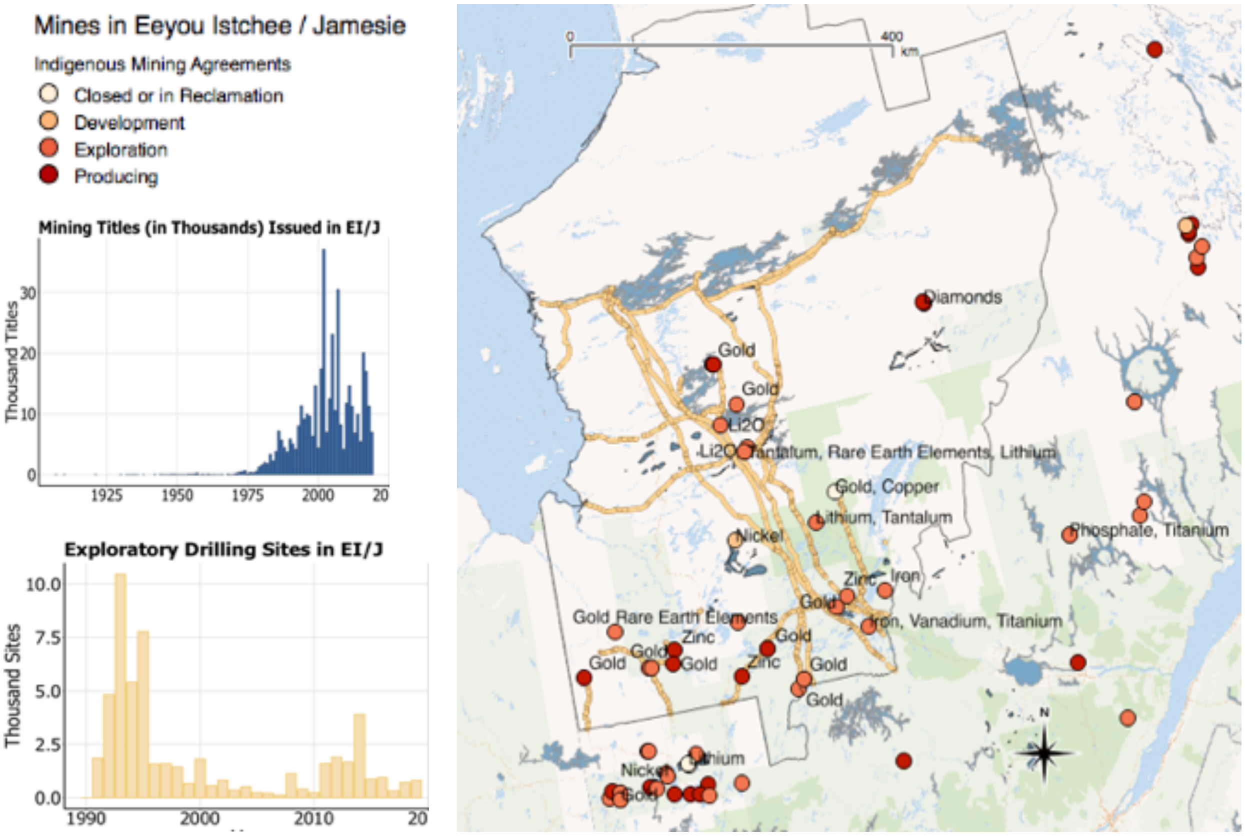

Figure 3-4. ***Agreements between Indigenous groups and Mining Companies in EI/J(Natural Resources Canada); active mines and projects, project status, and materials mined (SIGEOM).*** *Histograms of mining titles and exploratory drilling by year issued by the province of Quebec in EI/J by year (Compiled from SIGEOM data).*

Mining Activity Since 1970: Expansion of mining interests and activity in the region from 1970 is demonstrated by a steady increase in mining titles, exploratory drilling, active large-scale mines, and prospective mining areas. Based on data from SIGEOM (2019), **395,000** term-limited mining titles have been issued by Quebec in EI/J since 1970, (SI, Figure S3-17). Exploratory drilling has been undertaken at **54,725** sites (SI, Figure S3-18). Mining titles show a small increase between 1970 and 1975 during the JBP planning phase, with a sharp takeoff in 1980 after completion of the first dam

(Figure 3-4). Under the Plan Nord mining activity is poised to continue, with 1200 additional sites designated for exploratory drilling (Figure 3-5).

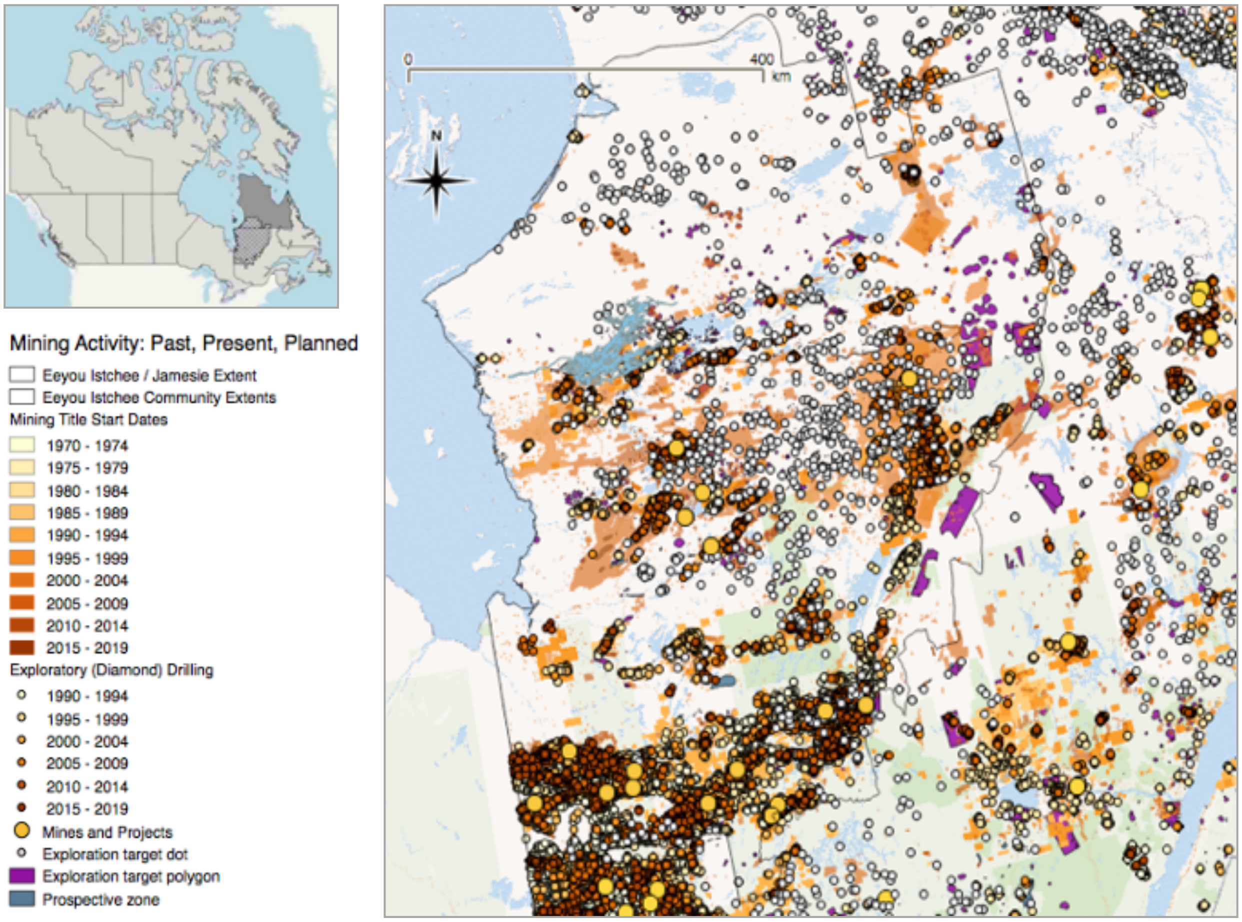

Figure 3-5. *Past, present, and planned mining activity in EI/J and adjacent areas. Data source: Quebec SIGEOM.*

3.1.5 Fire

<u>Cumulative Disturbance:</u> Since 1973 a total of **94,700 km^2** of boreal forest in EI/J have been affected by fire, based on CNFDB data, with 81,400 km^2 burned since 1984; 95% were attributed to lightning and 5% to humans (SI, Figure S3-14). Because the CNFDB

consists of polygons outlining the general extent of forest fires, this estimate is significantly higher than burned area estimates obtained from satellite imagery (Section 3.3).

3.2 Boreal Forest Disturbance Over Time

Based on the Landtrendr analysis undertaken for this study, the cumulative forested area identified as disturbed in EI/J during the 34-year period between 1984 and 2018 is **81,600 km^2**, totaling 22% of the 363,000 km^2 region, excluding 68,000 km^2 of water. There are wide variations in the amount of area disturbed each year; peaks occur in 1989, 1990, 1996, 2002, and 2013 (Histogram, Figure 3-6). This preliminary estimate, using only Landtrendr results, does not include the known extent of hydropower reservoirs constructed between 1975 and 2010 (see Section 3.3).

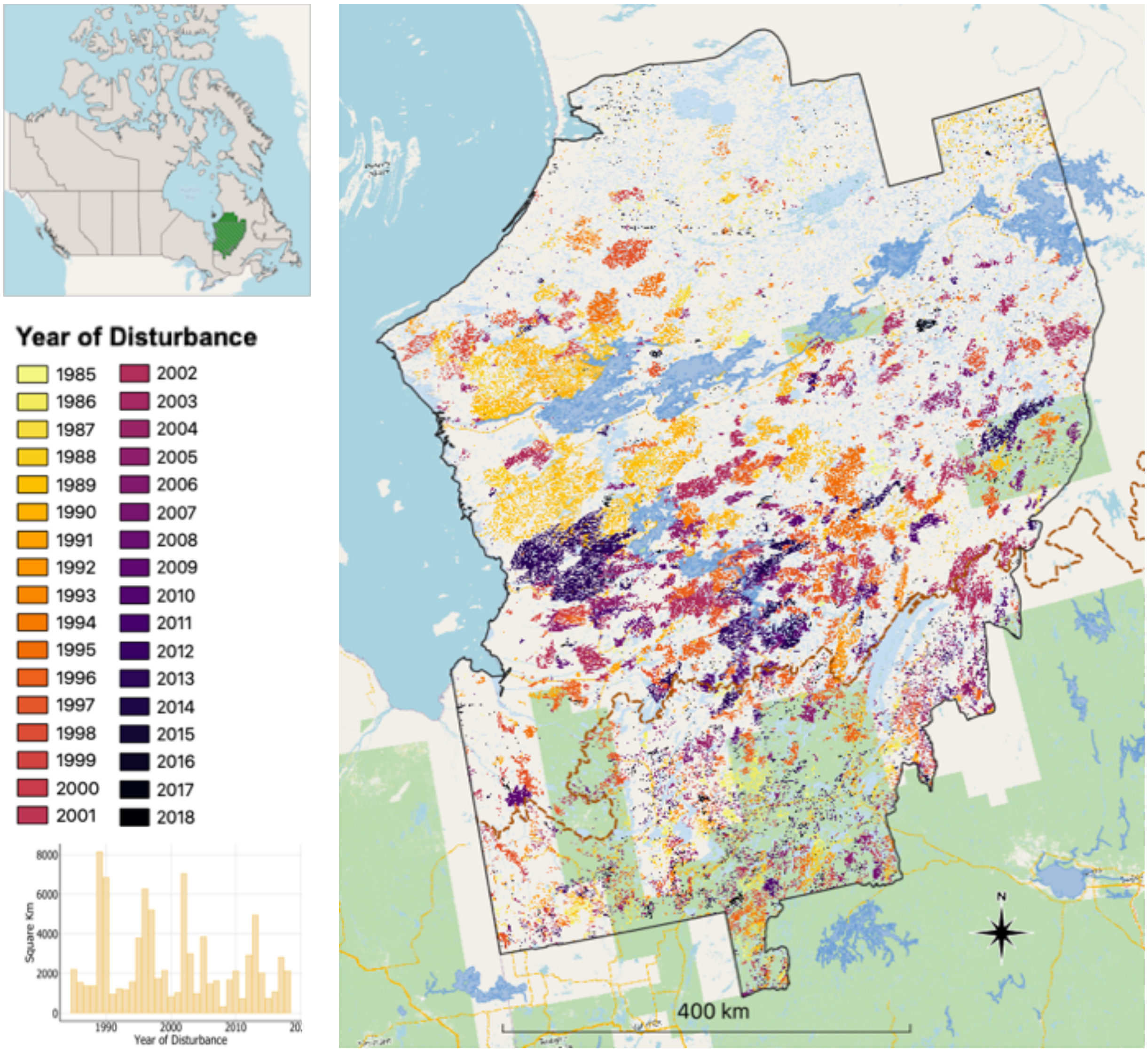

Figure 3-6. *Top left: Study region (green) within Canada. Bottom left: Histogram showing number of pixels disturbed each year from 1985-2018. Right: Landtrendr results for year of forest disturbance.*

3.3 Classifying Disturbance Type and Validating Landtrendr Results

Within the 81,400 km^2 delineated as fire zones in the Canadian National Fire Database (CNFDB), **50,000 km²** (58% of pixels) were identified by Landtrendr as disturbed

(Figure 3-7). Of the 19,100 km^2 identified as cutblocks in the BEAD dataset (Pasher et al 2010), **10,400 km^2** (55% of pixels) were identified by Landtrendr as disturbed, and **75 km^2** in the 188 km^2 identified as mines (42% of pixels) in the BEAD dataset were identified by Landtrendr as disturbed. Another 19,900 km^2 of Landtrendr-identified disturbed pixels did not fall within the boundaries of the validation datasets (SI, Table S3-5). While only **1580 km^2** out of 12600 km^2 identified in the BEAD dataset as hydropower reservoirs were identified as disturbed (Figure 3-7), most of the Phase 1 reservoirs were formed prior to 1984, the year Landtrendr detection began.

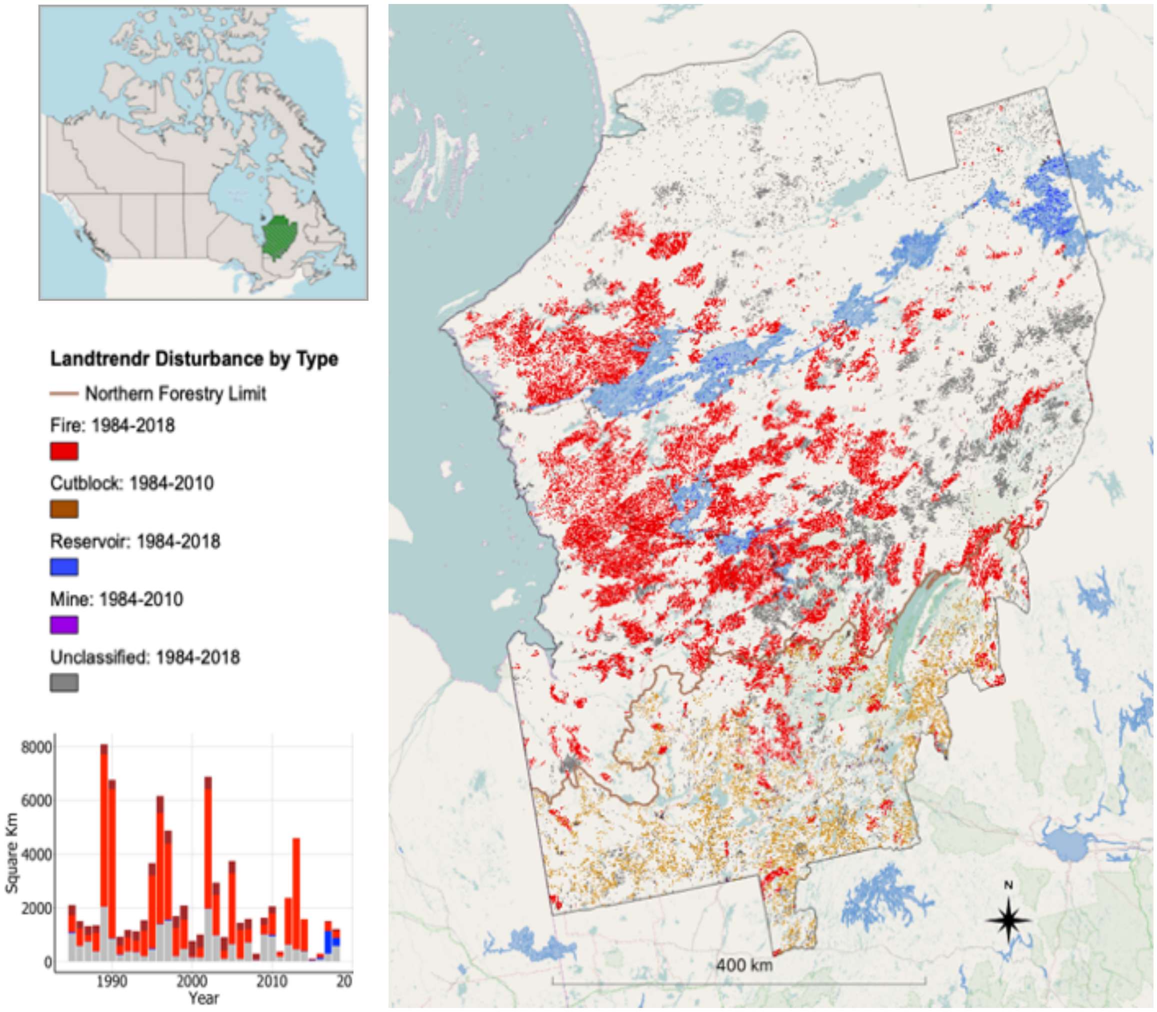

Figure 3-7. *Landtrendr disturbance, using validation datasets to identify disturbance type. Cutblock and mining data represent a snapshot from 2010 (Pasher et al., 2013) so successive disturbances of these types are not identified.*

3.3.1 Enhanced Estimate of Forest Disturbance by Type

The results obtained from combining Landtrendr with forest disturbance type data can be further enhanced to provide a more complete picture of disturbances since 1973 (Figure 3-8):

1) Landtrendr disturbances occurring between 2011 and 2018 in EI/J within the logging zone (Figure 3-3) that were not in areas designated as fire by the CNFDB were assumed to be cutblocks (SI, Figure S3-20a); values are consistent with years prior to 2011 in the BEAD dataset, which shows forest disturbance circa 2010 (Pasher et al., 2013). In addition to the cutblocks identified by (Pasher et al., 2013) up to 2010, based on Landtrendr results we estimate an additional **3000 km^2** of cutblocks between 2011-2018, bringing the total disturbance from logging to **13,500 km^2**.
2) Known values for years and areal extents of reservoirs formed as part of the James Bay Project were added.
3) Annual burned area estimates from the CNFDB (minus waterbodies) going back to 1973 were added.

In 11 of 28 years (1984-2018) disturbances due to logging were greater than those due to fire, even though the logging zone comprises just one-quarter of the overall region. Within the logging zone, 64% of disturbances are attributable to logging and 29% to fire. Including 12,600 km^2 of reservoirs, the cumulative forested area identified as disturbed in the entire region since 1975 is **93,700 km^2**, totaling 26 % of its total land area. Further including areal estimates of fire from 1975-1984 from the CNFDB brings the total to **106,000 km^2** or 29% of the region’s forest that has been disturbed since 1975.

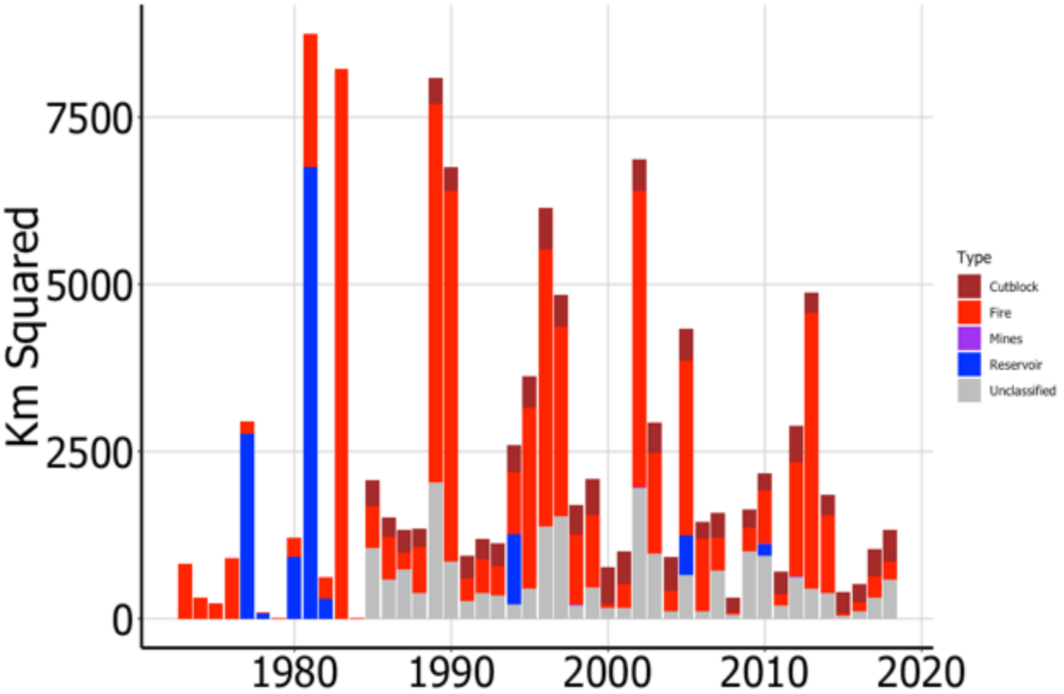

Figure 3-8. *Forest disturbance by type using a 'best available' combination of Landtrendr estimates and validation datasets since 1973. Satellite data begins in 1984.*

3.4 FEW+M nexus: Embodied energy, water, and materials

In the above section boreal forest disturbances due to hydropower, roads, logging, mining and fire were estimated. In this section we document the interdependence of forest disturbances, focusing on interlinked processes, impacts, and synergies. The major interdependencies among hydropower (energy + water), roads (infrastructure), and logging and mining (materials) are outlined here; in the next section we consider the impacts of these systems on fish and wildlife (food + land) in the context of embodied injustices.

Energy-Water: Hydropower generation inextricably links hydrological systems to energy production (water 'inputs' to energy). In EI/J, Quebec's energy system transformed the landscape and hydrology of the region. Hydropower, in turn, made possible other forms of extraction dependent both on energy and the transportation network needed for hydropower construction, which in turn enabled the extensive network of logging roads south of the forestry limit.

Energy-Water-Transportation (Interdependent Infrastructures): Power and transportation infrastructures are intricately connected. Major roads and high voltage powerlines run in parallel east-west along the La Grande River complex and run in parallel east-west in the logging zone. For much of the north-south corridor, they also occur in tandem (Figure 3-9).

Energy-Water-Roads-Logging-Mining-Wildlife: Throughout the region, mines are located near both hydropower transmission lines and roads (Figure 3-9). The one exception is the Renard Diamond Mine, which opened in 2014 and relies on natural gas for power: a road to the mine was built jointly by Renard Corporation and Quebec as part of the Plan Nord. The region south of the forestry limit has 11 of the region's 15 mines and four sawmills (Figure 3-9), with four more just below the southern boundary of EI/J (SI Figure S3-21). Increased human presence and infrastructure development, including mineral exploration and extraction, has resulted in broad disturbances to woodland caribou (Herrmann et al., 2014).

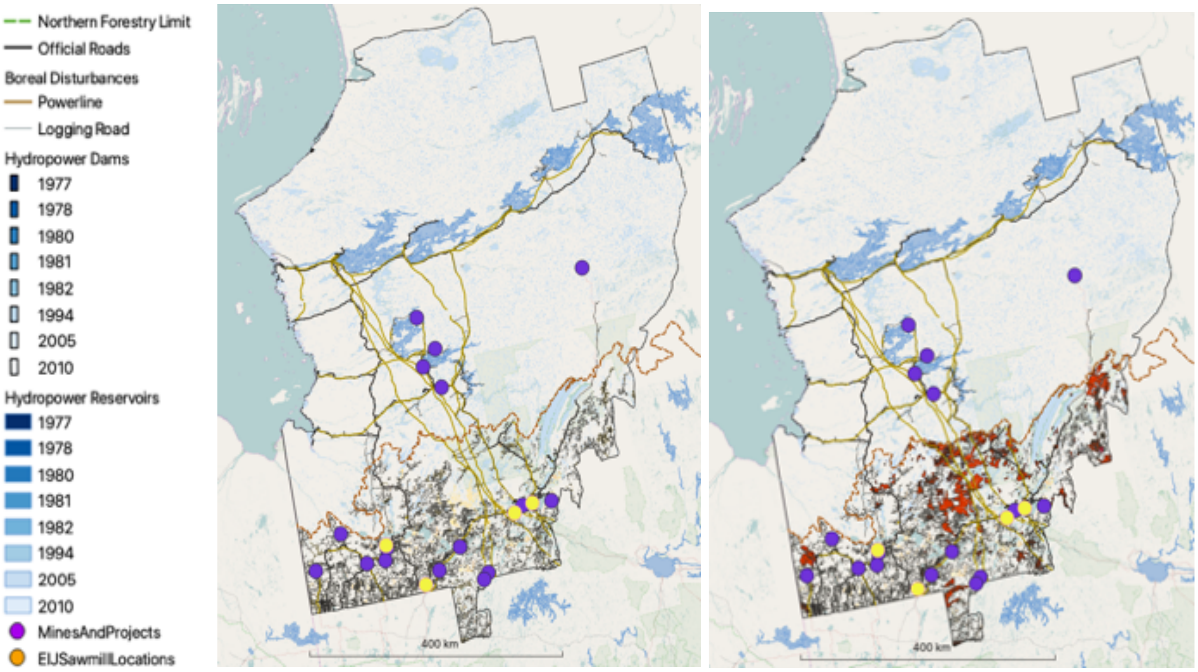

Figure 3-9. *The proximity of primary roads and high voltage powerlines throughout the region and the siting of mines and sawmills near this dual infrastructure (left). The occurrence of fire precludes logging; no logging roads were identified in this region (right).*

<u>Logging-Mining-Roads:</u> In the logging zone, roads initially built for logging are used for exploratory drilling by the mining industry; the densest drilling sites (Figure 3-10, purple circles) closely follow main roads running east-west. No logging roads occur in the regions deforested by fire; the only section of the area in EI/J below Quebec's commercial forestry limit not interlaced with roads.

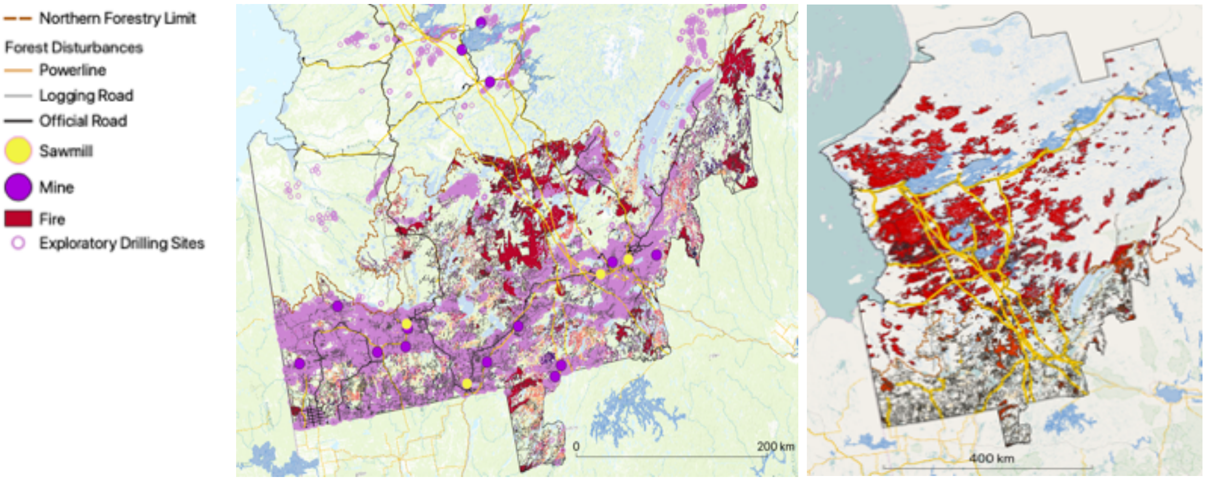

Figure 3-10. *Left: Mines, like sawmills, are adjacent to power and major road networks. Exploratory mine drilling is also clustered along primary and logging roads. Right: Fire and powerlines (yellow).*

Hydropower-Powerlines-Fire

North of the logging limit, disturbances are attributable primarily to fire (Figure 3-7). Fire regimes have been accelerating across Canada; the return interval for EI/J is 50-100 years, among the shortest in the country (Coops et al., 2018); 161 fires in the region since 1977 intersect powerline corridors (Figure 3-10, right). The CNFDB attributes 95% of the fires to lightning and 5% to humans.

3.5 Embodied Injustices at the resource nexus: Impacts, access, and control

In this section, we further explore forest loss, degradation and loss of wildlife through the FEWM+ENTS lens, emphasizing that decisions regarding energy, water, and materials have far-reaching and long-lasting transboundary impacts. We begin by presenting total forest losses and deforestation type in each of the nine Cree communities comprising Eeyou Istchee, linking this to wildlife captures in each community from 1989-2019. We then consider how the JBP and subsequent deforestation linked to energy and material extraction throughout the region has contributed to embodied food, water, energy, and material injustices with respect to FEWM *access* and *control* across these interconnected supply chains.

3.5.1 Forest Disturbances by Community

A crucial feature of the JBNQA was its designation of three land categories in the region (Section 2.1.1). Cree Nation boundaries are used in this section, spanning JBNQA Category 1, 2, and 3 lands that comprise traplines (traditional family hunting and fishing territories), rather than the minimal extent of Category 1 areas identified as Cree land on Quebec maps of Jamésie. There is considerable variation in both overall forest losses and most extensive forest disturbance type across the nine communities comprising the Cree Nation of EI. Five Cree Nations have territory falling partially or completely within the logging zone, and two have lost considerable forest area to reservoirs. Only one, Whapmogoostui, the northernmost community, has experienced less than 10% deforestation, while Eastmain has lost 40% of its forest, primarily to fire. The southern communities of Waswanipi and Oujé-Bougoumou, located inside the logging zone, have lost two and three times more forest, respectively, to logging than to fire (Appendix B, Table B-6). A closeup of Category 1 land in Waswanipi shows the change in logging patterns after the signing of the PDB in 2002, shifting from large swaths of clearcut land (Figure 3-11, yellow and orange) to smaller, more extensive mosaic cuts (Figure 3-11, red and purple) and the dense road networks needed for timber access and transport.

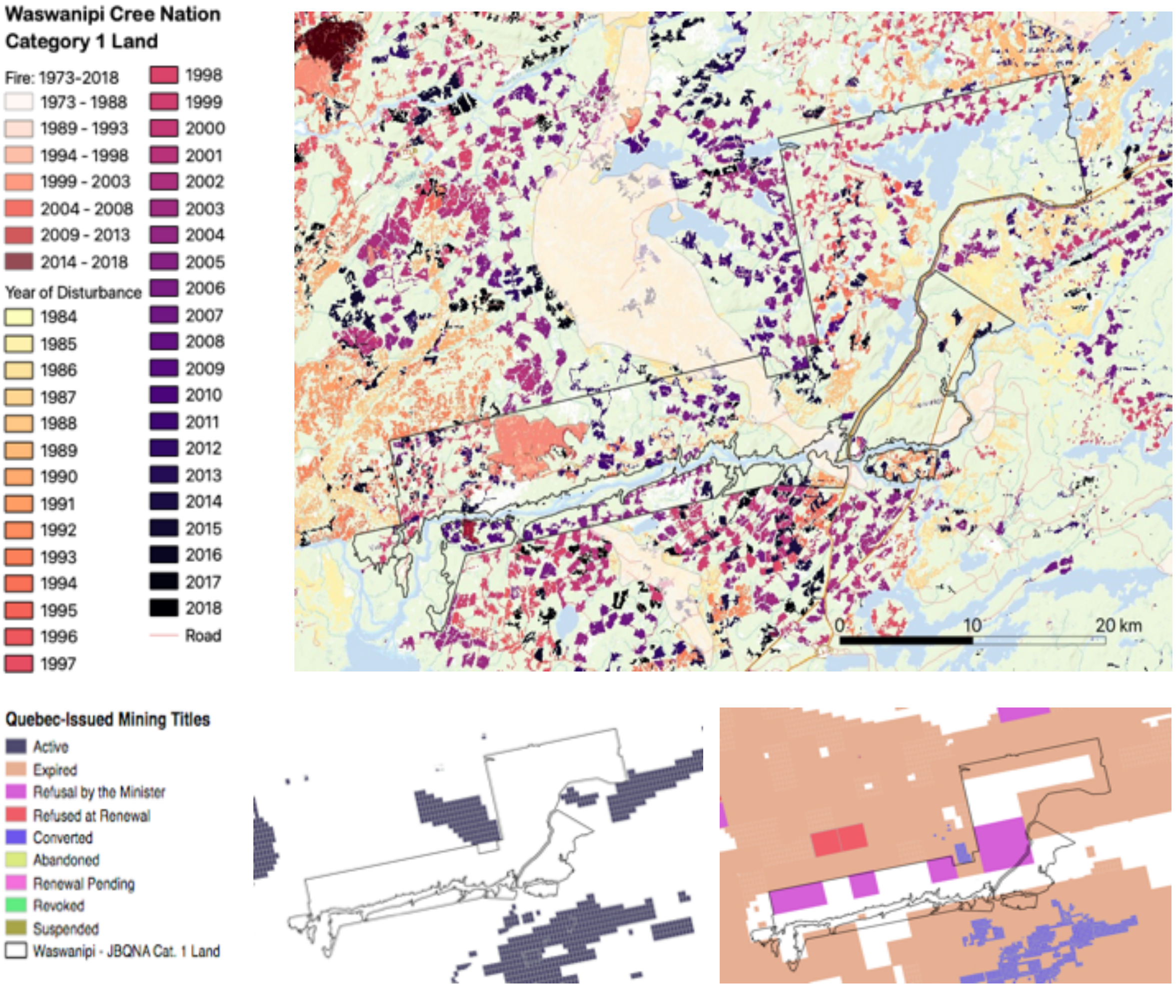

Figure 3-11. *Close-up of deforestation over time on the Category 1 land of Waswanipi in the southern section of Eeyou Istchee within the logging zone. Bottom left: Active mining titles extend to the boundary of Category 1 land; Bottom right: Earlier titles encroached on it*

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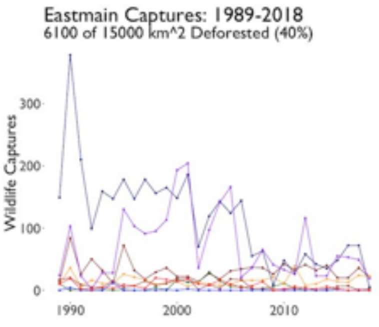
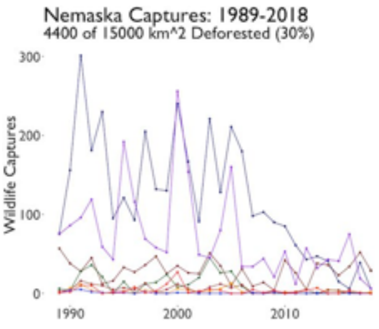
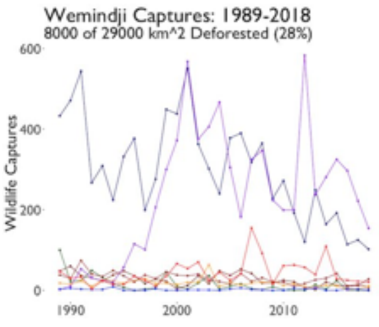
3.5.2 Declining Wildlife Captures: Food, Forests and Sovereignty

The pattern of declining wildlife captures is seen across all First Nations in EI, with southern communities directly impacted by logging having the sharpest dropoffs (Figure 3-12; SI Section III). Migrating moose and the endangered woodland caribou, traditionally a staple food in winter and early spring, have seen major declines. Caribou captures have dropped by more than 90% in five of eight communities (SI, Table S3-8). The northernmost Cree Nation, Whapmagoostui, has experienced the least amount of deforestation (6%), and is the only one in which there are more caribou captures than any other species. Captures of beaver, central to fur trading for centuries, have dropped by 76% to 96% in all communities between 1989 and 2018. The decline in moose reflects trends across the northeast in both Canada and the United States (SI, Figure S3-23). This quote from a Cree trapper, three years prior to the 2002 Paix des Braves Agreement (PDB), articulates the connections among roadbuilding, logging, and wildlife habitat loss:

> Our land is uncut now but I know Donahue [a forestry corporation] plans to build a road into it.... I am opposed to this road. This will seriously affect my hunting grounds. Ours is good hunting and fishing land... The road will change all that; it will damage the habitat and open it up to hunters and fishermen— I want all of this considered in a full environmental assessment but they won't do it. I know the government well… *They refuse to consider all development together...* We are pushed out of our land again and again. We are told to move our hunting grounds. I have seen this happen many times in Waswanipi. They concentrate the cutting too heavily in one place… The companies and the government don't listen to us. They take what is ours and push us aside. This must stop. (Affidavit of Allen Saganash, Sr, 22 July 1999 by Feit in Blaser et al, p 96-97: 2004; italics added)







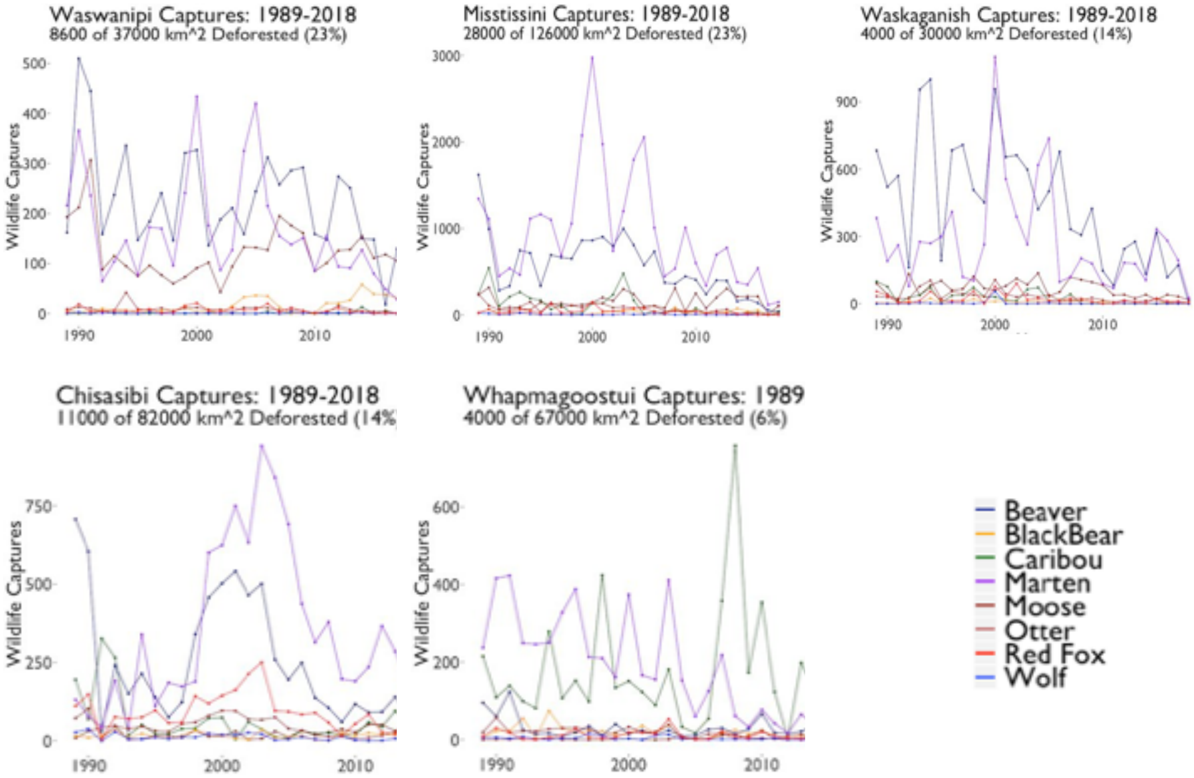


Figure 3-12. Wildlife capture data by year and species for the Cree Nations of Eeyou Istchee, in order of deforestation, highest to lowest. *Data Source: Cree Trappers Association wildlife capture data from 1989-2019 by community and species (https://www.creegeoportal.ca/cta/)*

The PDB adapted forestry regime strengthened the role of the Crees with respect to forestry governance in Eeyou Istchee, creating new consultative mechanisms at regional and local levels. The PDB set a precedent in Quebec whereby substantive changes were made to forestry rules to accommodate Aboriginal land use, affirmed through amendments to the provincial Forest Act, effectively creating two policy regimes in Quebec, one applying to the Crees and another to all other First Nations. Agreements similar to the PDB do not exist elsewhere in the province, and policies applying to other First Nations are significantly weaker. Moreover, the effectiveness of new procedural arrangements in EI has yet to be investigated, and “the prescriptive nature of the PDB itself -- based on measures agreed upon at the outset, leaves little room for meaningful input from the different actors involved in the process” (Teitelbaum et al., forthcoming).

3.5.3 Methylmercury contamination of fish: consequences of forest flooding

Methylmercury toxicity in fish was another unanticipated consequence of hydropower development (SI Section III). Highlighting the complex issues surrounding control over interconnected systems, Matthew Coon Come, Grand Chief of the Grand Council of the Crees from 1987-1999, describes the impact of the James Bay Complex on wildlife and Cree fishing as follows:

> “We have discovered that the boat access ramps are useless in areas where the trees are left standing underwater, because the trees block boat access to the shore. Furthermore, the fish are highly contaminated by mercury leaching out of the rotting vegetation; if we eat the fish, one of our staples, we get methylmercury poisoning” (Coon Come in Blaser el al. 2004: 158).

Following impoundment in the La Grande Complex, fish mercury levels rose by factors ranging from two to eight relative to the levels found in natural environments, according to a study commissioned by Hydro-Quebec. Mercury levels peaked 4 to 11 years after reservoir formation in non-piscivorous species (0.33 to 0.72 mg/kg) and 9 to 14 years after reservoir formation in piscivorous species (1.65 to 4.66 mg/kg). The same study found that mercury levels generally returned to baseline values 10 to 20 years after reservoir formation in non-piscivorous species and after 20 to 30 years in piscivorous species (Schetagne & Therrien, 2013). Consumption of piscivorous species such as pike, walleye and lake trout are now limited in the La Grande, Rupert and Eastmain reservoirs and rivers to as little as one meal per month. There is considerable variation in the extent of toxicity in the many lakes and rivers in the region. In contrast to declining wildlife captures, which more strongly impact southern Cree Nations, the highest levels of methylmercury toxicity in fish species providing a key food source are concentrated in territories in which reservoirs were formed, in the north and west of EI/J. Particularly impacted at present are the recently-constructed Rupert and Eastmain reservoirs and adjacent rivers (SI, Table S3-9).

3.5.4 Water

There are profound differences in perceptions of water in Indigenous and Western cultures; Yates et al. (2017) describe the distinct, but not necessarily mutually exclusive, ontologies of water-as-lifeblood versus water-as-a-resource. Matthew Coon Come also addresses multiple water-related struggles in EI:

> [Grandma] looked to the lake and said: 'One of these days they will come and they will block our rivers. They will make them flow backwards.' Then she looked to the mountains, and she said, 'I see something eating the trees.' And then she said, 'Even the very water that you drink, someday you will have to pay for it.' I have seen that vision come to pass. I have stood where the big dams have been built. I have seen where the rivers have been made to flow backwards. And every spring I am told in Mistissini that I cannot drink that water because it is contaminated, and I have to pay so that I can drink water (Coon Come, 2004).

In addition to the appropriation of the watercourses to produce energy and the resulting widespread, decades-long mercury contamination of fish, *access* to safe, reliable and sustainable sources of drinking water and sanitation systems are among the most pressing health issues facing First Nations communities across Canada (Basdeo & Bharadwaj, 2013; Bradford et al., 2016). In the early 1980s, failure of provincial and federal authorities to put adequate sewage systems in place in newly constructed settlements for Cree communities displaced by the James Bay Project resulted in a deadly outbreak of gastroenteritis (von Rosen, 2012).

3.5.5 Energy

In addition to the *impacts of* Quebec's energy system on the land and water of EI, and *control over* energy systems, there are also embodied injustices concerning *access to* energy. Across Canada, 260 communities and 15 commercial sites are considered remote, that is, not connected to either the North American electrical grid or the natural gas pipeline network (Energy and Mines Ministers' Conference, 2018). Of these, 77% rely on diesel fuel for power generation, 14% on hydropower, and 10% on local grids. Remote indigenous communities rely more on expensive, environmentally damaging, and aging diesel power generators than their non-indigenous counterparts, and this situation is even more pronounced in Quebec. In the rest of Canada, 83% of the 147 remote indigenous communities rely on diesel, and 15% on the grid, while 66% of the 87 remote non-indigenous communities rely on diesel, and 38% on hydro or a local grid. In Quebec, 82% of 22 indigenous communities rely on diesel and 14% on hydro; by contrast just 29% of 17 the province's non-indigenous remote communities rely on either diesel or heavy fuel oil and a full 71% have access to hydropower (Analysis of data from Indigenous and Northern Affairs Canada & Natural Resources Canada, 2016).

In EI/J, eight of the nine Cree communities are connected to the Hydro-Quebec grid, in part because of stipulations in the 1975 JBQNA and the 2002 Paix des Braves

Agreement (PDB) and in part because of the proximity of Eeyou Istchee to hydropower sources (National Aboriginal Economic Board 2014: 28). In 2002 the PDB contained a specific provision guaranteeing that Waskaganish in the southwest of the region would be connected to the HydroQuébec network within five years and Whapmagoostui in the north would be connected "as soon as possible" (Paix des Braves 2002: 25); Whapmagoostui remains unconnected 18 years later. Directly north of Eeyou Istchee is the Innuit region of Nunavik, which was also a party to the JBNQA; all 14 Innuit communities in Nunavik rely on diesel generators and none have an integrated grid (National Aboriginal Economic Board 2014).

3.4. Discussion

The disturbances presented above – hydropower, timber extraction, mining, roads, and fire – affecting the boreal forest in EI/J since the 1975 JBNQA are part of a wider history of colonial development across North America. The FEWM+ENTS approach, integrating embodied food, energy, water, and material injustices over time in the context of transboundary unsustainability, offers a powerful lens to highlight past and current injustices on which wide-ranging FEWS have been built and continue to depend. As implemented in this study, FEWM+ENTS also provides a monitoring framework to digitally document historical landscape change that can be used to improve stewardship of the working landscape and address ongoing embodied injustices at the nexus of FEWS and material extraction. We group FEWM+ENTS observations resulting from the EI/J case study as follows: 1) spatio-temporal patterns of boreal deforestation; 2) ‘anthropogenic’ verses ‘natural’ proximate drivers of deforestation 3) hydropower and transboundary sustainability 4) embodied injustices and multi-sectoral impacts; and 5) ongoing northern development and the critical importance of continued monitoring that is fundamentally interlinked with equity, justice and sustainability initiatives.

3.4.1 Boreal Forest Disturbances: Spatiotemporal patterns of extraction and deforestation

Quebec’s construction of a major hydropower complex in EI/J catalyzed more intensive private-sector development throughout the region. With this base established in the northern section of EI/J, successive waves of multi-sector resource extraction extended increasingly northward toward the La Grande River Complex beyond the logging zone, similar to events in neighboring regions (Massell, 2011). Development can be seen to intensify in fractal patterns, building on existing infrastructures, and repeating at multiple spatial scales across sectors. These patterns are evidenced by:

- The initial primary road network developed in tandem with and supported hydropower construction running north-south to the La Grande River and east-west along it.
- Major hydropower and road infrastructure fostered the construction of a dense logging road network below the northern limit for commercial forestry.
- Utilizing the same roads, logging was followed by intensive exploratory drilling by the mining industry in Ouje-Bougoumou and Waswanipi, the most southern Cree Nations in the region.
- Power-intensive mining operations and sawmills were co-sited with high-voltage transmission lines and primary roads.
- Mining operations expanded northward steadily since 1970: evidenced first by titles, then exploratory drilling, stretching further north above the limit for

commercial forestry. South of the forestry limit, exploratory drilling increased in density, closely following primary roads (SI, Figures S3-17 and S3-18).

- Hydro-Quebec planned to dam the Great and Little Whale Rivers north of the LaGrande, and the Nottaway, Broadback, and Rupert Rivers to the south. The Crees successfully blocked the Great/Little Whale plans, but the Rupert was developed in exchange for permanently dropping plans to develop the Nottaway and Broadback Rivers.

3.4.2 Deforestation by Type

Logging outweighs fire in forestry zone: Fire, by area, is the main cause of deforestation north of the forestry limit, but we find that 64% of disturbances within the logging zone are cutblocks and just 29% are due to fire. (Figure 3-7). Linear disturbances from roads in the logging zone, which comprises just 24% of the land in EI/J, amount to another 17,765 km. When the edge effects of logging and logging infrastructure are taken into account, forest degradation and loss are likely to be much more extensive than cutblock area alone indicates (Chaplin-Kramer et al., 2015; Smith & Cheng, 2016). In EI/J logging infrastructure becomes a permanent feature on the landscape, leading to further extraction, particularly mining, and facilitating non-native access and settlement. As in Ontario (Wildlands League, 2019), deforestation due to logging plus logging infrastructure in EI/J and in Quebec as a whole is likely much larger than the official forestry records indicate (2020 km^2 for Quebec in 2016 (Natural Resources Canada, 2018)). These additional impacts should be clearly understood amid proposals (Jobidon et al., 2015) to extend Quebec's limit for commercial forestry allocation further north.

Fire cannot be viewed as solely a ‘natural’ disturbance: Leveraging nexus-based insights that FEWS and material extraction are interconnected with, encompassed by, and have a profound impact upon the wider ecosystems which surround them, it would be misleading to conclude that fire as a ‘natural’ disturbance is the main cause of deforestation in EI/J. Reservoir formation accounted for a spike in forest disturbance as large as fire in the early years of the James Bay Project (Histogram 2). There are also several reasons why it is important to consider that at least some proportion of fires are not only anthropogenic but also, from a justice perspective, non-Native in origin:

1) The James Bay Hydropower Complex has significantly altered flow patterns and water discharge in EI/J. The Cree Vision for the Plan Nord calls for public discussion on the type of information needed on regional climate change and the hydrological consequences of northern hydroelectric development and a “thorough review of the adequacy of the basic framework for the collection of and access to hydro meteorological data in Northern Québec” (2011: 44).
2) The fire return interval of 50-100 years in the region surrounding the La Grande River complex is the most rapid (i.e. more frequent fires) in Eastern Canada and among the most rapid anywhere in the country. From 1985 to 2015, a total 6% of Canada's forested ecozones burned, with a significant national increasing trend in burned area of 11% per year over the past decade (Coops et al., 2018).
3) Our results suggest powerlines may be an unexamined cause of fire ignitions in the region. 161 fires in the region since 1977 intersect high voltage powerline corridors. Currently 5% of the fires in EI/J are attributed to human causes in the Canadian

National Fire Database. The remaining 95% are attributed to lightning, although eastern Canada has lower rates of fire due to fewer lightning strikes and wetter conditions than western Canada (Coops et al., 2018: 13). Powerlines are a significant and increasing cause of wildfire in many regions (Keeley & Syphard, 2018; Collins et al., 2016; Faivre et al., 2014; Miller et al., 2017). The combined effect of drier forests and atmospheric turbulence at fragmented edges (e.g. breaks at powerlines or roads) may exacerbate fire ignition, intensity, and spread in EI/J.

4) Climate change is increasing boreal forest wildfires (Amiro et al., 2001), with further increases expected this century due to more frequent and severe droughts (Terrier et al., 2013). Increasing fire incidence in combination with current rates of clear-cutting and mosaic harvesting are of major concern to the health of boreal forests across Canada (Bergeron et al., 2011).
5) The commercially valuable black spruce harvested from the boreal forest by timber companies in EI/J is often replanted with the much more combustible jack pine (Barlow, 2008; Henneb et al., 2020), which also is also predicted to push black spruce out of forest succession over time as fire frequency increases due to climate change (Boiffin & Munson, 2013; Sirois, 1993)
6) Changing this narrative around fire may undercut the federal and provincial justification for logging implicit in the contention that fire -- viewed as a purely ‘natural’ disturbance -- is the “dominant stand-replacing disturbance impacting forested ecosystems” across Canada (Coops et al., 2018: 2).

3.4.3 FEWM + Transboundary Unsustainability

FEWM+ENTS provides a critical lens that can inform ongoing efforts to transition to more just and sustainable FEWS and material supply chains across regional and international boundaries. The energy and materials extracted from EI/J have met demands of consumers in southern Quebec, neighboring provinces, and the U.S. since the 1970s: Hydro-Quebec (HQ) currently has an estimated surplus of about 40 TWh per year (Hydro-Québec, 2019); in 2019 the utility sold 208.3 TWh of energy, including 33.7 TWh (16%) exported to New England, New York State, Ontario and New Brunswick (Hydro-Quebec, 2020); Vermont, for example, relies on Quebec for about one third of its electricity supply (Vermont Department of Public Service, 2016). The U.S. is also a major consumer of the province's lumber and pulpwood. In the 1990s and early 2000s the Crees were successful in leveraging the electricity supply chain to gain support in the United States to block Hydro-Quebec's planned expansion of the James Bay complex into the Great Whale, Broadback and Nottaway Rivers (von Rosen, 2013; McRae, 2004). The Cree campaign involved extensive efforts to raise awareness of its impacts to Hydro-Quebec's intended markets in New York, Vermont, and Maine (von Rosen, 2013) and the promotion of energy conservation as a crucial way to meet increasing energy demand in the U.S.

The argument that conservation is a vital way to meet demand also holds for Quebec. Currently the James Bay complex operates at about 70% of its generating capacity of 17,200 MW and comprises half the total installed capacity in Quebec. The power oversupply in Quebec has led to inefficient electric baseboards as the most common form of home heating throughout the province, while northern indigenous communities still rely on diesel generators for power. In 2017, annual electricity consumption per capita in Quebec (population 8.5 million) was 21 MWh, compared to 9.5 MWh in neighboring Ontario (population 14.6 million). Quebec's per capita electricity consumption is 44% more than the national average; its higher consumption is driven by the presence of high-electricity consuming industries such as aluminum smelting, and reliance in the residential and commercial sectors on electric baseboard heating (SI, Section Vb).

There is intense debate about whether large hydropower should be considered renewable as more governments across North America adopt higher renewable energy targets. In 2018 Hydro-Quebec secured a 20-year contract to supply Massachusetts with 9.45 TWh of energy per year, and is now building a 1200 MW interconnection, the New England Clean Energy Connect (NECEC), to deliver electricity to the New England grid via Maine, after a similar initiative to deliver hydropower via New Hampshire was defeated in that state. A strong clean energy rhetoric surrounds these initiatives (Hydro-Quebec, 2020). In addition to the carbon footprint of newly created hydropower reservoirs (Deemer et al., 2016; Teodoru et al., 2012), the cumulative boreal deforestation in EI/J beginning with, and dependent on power from, the James Bay hydroelectric complex, indicate that the assertation of the region's hydropower as 'clean' should be carefully examined.

3.4.4 FEWM+ Embodied Injustices: “They refuse to consider all development together”

An important takeaway from this case study is that multi-sectoral impacts leading to forest degradation and loss are ultimately more damaging than the sum of their parts, affecting interdependent social-ecological systems at multiple spatial scales. While siloed and atemporal metrics can obscure cumulative losses and combined impacts in tandem, the FEWM+ENTS framework supports collection of multi-sectoral data over time that permits causal and correlative patterns to be detected.

In EI/J several forest disturbance types related to the region’s development– hydropower, mining, logging, roads, and fire – interact in multiple reinforcing ways. Broadly speaking, hydropower dramatically reshaped the landscape, requiring the construction of an arterial road network, running in tandem with high voltage powerlines. Hydrological reengineering and powerlines have likely boosted ignition risk, a phenomenon which merits further study, and can partially account for accelerating burn cycles in the region. Sawmills and mines require electricity and transportation infrastructure and roads; exploratory mining closely follows major roads in areas opened by logging. In the same way that the combined impacts of hydropower, roads, logging, mining, and fire have led to forest loss and land and water degradation throughout Eeyou Istchee that are ultimately more damaging than the sum of their parts, so too are the interlinked embodied FEW+M injustices resulting from these activities.

These mutually reinforcing injustices are intertwined with non-Native extractivism, permanently altering the landscape and damaging the boreal ecosystem, and facilitating non-Native settlement. These embodied injustices take on several dimensions: Quebec and Canada were able to wrest control over land and water in EI/J from Native Peoples in order to generate energy and extract timber and minerals for the benefit of distant populations, resulting in significant boreal forest loss and destruction of fish and wildlife habitat. This in turn deprived the Crees of access to traditional foods and safe drinking water, upending traditional ways of life, and largely excluding the Crees from economic development of the region. Even after the passing of the JBNQA, it was a decades-long process for the Crees to push the provincial and federal governments to honor the commitments made in the Agreement: “It took until 1987 to get the Cree School Board fully funded. It took until 2002 to get the Health Board fully funded. In the meantime the social and health problems of the communities were encountering were growing” (Craik in von Rosen, 2012).

3.4.5 Future considerations

The 2011 Plan Nord, Quebec’s 25-year, $80 Cd billion plan to intensify resource extraction in the 1.2 million km^2 territory in Quebec north of the 49th parallel, applies to 72% of Quebec’s total area, including all JBNQA lands. Its aims are to enable resource development by 2035, setting aside 50% for “non-industrial purposes, environmental protection, and safeguarding of biodiversity” (Gouvernement du Québec, 2015: 13). The Plan Nord has generated considerable concern among Aboriginal, environmental, and scientific communities. The 2011 Cree Government response, the *Cree Vision of Plan Nord* (CVPN), states that the Plan Nord must respect Cree rights as articulated in

Constitution of Canada, the JBNQA, and the Paix des Braves (PDB), including the nation to nation relationship between the Crees and Quebec outlined in the PBD.

The FEWM+ENTS approach to the nexus illustrated in this paper, focusing on *impacts* on, *access* to, and *control* over the FEW/ resource nexus, implicitly supports the perspective articulated in the CVPN: that development activities are interconnected, with impacts reverberating across the land and the people inhabiting it. The CVPN further states that past industrial development must be taken into account in the Plan Nord's goal to protect 50% of the territory. In particular, timber harvesting both north and south of the northern limit of allocation "should be considered as 'industrial' under the Plan Nord 50% protection scheme" (CVPN, 2011: 103). Given the extensive nature of logging operations within the current forestry zone in EI/J, this provision would likely significantly curtail the area open to development.

<u>The Need for Monitoring</u>: Uncertainties relating to "50% Protected Area" illustrate that monitoring is needed to document the nature, scope and impacts in all sectors of industrial activity, including energy, forestry, and mining, which will be affected by the Plan Nord (CVPN, 2011). The FEWM+ENTS lens, building on FEW /resource nexus insights and the concept of embodied energy injustice, offers an important framing for the ongoing monitoring needed to document the nature, scope and impacts of hydropower, logging and mining across their interlinked supply chains. Specifically, the CVPN asks: "What industrial activity has taken place in the past? Where, by whom, with what environmental, social and health impacts in the Territory?" noting:

> It is impossible to answer these questions with any assurance of accuracy. A rational development strategy, such as the Plan Nord purports to be, requires the establishment of baseline information to determine the "before" and the "after" of existing industrial activity and of future industrial activity associated with the Plan Nord (CVPN, 2011: 106).

The CVPN also calls for a thorough review of the technical aspects of monitoring, stating this is essential for development of future policy recommendations concerning the Plan Nord. The CVPN asserts that Quebec's Ministry of Natural Resources and Wildlife (MNRW) has not shown willingness to prioritize the health of the forest ecosystem over timber extraction, calling for Quebec to suspend tree cutting in areas with woodland caribou and to consult all parties to create a recovery plan. With respect to Cree rights more broadly, "the Government of Quebec must make a definitive statement rejecting suggestions to amend the exclusivity of the Hunting, Fishing and Trapping Regime …in the JBNQA" (CVPN, 2011: 56). The Cree Government also calls for rigorous attention to environmental evaluation, restoration and monitoring of the past mistakes with respect to mining and emphasizes the need to inspire public trust, noting that "outstanding environmental impacts of past mining activities in the region have …created a climate of mistrust" (CVPN, 2011: 100). With respect to embodied injustices stemming from development as whole, the CVPN asks, "Who will bear the human costs of economic development in the North?" and concludes:

> Northern populations are already at a disadvantage due to their remote location and suffer considerable health and social inequities compared to the rest of Quebec. Profiting from the natural resources and tourism potential in the North at their expense would be unjust, further increasing inequities rather than helping those who need it most (CVPN, 2011: 113).

3.5. Conclusion

This study extends the FEW/resource nexus to include Materials, Embodied iNjustices, and Transboundary unSustainability (FEWM+ENTS), using a historical perspective to examine proximate causes of deforestation in a contested landscape that is now the site of the largest hydropower complex in the Western Hemisphere and poised for a new wave of northern development, initiated by the province of Quebec and reflective of trends throughout Canada. We address several recent critiques of the nexus approach, particularly its failure to consider the political production of the nexus, that is, "the contested relationships, processes and technologies through which [food], energy and water become enrolled in nexus interactions" (Williams et al., 2014: 4). Through FEWM+ENTS framing and analysis, we trace and map ecosystem disturbances to the region, identifying the year and type of forest disturbance. Rather than focusing primarily on the *inputs* of water to energy, we focus on the reverberating social-ecological *impacts* of the energy system on the region as whole, as hydropower, logging, mining, and fire have cumulatively deforested at least 26% of the boreal forest in EI/J since the early 1970s, excluding the edge effects of nearly 20,000 km of roads initially built for timber extraction in southern EI/J. Moreover, the large burned area in EI/J cannot be attributed solely to natural causes, and ignition of fire from powerlines may be an unexamined cause of fires in the region.

We further identify interdependencies among forest disturbance types and link embodied FEWM injustices to transboundary resource consumption and control, emphasizing that the extensive ecological degradation documented here undermines the ‘clean’ and ‘sustainable’ narratives surrounding electricity and material exports from the region. Logging is not only the main cause of deforestation in the southern quarter of EI/J, it also serves as a gateway to further extraction, territorial control, and permanent non-Native settlement. The boreal forest is of global ecological significance, playing a pivotal role in carbon cycling and biodiversity, and providing crucial habitat for fish and wildlife that have supported Aboriginal People for millennia. The boreal forest of Canada may be as consequential for global climate change mitigation as the rainforests of the Amazon, and is further threatened by intensive development north of the 49th parallel, which can be seen to mirror at northern latitudes the trajectories of tropical deforestation and development.

In extending the concept of embodied energy injustice to include nexus interactions among FEWS and material supply chains, we focus not only on *inputs* to and *impacts* of these systems, but also on *access* to and *control* over FEWM. Precisely because it is still an emerging concept, the nexus offers an opportunity, particularly at the resource frontier, to re-examine approaches to the social-ecological impacts of complex interacting systems rather than specific projects, such as a mine, power plant, or timber allocation, as isolated activities with narrowly-defined environmental impacts. FEWM+ENTS can provide a powerful lens for monitoring nexus interactions through which the interconnected nature of ongoing territorial expansion, entangled social-ecological changes, and embodied injustices come into sharper focus. This lens opens up the possibility of seeing more clearly a whole that is greater than the sum of its parts, and thus facilitates awareness of the emergent properties of these rapidly developing systems in both place-based and technological ‘frontiers’, in which emerging technologies are rapidly accelerating extractive capabilities.

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CHAPTER 4: CARBON AUTOCRACY: THE GLOBAL OIL AND GAS EXTRACTION NETWORK, STATE-FIRM RELATIONSHIPS AND INTER-FIRM DEPENDENCIES, 2014-2018

Abstract

Publicly available sources for global energy data generally depict national-level fossil fuel extraction and related processes. These sources do not systematically track the transnational activities of the world's major oil and gas producers, confounding efforts to trace environmental, social, and climate impacts of the fossil energy system to specific actors, policies, and the dynamic relations between sovereign nations and extractive corporations. Here we examined the a new, spatially-explicit dataset using publicly available annual reports and operating statements of the top 26 global oil and gas companies based on annual production. Using this dataset, we conducted multilayer and multiplex network analyses of the global production network from 2014 to 2018. During this key period, international climate mitigation efforts coalesced in the Paris Agreement, large scale renewable energy alternatives became increasingly viable, and pro-fossil fuel interests gained increasing traction in politically conservative "populist" movements in key oil and gas producing countries around the world. We represented countries, state-owned oil companies, hybrid state-investor companies, and investor-owned corporations as network nodes, with weighted network edges indicating the flows of oil and gas among resource-holding countries and oil and gas companies. This system-wide perspective of the global oil and production network offers insights into the structure of complex and rapidly-shifting global energy geopolitics. The prevalence of joint ventures and equity holdings across investor-owned and hybrid companies emphasizes the tight interdependence among transnational oil and gas interests and cooperation ('collusion') in the face of existential threats to the industry that crystallized around the decisive US election of 2016. At a system level, the interconnectedness, global reach, and combined power of the major private, hybrid, and state oil and gas producers point to the necessity for a supply-side approach to the reduction of global carbon emissions.

4.1. Introduction

The global transition to low-carbon energy systems, while increasingly urgent, is also intensely contested, as evidenced by several rapid and seemingly contradictory shifts. The past decade has seen the incorporation of large-scale renewable energy into the electric grid, binding commitments to reduce global greenhouse gas emissions in the landmark 2015 Paris Agreement, and the increasing electrification of the transportation system, as well as surging production of shale oil and gas through "fracking" (i.e. High Volume Hydraulic Fracturing (HVHF) in combination with horizontal drilling). Fracking propelled the United States to become the top producer of petroleum and natural gas in the world, surpassing Russia in natural gas in 2009 and Saudi Arabia in petroleum in 2013[1]. Commercial-scale fracking also occurs in Canada, China, and Argentina, amid vocal efforts in other regions to halt the process. The tensions between entrenched fossil fuel interests and the growing movement to transition away from them are reflected in ongoing political struggles in countries crucial to the global oil and gas production network and attempts by transnational fossil fuel interests to influence political processes in these countries. In order to effectively govern the global transition away from fossil energy, it is necessary to clearly outline and characterize the rapidly-changing oil and gas production network and its complex interdependencies at the system level. This effort is especially urgent given the industry's motivation and ability to obstruct, stymie, and derail meaningful efforts at a large-scale energy transition across national borders.

Publicly available data are essential tools for fostering public oversight of the global fossil fuel industry, and as such have been the target of high-level obstruction. Regularly scheduled meetings in the USA of the Extractive Industries Transparency Initiative, an international effort involving stakeholders from government, energy companies, trade organizations, and civil society groups seeking to track all payments to governments were unilaterally cancelled by the Trump administration in early 2017[2]. Weeks after Trump's inauguration in 2017, the Republican-controlled House passed a resolution nullifying a provision in the 2010 Dodd-Frank Wall Street reform law requiring all oil and gas companies listed on the US stock exchange to publicly report all taxes, royalties, fees, dividends and bonuses paid to foreign governments or officials (2019: 352)[2].

While there are several major publicly-available datasets constructed by public agencies and industry groups that include detailed information on fossil fuel production, consumption, and trade patterns[3–5], they generally provide data at the national level, with additional sources providing data for some countries at the subnational level[6]. Third party groups addressing firm activities tend to focus on one section of the whole system or on the activities of one company[7].However, none of these sources consistently track or integrate the activities of all of the major firms engaged in fossil fuel extraction, obscuring the central role of transitional private and hybrid state-private interests in a complex global regulatory and political landscape. This constitutes a major shortcoming in the effort to effectively reduce carbon emissions at the global scale.

To undertake this analysis of oil and gas extraction across countries at the firm level, we developed a new spatially-explicit dataset of global oil and gas production using publicly available data, including annual reports, operating statements, and SEC filings of the top 26 oil and gas companies based on millions of barrels of oil equivalent per day (mboed) produced in 2016 (Table 4-1). This dataset consists of more than 7600 records for exploration, reserves, production, and refining by the 26 largest companies between 2014 and 2018. Each record includes the name of the company, the country in which the operation occurred, the quantity (if available), unit, exact location if given, whether the operation is a joint venture and venture partners if listed, year, source, and if the original record was not in table form, the text from which the record was constructed (Table 4-5). There are over 5300 records for production, including 3000 at the national level, with separate entries for liquids, gas, and total hydrocarbons. Another 2100 records describe extraction at the subnational level and 400 are aggregated to the regional or continental level. Also included are about 500 records for major development projects in the pre-production phase as well as acreage held as part of active concessions.

Using this dataset we present a high-level description of current global oil and gas extraction, and construct a directed, weighted network of global oil and gas production from 2014 to 2018. We analyze this network according to established methods, including the application of machine learning for community detection within the network and highlight key trends and hotspots in the network.

4.1.1 The Global Oil and Gas Production Network

We depict oil and gas extracting companies, or firms, (whether exclusively private, state-controlled, or some combination thereof) and sovereign nation-states as network nodes, drawing on a notable illustration of the global production network (GPN) applied to oil[8]. That study from 2008 identified two defining tensions in the GPN for oil influencing its organizational structure and geographies: 1) the tension between resource-holding states and resource-seeking firms and 2) the distribution of value between producers (both states and firms) and consumers. Although that work also relied on national-level production and consumption data[3] and did not capture more recent social, political and environmental dynamics and risks of various state relationships to the fossil fuel industry, it was notable in prioritizing inter-firm and firm-state relationships. This conceptualization was offered as an alternative to the 'resource curse' hypothesis, which posits that states rich in natural resources tend to have less democratic governance. Bridge[8] also identified three structural imperatives that distinguish it from other sectors: 1) the *resource (access)* imperative to replace constantly depleting reserves, with resource-seeking firms negotiating with resource-holding states over the terms of access and firms competing for access to and control over reserves; 2) the *technological* imperative to reduce costs to gain competitive advantage, which manifests itself in the aggressive pursuit of economies of scale in production and refining, and in transportation; and 3) the *ecological* imperative to reduce carbon emissions worldwide as the energy needed to extract oil from increasingly hard to reach areas, including subsurface shale and deepwater deposits is increasing, such that firms "nominally in the business of producing oil (rather than consuming it) top the ranks of carbon dioxide emitters" (2008:18)[8].

The GPN approach insists "on a relational understanding of production and the ways in which inter-firm competition structures the organization and geographies of the production network" (2008: 406)[8]. The approach also highlights more recent challenges to effective governance of the global transition to a low-carbon energy system, particularly the vital role of national regulation of the fossil fuel extractive industry and the many instances in which such regulations fail in their mandates of adequate environmental, health, social and labor protection. Mitchell outlines four features of the political economy of oil in the 20th century: 1) the extraordinary rents that could be earned from controlling the production and distribution of oil, 2) the difficulty in securing those rents due to the overabundance of supply, 3) the pivotal role of Saudi Arabia in maintaining oil scarcity, and 4) the collapse of older colonial methods of imposing anti-market corporate control of Saudi oilfields, such that oil profits depended on working with those forces that could guarantee the political control of Arabia…the multinational oil corporations sought to secure and enlarge these rents, in a rivalrous collaboration with the governments that controlled the oilfields" (2013: 229)[9].

The crucial role of the US, Russia Saudi Arabia in the global production of oil is not new: Saudi Arabia developed into one of the three very large producers in the 1970s, and by the 1990s these countries each produced two or three times as much oils as any of the other producers among the top dozen[9]. Mitchell, in the book *Carbon Democracy*, highlights Saudi Arabia's importance not just in its abundance of supply, but in its pivotal role in the system of scarcity:

> With a population about one-tenth the size of Russia's and 1/16th the size of the US, Saudi Arabia could afford to keep part of its production capacity switched off. By the 1990s, this unused capacity (then estimated at 3 million barrels per day) was close to or exceeded the total production of any other country except Russia and the US. The excess allowed Saudi Arabia the ability to play the role of 'swing' producer, threatening to switch its surplus on and off to discipline other producers who tried to exceed their production quotas. It did so in collaboration with the United States, on whom it depended for military protection. As a result of these three factors – inelastic demand, overabundance, and the Saudi surplus – the possibility of large oil rents anywhere in the world in the second half of the twentieth century depended on the political control of Arabia (2013: 207).

De Graff [10] also utilizes a network approach, focusing on the underlying relations between different companies, observing a shift toward "a more multipolar and hybrid global energy order in which the rise of statist actors from outside the Western core …is generating more hybrid forms of cooperation, new alliances and dynamics and a blurring of categories." This relational approach is offered as an alternative to the 'National Oil Companies (NOCs) vs Investor Owned Companies (IOCs)' view, or 'net-exporters vs net importers"**,** in which power dynamics are seen to shift based on the price of oil and forces of demand and supply. Using social network analysis to map the joint ventures, wholly-owned subsidiaries abroad, equity interest, and operating/service contracts of state-owned companies[3] in 1997 and again in 2007, De Graaff found that NOC expansion took place at least in part through increasing integration with IOCs. Although NOCs might seem to have 'gained' power –partly driven by high oil prices – and IOCs might be seen to have 'lost' power, they were also seen to increasingly *join forces*, with the further implication that during this period they became increasingly interdependent[10].

To guide our dataset conceptualization and network modeling, the processes of exploration, production, transportation, refining, processing, and consumption from the GPN model were transformed into network layers (Figure 2). Additional layers for reserves and development were added to the dataset and 'consumption' was recast as sales. The current analysis focuses on upstream operations, with data on mid and down-stream operations to form the basis of a follow-on study. The multiplex network model used to develop this dataset (Figure 2) encompasses states, firms, processes and products. GPN state and firm functions[8] are listed for reference. They are largely based on the functions of IOCs, with state-owned firms having the potential to play a different role in

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[3] Saudi Aramco, Gazprom, National Iranian Oil Company, Petroleos de Venezuela, S.A. (PDVSA), and China National Petroleum Corporation (PetroChina)

countries with national oil companies and hybrid firms, in which the corporation itself can be seen to be held accountable to the public.

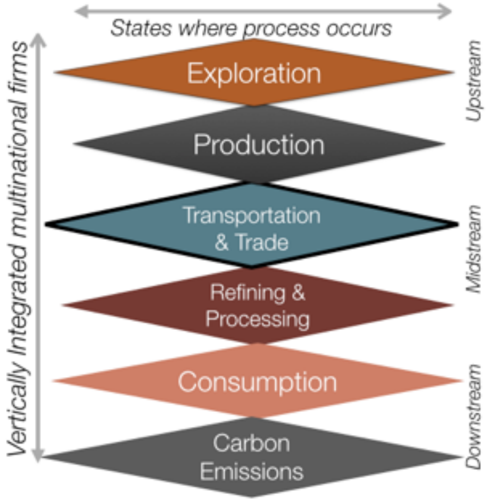
GPN State Functions	Multilayer approach to Global Production Network for oil and gas	GPN Firm Functions
"Resource holder: Exp, licenses; Taxation, health & safety and env regulations" ***1800 records***		Seismic data; drilling tech; demand forecasting; Project management, *Political Risk*
"Resource holder: production concession; Taxation, health & safety and env regulations" ***5300 records***		Construction; Project Management; equity partners (other oil firms); Debt (banks); Staff, crew, camp services
Taxation, health & safety and env regulations		Shipping, pipelines, terminal operators, risk management
Taxation, health & safety and env regulations ***500 records***		Wholesalers, retailers; individuals, institutional and corporate consumers
Taxation, health & safety and env regulations		Wholesalers, retailers; individuals, corp. consumers
Taxation, health & safety and env regulations		Carbon offset brokers; sequestration projects

Figure 4-1. *Multiplex representation of the generalized global production network used in this study, focusing on upstream and midstream activities.*

4.2. Results

We provide a quantitative summary of the global hydrocarbon production system and present key results of our analysis of network properties by company and year (Layer 2 in Figure 4-1). We model global oil and gas production as: 1) a multiplex network in which different company types (NOCs, Hybrids, and IOCs) are represented as separate layers, with each layer having different companies, and 2) a multilayer network in which each year is represented a separate layer and the same companies appear in all layers. Well-known methods are used to determine network centrality, correlation, and clustering/community detection.

4.2.1 System-Wide Overview

The top 26 global oil and gas companies accounted for approximately 67% of annual output during the period from 2014 to 2018 (55700 of 81900 kboed), and fall into three general categories corresponding to 1) their level of international activity in the arena of upstream operations and 2) the extent to which they are privately-owned. Apart from fully state-owned companies (NOCs) and fully private companies (IOCs), a third category can be distinguished[10]: 'Hybrid' companies, which are partly state owned and partly owned by private investors; in some cases banks and other oil companies have significant holdings. Four of the seven Big Oil companies are headquartered in European countries (Britain's BP, Holland's Royal Dutch Shell, France's TotalSA, and Italy's EniSpa) and other three (ExxonMobil, Chevron and ConocoPhillips) have headquarters in the USA (Table 1-1). All Big Oil companies are headquartered in countries that do not have nationalized or hybrid firms. Moreover, Germany, Denmark and other European countries without Big Oil firms and fewer conventional oil and gas reserves are structurally better positioned to advocate for renewable energy, without having to contend with vested private in-country opposition from the multi-national oil and gas sector. With the exception of Petronas, NOC countries are also members of the Organization of Petroleum Exporting Countries (OPEC).

National Oil Companies (NOCs): The NOCs in this group are, in descending order of net hydrocarbon production in 2018 (where 2018 data is available): Saudi Aramco (#1), Abu Dhabi National Oil Company (#4), National Iranian Oil Company (#5), Iraq's Basra Oil Company (#10), Kuwait Petroleum Corporation (#); Petroleos de Venezuela (#15), Petronas in Malaysia (#18), Sonatrach in Algeria (#19), Qatar Petroleum (#21), and Nigerian National Petroleum Company (#26).

Hybrid NOC/Investor Owned Companies include the Russian majority state-owned companies Gazprom (#2) and Rosneft (#3) as well as PetroChina (#6), CNOOC (#23), and Sinopec (#25), all majority owned by the Chinese government. Brazil's Petrobras (#14), Mexico's Pemex (#16), and Norway's Equinor (#20) round out this group.

Investor-Owned Companies (IOCs, including 'Big Oil') 'Big Oil' refers to seven of the world's largest privately-owned IOCs, also known as the 'supermajors,' including: ExxonMobil (#7), BP (#8), Shell (#9), Chevron (#12), TotalSA (#13), EniSpa (#22), and ConocoPhillips (#24). Moscow-based Lukoil (#17), with extensive retail operations in the US, is the only IOC in the top 26 that is headquartered in a country that also has one or more NOCs.

Hybrid companies have an international presence in oil and gas production that is generally less than Big Oil and more than fully state-owned NOCs. Pemex and Petronas are outliers in this framework: Pemex is 75% state-owned but operates solely within Mexico and Petronas is 100% owned by the Malaysian government but engages in exploration and extraction in 23 countries on six continents and markets petrochemicals and lubricants worldwide. Among the NOCs, there are steep variations in how much extraction by outside firms is permitted: Saudi Arabia, Iran, Abu Dhabi, and Kuwait allow very little direct outsider production (roughly about 5%), although Saudi Aramco partners with ExxonMobil, Shell, Sinopec, TotalSA, and Chevron in refineries in Saudi Arabia and partners with Shell in refining operations in Toyko, with Sinopec and ExxonMobil in refining in China and with Petronas in petrochemical processing in Malaysia, among others. By contrast, Qatar Petroleum and Nigerian National Petroleum Company only account for about 40% of in-country production, and have a large Big Oil presence, while 2017 estimates (the most recent available) have Iraq-owned production at 70%.

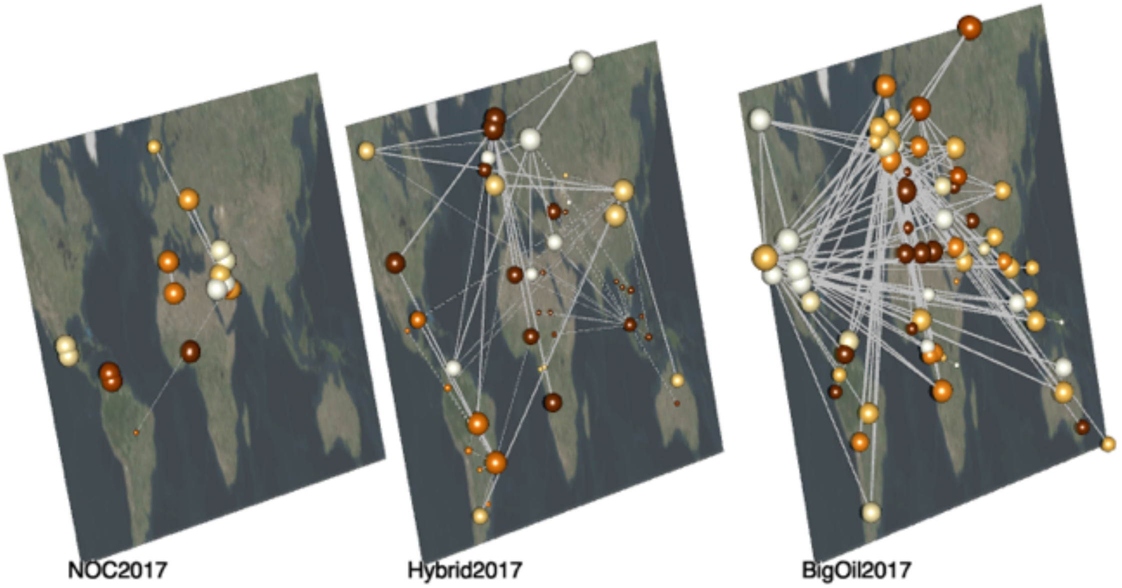


Figure 4-2. *Multiplex network showing total hydrocarbon extraction extracted from countries by companies, with NOCs, Hybrid companies, and BigOil/IOCs as separate layers in 2017 (the most recent year with data for all 26 companies). Nodes are colored by communities within each layer and sized according to the weights of their edges.*

Together these 26 companies directly employed more than 3 million people in 2018 (Table 1-1). The reach of the industry is much more extensive than direct employment figures indicate: the oil and gas drilling sector, comprising companies that explore for, develop, and operate oil and gas fields, alone makes up around 3.8% of the global economy, or 3.3 trillion of the estimated global GDP of 86 trillion in 2019[11]. In the United States it has been estimated that the oil and gas industry accounted for up to 5.6% of total employment in 2015, combining operational and capital investment impacts, and amounted to 10.3 million full-time and part-time jobs, according to a study commissioned by the industry[12].

Table 4-1. *Key figures describing the top 25 global oil and gas producers as measured by millions of barrels of oil equivalent produced per day in 2018. NOCs are shown in pink, Hybrids in gray, and IOCs in orange.*

Company	**Country HQ**	**Year Founded**	**Type**	**Hydrocarbon Prod. In 2018 (mboed)**	**Employees in 2018**
1. Saudi Aramco	Dhahran, SA	1933	NOC/OPEC	13.60	70762
2. Gazprom	Moscow, Russia	1989	Hybrid: 50% state owned	10.19+	466100
3. Rosneft	Moscow, Russia	1993	Hybrid: X% state owned	5.82	302100
4. ADNOC	Abu Dhabi, UAE	1971	NOC/OPEC	4.67*	55000
5. National Iranian Oil Company	Tehran, Iran	1951	NOC/OPEC	4.50*	104000
6. Petrochina	Beijing, China	1999	Hybrid: X% State-owned	4.09	506000
7. Exxon Mobil	Irving, TX	1911	Big Oil	3.83	69600
8. BP	London, England	1909	Big Oil	3.68	74000
9. Royal Dutch Shell	The Hague, Netherlands	1907	Big Oil	3.67	18000
10. Iraqi Oil Ministry	Bagdad, Iraq	1966 1987	NOC/OPEC	3.59*	

		2018			
11. Kuwait	Kuwait City, Kuwait	1980	NOC/OPEC	3.19	10984
12. Chevron	San Ramon, CA, USA	1879	Big Oil	2.93	48596
13. TotalSA	Courbevoie, France	1924	Big Oil	2.78	104000
14. Petrobras	Rio de Janeiro, Brazil	1953	Hybrid: 64% state-owned	2.77	62700
15. Petroleos de Venezuela	Caracas, Venezuela	1976	NOC/OPEC	2.73*	
16. Pemex	Mexico City, Mexico	1938	Hybrid: 75% state-owned	2.58	124660
17. Lukoil	Moscow, Russia	1991	IOC	2.35	103600
18. Petronas	Kuala Lumpur, Malaysia	1974	NOC	2.32	49911
19. Sonatrach	Algiers, Algeria	1963	NOC/OPEC	2.27	120000
20. Equinor	Stavanger, Norway	1972	Hybrid: 67% state owned	2.11	20525
21. Qatar Petroleum	Doha, Qatar	1974	NOC/OPEC	1.92	14000
22. EniSpa	Rome, Italy	1953	Big Oil	1.85	33000
23. CNOOC	Beijing, China	1982	Hybrid: CNOOC state/ CNOOC Ltd investor-owned	1.30	99000
24. ConocoPhillips	Houston, TX, USA	1875	Big Oil	1.28	10800
25. Sinopec	Beijing, China	2000	Hybrid: Sinopec Group state owned/ Sinopec Ltd investor-owned	1.24	249000
26. Nigerian National Petroleum Company	Abuja, Nigeria	1977	NOC/OPEC	1.19	

**2018 production figures not available; 2017 used. **Total national production for Iran from BP Statistical Review used in lieu of company publications. +plus equity affiliates*

4.2.2 Network Properties

In its simplest form, a network is comprised of entities, or ‘nodes,’ and the interactions, or ‘edges,’ between them. Networks having multiple types of interactions can be modelled using a layered, or “multiplex” network, in which the nodes are constant across layers and each layer represents a different type of interaction, or network edge (Baggio et al 2016: 1). Moreover, interdependencies between layers can have profound effects on the entire system, including behavior which cannot be predicted by studying each layer in isolation. The complexity of the global production network for oil and gas lends itself to multiple types of network modeling. Here we construct networks focusing on:

1. Company type, using a multiplex network with separate layers representing NOCs, Hybrid companies, and IOCs, repeated for multiple years as separate multiplex networks that can be compared.
2. Temporal changes, using a time series network (including all companies in top 26) for each fuel type for total hydrocarbons, repeated for oil and gas separately, with each year from 2014 to 2018 representing a separate layer.

We analyze these networks using the following metrics: 1) network centrality, in terms of the strength of each node (how much oil and gas flows *from* each country *to* each company), as well as the degree of each node in the network (the number of countries in which companies extract oil), 2) correlation among multiplex networks, treating years and company types as network layers, and 3) community detection using the Louvain method.

We also construct a weighted network illustrating joint ventures and equity holdings in *other* firm operations at the field level in 2014 and 2018 for the hybrid Norwegian state-investor owned company Equinor, which was one of only two companies whose annual reports: a) consistently listed the percentage of its equity holdings in all partner-operated fields (Conoco-Phillips was the other), b) named the partner company acting as operator for that field, and c) provided the amount extracted from that location. Although only two companies in the top 26 consistently supplied this information for 2914-2018, it nonetheless provides a window into the joint operations among the major producers.

4.2.2.1 Network Centrality Metrices: Flows Among Nation-States and Companies

There are notable differences in the degree centrality and node strength of total hydrocarbon production in aggregate, as well as patterns that emerge when considering oil and the more regionally-bounded natural gas networks separately (Table 1-2). The total hydrocarbon category is more comprehensive than liquids or natural gas, because there are some firms for which country and field-level production is not disaggregated into oil and gas. (This is notably the case with Equinor, which reported total hydrocarbons only and therefore is not represented in gas and oil networks.)

Table 4-2. *Each node and fuel type as single layer networks, aggregated across all years.*

Metric	Big Oil THC	Hybrid THC	NOC THC	Big Oil Liquids	Hybrid Liquids	NOC Liquids	Big Oil Gas	Hybrid Gas	NOC Gas
Nodes *N* (Company; Country)	7 63	9 63	10 14	7 63	6 20	10 12	7 59	6 18	10 10
Edges *m*	768	412	52	624	107	51	667	89	46

Average degree	11.0	5.72	2.16	8.91	4.1	2.3	10.1	3.7	2.3
Node strength (weighted degree) Sum of weights/N /5=kboed per year	260	400	1709	144	484	1322	118	491	612
Pearson Correlation Assortativity	-0.85	-0.72	-0.59	-0.87	-0.61	0.34	-0.78	-.62	1
Community Detection: Modularity	0.07	0.05	0.07	0.06	0.07	0.07	0.08	0.07	0.07

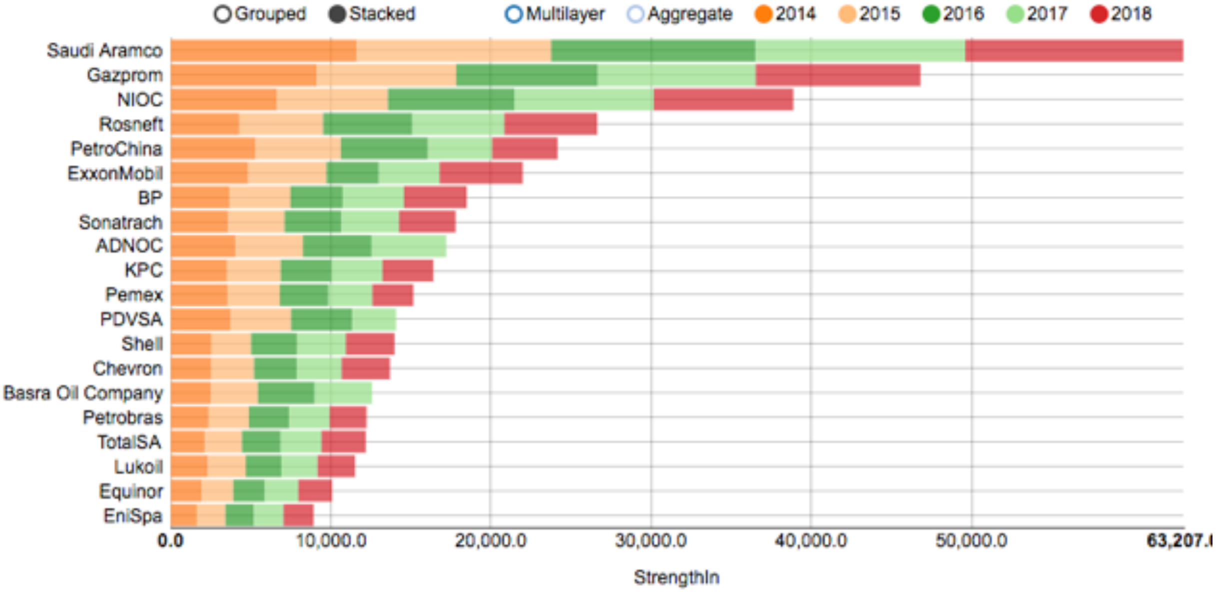
4.2.2.1.1 Total Hydrocarbons

Node strength

The special role of Saudi Arabia in the oil production network is evident in the quantity of total hydrocarbons going to Saudi Aramco, compared even to the next largest hydrocarbon producer, Gazprom (Figure 4-3a; StrengthIn). The National Iranian Oil Company (NIOC), Rosneft, and PetroChina round out the most extractivist five companies over the past years. Notably, Big Oil is absent from this group, with ExxonMobil and BP occupying the sixth and seventh places respectively, although in 2018 ExxonMobil outproduced PetroChina to be the fifth largest extractor that year (Figure 4-3a, red segments).

A different narrative emerges from the country perspective (StrengthOut); in this case the largest volume of total hydrocarbons flows from Russia to the world's largest oil and gas companies (Figure 4-3b), primarily to its hybrid state-private companies Gazprom and Rosneft (in the second and fourth spots respectively for total hydrocarbon extraction), as well as the IOC Lukoil. While the USA is the top extractor of hydrocarbons overall (BP Stats 2019), it occupies fifth place in terms of oil and gas extracted by the top 26 global producers, behind Saudi Arabia, Iran and China as well as Russia.

a) **Total Hydrocarbon Production: Strength In – To Companies (kboed)**



b) **Total Hydrocarbon Production: Strength Out - From Countries (kboed)**

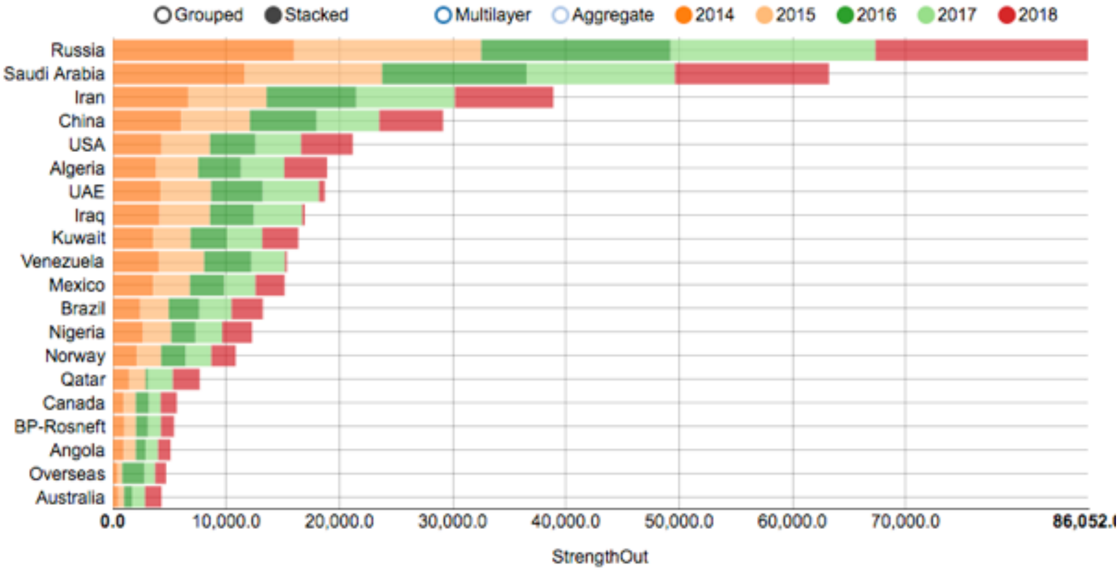


Figure 4-3. *Total Hydrocarbon Production, Network Node Strength: 2014-2018. a) Strength in: total flow of total hydrocarbons to all companies by country by year. b) Strength out: total flows from all countries to the Top 26 companies.*

Node Degree

While the volume of inputs and outputs highlights the importance of Russia, Saudi Arabia, China, and their respective NOC and hybrid companies, an examination of node degree highlights the central role of Big Oil in the global network. This metric represents the number of countries in which each company is actively extracting oil and gas (in-degree). Six of the seven big oil companies occupy the first six spots, in descending order: Total, Chevron, EniSpa, Shell, ExxonMobil and BP ranking first through sixth respectively (Figure 4-4a). Conversely, the number of companies extracting oil and gas from each country is represented by the node out-degree. A different picture emerges here: Canada has the largest number of Top 26 companies extracting oil and gas within its boundaries, followed by the USA and the UK, and then Russia, China, Venezuela, Norway, Nigeria and Iraq (Figure 4-4b).

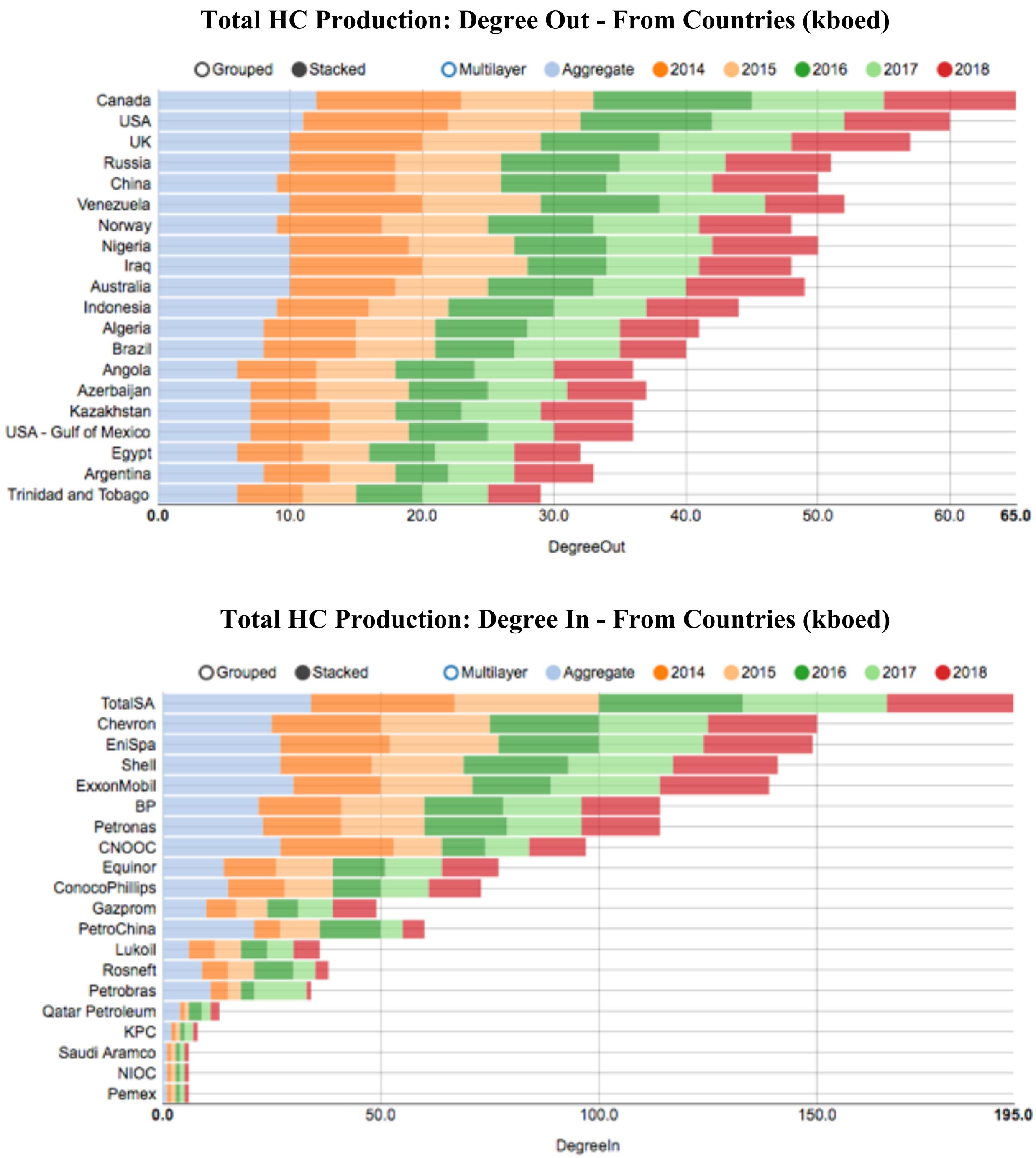


Figure 4-4. *Total Hydrocarbons, Network Degree: 2014-2018: a) Degree in: number of countries in which each firm is extracting oil and gas; b) Degree out: number of firms extracting oil and gas from each country.*

4.2.2.1.2 Crude Oil and Other Liquids

The crucial Saudi role in oil production is further illustrated by the amount of crude oil and other liquids originating from Saudi Arabia (Figure 4-5b) going to its national oil company, Saudi Aramco (Figure 4-5a); this quantity is more than double that of the next largest oil producer, NIOC in Iran. Rosneft sits just behind NIOC, with Kuwait Petroleum Company and PetroChina nearly tied for fourth and fifth, with Big Oil appearing in the form of ExxonMobil in sixth place, followed by Iraq's Basra Oil Company and BP. From the country perspective, Russia is in second place behind Saudi Arabia for oil extraction, followed by Iran, Iraq[*], China, Kuwait, the United Arab Emirates, highlighting the pivotal role of the Middle East in global oil production and the prominence of Russia and China in the network. This group is followed by the Western Hemisphere producers, with the USA ranking eighth, followed by Brazil, Venezuela and Mexico.

a) Liquids Production: Strength In - To Companies (kboed)

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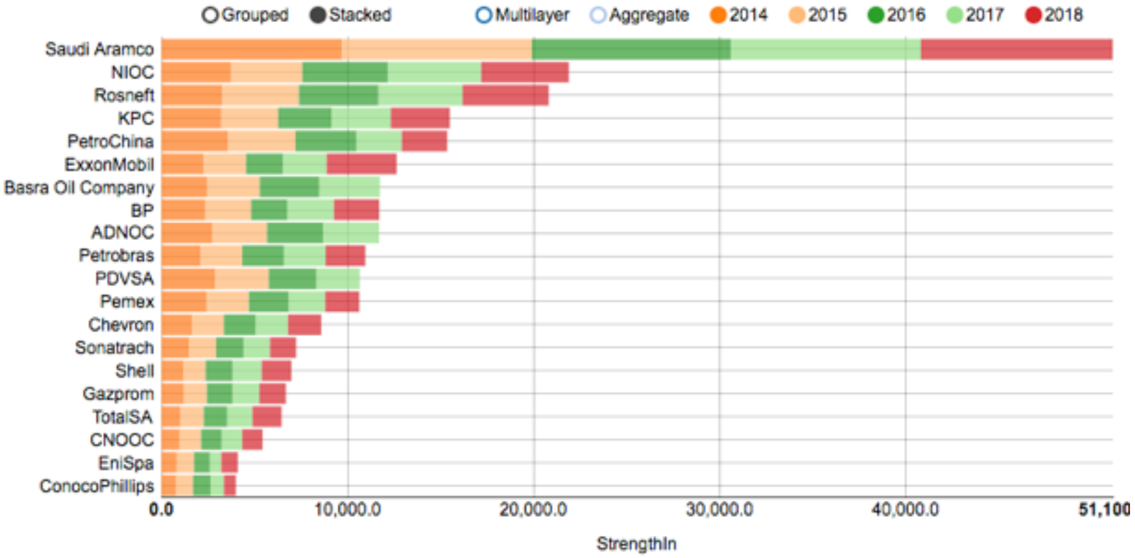
[*] 2018 data not available.



Liquids Production: Strength Out - From Countries (kboed)

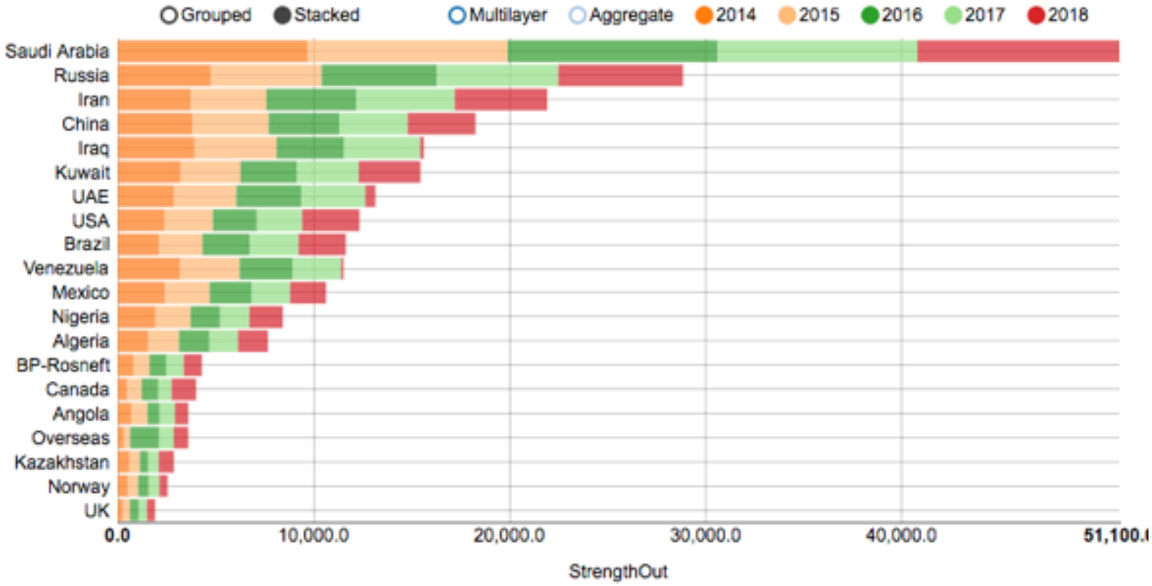
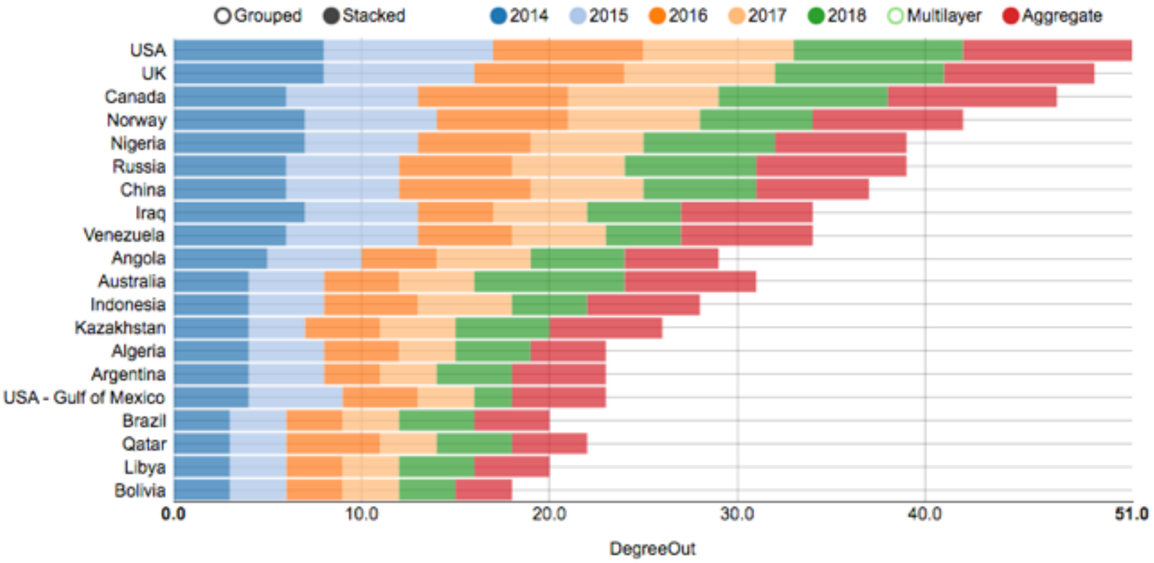


Figure 4-5. *Liquids, Node Strength: 2014-2018. a) Strength in: total flow of crude oil and other liquids to each company from all countries listed in the dataset by year. b) Strength out: total flows from each country to the Top 26 companies.*

The seven Big Oil companies occupy the first seven places in the ranking of in-degree for liquids, followed by the hybrid state-investor companies Gazprom, PetroChina and

CNOOC, again illustrating the expanding role in worldwide extraction of Russia and China (Figure 4-6a). In terms of node out-degree, the USA ranks first with respect to the number of companies in the top 26 extracting oil within its boundaries. Much of the activity in the USA occurs in the Gulf of Mexico (also shown separately to indicate how many companies are present in this region alone). The USA is followed by the UK and Canada, which also do not have national oil companies (Figure 4-6b). This group is followed by Norway, Nigeria, Russia, China, Iraq, and Venezuela, all of which do have either NOCs or Hybrids, and some degree of foreign involvement in oil extraction, in the latter two instances marked by recent violence.

Liquids Production: Degree Out- From Countries (kbd)



Liquids Production: Degree In - To Companies (kbd)

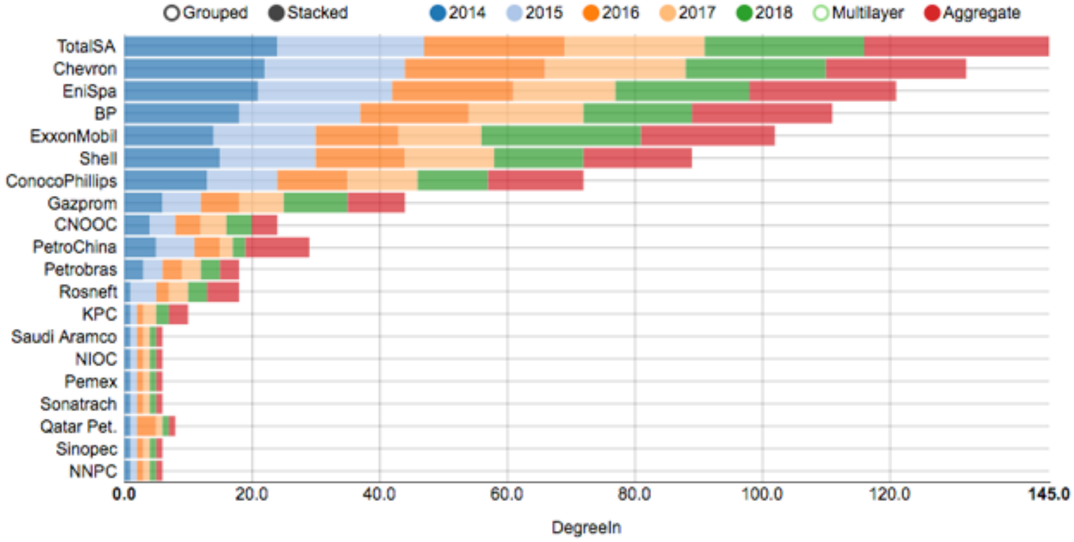


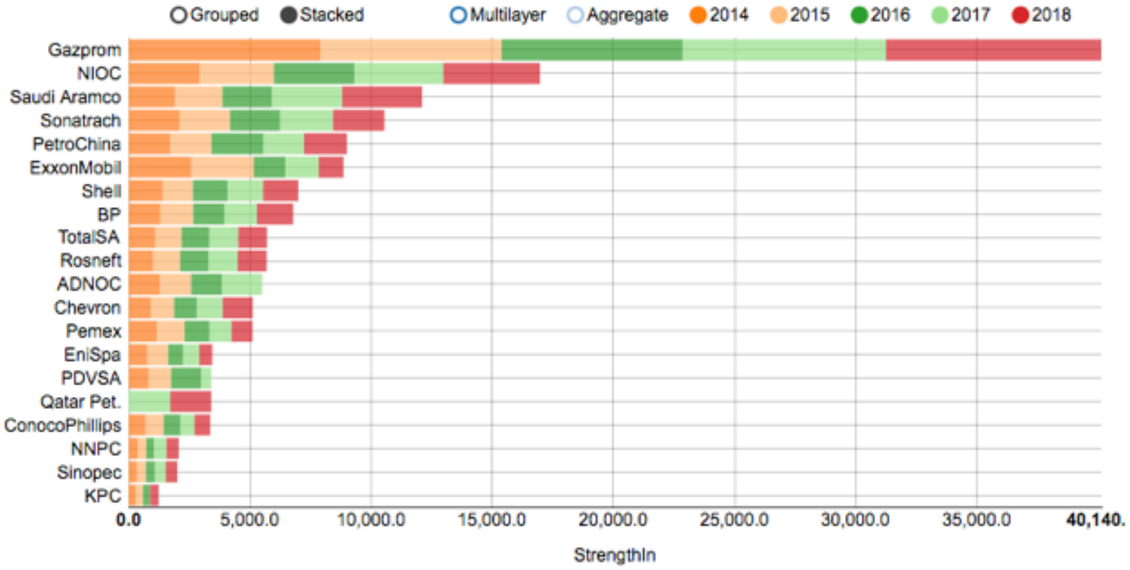
Figure 4-6. *Liquids, Node Degree: 2014-2018. a) Degree in: number of countries in which each firm is extracting crude oil and other liquids; b) Degree out: number of firms extracting crude oil and other liquids from each country.*

4.2.2.1.3 Natural Gas

Gas production among the top 26 companies is dominated by Gazprom, followed by NIOC, Saudi Aramco, Algeria's Sonatrach, and PetroChina, nearly tied with ExxonMobil, and Shell, BP, TotalSA and Rosneft rounding out the top ten (Figure 4-7a). The difficulty in accessing accurate data is illustrated by Qatar Petroleum's position, however, which would also be in the top group if accurate data were available for 2014-2016. In 2018 Gazprom accounted for 12% of the world's natural gas production (falling to 11% in 2016 from 12% in 2014) and holds 16% of the world's reserves and 71% of the reserves in Russia[13].

Russia dominates natural gas production by country, more than double that of Iran (second), while the USA ranks sixth (Figure 4-7b), even though the Russian Federation produced 64.74 bcf and the USA produced 89.1 bcf in 2018 (BP Stats 2019). This discrepancy can be explained in terms of how much of each country’s gas is going to the major producers: whereas ExxonMobil produced 2.78 bcf in the USA per day in 2018, in the same year Gazprom produced 48.24 bcf per day in Russia. An examination of the unweighted node out-degree shows a different picture than node strength: here the USA and UK are tied for the top spot, followed by China, Australia, Canada, Norway, Nigeria, Indonesia, and then Russia (Figure 4-8b).

Natural Gas Production: Strength In - From Countries (kboed)



Natural Gas Production: Strength Out - From Countries (kboed)

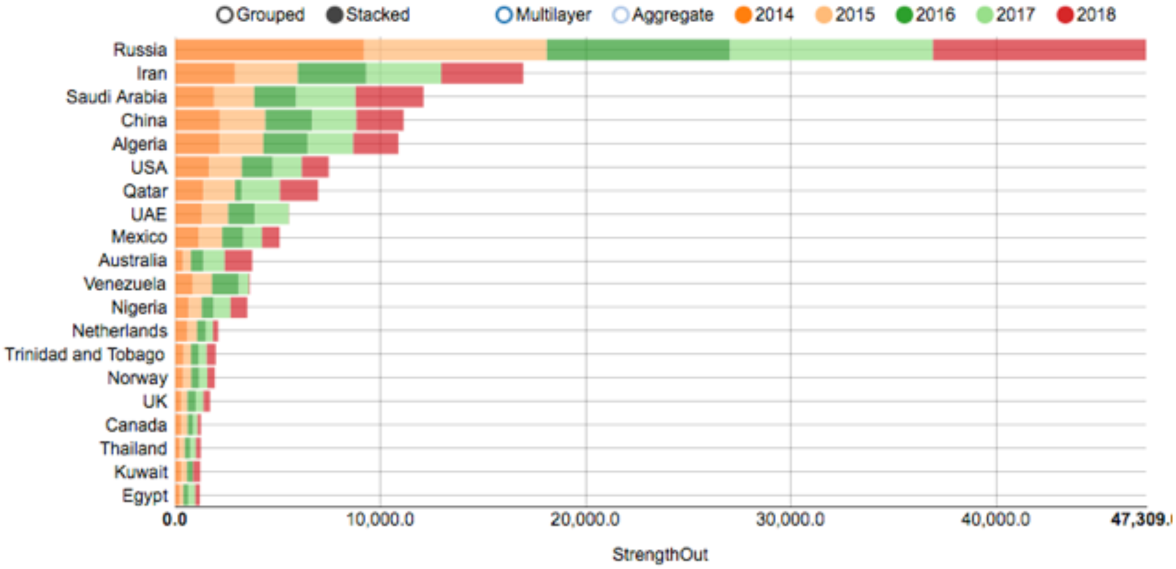
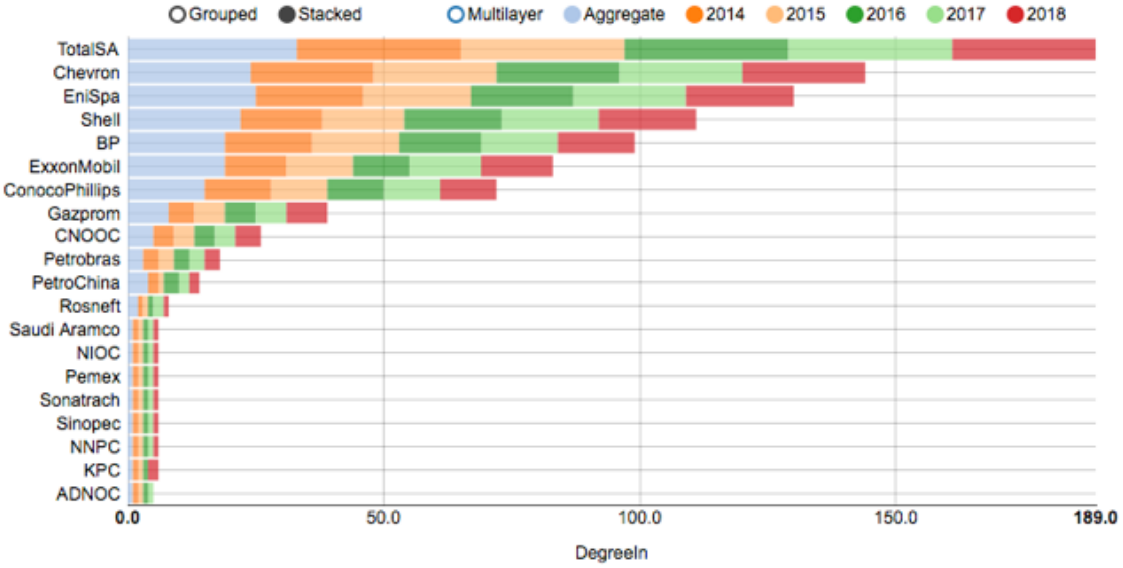


Figure 4-7. *Natural Gas, Network Strength: 2014-2018 a) Strength in: total flow of crude oil and other liquids to each company from all countries listed in dataset by year. b) Strength out: total flows from each country to the 26 companies included in this dataset.*

Natural Gas Production: Degree In - To Companies (kbd)



Natural Gas Production: Degree Out - From Countries (kbd)

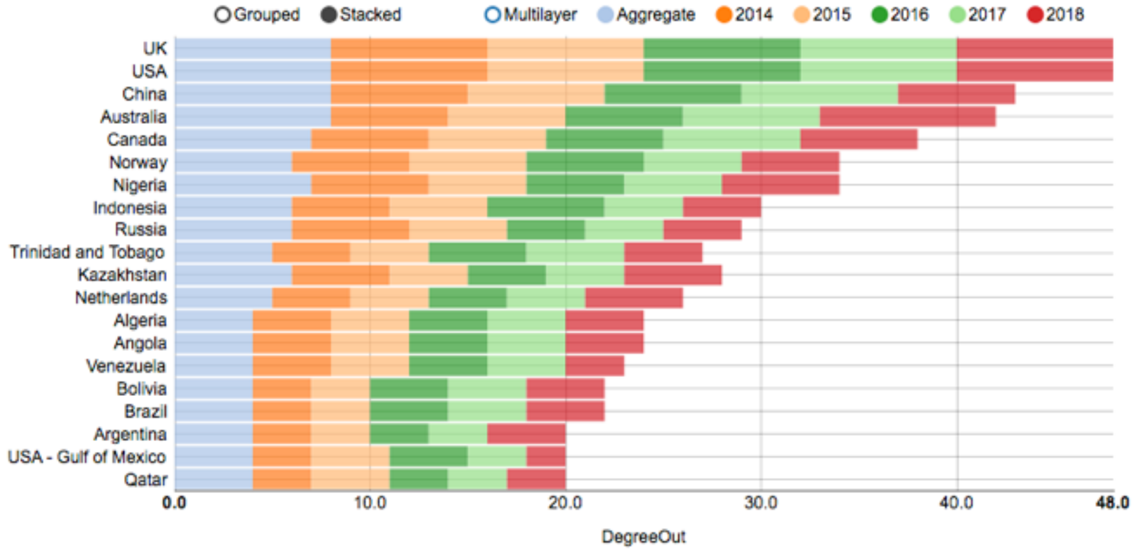


Figure 4-8. Natural Gas, Node Degree: 2014-2018. *a) Degree in: number of countries in which each firm is extracting crude oil and other liquids; b) Degree out: number of firms extracting crude oil and other liquids from each country.*

4.2.2.2 Correlation

This section examines interlayer correlation for two separate networks: a multiplex network, with each company type represented by a separate layer, and a multilayer network in which each year from 2014-2018 is a separate layer.

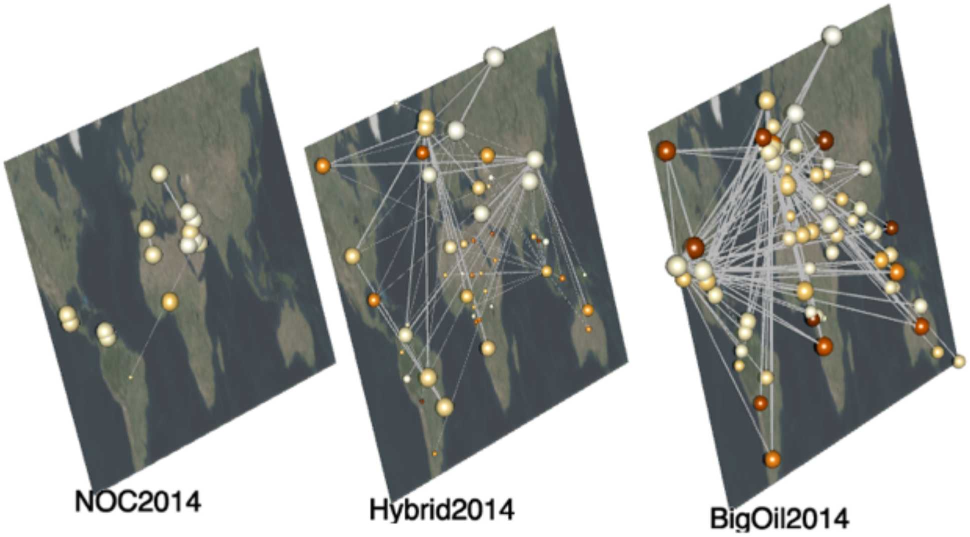
4.2.2.2.1 Correlation by Company Type

The interlayer Spearman correlation measures the assortativity of multiplex networks: while positive correlations indicate that nodes that are highly active in one layer are also highly active in a corresponding layer, negative correlations indicate that nodes that are highly active in one layer have lower activity in another layer. Because *companies* are exclusive to particular layers (ExxonMobil, for example, only appears in the IOC/BigOil layer), this metric indicates the likelihood of *countries* in which either IOCs, NOCs, or

Hybrids are active for companies from another category to be active in those countries as well. Countries in which NOCs are extracting oil are slightly disassortative with Hybrid companies, and more disassortative with IOCs; by contrast hybrid and IOCs tend to be active in the same countries. Moreover, both these trends have become more pronounced since 2014: NOCs are becoming slightly more disassortative (indicated by increasingly negative correlations) with Hybrid and IOCs, Hybrids and IOCS are becoming more assortative (indicated by increasingly positive correlations; Table 4-3).

Table 4-3. *Interlayer Spearman correlation.*

Metric	Network	NOC-Hybrid	NOC-BigOil	Hybrid-IOC
Spearman Correlation	Tot HC: 2018	-0.226	-0.237	0.290
	Tot HC: 2014	-0.177	-0.228	0.176
Spearman Correlation	Liquids: 2018	-0.195	-0.15	0.148
	Liquids: 2014	-0.145	-0.166	0.123
Spearman Correlation	Natural Gas: 2018	-0.188	-0.208	0.092
	Natural Gas: 2014	-0.186	-0.220	0.049



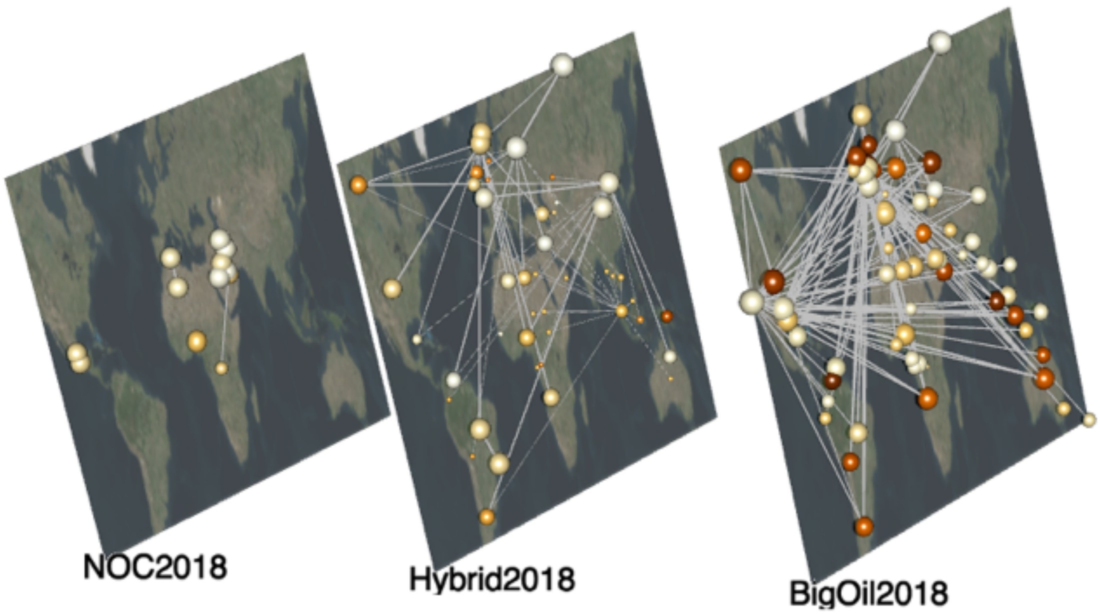


Figure 4-9. *Total hydrocarbon extraction represented as a multiplex network, shown in 2014 (top) and 2018 (bottom).*

4.2.2.2.2 Correlation by year

The year 2016 was pivotal, as most of the top 26 oil and gas companies reported major financial losses following a drop in oil prices beginning in 2015 and pro-fossil fuel Republican candidate Donald Trump emerged as the US president-elect. The inter-layer Pearson correlation (Figure 1-10) measures the extent to which layers having the same nodes are similar to each other and can be applied to the multi-layer network in which each year from 2014 to 2018 is represented as a separate layer (Figure 1-11). Here 2016 stands out as different from the other years, with the years 2017 and 2018 looking more like 2014, signifying a roll-back or return to the level of activity and relationships prior to 2015 and 2016.

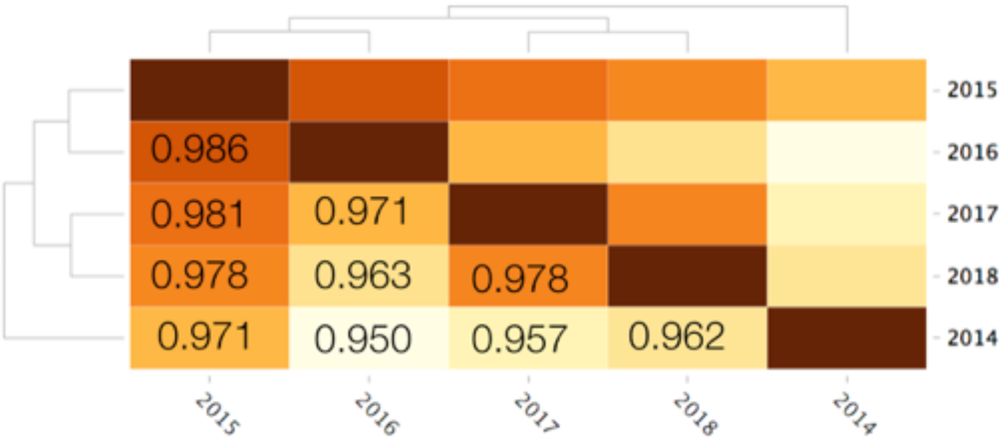
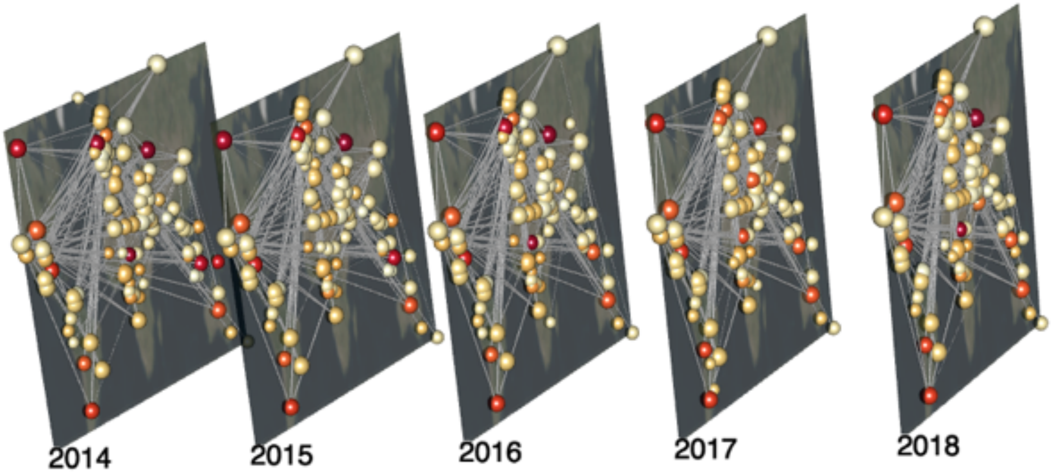
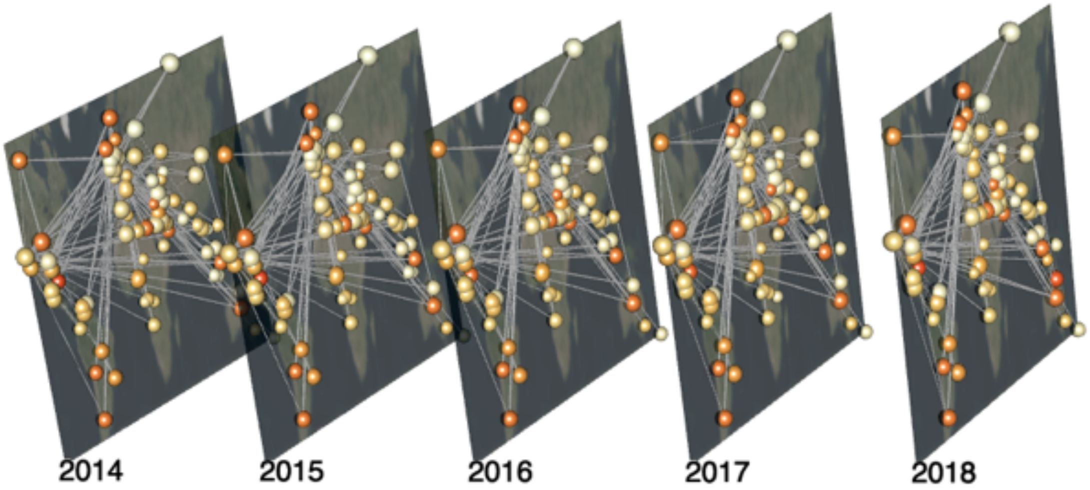


Figure 4-10. *Interlayer Pearson correlation for time series multi-layer network for total hydrocarbons.*

a) Total Hydrocarbons



b) Natural Gas



c) Liquids

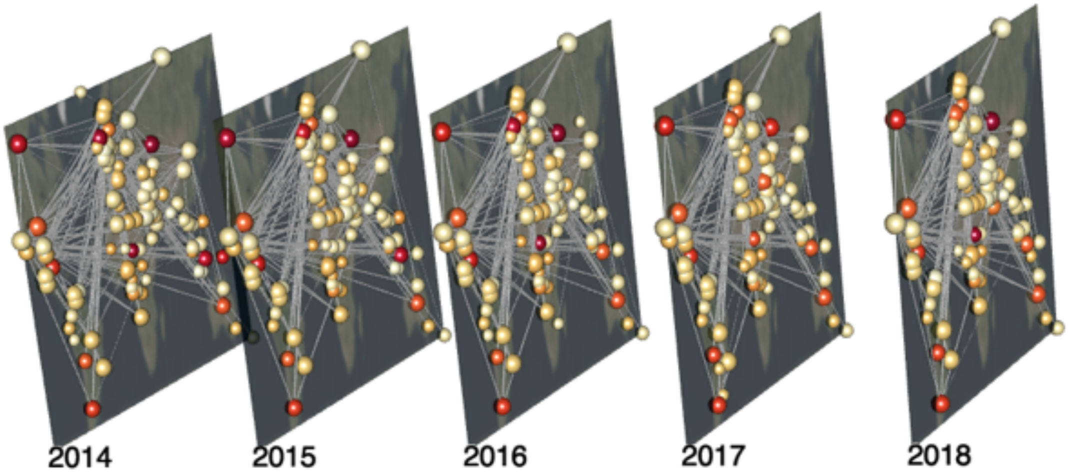


Figure 4-11. *The multi-layer networks for total hydrocarbons, natural gas, and liquids, depicting each year as a separate layer.*

4.2.2.3 Clusters/Community Detection

Community detection using the Louvain method to determine modularity shows clusters (groups of producers operating in the same countries/groups of countries with the same companies) within networks for oil, gas, and total hydrocarbons As expected, the level of modularity is lowest for total hydrocarbons (0.066) because it aggregates oil and gas extraction, which are concentrated in different regions. This contrasts with the somewhat higher modularity of oil (0.104) and much higher modularity of gas (0.269) networks. In 2017, BP, Rosneft, Gazprom, Lukoil, Venezuela's PDVSA, and Basra Oil Company can be seen to form a cluster, as do Chevron, Sinopec and PetroChina, as well as Shell, Exxon, and Nigeria's NNPC (Figure 1-13). In the gas network (with all years represented), other clusters emerge, including ExxonMobil, ConocoPhillips, Petrobras and Qatar Petroleum, as well as another including Gazprom, TotalSA, ADNOC and Basra Oil Company (Figure 1-14a). The latter group, joined by PDVSA, also forms a cluster in the oil network, as do Shell, ExxonMobil, Petrobras and NNPC (Figure 1-14b).

Further structure is evident in the clusters within NOC, Hybrid and BigOil taken as separate networks. Each NOC (Figure 1-15a) constitutes its own community, reinforcing the picture of NOCs acting independently with respect to extraction. Since all the NOCs are also OPEC members (except Petronas, which is depicted in the Hybrid group), their seeming isolation is countered by the community formed by OPEC to address production targets, benchmarks and oil price influencing in international markets. In the hybrid network, three clusters of two companies each emerge (Figure 1-15b): 1) Lukoil and Gazprom, 2) PetroChina and Sinopec, and 3) Petrobras and Equinor. While the first two can be seen to reflect ownership by their respective states Russia and China, the third indicates similarities between Petrobras and Equinor, both having major offshore and deepwater resources in their respective home countries (Brazil and Norway), as well as a presence in the Gulf of Mexico and offshore Nigeria, but while Equinor is present in Brazil, Brazil is not in Norway.

While Big Oil companies are active in many of the same countries, they can also be seen to specialize in specific regions. In the gas network there are two clusters: 1) ExxonMobil and ConocoPhillips form a cluster (both operating in Canada, Norway, Indonesia, Russia, UK, USA, Qatar, Libya, Malaysia, and Timor-Leste) and 2) TotalSA and BP (both operating in Algeria, Angola, Argentina, Azerbaijan, Bolivia, Oman, Trinidad and Tobago, Gabon, Yemen, Italy and France). In the oil network TotalSA and Shell (both operating in Norway, Oman, Brazil, Denmark, Gabon, and Brunei) form the only cluster. [Note: all these companies operate in other regions, but these are identified as clusters with more links among them than to nodes outside their cluster.]

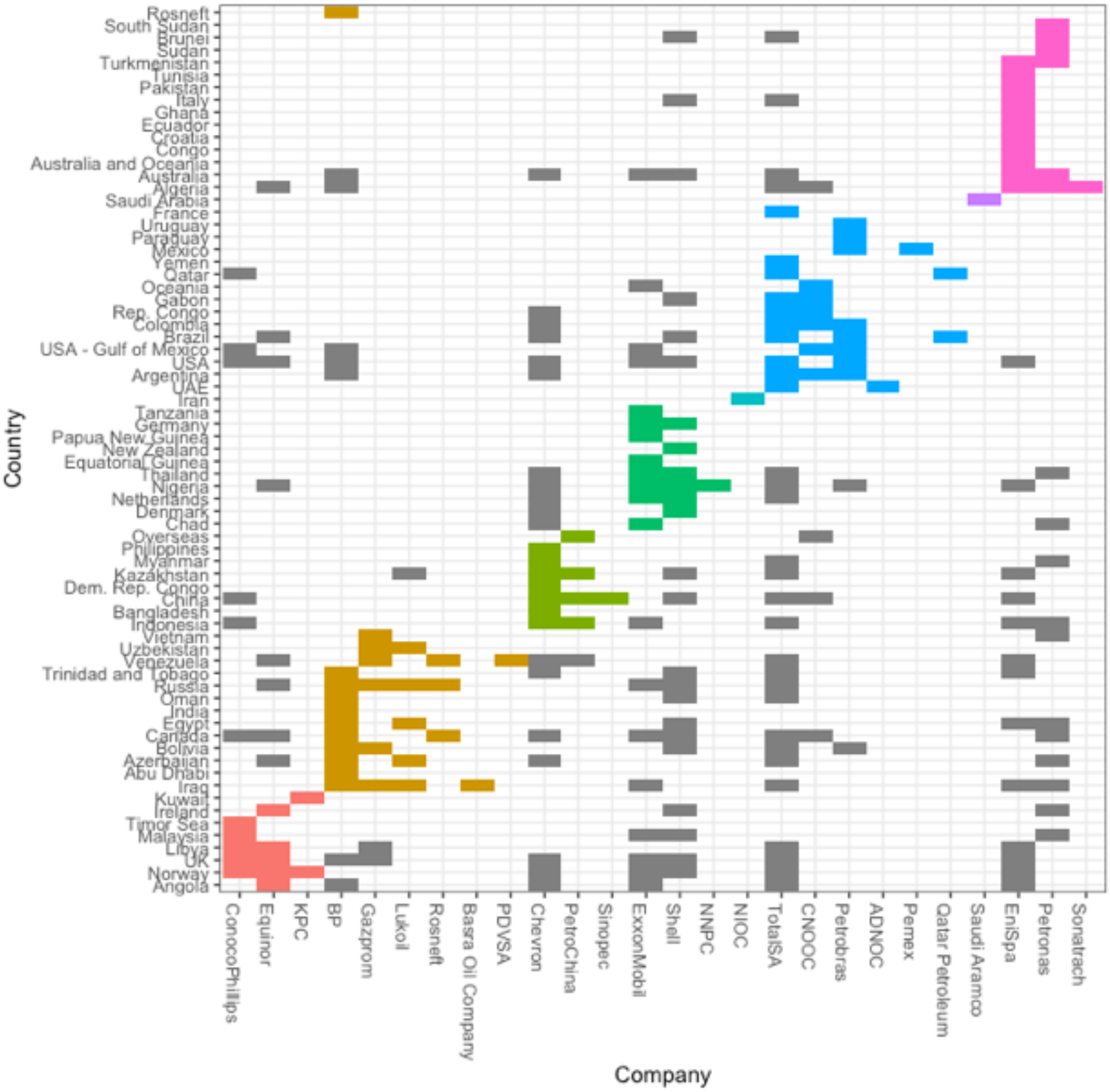


Figure 4-12. *Communities in the total hydrocarbons network in 2017 for all 26 companies. BP's 20% equity holding in Rosneft is represented separately, with Rosneft appearing in the country category to signify this relationship.*

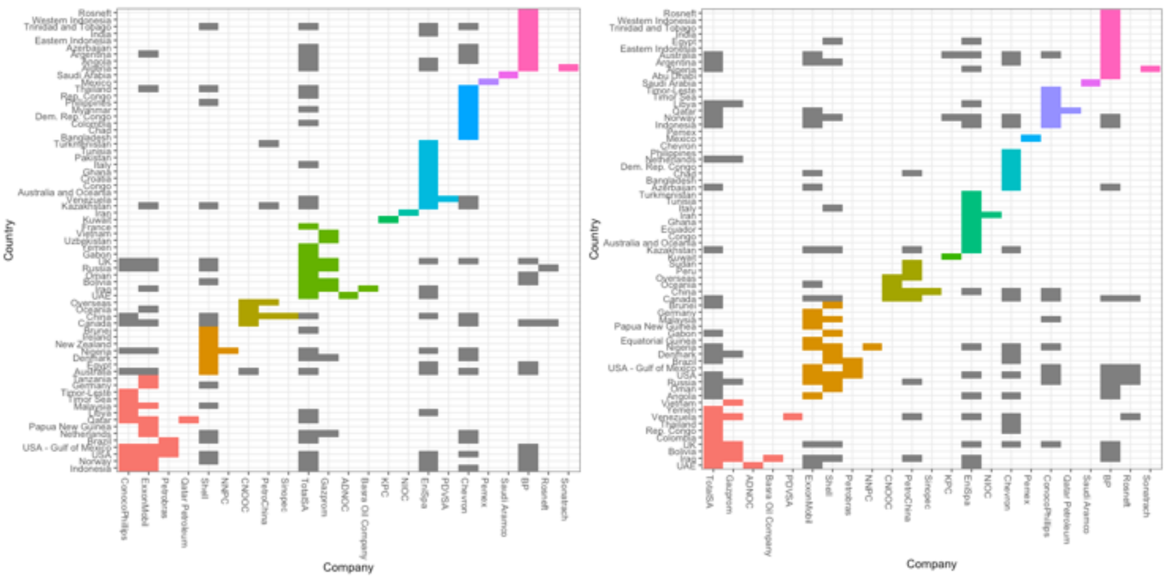


Figure 4-13. *Gas (a-left) and liquids (b-right) for all companies across 2014-2018. The gas network displays more modularity (0.269) than the liquids network (0.104).*

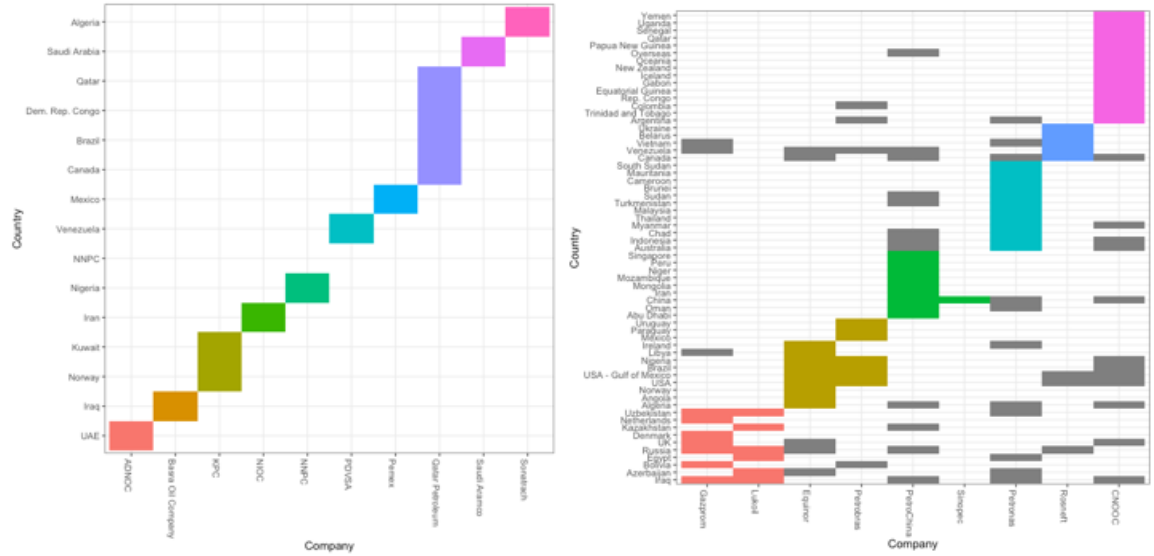


Figure 4-14. *Communities for NOCs (excluding Petronas, a-left) and Hybrids + Petronas (b-right) production for total hydrocarbons.*

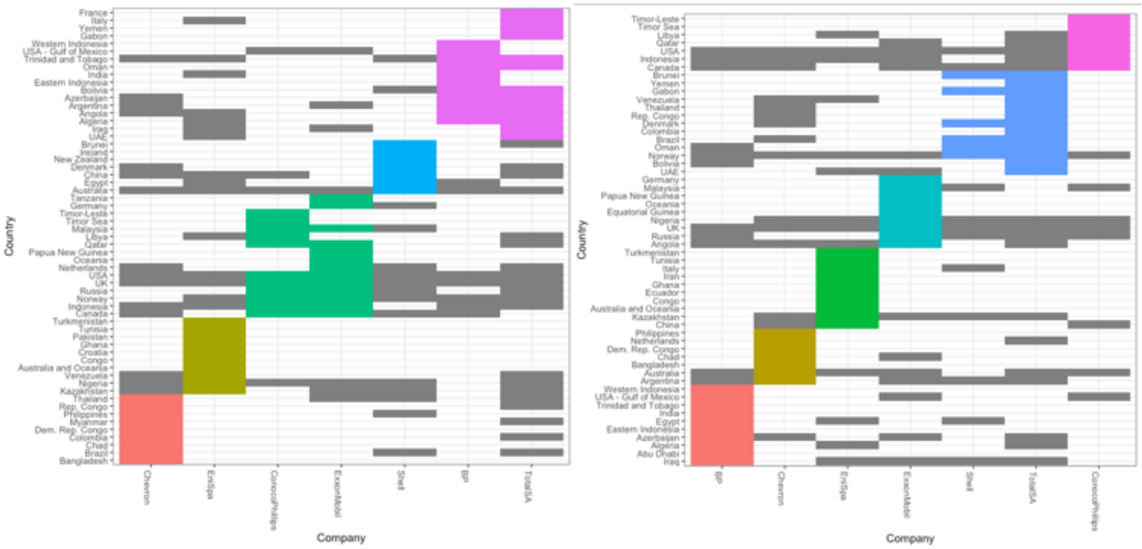


Figure 4-15. *Communities for gas (a-left) and liquids b-(right) production of Big Oil.*

4.2.3 Equity Holdings and Joint Ventures

Joint ventures and equity holdings are widespread throughout the industry, but inconsistently documented in annual reporting and other publicly available data sources. Even with reporting gaps, however, 1180 of some 2050 records at the subnational level in this dataset indicate some type of joint ownership with other companies, most commonly in the form of joint ventures through equity holdings. Equinor and ConocoPhillips were the only companies not only to consistently list their equity holdings subnationally at the oilfield level, but also to specify which companies operated them, making it possible to partially map the joint ventures using an ego network (the view of the network from the perspective of single node).

4.2.3.1 Norway / Equinor

In 2014, Equinor's equity holdings in 32 partner-operated locations (primarily abroad) ranged from 0 to 60%, with an average of 22%. Equinor's 19-odd partners who were oilfield operators in 2014 include all seven Big Oil companies, NOCs PDVSA and Sonatrach, as well as major US companies Anadarko and Chesapeake Energy (Figure 1-17a). The company's equity holdings in the 41 locations in which it was the operator (39 in the North and Norwegian Seas, one in Canada and one in Brazil) ranged from 0 to 85%, with an average of 44%; its non-operating partners holding the rest of the equity in these ventures were not listed in the company's annual reports.

In 2018 the number of Equinor's partner-operated locations increased by 25% from 32 to 40, including two wholly-owned subsidiaries, one in Brazil and one the USA; equity shares ranged from 0 to 100%, with an average of 27%, illustrating that oil and gas-field operators are often minority shareholders in specific ventures. Equinor's 25-odd partners who were operators in 2018 included five of the seven Big Oil companies, Sonatrach and Anadarko; new to the list were Sinopec and Petrobras, with Venezuela's PDVSA and Chesapeake Energy no longer appearing (Figure 1-17b). Equinor's equity holding in the 36 locations in which it was the operator ranged from 13.04% to 70%, with an average of 45%. Notably absent from these lists however, are the *other* non-operating equity holders in which either Equinor or another company was the operator, making it very difficult to map the complete ownership network among oil and gas companies.


ConocoPhillips-Norway
ExxonMobil-Angola
Chevron-Nigeria
Suncor-Canada
Eni Norge AS-Norway
Equinor/others-USA
GDFSuez-Norway
Talisman/Statoil-USA
BP Norge AS-Norway
TotalSA-Angola
Chevron-USA
Sonangol P&P-Angola
PDVSA-Venezuela
Equinor
BP-Azerbaijan
ExxonMobil-Norway
TotalSA-Libya
Repsol-Libya
Shell-Norway
Sonatrach/BP/Statoil-Algeria
BP-Angola
Anadarko-USA
Marathon Oil-Norway
HMDC-Canada
ConocoPhillips-UK
Chevron-UK
TotalSA-Russia
Chesapeake/Statoil-USA

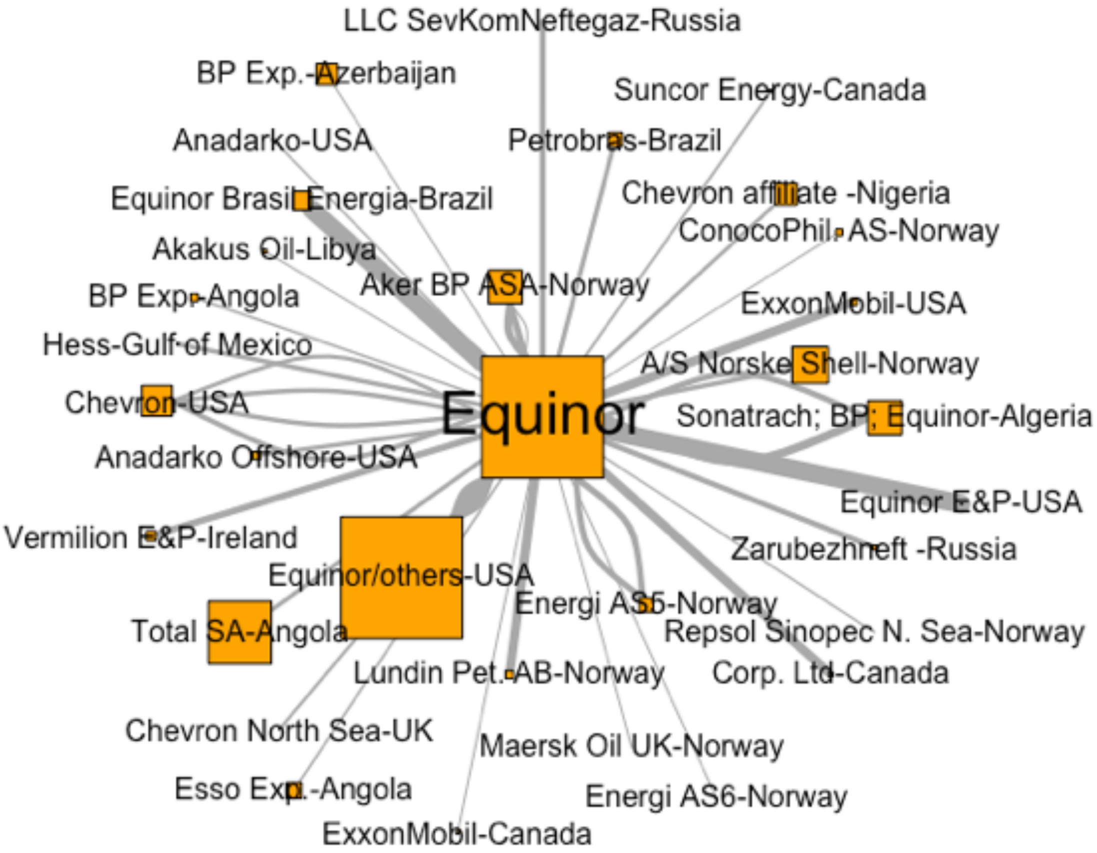


Figure 4-16. *Equinor's equity holdings in partner-operated fields in 2014 (top) and 2018 (bottom). Nodes sized by volume, edges weighted by percent equity, ranging from 0 to 60% in 2014 and 0 to 100% in 2018. Multiple edges between Equinor and a specific node indicates multiple locations in that country with that operating partner.*

4.2.3.2 Nigeria / NNPC

Nigeria's distribution of concessions by lease contract types offers another instructive example of state-firm relationships in the global network: 42% of concessions are Production Sharing Contracts (PSCs), with about forty companies holding production contracts/leases. Between 2014 and 2018 the production capacity of PSCs has steadily increased, averaging 3% growth, to account for about 35% of total production (NNPC 2018 AR, p 12-15). Another 34% of concessions were Joint Ventures (JV), 23% sole risk, and 1% service contracts (this breakdown remained roughly the same between 2014-2018). The top extractors of total hydrocarbons (measured in kboed) in 2018 in Nigeria were NNPC (1205), TotalSA (284), Shell (259), Chevron (241), ExxonMobil (221), EniSpa (100), CNOOC (59), and Equinor (43). The total amount (1256) going to these predominantly Big Oil companies was larger than the Nigerian state-owned NNPC share. In 2018 JV arrangements accounted for about 55% of aggregate production, while indigenous oil companies' production capacity accounted for 12.5% of aggregate production[14].

The top destinations for Nigerian crude oil (in million barrels per year) in 2018 were India (92), Spain (86), Netherlands (65), South Africa (50), France (47), USA (44), Philippines (34), UK (31), Sweden (26), Indonesia (23), Canada (22), Brazil (15). At the same time, over 80% of the petroleum products consumed in Nigeria is imported, while Nigeria's four state-owned refineries operate well below their capacity of 445,000 barrels per day. The pump prices of gasoline products (excluding diesel) are subsidized by the government, monies that "could have been used to provide infrastructure or provide better quality education or health facilities" (2019: 12)[14]. Nigeria's Dept of Petroleum resources notes a deficit of 2.6 million barrels per day between demand and supply of petroleum products in Africa in 2018 and that more could be done to realize the government's aspiration of making Nigeria a refining hub in Africa[14].

4.3. Discussion

These results illustrate the scope and complexity of current global oil and gas operations, providing a window into their historical roots and the continuing influence of this history on the network's organization, interdependence, and disparity, even as the entire production system continues to experience rapid changes. In this section we supplement the findings above with further evidence of the degree to which IOCs, NOCs, and Hybrid companies have variously joined forces in the face of existential threats to the industry, before highlighting key elements of the above analysis as they relate to ongoing efforts to achieve effective international oversight of the oil and gas industry.

4.3.1 Rivalrous collaboration and strategic cooperation

Several ownership structures indicate not only the increasing interdependence among these companies but also active joining of forces through 'rivalrous collaborations' and shifting alliances, which can be difficult to discern solely through an analysis of the countries in which they operate. Another defining characteristic of the current system is a lack of transparency and accountability: In 2013 BP was identified to have 1180 affiliated companies and subsidiaries, with up to 12 levels of ownership[15]. Types of ownership structures include not only joint ventures through various subsidiaries and equity holdings (as were mapped for Equinor in the preceding section) but also operating and service contracts and strategic cooperation agreements[10]. BP's 2014 Annual Report outlines this multi-pronged approach to applied to exploration: "The group explores for oil and natural gas under a wide range of licensing, joint arrangement and other contractual agreements. We may do this alone or, more frequently, with partners" (2015: 26)[16].

In 2015 BP announced the formation of "a new ownership and operating model" with Chevron and ConocoPhillips designed to move two significant BP deepwater discoveries in the Gulf of Mexico closer to development and provide expanded exploration access. The plans, which also involve Petrobras, shed light on the degree to which the oil majors have merged operations:

> BP sold approximately half of its current equity interests in the Gila field to Chevron in December and sold approximately half of its equity interest in the Tiber field in January 2015. BP, Chevron and ConocoPhillips also have agreed to joint ownership interests in exploration blocks east of Gila known as Gibson, where they plan to drill in 2015. As a result of the agreements, BP, Chevron and ConocoPhillips will have the same working interests across Gila and Gibson and any future centralized production facility. Chevron will hold equity interest of 36%, BP 34% and ConocoPhillips 30%. In Tiber, BP and Chevron will each hold equity interest of 31%, Petrobras 20% and ConocoPhillips 18%. Chevron will operate Tiber, Gila and Gibson. Operatorship is expected to be transferred after BP finishes drilling appraisal wells at Gila and Tiber. BP believes combining the technical strengths and financial resources of these three companies will provide greater efficiency through scale, reduce subsurface risk and increase the likelihood of achieving a future commercial development (2015:213)[16].

The relationship between Big Oil companies BP and ExxonMobil and Russia's Rosneft within the rapidly-shifting wider geopolitical context has been well-documented[2]. BP owns 20% of Rosneft[17], which until 2020 was majority-owned by the Russian government, whose stake dropped at that point from just over 50% to 40%, as part of a deal by which Russia acquired Rosneft's Venezuelan assets (including the U.S based Citgo chain). Analysts speculated the move was to limit potential US sanctions on Rosneft at a time when the US and Saudi Arabia were considering cutting production and did not want Russia to increase output[18]. ExxonMobil and Rosneft signed a Strategic Cooperation Agreement in 2011 for joint exploration and production in the Kara Sea, Black Sea, and West Siberia, with additional joint venture agreements in 2014 for additional blocks in the Russian Arctic across the Kara; Laptev; and Chukchi Seas (ExxonMobil interest: 33 percent), covering an area of more than 150 million gross acres. In its 2014 annual report ExxonMobil noted that "currently, certain exploration activities in Russia are precluded under applicable U.S. and European sanctions" (2015: 44)[19]. ExxonMobil and Rosneft also have a joint cooperative agreement for exploration offshore of Mozambique.

In addition to production sharing agreements (PSAs) with countries in which IOCs operate, cooperative agreements are a primary example of the merging of interests among various IOC, and Hybrid companies extracting oil and gas abroad. China's Belt and Road Initiative has driven efforts by PetroChina to deepen and broaden its ongoing international oil and gas cooperation through a variety of cooperation agreements and memorandums with the governments of Russia, Venezuela, Peru, Mozambique, Algeria, etc. and their energy companies. CNPC and Gazprom signed an MOU to promote cooperation in underground gas storage and gas power generation projects in China and seek a wider range of joint venture and cooperation opportunities" (2016: 30-31)[20]. In Qatar, the Qatargas consortium includes Qatar Petroleum, TotalSA, ExxonMobil, ConocoPhillips, Shell and other partners. RasGas is 70% owned by QP and 30% owned by ExxonMobil[21].

Many other joint ownership arrangements exist among the major global producers: in 2018 it was announced that the oil producing country of Qatar (a British protectorate from the early1900s until 1971, with a current population of 2.8 million) acquired a 19% stake in Rosneft, although details were murky, and ConocoPhillips owned 20% share of Russian IOC Lukoil until 2010. In 2016 Rosneft acquired a 49% stake in Essar Oil, the second largest private oil company in India, while Netherlands-based Trafigura Group Pte and Russian investment fund United Capital split another 49% equally[22].

4.3.2 Implications for Governance

The well-known resource curse theory holds that countries depending upon petroleum resources for a large part of their earnings from exports tend to be less democratic, and the less oil a country produces, and the faster its production is declining, "the more readily the struggles for democracy unfold" (2013:1)[9]. In response to this simple formulation, "which largely assumes land and resource access rights have been settled and which focuses on political conflicts arising from the allocation of revenues rather than the wresting of land and resources," the GPN approach focuses on inter-firm and firm-state relationships and addresses "the ways in which inter-firm competition structures the organization and geographies of the production network," creating space to address how the structure of the global oil production network affects the ability of resource-holding states to (re)negotiate ground rent" (2008: 406)[8].

At this point in time, given the interconnectedness, global reach, and combined power of the major private, hybrid, and state oil and gas producers, effective international governance is essential to achieve a just transition. Within this context, the following observations can be made with respect to the network metrics of centrality, correlation, and community detection presented in Section 4.3:

Centrality: Saudi Arabia, by virtue of its sheer supply (node strength) and modest domestic demand, has the ability to dominate global supply. Although output of the Big Oil/ IOCs is smaller than the top six state-owned and hybrid companies, the IOCs extract hydrocarbons from more countries than any other type of producer (node degree), an arrangement that may be seen as a direct legacy of centuries of colonial rule that in some parts of the world did not end until the 1970s.

Correlation: By and large hybrid and IOCs are increasingly extracting oil and gas from the same countries (Spearman correlation), which are not countries in which NOCs are active (with the exception of Iraq, which has seen multiple Big Oil and Hybrid companies step in since the Iraq War). This statistic can be explained not only by partnerships among IOCs and Hybrid companies but also by ongoing US efforts to drive Iranian oil and gas exports to zero and recent unrest in Venezuela.

Community Detection: There is a modest degree of modularity in the oil and gas production networks, illustrating the inter-group alliances among IOC, Hybrid and NOC companies that indicates focused activities in particular regions and shows some movement from year to year: In 2017 BP, Rosneft, Gazprom, Lukoil, Venezuela's

PDVSA, and Basra Oil Company formed a cluster, as did Chevron, Sinopec and PetroChina, as well as Shell, Exxon, and Nigeria's NNPC.

Moreover, an intricate global network of joint ventures, equity holdings and cooperative agreements effectively 'sits under' the more straightforward network of companies extracting oil and gas from specific locations within specific countries, about which there is very little comprehensive publicly available information. These relationships illustrate the increasing risks of extracting oil and gas from ever more remote locations, the merging of operations, and the combined motive for ensuring nation-states around the world allow their investments and operations to continue unimpeded.

Together these findings indicate:

- <u>The Hidden Cost of Obtaining 'Access to Rent':</u> The ongoing presence of Big Oil in resource-rich regions around the world, now predicated on "the negotiation of ground rent with resource-holding states," is both unsustainable and unjust, benefiting both from corrupt autocratic rulers willing to 'negotiate' and wars when resource-holding states do not wish to take part in such negotiations.
- <u>The Role of Big Oil</u>: Although the three Big Oil companies in the USA and four in Europe (UK, Holland, France, and Italy) are private entities, they play critical roles as producers and suppliers in their home countries, acting vehicles of state power and exerting hidden influence on political processes to maintain their position, particularly as efforts to transition away from them intensify. As has been shown they also have deep ties to other fossil producers around the world,

effectively forming a subterranean coalition with formidable influence in virtually every country in the world.

- Centralized Control and Price Fixing: Although the US and Russia produce more total hydrocarbons than Saudi Arabia, there is a stark difference in the contribution these countries make to the top 26 global producers of oil and gas. This has led to a complex interplay between OPEC and Russia (termed OPEC+), and US that is rapidly changing. It has been further noted that "despite Trump's longstanding disdain for OPEC, he has managed to make the United States its 'shadow member.' Washington's influence is a reversal from a decades-long vulnerability to OPEC's decisions" [23].
- Information spreading: Big Oil companies and companies with many extractors can also be seen as 'information spreaders' on network through which new extractive processes and technologies are circulated; the prevalence of co-ventures also serves this function.

A necessary precursor for effective governance of global carbon emission reductions is open, transparent data spanning the entire global production network for the entire life cycle of fossil fuels, from exploration to emissions, documenting not only in-country production and consumption, but crucially also the activities of the global oil and gas companies responsible for extracting these resources and influencing global prices. Although there have been many grassroots efforts to develop this kind of information, there are structural reasons why it does not already exist in usable form for the general public and is hard to develop.

4.3.2.1 Supply-side approach to carbon emissions

This network approach points to not only to the potential efficacy of globally coordinated supply-side management of carbon emissions, but arguably to its necessity, given the ability of the industry to derail transition efforts that do not directly address their fate in ways they either buy into or cannot effectively undermine. System-wide fossil fuel oversight could be linked to implementation of the Paris Agreement, and relatedly supply-side accountability for carbon emissions. Mirroring the taxonomy of policy instruments in the Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report*[24] for demand-side reduction, similar supply-side policies have been proposed, including taxes, removal of producer subsidies, trade allowances and credits, as well as regulatory approaches, government provision of goods and services[25]. Key questions remain, however, concerning international equity and fairness in the adoption of supply-side policies, as well as the conditions under which governments "might forgo extraction and associated economic rents, and how jurisdictions implementing supply-side policies might take 'credit' for their supply-side 'contributions', given that emission reductions may occur largely beyond their borders" (2015:16)[25]. Nationalization has been proposed as another option to manage the transition away from fossil fuels: the case has been recently made that, "as global oil demand craters and crude oil floods an already oversupplied market" during the COVID-19 crisis, the U.S. government "should assert long-term ownership and control over its fossil fuel companies" (2020: 1,6)[26]. Implications for the international context are uncertain, however, and it is unclear how a transition to public ownership in the U.S. would affect international production, international climate and trade agreements, and carbon leakage and accounting, as well as escape by multinationals abroad. It is also important to consider which countries' oil and gas companies currently do have a mandate to act in the public interest (or have had one and were undermined or ousted by private interests). As we have seen, global multinationals effectively wield and manipulate what can be seen as *de facto* state power across national boundaries.

4.4. Conclusion

Network analysis offers a useful set of tools to illuminate the interdependencies and strategic alliances among global oil and gas firms and nation-states around the world dependent on the extraction of these resources, and insights from such analysis can be used to inform effective global governance of the transition away from fossil fuels. As this study has shown, the oil and gas industry is driven by *competition* for access to resources and markets; *cooperation* in the form of joint ventures, equity holdings, production control, and price influencing; and, at this point in the unfolding energy transition, what may be characterized as *transnational industry-state collusion* to obstruct, stymie and delay this transition for as long as possible. We contend that system-wide analysis is necessary to support system-wide oversight and this oversight is an essential component of global transitions governance. The Global Production Network for Oil and Gas Dataset developed for this analysis represents one step in the ongoing effort to shed light on the activities of the global fossil fuel industry and the opaque relationships among oil and gas companies and nation-states around the world. In conjunction with traditional national-level energy data, ecoregions, agriculture, water scarcity and other spatial layers, this dataset can be used to assess transboundary social-ecological harms and embodied energy injustices traceable to complex multi-scalar and multi-system fossil fuel production processes.

4.5. Methods

4.5.1 Constructing the Global Oil and Gas Production Network Dataset

The dataset used in this analysis was constructed from publicly available sources, emphasizing the paucity of data concerning firm-level activities compared to national-level data on fossil fuel extraction. Annual reports and SEC filings provided the bulk of the data sources for hybrid and investor-owned companies and the NRGI dataset provided data for the majority of NOCs; gaps in the NRGI dataset were supplemented by other sources where available, such as the 2018 Pemex Statistical Yearbook. Given the much higher accuracy of proprietorial industry data sources than public sources, figures were validated where possible using data from Ryder Energy (U-Cube data) and Carbon Underground. Data was compiled using R, JMP and Python, with sources noted and links provided R in the ‘CreateRepository’ script. Network modeling was done in R using the igraph package. Multilayer network visualization and analysis was also undertaken in MuxViz, which runs on R and Octave.

Table 4-4. Data model for the Global Oil and Gas Production Network Dataset.

Process	Company	Country	Year	Location	Weight	Unit	Source	Notes	Joint Venture Status
Exploration									
Reserves									
Development									
Production									
Refining									
Sales									
Emissions									

4.5.2 Data limitations and uncertainties

Compilation of non-standardized data from widely disparate sources posed a number of challenges. Among these are:

- There is no single format for US SEC Form 20-F filings for foreign companies; they were sometimes collapsed into the same document as the annual report. Where they were separate, SEC filings and annual reports occasionally listed different amounts for production (such as EniSpa); in this case data from the more recent publication was used.
- Subnational location data was often scattered throughout 'operational highlights' narratives rather than in table form. Varying amounts of detail were provided for specific projects, countries or locations; actual volumes extracted were not always given and when they were, they were inconsistently separated into oil and gas or amalgamated. Similarly data for geographic locations variously reported details and quantities at the project, formation, play, state, regional, or basin level.

- Virtual all companies report only net, rather than gross, production totals, thereby not providing a clear picture of how much energy is consumed in the production process.
- There are numerous data gaps: many companies do not provide readily accessible data on the location of their operations within counties, and/or do not report quantities. Petronas, the state-owned Malaysian oil and gas company which conducts major exploration and production operations abroad, for example lists the countries in which it extracts oil and gas in its annual reports but does not provide quantities. PetroChina and CNOOC aggregate volumes extracted abroad under the category "Overseas."
- Data gaps in some cases are due to deliberate lack of transparency: in Europe, Asia, Africa, and South America, Shell lists an "Other" category comprised of "countries where 2018 production was lower than 7,300 thousand barrels or where specific disclosures are prohibited" (2018: 49) in Asia the total for Shell falling into this category in 2018 was 28,769 barrels[27].
- Geographic regions are aggregated and referred to differently (i.e. Australia and Oceania, Oceania, Middle East, Middle East and North Africa).
- Production from equity-accounted entities/subsidiaries is not handled consistently: some include equity holdings as part of total production, others list it separately (in a few cases it was not clear which was the case). Non-operating partners in co-ventures are generally not listed. BPs 20% equity holding of

Rosneft: In the Annual Report BP reports production by country for equity holdings of Rosneft as "Rosneft (Russia, Canada, Venezuela, Vietnam)"

- National Iranian Oil Company figures rely on the BP Statistical Review for the country of Iran, although Shell and CNOOC/PetroChina, Rosneft have listed operations and/or exploration of opportunities there, so these totals should be considered an approximation.

4.5.3 Network Metrics

The following well-known network properties were used to analyze these networks[28–30]:

a. *Average degree*: <*k*> the average number of links per node in the network, obtained by dividing the total number of links (m) in the network by the number of nodes *N*.

b. *Node strength, s*: The sum of weights attached to ties belonging to an individual node.

c. *Transitivity / clustering coefficient*: of the degree to which nodes in a graph tend to cluster together: Local clustering coefficient C_i for directed graphs,

$$C_i = \frac{|\{e_{jk}: v_j, v_k \in N_i, e_{jk} \in E\}|}{k_i(k_i - 1)}$$

where e_{jk} is the edge between vertices v_j and v_k for immediately connected vertices in neighborhood N_i with set of edges E in the full graph G with set of vertices V.

The global clustering coefficient for networks is:

$$C = \frac{3 \times number\ of\ triangles}{number\ of\ all\ triplets}$$

d. *Interlayer Assortativity coefficient, r:* (Pearson correlation coefficient): the extent to which network nodes are linked to nodes with similar properties (often measured in terms of degree). In directed graphs, in-assortativity and out-assortativity measure the likelihood of nodes to link to others with similar in- and out- degrees as they have. Assortitativity, r, ranges between -1 (fully disassortative), 0 (non assortative), and 1 (fully assortative)

$$r = \frac{\sum_{jk} jk(e_{jk} - q_j q_k)}{\sigma_q^2}$$

where q_k is the distribution of the remaining degree (that is, the number of edges leaving the node, excluding the edge that connects the current pair), e_{jk} is the joint probability distribution of the remaining degrees of the two vertices, and σ is a scaling term.

e. *Spearman Correlation,* $\rho_{\alpha\beta}$: the strength s_α of countries in one layer compared to their strength s_β in other layers

$$\rho_{\alpha\beta}(pq) = 1 - \frac{6\sum_{i=1}^{N}[r_\alpha^{(i)}(p) - r_\beta^{(i)}(q)]}{N(N^2 - 1)}$$

where *p; q* = ingoing, outgoing, or total strength, and $r_\alpha^{(i)}(p)$ is the rank of node *i* in layer α. Strong positive correlations indicate countries that are very active in one layer are also very active in another layer and, conversely, strong negative correlations indicate countries active in one layer are much less active in another layer [31].

f. *Multiplexity, g(v)*: is the shortest path among nodes in a connected graph such that the number of edges or the number of weights (for weighted graphs) is minimized for every pair of nodes. Betweenness centrality for each node is the number of shortest paths that pass through that node.

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} is the total number of shortest paths from vertex s to vertex t and $\sigma_{st}(v)$ is the number of such paths that intersect v.

g. *Modularity, Q:* is defined as a scalar value between -1 and 1 measuring the density of links inside communities compared to links between communities[28,32]. In the case of weighted networks it is defined as

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j)$$

Implemented in igraph and muxviz using the Louvain method for finding community structure by multi-level optimization of modularity[33].

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CHAPTER 5: CONCLUSION

The Food-Energy-Water (FEW) nexus framing of interdependencies among systems offers the promise of integrated, holistic thinking to guide transitions to just and sustainable FEW systems. At the same time, however, the nexus has been characterized as a ‘buzzword’ that merely recycles prior work, notably in integrated water resources management, and furthermore does little to address the historical roots and structural underpinnings of current global inequities in FEW systems. This dissertation has addressed such critiques through two case studies in which the nexus analysis has been used to focus on what might be termed the ‘collateral damage’ of current energy systems, focusing on extractive impacts of fossil fuels and hydropower on the regions in which the energy is sourced. Also undertaken in this dissertation was a focused look at the structure of the hydrocarbon underpinnings of this rapidly-shifting energy system at the global scale, using network analysis to focus on intra-industry and carbon-state relationships and explore its recent dynamics.

Chapter 2 illustrated the potential of the nexus approach to identify inter-connections between demand and supply networks through an integrated assessment of the FEW nexus in the Denver region, addressing embodied FEW as well as ecosystem impacts and risks at the municipal, country, and regional scales. The widening of the nexus to encompass *impacts* as well as *inputs* to FEW systems in the Denver region placed hydraulic fracturing firmly within the FEW nexus scope. Chapter 3 used the Landtrendr algorithm to quantify deforestation by type in Eeyou Ischee/Jamésie after the James Bay Project began in the 1970s, further extending the nexus to include materials and address the critical, often overlooked issues of embodied FEW injustices and transboundary sustainability (FEWM+ENTS) as essential to nexus analysis. This approach, with its attention not just to FEW *inputs* and *impacts* but also *access* to and *control* over FEW systems, provides a framework for monitoring these interconnected components.

Chapter 4 employed a network analysis to identify patterns in global oil and gas production from 2014-2018, delving into inter-firm and firm-state relationships as pressure to transition away from fossil fuels has intensified. It also considered the ‘collateral damage’ of an energy system predicated on the ability of American and European Big Oil firms to leverage the structural advantages of a colonial past and their continuing support of repressive regimes in oil rich regions around the world. This chapter quantified material extraction in terms of the net volumes of oil and natural gas reported by the top 26 companies within a system predicated on the extraction of large rents from oil, accomplished by controlling what had been an abundant supply in the Middle East for much of the twentieth century and thus creating artificial scarcity. And from this manufactured scarcity, of course, came the ability to control oil prices, and the price of oil, it turned out, was closely tied to the price of food. The effect of the four-fold rise in oil prices between 2005-2008 caused the global price of food staples to double, an increase caused by extreme weather events, “rising production costs due to the heavy use of petroleum products in industrial farming and synthetic fertilizers, and the widespread conversion of corn from a food crop to an industrial energy crop” (Mitchell 2013: 257).

A number of key conclusions that firmly link food, energy, and water systems to transboundary sustainability and embodied injustice can be drawn from the three inter-related studies that comprise the main chapters in this dissertation. First, these investigations all address the tensions arising from fossil energy and large-scale hydropower extraction at their sources: from the Niobrara Shale in the Denver Region, USA; from the La Grande, Eastmain, Rupert and Caniapisau Rivers in Eeyou Istchee/ Jamésie, Quebec, Canada; and from crude oil and natural gas extractive sites worldwide. The immediate negative environmental and health impacts and harms of large-scale energy systems are generally experienced most intensely by local inhabitants of a region for the benefit of generally distant consumers, from whom these social and ecological harms are either rendered opaque or kept entirely hidden. As this dissertation has illustrated, these local-distant tensions between energy production and consumption occur on multiple spatial scales, ranging from urban-regional, to provincial-national, to global.

Second, and following from this, in order for embodied injustices arising from interlinked food-energy-water-material systems to be adequately addressed, the complex FEWM supply chains across the life cycles must be rendered transparent. These essential systems variously involve the extraction, production, flow, processing, distribution, consumption, treatment, disposal, and related emissions and have inequitably distributed impacts and consequences at each step, building on locked-in infrastructures and historical conditions that are rife with structural racism and inequity. In the case of Eeyou Istchee/Jamésie, the comparatively straightforward hydropower supply chain was a key factor in the Cree public relations strategy to appeal directly to consumers in Vermont and New York State to halt efforts by Quebec to dam the Great Whale River in 1990s. At the same time, however, as the EI/J case illustrates, supply-chain transparency alone is not enough to dismantle systemic forces that privilege FEWM access and control by specific groups.

Third, FEWM supply chain transparency is closely linked to data availability, and significant data gaps characterize each of these three studies, either because nexus relationships have not yet been conceptualized to permit systematic data capture (i.e. energy used for water distribution or food warehousing), or ecological impacts are not monitored (i.e. water withdrawals from the Denver Basin Aquifer; ongoing water contamination and mercury levels in fish species throughout EI/J), or are not made available to the public (i.e. the amounts of money paid by oil and gas companies to governments or state officials worldwide). The national non-profit Frac Focus Chemical Disclosure Registry (used in Chapter 2 to identify the amount of water used for fracking annually in the Denver Region), is managed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission and lists the chemicals used for each frack job by company, and includes data about water quantity, but all states do not require companies to publicly disclose this information. Additionally, the use of subsidiaries and affiliates often make it difficult to trace local oil and gas activities back to the major oil companies that have vested interests in them.

While Chapter 3 relied on remote sensing data, this stream of information can also present barriers to access by grassroots advocacy groups. The EI/J case also illustrated the urgent need for the accurate monitoring of extractive activities, as well as the development of a suitable monitoring framework capable of assessing the interlinked social and ecological impacts of increasing provincial investment in northern resource extraction.

Chapter 4 initially began with the effort quantification of embodied water in the global extraction, trade, transport and consumption of coal, oil and natural gas using the UN Comtrade database. This exercise illustrated that most data is collected and disseminated at the national level, notably overlooking the key role of integrated multinational firms in extracting, transporting, and selling fossil fuels around the world. As such Chapter 4 is intended to serve as a starting point for a wider analysis of global food, energy, and water systems that can also integrate corporate actors into supply chain networks.

Fourth, these three studies all provide examples in which recent technological developments have accelerated resource extraction in ‘frontier’ areas, from the far north to the deep subsurface: hydraulic fracturing of shale deposits, while not new *per se*, only became commercially viable in the 2000s and enabled the US to once again surpass Saudi Arabia and Russia as the world’s largest oil and gas producer in 2013. Automated tree harvesting processes have vastly increased the amount of timber that can be extracted from remote northern locations, and state-of-the-art sawmills using automated scanning and cutting machinery can process this timber more quickly than was previously possible, allowing each log to be cut into the most profitable dimensions at current market prices.

These four observations – concerning local extraction versus distant consumption, the need for transparent supply chains, the lack of data availability, and the acceleration of resource extraction due to technological change – are all illustrative of the larger issue that collective oversight and broad public engagement are needed within complex socio-technical systems to foster the transition to FEWM systems that are both just and sustainable at multiple spatial scales.

5.1 Directions for Future Research

Several areas for future research have emerged from each of the main chapters. The work undertaken in Chapter 2 sets the stage for FEW nexus analysis to articulate the need for more and better data on system and trans-boundary interconnections that are vital to assessing the impact of fracking on regional water quality and soil fertility that so far have not been systematically undertaken.

The examination in Chapter 3 of embodied FEW injustices in EI/J stemming from the James Bay Hydroelectric project through the region's deforestation since 1975 points to several areas for further study. Although that chapter did not focus on quantifying the inputs from one system required for another, this more conventional approach to the nexus (e.g. how much water is required to generate each megawatt of electricity) in EI/J is also of interest, with the caveat that it needs to be considered alongside the other crucial nexus components identified in that chapter. On the topic of boreal deforestation using Landtrendr, areas for further study include: a) supplementing Landtrendr results with automated random forest approaches to detect disturbance type rather than relying exclusively on external datasets; b) using Landsat Band 5 to distinguish between fire and clearcutting; and c) using NDVI to distinguish mining disturbances from clearcutting and fire. Propensity score matching could be used to determine the link between mining and deforestation (e.g. Sonter et al., 2017) as well as the impact of protected areas on neighboring parcels.

Areas for future inquiry from Chapter 3 also include a closer examination of the links between hydropower and fire frequency in the Eeyou Istchee/Jamésie, particularly the origin of fires, severity, and proximity to electrical power infrastructure. In addition to quantifying the full extent and impact of logging infrastructure left in post-logging areas in Quebec, similar to the Ontario (Wildlands League, 2019), the links between logging infrastructure and other extractive and settlement activities warrant closer examination. It would also be instructive to apply the FEWM+ENTS monitoring lens to other regions and ecosystems, focusing on nexus inputs, impacts, control, and access along integrated food, energy, water, and extractive supply chains. This could form the basis for a more rigorous assessment of the social-ecological impacts of complex interacting systems over time that transcend local and regional boundaries.

The analysis of the global oil and gas production network undertaken in Chapter 4 likewise points to several areas for further study. The outsized impact of the fossil fuel industry on global geopolitics highlights the need for data sources that provide a clear picture of the scale and scope of its activities in the face of intensifying efforts to transition away from fossil fuels, as opposed to focusing primarily on country level analysis of production and consumption. In particular energy transitions research should more thoroughly explore the powerful pushback from a complex set of transnational actors against deep decarbonization and their corresponding ability to control national political agendas, as has notably happened in the USA, UK, Brazil, and India in recent election cycles, aligned with divisive right-wing political movements. Although this dataset and analysis is concerned primarily with the flows of oil and gas between companies and countries, these flows are fundamentally tied to the price of oil and the gains to be made by companies (particularly those in the private sector and state-owned companies focused on oil and gas exports). A similar analysis could be taken to map the corresponding flows of money. Automated text data mining could also be employed to analyze the annual reports of the top oil and gas companies and to perform a sentiment analysis; text mining of company publications would also enable temporal patterns and geographic and operational clusters to be detected. The use of automated techniques would also facilitate the analysis of more companies, permitting the assessment of a broader swath of the oil and gas industry.

5.2 Connection to Ongoing Events

As I write this conclusion, less than one week before the 2020 presidential election, the United States is in the midst of another surge in COVID-19 cases ahead of what promises to be a difficult winter. Among other massive disruptions to societies worldwide, the ongoing pandemic has had a profound impact on oil and gas consumption, causing prices to fall sharply and destabilizing the industry, prompting many questions about its ultimate impact on the pace and trajectory of the energy transition. We stand at a number of crossroads at this particular moment, and the convergence of right-wing political movements based on racism and xenophobia with the interests of the global fossil fuel industry to stave off the renewable energy transition is both alarming and familiar. In this context the notion of transnational “collusion” involving the Trump administration and Russia should be extended to encompass political activities at the nexus of Big Oil, hybrid state-private, and national oil companies worldwide. The degree to which these activities are permitted is precisely the degree to which the world’s largest oil and gas companies have integrated their operations and financing with state entities and global capital, structurally positioning themselves to stave off and control the parameters surrounding the transition for as long as possible by whatever means are at their disposal.

5.2.3 Global Climate Justice, Revisited

Global climate justice considerations generally focus on the fact that countries that have emitted the least carbon are now in the position of 1) facing significant climate consequences in the form of aridification, flooding, drought, extreme weather that they did not cause and 2) being unable to use fossil fuels as a pathway to development as rich countries have. But there is a significant climate justice argument on the supply side as well: the Global South has endured authoritarian regimes, repressive governments and ongoing wars meant to de-stabilize oil-producing regions even as its oil and gas is sent to wealthy nations. From this vantage point, not only are developing countries not responsible for carbon emissions, but their communities and ecosystems continue to bear the social, ecological and political costs.

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APPENDIX A. CHAPTER 2 SUPPLEMENTARY MATERIALS (SM)

THE FOOD-ENERGY-WATER NEXUS, REGIONAL SUSTAINABILITY, AND HYDRAULIC FRACTURING: AN INTEGRATED ASSESSEMENT OF THE DENVER REGION

This paper implements a regional systems framework for the trans-boundary FEW in the Denver region, USA. Additional details about our methods, data sources, calculations, and results are provided below.

Methods

Our characterization of multi-level regional FEW systems relied on an initial ‘desktop’ review of FEW indicators as well as ongoing stakeholder engagement. An inventory of publicly available datasets quantifying municipal and regional FEW production, consumption, and embodied FEW was conducted. For assistance in identifying relevant datasets and to gain additional perspectives on regionally important FEW nexus topics, we met with analysts from regional utilities including Xcel Energy and Denver Water, data providers at the Denver Council Region of Governments, infrastructure consultants, and city sustainability coordinators.

Data sources

Many of the key data sources for energy, transport, demographic, and crop at the county level are federally administered (including USDA, USGS, EIA, FAF4). Data on the monitoring of oil and gas wells is available at the state level, while municipal boundary data is available from regional planning organizations.

Where data was not already available in GIS format, we created geo-referenced maps based on state, county, and regional boundary files. We also co-identified publicly available data sources for FEW supply and demand metrics with regional FEW experts.

We used county and municipal level data within Denver region over a ten-year period. This allowed not only for consideration of sub-regional inequities but also changing consumption patterns over time.
We quantify the following framework components at the municipal, county and region-wide level:

1. Intra-regional energy and water demand + food imports
2. Intra-regional energy and water supply + food exports and agricultural production
3. Trans-boundary flows of food, energy, and water
4. Food, energy, and water system interdependencies
5. Ecosystem impacts and health risks of regional food, energy, and water systems

Demand for energy was derived from Xcel Energy's Community Energy Reports for 2015 at the municipal and county level and mapped using ArcGIS. County-level demand for water relied on United States Geological Survey (USGS) Water Use Data for the Nation for the years 2000 and 2010. Electricity and natural gas usage at the municipal and county level was obtained from Xcel Community Energy reports for 2015. **Imports** of food-related products were derived from the Freight Analysis Framework (FAF4).

Supply of food was derived from exports of food-related products in FAF4 for 2012-2015. Maps of farmland used the United States Department of Agriculture's Cropland Data Layer for 2015. The map of regional electricity generation capacity and primary fuel used data from the Energy Information Administration (SM Figure 2). County level energy production data were obtained from the Colorado Oil and Gas Conservation Commission. **Exports** of food-related products were derived from the Freight Analysis Framework (FAF4).

Trans-boundary flows of food and energy were derived from the Freight Analysis Framework, Version 4 developed by the Center for Transportation Analysis. Trans-boundary water flows were obtained from Colorado's Water Plan (2015) and the South Platte Basin Implementation Plan (2015).

Embodied water and energy ($W_{quantity} \rightarrow F$; $W_{quantity} \rightarrow E$; $E_{input} \rightarrow W$; $E_{input} \rightarrow F$; $F_{input} \rightarrow E$) utilized USGS Water Use Data for irrigation and thermoelectric power, Denver's Water Withdrawal Footprint for Energy Supply (Cohen and Ramaswami, 2014) and estimates of varying water and energy intensities of crops grown in different counties (Fisher 2014). The quantity of water used in hydraulic fracturing at the well level was obtained from fracfocus.org.

Ecosystem impacts from FEW systems ($E_{impact} \rightarrow W$; $E_{impact} \rightarrow F$; $F_{impact} \rightarrow W$; $W_{quality} \rightarrow F$; $W_{quality} \rightarrow E$;) used socioeconomic data from the Denver Region Council of Governments, the American Community Survey, and the Energy Information Administration. Data on oil and gas spills, violations, and public complaints were obtained from the Colorado Oil and Gas Conservation Commission's Daily Activity Dashboard; data on Class II injection wells came from fractracker.org.

Results

A-1. Food, energy, and water demand

City-wide and per capita FEW consumption within the region varies widely. Aggregate energy demand is greater in more densely populated cities and towns, but per household demand in these areas tends to be lower. Denver and Boulder, for example, consume the most electricity and natural gas in aggregate but have the lowest energy consumption per household (Figure 5a). Reflecting the water intensity of Weld County's food and energy production, Weld County (2010 population 254,000) consumed three times more water than the city of Denver (2010 population 603,000). Major crops include winter wheat, corn, alfalfa and camelina (Figure 7).

Food: The demand for food can be quantified from the food consumption data from USDA or FAO's food balance sheet. Given the focus of this paper on impacts of energy extraction on food and water systems, we do not offer this calculation here. We do however note that imports of food to the Denver region (based on the FAF4 dataset) in 2015 totaled 16745 ktons (including imports from Denver to itself). We also note that imported goods can be further processed and re-exported, so these numbers should be interpreted with caution.

Water: The Denver region sits atop a series of four interconnected and largely non-renewable groundwater reserves, collectively known as the Denver Basin Aquifer, which have been extensively drilled to support the region's water needs (Figure 1). Water wells are concentrated in Boulder, Broomfield and Weld Counties. Aquifer pumping has increased steadily from an estimated 40 ft3/s in 1953 to 170 ft3/s in 2003; actual pumping is not monitored (Paschke *et al.* 2011). The state is facing an anticipated 163 billion gallon (500,000 acre-feet) water shortfall by 2050, twice the amount currently used by Denver Water's 1.3 million residents (Colorado Water Conservation Board 2015; Finley 2014). The projected gap includes the loss of up to 424,000 acres of farmland statewide (Finley 2014).

In 2000, a total of 12,622 Mgal/day were withdrawn in the state of Colorado for irrigation (90.5%), industry (1.3%), public supply (7.1%), and thermoelectric power (1.1%). In 2010, withdrawals had declined to 10,778 Mgal/day, reflecting competing demand from growing municipalities, while water use by sector statewide was roughly the same for irrigation (90.1%), industry (1.3%), public supply (8%), and thermoelectric power (0.7%). This trend of decreasing overall use is evident in the Denver Region, where total water withdrawals fell from 1870 Mgal/day (2000) to 1403 Mgal/day (2010). [Put in 2015 #s] Unlike the rest of Colorado, however, water use by sector shifted in the Denver Region, reflecting its growing population: public supply rose from 29% of total water withdrawals in 2000 to 39% in 2010, while irrigation fell from 65% of withdrawals in 2000 to 54% in 2010.

Using figures from the USGS Water Use for the Nation dataset, a total of 12,622 Mgal/day were withdrawn in 2000 in the state of Colorado for irrigation (11420/12,622), industry (164/12,622), public supply (899/12,622), and thermoelectric power (138/12,622). In 2010, a decade later, the state withdrew a total of 10,778 Mgal/day for irrigation (9715/10778), industry (139/10778), public supply (848/10778), and thermoelectric power (77/10778). Regional and within region comparisons:

Calculations:
2000

Irrigation (11420/12,622)=90.5%
Industry (164/12,622), =1.3%
public supply (899/12,622), 7.1%
thermoelectric power (138/12,622). 1.1%

2010
Irrigation (9715/10778)=90.1%
Industry (139/10778)=1.3%
public supply (848/10778)=8%
thermoelectric power (77/10778). =0.7%

Final
A total of 12,622 Mgal/day were withdrawn in 2000 in the state of Colorado for the following uses: irrigation (90.5%) industry (1.3%), public supply (7.1%), and thermoelectric power (1.1%). In 2010, a decade later, the state withdrew a total of 10,778 Mgal/day for irrigation (90.1%), industry (1.3%), public supply (8%), and thermoelectric power (0.7%).

[Energy data excludes Clear Creek and Gilpin Counties.]

Data Gaps: Xcel reports were not available for prior years (and have since been removed from the utility's website).

A-2. Regional food, energy, and water supply

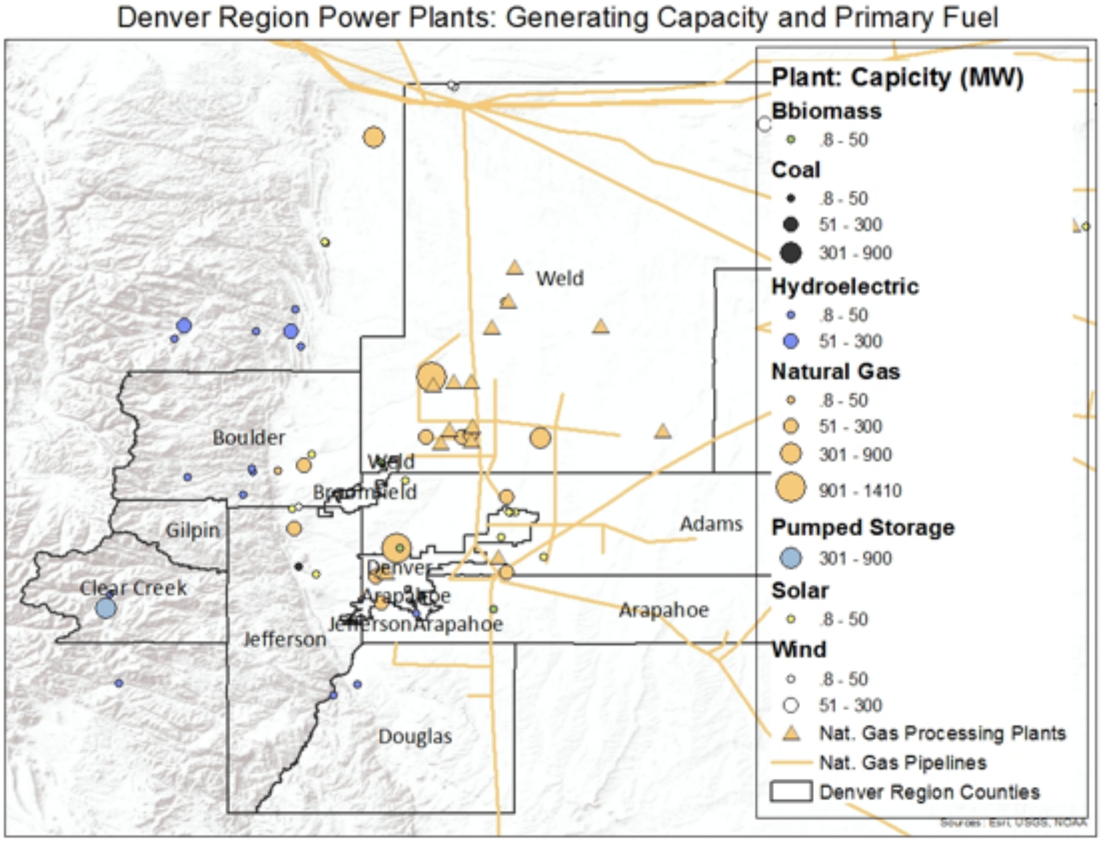


Figure A-1. *The locations, capacity, and primary fuel of the fleet of the region's power plants in 2015. Data Source: EIA, 2015.*

Food: The supply for food is equal to the sum of production within the region, imported quantity, and change in stock (supply = production + import + change in stock). Supply for local utilization = Production + imports - exports + changes in stocks (FAO nd; Okrent and Alston 2012). Given the focus of this paper on impacts of energy extraction on food and water systems, we do not offer this calculation here. We do, however, note that exports from the Denver region (based on the FAF4 dataset) in 2015 totaled 14106 ktons (including exports from Denver to itself). We also note that imported goods can be further processed and re-exported, so this number should be interpreted with caution.

A-3. Transboundary flows of food, energy, and water

National maps of energy and food imports to Denver at the city-region level were created using the Freight Analysis Framework, Version 4 Regional Database.

Agricultural / Food imports were mapped using all the entries for live animals/fish, cereal grains, other agricultural products, animal feed, meat/seafood, milled grain products, other foodstuffs, and alcoholic beverages for which Denver was the destination in 2015.

Agricultural / Food exports were mapped using all the entries for live animals/fish, cereal grains, other agricultural products, animal feed, meat/seafood, milled grain products, other foodstuffs, and alcoholic beverages for which Denver was the source in 2015.

The region is a net food importer: The total volume of food-related commodities imported into the region was 16745 ktons in 2015, compared to 14106 k tons of food-related commodities exported from the region in the same year.

Up to 39% of the food-related commodities produced in the region may be consumed in the region: (Food related imports from Denver to Denver) / (Food related imports from anywhere to Denver, including imports from Denver to itself) = (6.5 megatons)/(16.7 megatons) = 0.39. It should be noted, however that imported goods can be further processed and re-exported.

Energy imports were mapped using all the entries for coal, crude petroleum, gasoline, aviation turbine fuel, and ethanol (includes kerosene, and fuel alcohols), fuel oils (includes diesel, bunker c, and biodiesel), other coal and petroleum products, not elsewhere classified for which Denver was the destination in 2015. Energy exports were mapped using all the entries for coal, crude petroleum, gasoline, aviation turbine fuel, and ethanol (includes kerosene, and fuel alcohols), fuel oils (includes diesel, bunker C, and biodiesel), other coal and petroleum products, not elsewhere classified for which Denver was the source in 2015.

The region is a net energy exporter: The total volume of energy-related commodities imported into the region was 37,000 ktons in 2015, compared to 63,000 ktons of energy-related commodities exported from the region in the same year.

Table A-1. *Summary of import export stats of energy and food for the Denver region derived from the FAF4 database.*

	Denver to itself (ktons)	**D to itself: Millon $**	**D. to/from elsewhere (ktons)**	**D. to/from elsewhere Million $**	**Total (ktons)**	**Total Million $**
Ag Exports	6540	6417	7567	7371	14106	13774
Ag Imports	6540	6417	10206	11143	16746	17560
Energy Exports	4657	2704	62703	16948	67360	19652
Energy Imports	4657	2704	37039	6968	41696	9672

Water: Local food production and municipal water supplies rely on large-scale, trans-boundary water diversion projects. The Colorado Big Thompson Project (C-BT), originally constructed in the 1930s for irrigation, diverts about 220,000 acre-feet of water per year from the Western slope of the headwaters of the Colorado River. The water is delivered 13 miles to the eastern Front Range. More than 33 cities and towns in northeastern Colorado, including Fort Collins and Boulder, are served by the project, which provides a secondary water source for approximately 830,000 people.

A-4. Food, energy and water system interdependencies

$W_{inputs} \rightarrow E$: Total water use on the Niobrara Shale annually from 2013-2107 was calculated using the full FracFocus Chemical Disclosure Registry downloaded from http://fracfocus.org/data-download. Annual totals were obtained by summing the TotalBaseWaterVolume column for all jobs with a value in the 'JobStartDate' field in that year for all the counties in the Denver region, as well as the neighboring counties of Larimer, Elbert and Morgan (also on the Niobrara Shale). The amount of water per well was obtained by dividing this total by the number of wells (obtained from number of unique entries in WellName field) registered that year in the relevant counties.

$F_{input} \rightarrow E$**:** The town of LaSalle in Weld County is also home to Heartland Biogas, of the largest biogas facilities in the country, which began operating in 2015. The facility uses cattle manure and food waste to produce up to 4,700 MMBtu of biogas daily, and is under contract to provide the renewable fuel to the Sacramento Municipal Utility District in California. The facility was shut down in early 2017 due to complaints by residents about the overpowering odors, and has yet to reopen (Runyon 2016; Marmaduke, 2017).

$E_{input} \rightarrow W$: Public drinking water systems in the U.S. consume approximately 39.2 billion kWh per year; this corresponds to roughly 1% of total electricity use nationwide. Municipal wastewater treatment systems consume about 30.2 billion kWh annually, or about 0.8% of total electricity use nationwide (Pabi *et al.* 2013).

$E_{input} \rightarrow F$**:** The energy intensity of food production varies across the region. The estimated energy intensity for small-scale potato, onion, carrot, and tomato growing in the city of Denver, where potable tap water is used for irrigation, is 119 kWh/AF (365 per Mgal). In Alamosa County, by contrast, where pumped irrigation is used, the site-specific energy intensity for potato crops was recorded to be 12.8 kWh/AF (Fisher 2014).

Winput→Electricity Thermoelectric power generation also relies heavily on surface water supply for power system cooling. Nationally, water withdrawals for this purpose are the single largest consumer of water, comprising 45 percent of total withdrawals in 2010 (Maupin *et al.,* 2014). In 2010, regional electricity generation required roughly 18 million gallons per day (USGS 2014). Cohen and Ramaswami (2014) estimate the total mean water withdrawal footprint of Denver's energy supply in 2005 to be 22,070 million gallons (83,545 million liters) per year, including building energy use and transportation fuels.

Table A-2. *Industry-reported water use for hydraulic fracturing on the Niobrara Shale. Data derived from the FracFocusRegistry database (fracfocus.org).*

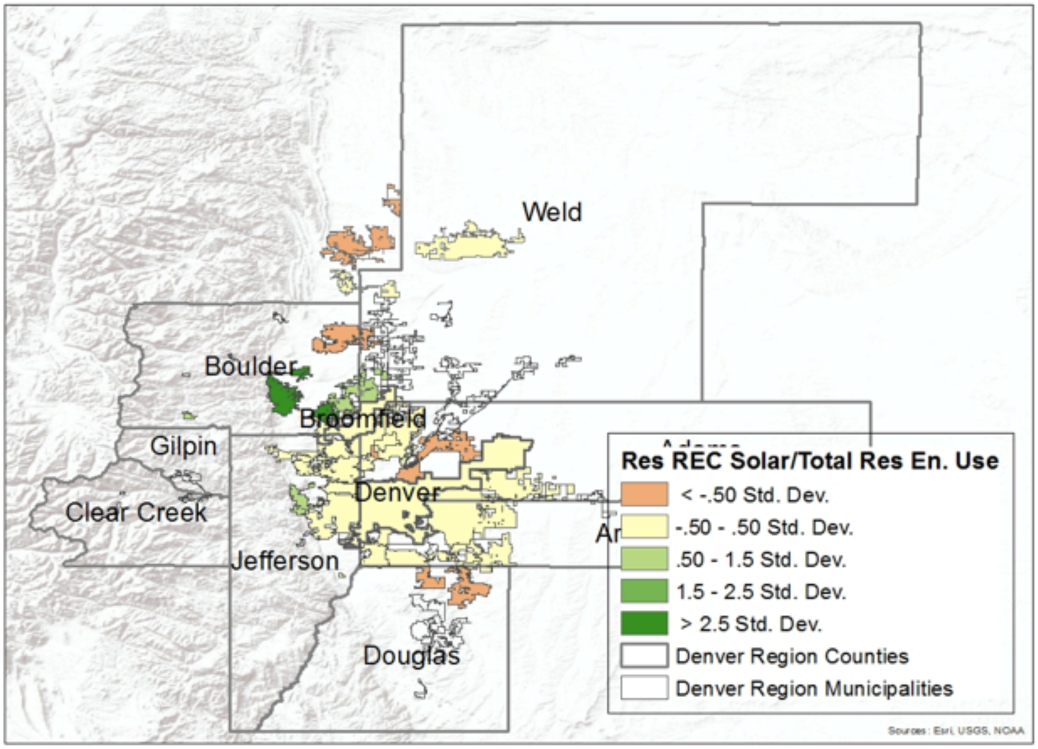
Year	Total Base Water Volume (Million Gallons)	#Wells	Average per well (Million Gallons)
2012	739.12	1797	0.41
2013	3160.43	1302	2.43
2014	5750.71	1449	3.97
2015	5452.77	1117	4.88
2016	4915.53	721	6.82
2017	9774.93	1111	8.80

A-5. Ecosystem impacts and health risks of regional food, energy, and water systems

Proportion of energy from renewables in the residential sector in the Denver region in 2015 was mapped using municipal level data from Xcel Energy's Community Energy Reports. The number of residential customers participating in wind source and solar garden programs was divided by the total number of customers, yielding a percentage. The results were then mapped according to standard deviation.

A-6. Proximity to Energy Extraction and Thermoelectric Power Generation

Although energy production and electricity generation are significant regional activities, the associated health risks of living adjacent to these facilities are not distributed evenly across the population. Wealthier communities are more readily able to participate in renewable energy programs like Solar Gardens and Renewable Energy Credits (Figure 11). Low-income, non-minority communities are dispersed throughout the region while minority and minority plus low-income communities are concentrated within Denver (Figure 12).



Sources: Esri, USGS, NOAA

Figure A-2. *Proportion energy from renewables in the residential sector in the Denver region in 2015.*

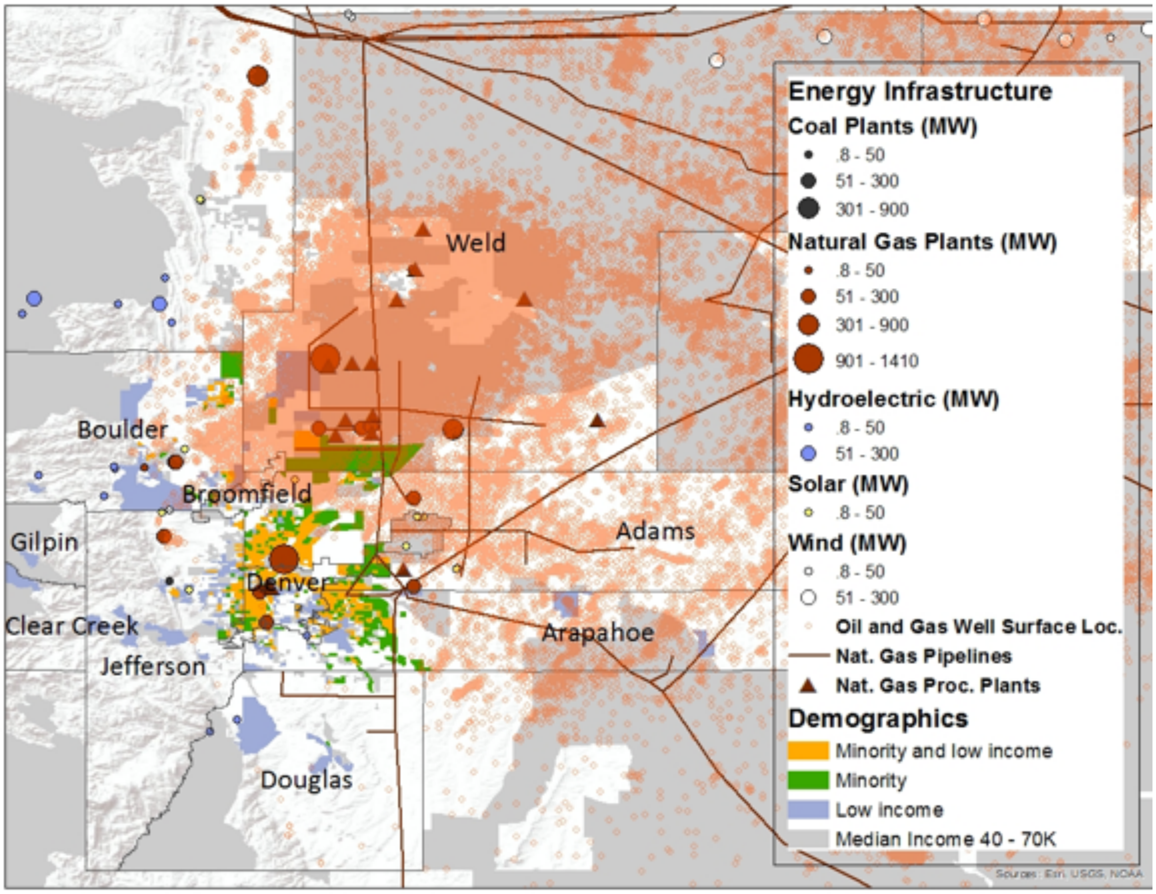


Figure A-3. *The spatial distribution of minority, low-middle income communities in the region. The surface locations of the regions 44,000+ oil and gas wells are depicted in orange. Also shown is the electricity-generating capacity of hydro (left) and wind (upper right). Data Sources: Denver Region Council of Governments 2015, Energy Information Administration 2015.*

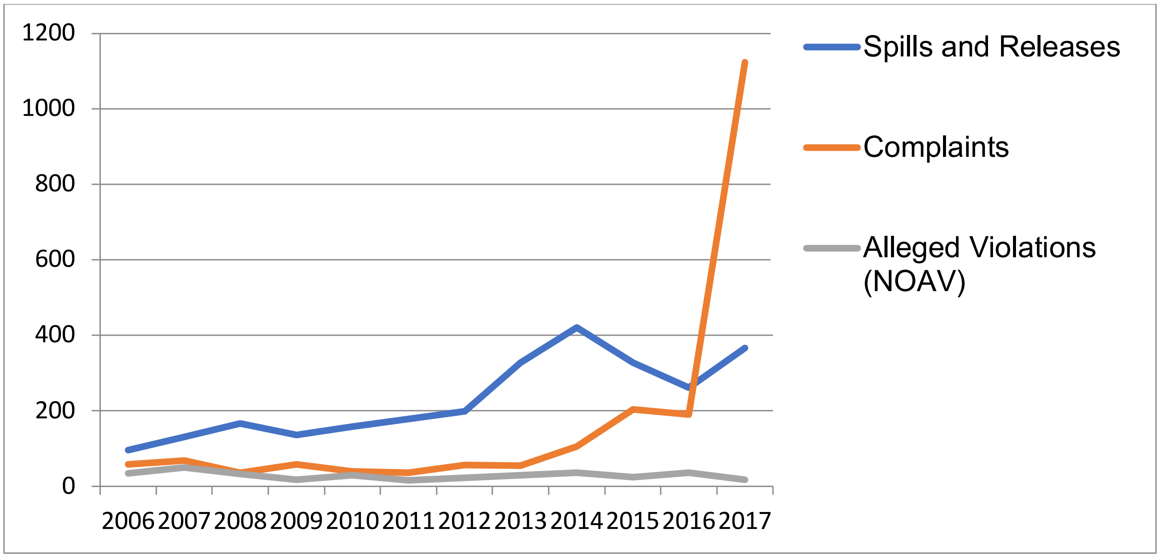
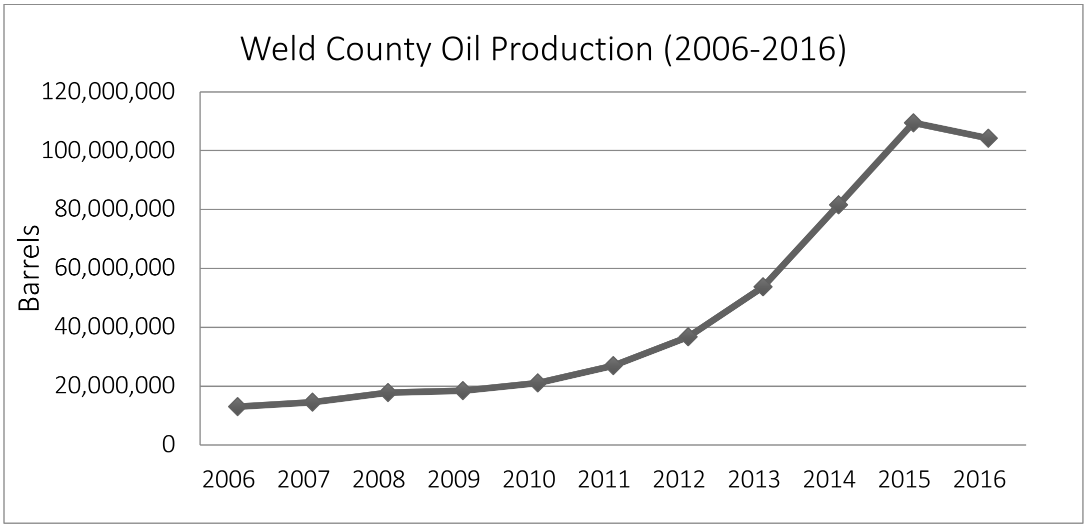


Figure A-4 *Spills and releases, public complaints, and alleged violations in Weld County from 2011 to 2017. Data obtained from the Colorado Oil and Gas Conservation Commission Daily Activity Dashboard (http://cogcc.state.co.us/DAD.html) and the Colorado Oil and Gas Information System (http://cogcc.state.co.us/cogis/).*



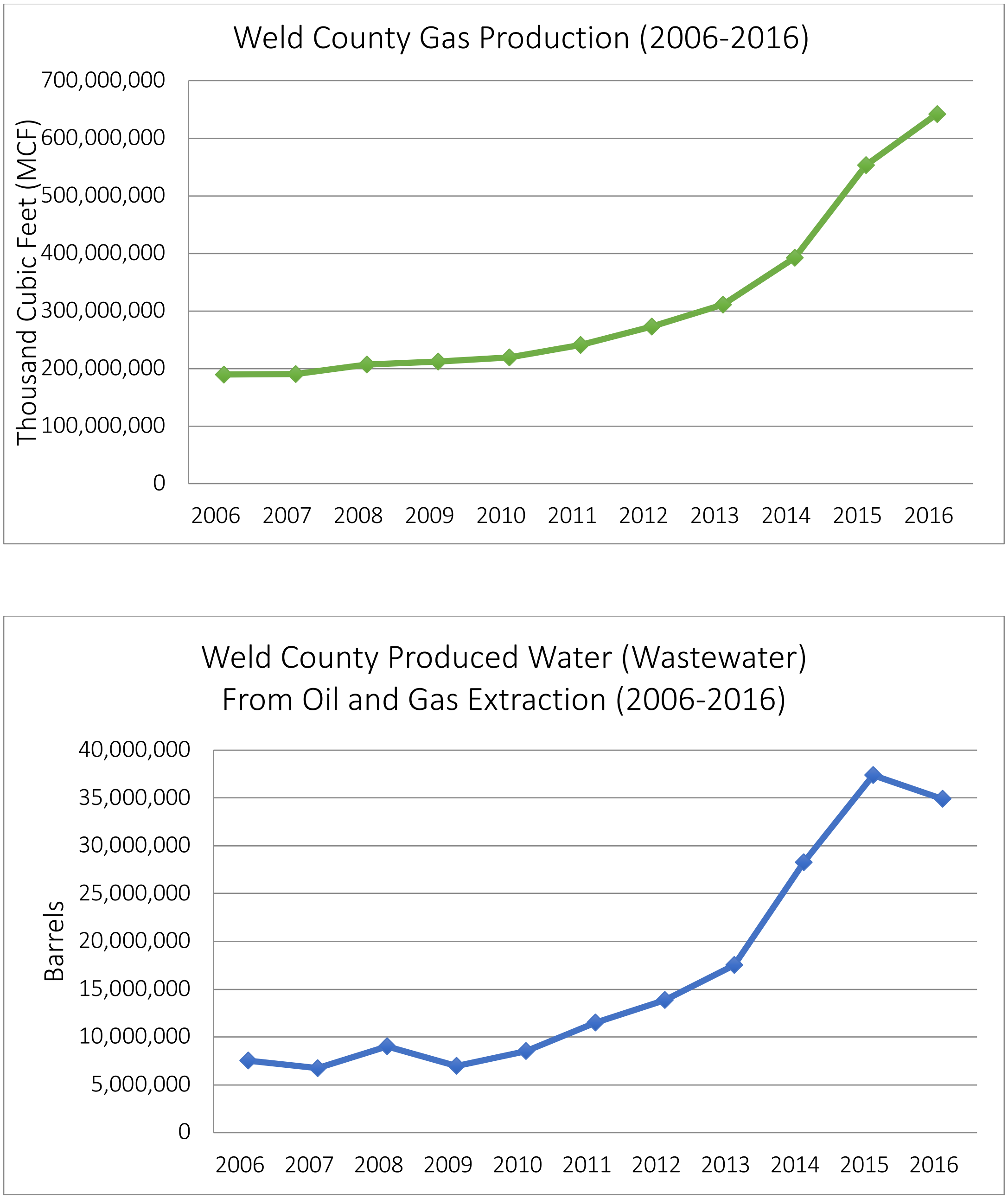


Figure A-5a-c. *Weld County oil and gas production from 2006 to 2016, as well as produced water. Hydraulic fracturing accounts for the sharp increase beginning in about 2012.*

APPENDIX B: CHAPTER 3 SUPPLEMENTARY INFORMATION (SI)

THE FOOD-ENERGY-WATER-MATERIAL NEXUS AND EMBODIED INJUSTICES: THE ROLE OF HYDROPOWER IN DEFORESTATION IN EEYOU ISTCHEE/NORTHERN QUEBEC

B-I Introduction

Linkages between mining and the FEW/resource nexus

Mining requires land for exploitation of ores and for waste disposal: an estimated 60 billion tons of material are moved each year (Humphreys, 2017). Mining also depends on large water inputs: an average of 172 tons (thousand liters) is needed to produce one ton of copper, and 600–700 tons to produce 1 kilogram of gold. Large quantities of energy are also needed for mineral processing, representing one quarter of metal production costs. As pressure on FEWS increases, linkages to mining have become more important, and may constrain mining development more than physical availability of mineral ores (Humphreys, 2017).

Forest Management in Canada

Canadian provinces, which are primarily responsible for forest management, have historically disregarded and ignored First Nations in resource development (Ross et al., 2002):

> Aboriginal Peoples are still largely excluded from forest allocation and management… provincial governments have allowed industrial developments to radically alter the lands and resources used by Aboriginal Peoples... Aboriginal and treaty rights, notably land and resource-related rights such as the rights to hunt, trap, fish and gather, and to use forest resources for their own benefit, are directly and often negatively affected by industrial forestry activities. Lack of recognition and protection of the rights of Aboriginal Peoples on traditional lands

> allocated to forest companies has resulted in the implementation of policies and management systems that do not meet the needs of Aboriginal Peoples, are foreign to their values and management systems and endanger their very existence (Ross et al., 2002: 4).

As articulated by Matthew Coon Come, former Grand Chief of the Grand Council of the Crees, the appropriation of land and water in Eeyou Istchee to supply energy to distant populations deprived the Crees of their means of subsistence, constituting the most basic of injustices:

> There is something fundamentally wrong that needs to be identified here. At the same time that these negotiations concerning the JBNQA were taking place, Canada was participating in the development of the International Covenant on Social, Economic and Cultural Rights at the United Nations. Article 1 provides that: 'Under no circumstances shall a people be deprived of its own means of subsistence.' Yet this is precisely what had just been done to us, as the waters of the La Grande hydroelectric mega-project rose around us and flooded our ancestors' graves. I believe that the governments knew then what they were doing: depriving the Cree people of our own means of subsistence in violation of our fundamental human rights (Coon Come, 2004: 157).

Impact of Logging Infrastructure on the Boreal Forest in Canada

In a recent study, the annual deforestation rate of the Canadian province of Ontario jumped to seven times the official forestry rate for the entire country when commercial logging infrastructure (including roads to access and remove timber, landings for log storage, road pull-offs, staging areas, localized digging and wayside pits for road-building material, tree waste processing areas, and waste log piles) was taken into account, although the Ontario officially accounts for just 17% of Canada’s logging (Wildlands League, 2019).

Using “analytical eclecticism” in extending the FEW nexus

Alongside nexus critiques, many have called for more critical, theoretically informed perspectives (Allouche et al., 2014; Foran, 2015). Leck et al. (2015) propose the use of *analytical eclecticism*, defined by Sil and Katzenstein as an intellectual stance utilizing “theoretical constructs embedded in contending research traditions to build complex arguments that bear on substantive problems” (Sil & Katzenstein, 2010: 411). This approach can guide nexus research in navigating disciplinary boundaries, specifying how “different causal factors might coexist as part of a more complex argument” relevant for research, practice, and facilitating dialogue among disciplines and stakeholders (Leck et al., 2015: 451-452). In widening the FEW / resource nexus to include embodied injustices and transboundary sustainability (FEWM+ENTS), we employ this approach.

Embodied Injustices

Healy et al observe that conceptualizations of embodied energy injustices can: 1) help situate chains of energy injustices and place-based energy struggles within wider national and regional energy politics and 2) address regulatory gaps in energy governance by expanding the scope of energy decisions and processes, thus providing a framework to situate and understand place-based injustices as part of an unjust global order (Healy et al., 2019).

Table B-1. *FEWM nexus interactions and embodied injustices and transboundary unsustainability (FEWM+ENTS) framework.*

Inputs: x ‘for’ y	**Impacts: x ‘on’ y**

Definition: The FEWM inputs to food, water, energy systems and materials across the life cycle *Examples:* o Water 'for' energy: hydropower; surface water withdrawals for thermoelectric power generation o Water and energy 'for' food: volume of water for crop irrigation, energy used for water pumping o Energy 'for' mining *Note*: Nexus studies often focus here, particularly quantifying inputs/flows from one system to another	*Definition (two-fold)*: 1) Impact of FEWM systems on each other and the wider ecosystem across FEWM life cycles; 2) Disproportionate environmental and health *impacts* at the FEWM nexus on vulnerable and disenfranchised communities *Examples*: o Food/Land 'on' Water: Impact of fertilizer on aquatic ecosystems o Impact of Barrick Gold Corporation's planned Pascua–Lama project using open pits and cyanide leaching for ore recovery on glaciers and water supporting indigenous agriculture in the Huasco Valley, Chile (Urkidi & Walter, 2011) *Note*: Mandated environmental impact assessments and the environmental justice movement address this
Access 'to': *Definition*: Equitable access to food, energy, water, materials and land; lack of access to x is correlated with lack of access to y *Examples:* Lack of access to FEW at the global scale: o 800 million people are hungry and 2 billion experience moderate or severe food insecurity (FAO et al., 2019) o 1.2 billion live in water-scarce regions (Bigas et al., 2013) o 1.2 billion do not have access to electricity o More than 2.7 billion rely on traditional biomass for cooking (WEO, 2016) *Note*: Development projects sometimes address this	**Control 'over'** *Definition*: Structural issues of how FEWM systems have been developed, how they interact, and how benefits and harms are distributed across populations *Examples:* o Institutions that control regulatory processes disproportionately allow siting of toxic facilities near communities of color in the U.S. o Provincial control of industrial development in forests in Canada, systematically excluding Aboriginal Peoples from forest resource management (encompassing food, water, and livelihoods) *Note*: Environmental justice/reform/transition efforts address this

These four interrelated dimensions – inputs, impacts, access, and control – at the FEWM nexus are essential to providing a more complete picture for research and policy addressing nexus topics. The spatial component to each of these dimensions can be mapped and monitored over time and across large distances. These capacities are especially salient for just and sustainable transitions, as FEW systems, governance structures, policies, and transboundary supply chains receive increasing scrutiny.

Transboundary Unsustainability: Linking Production and Consumption Through Infrastructure: 'Nexus infrastructures' are highly interdependent: transportation, for example, enables the building of energy and water distribution networks and is necessary for resource extraction, while transport/rail vehicles are in turn dependent on fossil fuels and/or electricity for power.

B-II. Data and Methods

Table B-2. *Datasets used in this analysis.*

Data Type	Source
Satellite imagery	The Landsat Data Archive was accessed via the Google Earth Engine platform.
Fire	The Canadian National Fire Data Base (CNFDB) (Canadian Forest Service, 2019) was used as an accurate reference map depicting the year and cause of historical disturbances due to fire, following a number of studies that have taken this approach (Coops et al., 2018; Schroeder et al., 2011).
Boreal Forest Disturbances (Pasher et al., 2013): o Logging o Mining o Reservoirs o Roads o Powerlines	Environment Canada's 2010 Boreal Ecosystem Anthropogenic Disturbances Dataset (BEADD) (Pasher et al., 2013) contains digitized polygonal and linear disturbances for the entire boreal forest in Canada manually at 1:50000 scale (500 m) using Landsat imagery from 2008-2010, providing a snapshot of disturbances circa 2010. The polygonal disturbances layer helped identify cutblocks, reservoirs, and mines; the linear disturbances layer was used to identify roads and power lines.

Water Bodies	The EC/JRC’s Global Surface Water dataset ‘occurrence’ layer was used to mask known waterbodies from the Landtrendr results showing forest disturbances (Pekel et al., 2016)
Hydropower	The Global Reservoir and Dam (GRanD) Database Version 1.3 (Lehner et al., 2011) contains the spatial extent of James Bay Complex hydropower reservoirs, dam locations, and year of construction.
Roads	The Statistics Canada Road Network File (2019) contains digital road line coverage of Canada, including linear extent, type, rank, and class, but not the date of construction.
Mining	Quebec’s Système d’Information Géominière (*SIGÉOM à La Carte*, n.d.) contains georeferenced, temporal data on expired and active mining titles, exploratory drilling, current mining operations, and prospective mining areas. Natural Resources Canada’s interactive map of indigenous mining agreements listing specific mining companies was also used (Natural Resources Canada, n.d.)
Energy	The Atlas of Canada – Remote Communities Energy Database contains information about 276 remote communities in Canada including name, province, main power source, annual fossil fuel generation, and community classification (Indigenous and Northern Affairs Canada & Natural Resources Canada, 2016).
Mercury Levels in Fish	*Healthy Fish Eating in Eeyou Istchee* (Cree Health Board) and the *Northern Fish Nutrition Guide* (Blanchet, n.d.)
Wildlife Capture Data	Cree Trappers Association Big Game Survey Data and Trapline Capture Reports contain data on caribou, moose, black bear, and 15 small game species from 1989 to 2018 in eight Cree communities within Eeyou Istchee (*CTA - GeoPortal for Eeyou Istchee*, n.d.).

B-IIa. Study Area

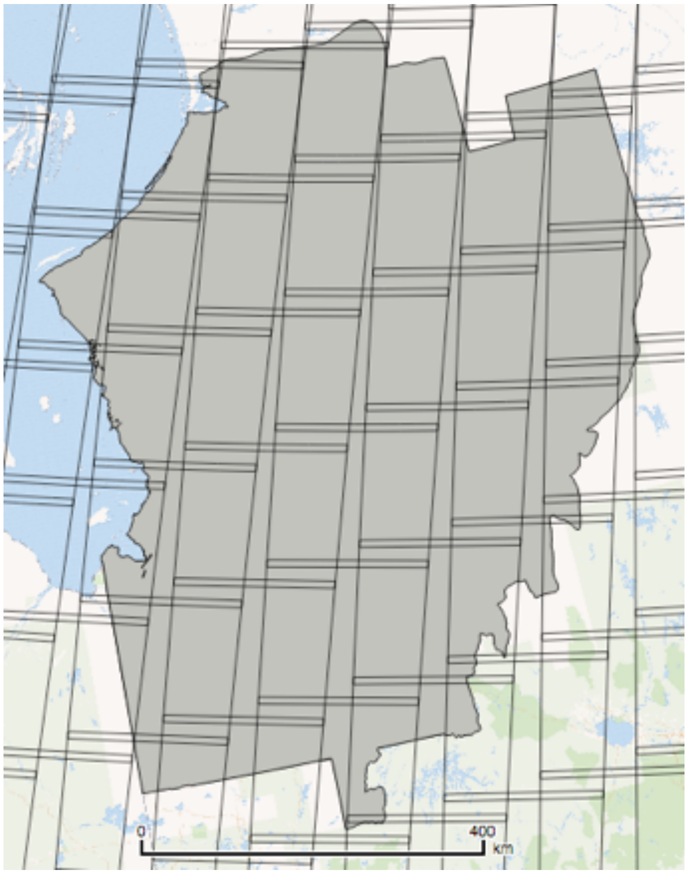


Figure B-1. *The Eeyou Istchee / Jamésie study area is comprised of 31 individual Landsat scenes, spanning paths 13-20 and rows 20-26.*

<u>Overlapping boundaries</u>

The southwestern portion of Jamésie that does not overlap with Eeyou Istchee is part of the traditional territory of the Wahgoshig First Nation (formerly known as the Abitibi Band of Abitibi Indians).

<u>Additional Context</u>

The Quebec Boundary Extension Act, 1898 and the Quebec Boundaries Extension Act, 1912 passed by the Parliament of Canada together tripled the territory of Quebec to its current boundaries, encompassing lands inhabited by Aboriginal Cree, Innu, Naskapi, and Inuit, and spanning more distance north to south than any other province. Hydro-Quebec planners first inventoried the region's rivers in the late 1950s, although Hydro-Quebec was not initially supportive of launching the James Bay Project (JBP). Quebec's development efforts began in 1971 with the stated goal of promoting "economic development and the development and exploitation of natural resources, other than hydro-electric resources falling within Hydro-Québec's mandate" (James Bay Region Development Act, 1971). Supporters of the JBP, which was dubbed "The Project of the Century," rallied around the political slogan *Maître Chez Nous* ("Masters of Our Own House"), originally derived from the Liberal Party's 1962 provincial election campaign. Anticipating growing energy demands of Quebec's growing population, the JBP was an attempt by Quebec Premier Robert Bourassa's Liberal Party in the early 1970s to create 100,000 jobs and redirect Quebec separatist sentiment toward 1960s-era economic nationalism at a time when the newly-launched Parti Québécois was on the rise. The JBP was the Liberal alternative to the Parti Québécois independence project: in Bourassa's words, the JBP was the "key to the political stability of Quebec," functioning as "a symbolic gesture stimulating hope and collective pride" (McCutcheon, 1998: 33).

Jean Chrétien, Minister for Indian Affairs and Northern Development for Canada (who would later become Prime Minister of Canada), at the time called the region "the last frontier to open in North America," stating the federal position that "we cannot afford to make too many mistakes" as Quebec sought to develop the region (von Rosen, 2010).

The Grand Council of the Crees (2011) describe the external development of Eeyou Istchee as occurring in four waves 2015: beginning in the 1950s and 60s with Canadian military-operated radar defense lines, continuing with the 1971 James Bay

Region Development Act in Quebec, leading to the 1975 James Bay and Northern Quebec Agreement, and culminating in the Plan Nord, a 25-year, C$80 billion effort to engage in continued resource extraction applying to all of Quebec north of the 49th parallel, launched by Quebec in 2011 and reaffirmed in 2015 (Québec (Province) et al., 2011; Gouvernement du Québec, 2015). The Plan Nord, including lands covered by the JBNQA, is seen by Quebec as one of its most ambitious projects (Québec (Province) et al., 2011: IX).

Ecoregions

The boreal forest ecoregions comprising the study area (Figure 1) include the Taiga Shield, Hudson Plain, Northern Forest Softwood Shield, and Northern Forest Mixed Hardwoods Shield according to the North American Terrestrial Ecoregions Classification System (Wiken et al., 2011). Most of the commercial forestry licensed by the province of Quebec within EI/J occurs in this ecoregion (Map 1a) and in the Northern Forest Mixed Hardwoods Shield to the southeast, containing maple, birch, aspen, spruce, balsam fir, hemlock, and pine. Commercial timber extraction is concentrated in the southern region, where there are processing mills, road infrastructures, and heavily forested environments, all of which decrease to the north, along with increasing operational constraints (e.g. steep terrain, bogs, lakes, and rivers) (Jobidon et al., 2015) and declining commercial values (Beaudoin et al., 2014).

B-IIb. Methods

Landtrendr relies on relative radiometric normalization and cloud screening rules to create on-the-fly mosaics of multiple images per year; for each pixel temporal trajectories of spectral data are extracted. Temporal segmentation strategies use straight line segments to model important trajectory features and eliminate noise; control parameters and threshold-based filtering are used to reduce the role of false positive detections (Kennedy et al., 2010, 2012).

The Normalized Difference Vegetation Index (NDVI) and Landsat Band 5 were also tested. In order to determine if reservoir formation between 1984 and 2018 could be detected (Section 3.3), water was not masked in the initial Landtrendr analysis. To more accurately estimate deforested land throughout the study area, the Global Surface Water occurrence data layer (Pekel et al., 2016) was applied to the Landtrendr result; pixels with values from 10-100 were classified as water and masked from the final map of disturbed area. The Landtrendr algorithm was run using NBR for all scenes from 1984 (the earliest year with sufficient data to enable this technique) to 2018.

B-III. Forest Disturbances by Type

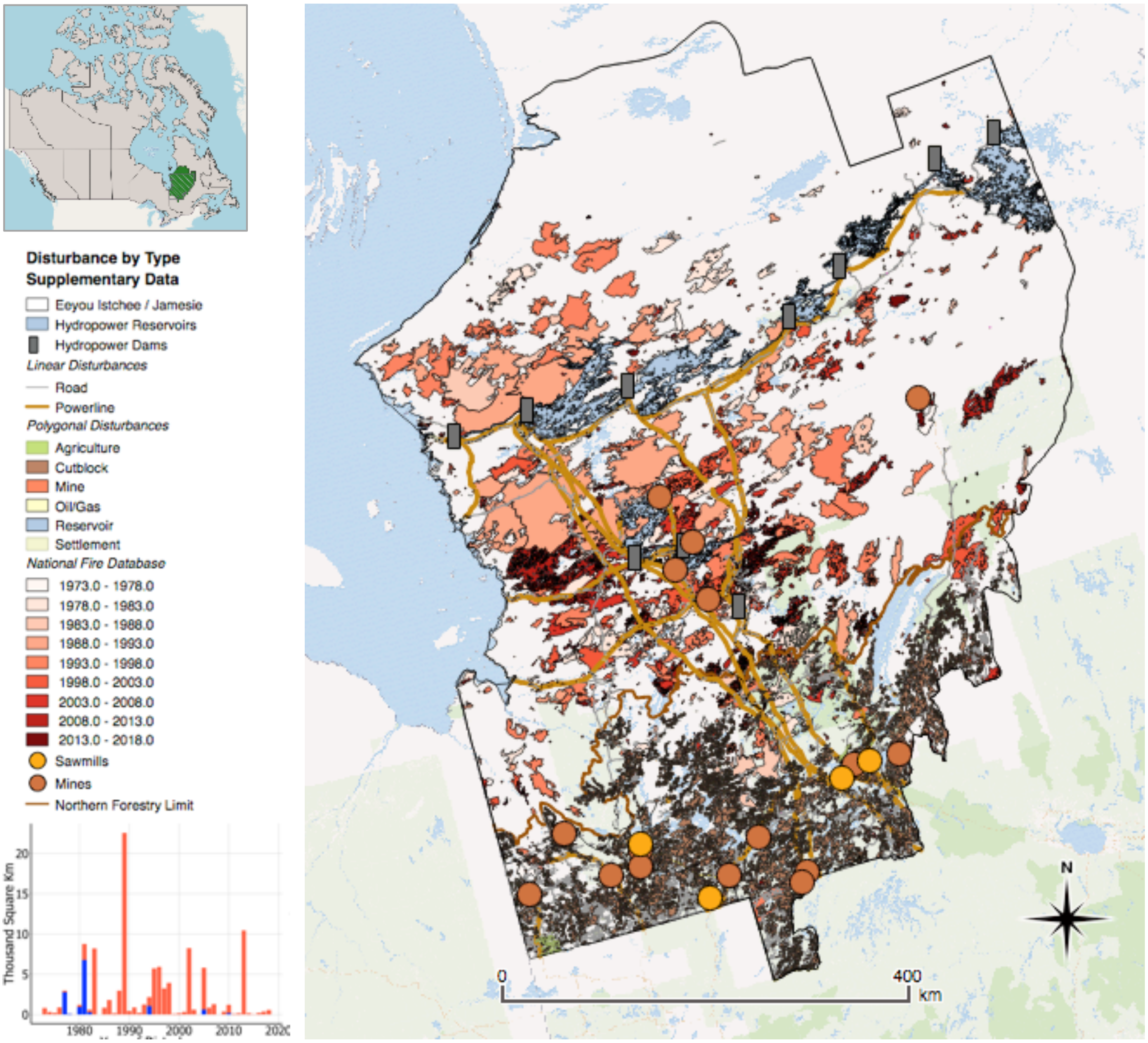


Figure B-2. *Validation datasets depicting boreal forest disturbances in EI/J. Mining is shown separately in Section 3.2.4 and Figures S3-1x and S3-1x. Data sources: (Canadian Forest Service, 2019; Pasher et al., 2013).*

B-IIIa. Hydropower

The full complex consists of a series of ten hydropower dams on the eastern rivers flowing into James Bay, owned and operated by Hydro-Quebec, the province's public electric utility (Déry et al., 2018). The James Bay complex is the largest in the Western Hemisphere; in 2019, its installed generating capacity totaled 17,268 MW (*Hydro-Quebec 2019 Annual Report*, 2020).

In 1992 Quebec suspended the Great Whale Complex after prolonged Cree opposition, culminating in New York State canceling its contract with Hydro-Quebec. In 2002, as part of the Paix des Braves Agreement setting out a Nation-to-Nation relationship between the Grand Council of the Crees and Quebec, the Nottaway, Broadback and Rupert (NBR) Complex, which would have resulted in the flooding of over 8000 km^2 of land, was also abandoned. In return, the Crees agreed to the construction of the Eastmain and Rupert projects, involving the partial diversion of the Rupert River and the construction of a series of dikes and dams along the Eastmain and Rupert Rivers, causing the Eastmain to partially dry up and 975 km^2 to be flooded. The Paix des Braves also provided for joint Cree and Quebec management of mining, forestry and hydropower resources.

Pre-1975	1975-1980	1980s

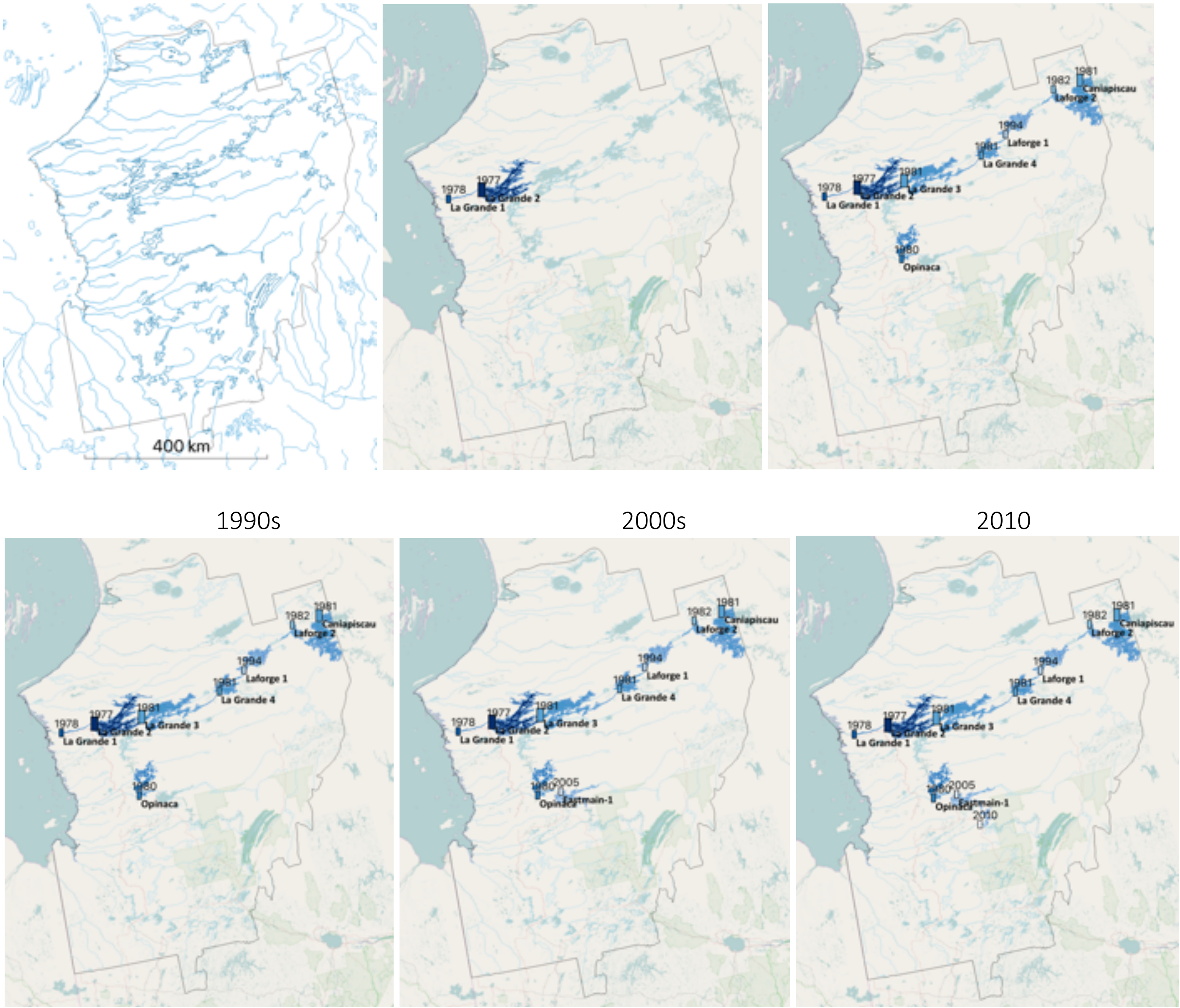


Figure B-3. *Dam and reservoir construction in Eeyou Istchee / Jamésie by decade from 1970 to 2010. Data sources: 2019 GranDam Database (Lehner et al., 2011) and the National Hydrographic Database Rivers dataset (Secretariat, 2019).*

Year	River	Reservoir	km²	Generating Cap (MW)
1977	La Grande	La Grande 2	2759	5616
1978	La Grande	La Grande 1	78	1436
1980	Eastmain	Opinaca	929	768
1981	La Grande	La Grande 3	2401	2417
1981	Caniapiscau	Caniapiscau	3543	469
1981	La Grande	La Grande 4	806	2779
1982	Laforge	Laforge 2	293	319
1994	Laforge	Laforge 1	1048	878
2005	Eastmain	Eastmain-1	591	480
2010	Rupert	Rupert	172	

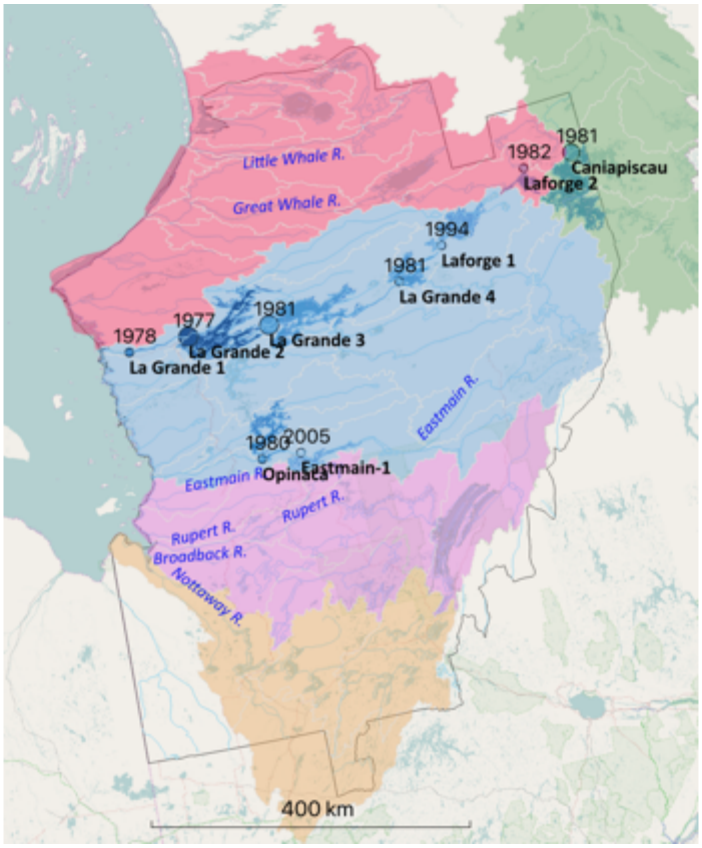


Figure B-4. *James Bay Complex dams, reservoirs, power station capacity, and major drainage basins modified by the project. From north to south: Great and Little Whale, La Grande, Rupert and Broadback, and Nottaway drainage basins. Data Sources: GrandDam Database and Hydro-Quebec, 2019:* http://www.Hydro-Quebec.com/generation/centrale-hydroelectrique.html *National Hydrographic Network; GranDam Database and Lakes and Rivers.*

B-IIIb. Mining

Of the approximately 395,000 term-limited mining titles issued by the province of Quebec in EI/J since 1970 approximately 78,100 are active; 285,000 have expired; and 3600 were revoked, suspended or refused (*SIGÉOM | Système d'information Géominière | SIGÉOM à La Carte*, 2019).

Table B-3. *Active Agreements between Indigenous groups and Mining Companies in EI/J. Data source: Atlas Canada Indigenous Mining Agreements (*https://atlas.gc.ca/imaema/en/*) (Natural Resources Canada & Treasury Board of Canada Secretariat, n.d.)*

Project name	Mining company	Signatories	Agreement type	Project status	Year signed	Commodities
Bachelor Lake	Metanor Resources Inc.	Waswanipi (Cree Nation of), Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority	Socio-Economic Agreement	Producing	2012	Gold
BlackRock Mining Project	BlackRock Metals	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority, Oujé-Bougoumou Cree Nation	Impact and Benefits Agreement	Exploration	2013	Iron, Vanadium, Titanium
Croteau Est and Waconichi	Northern Superior Resources Inc.	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority, Oujé-Bougoumou Cree Nation	Other	Exploration	2013	Gold
Douay	Aurvista Gold Corporation	Conseil de la Première Nation Abitibiwinni	Other	Exploration	2014	Gold
Éléonore	Goldcorp Inc.	Cree Nation of Wemindji, Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority	Cooperation Agreement	Producing	2011	Gold
Hopes Advance Project	Oceanic Iron Ore Corp.	Makivik Corporation, Nunavik Landholding Corporation of Aupaluk	Letter of Intent	Exploration	2011	Iron
Lac Rocher	Victory Nickel Inc.	Waswanipi (Cree Nation of)	MOU	Development	2007	Nickel
Moblan West	Perilya Limited	Cree Nation of Mistissini, Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority	Other	Exploration	2013	Lithium, Tantalum
Montviel Project	Geomega Resources Inc.	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority, Waswanipi (Cree Nation of)	Other	Exploration	2011	Rare Earth Elements
Renard Diamond Project	Stornoway Diamond Corp.	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority, Cree Nation of Mistissini	Impact and Benefits Agreement	Producing	2012	Diamonds
Rose Tantalum-Lithium	Critical Elements Corp.	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority, Eastmain (Cree Nation of)	Other	Exploration	2012	Tantalum, Rare Earth Elements, Lithium
Whabouchi Property	Nemaska Lithium Inc.	Grand Council of the Crees (Eeyou Istchee) / Cree regional Authority	Other	Exploration	2014	Lithium
Windfall Lake	Osisko Mining Corp.	Waswanipi (Cree Nation of), Grand Council of the Crees	Exploration Agreement	Exploration	2012	Gold

		(Eeyou Istchee) / Cree regional Authority				

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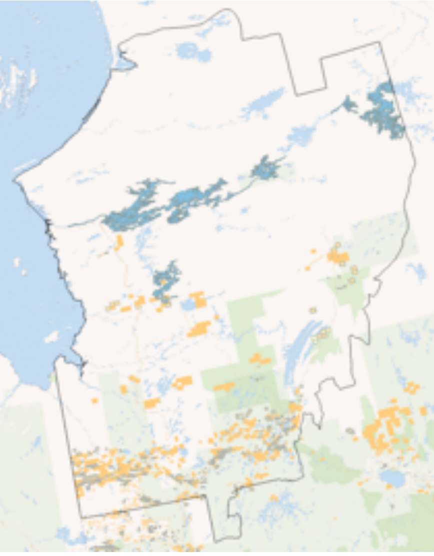
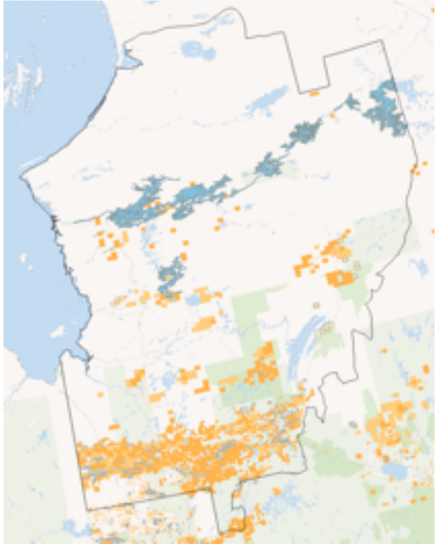
1970-1979

1970-1984

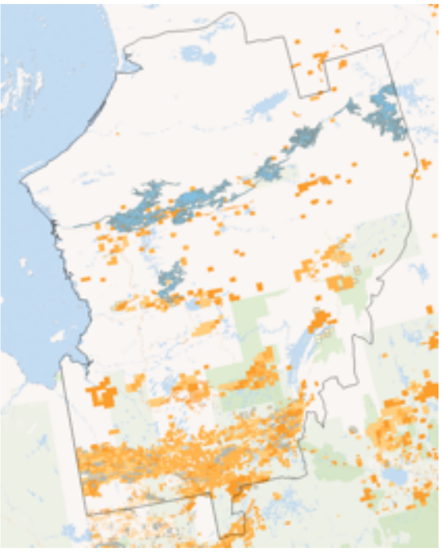
1970-1989



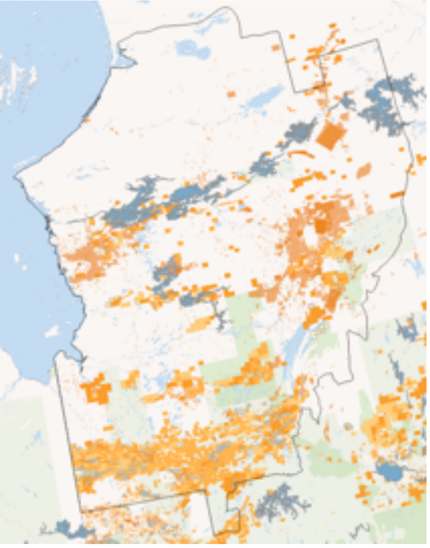
1970-1994



1970-1999



1970-2004



1970-2009

1970-2014

1970-2019

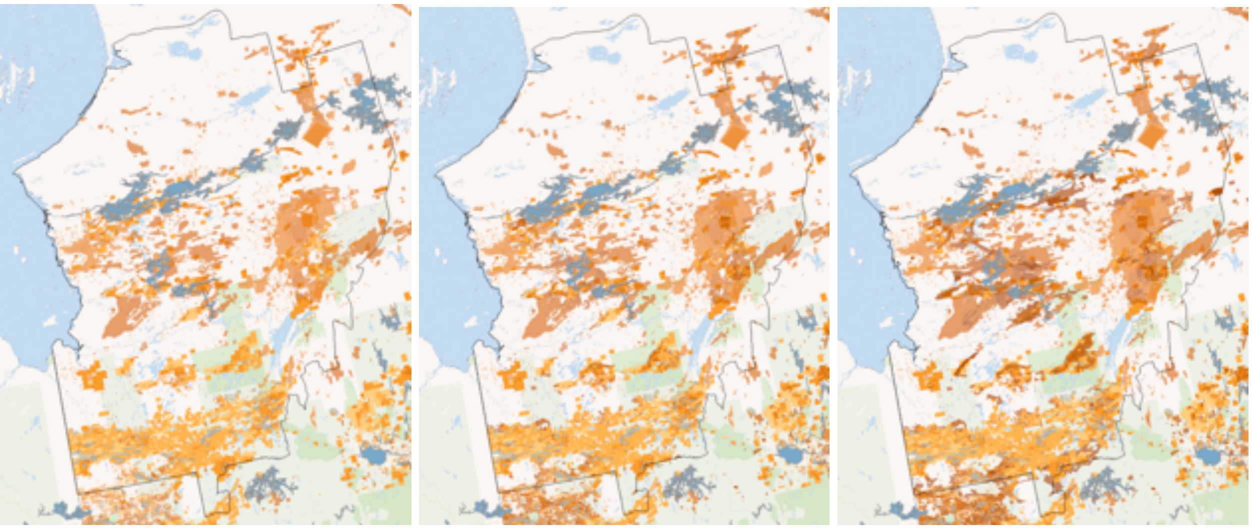
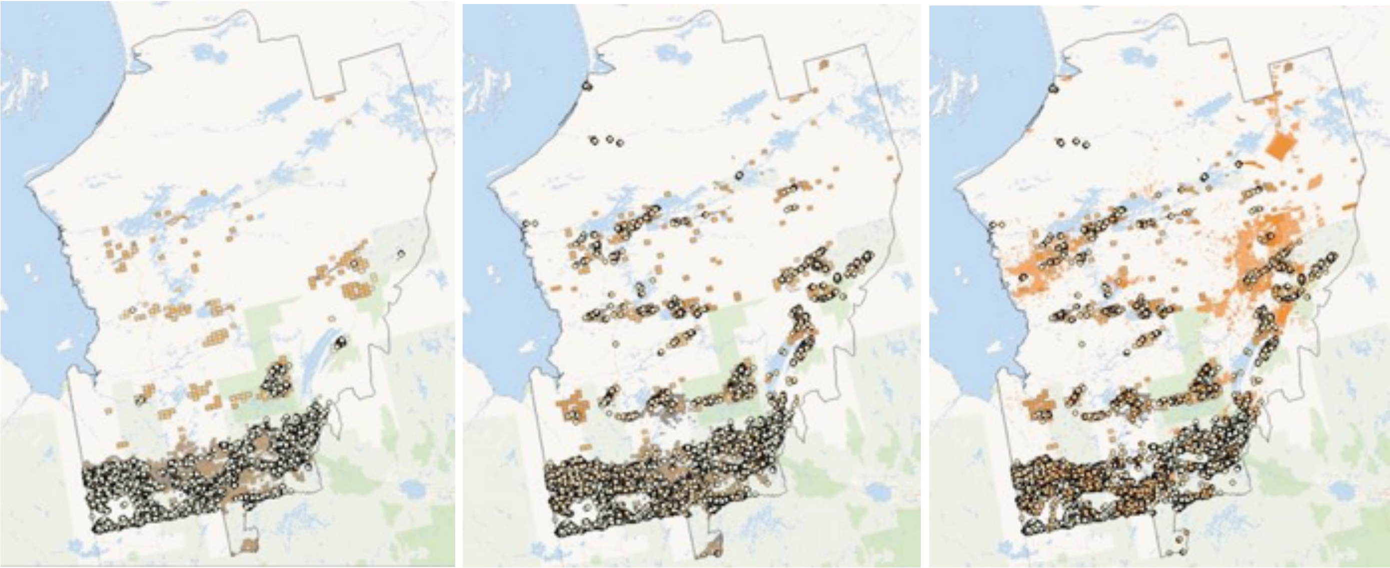


***Figure B-5**. Start date of mining titles (leases) from 1970-2019. Data Source:* (*SIGÉOM | Système d'information Géominière | SIGÉOM à La Carte*, 2019)

1990-1994 1990-1999 1990-2004



1990-2009 1990-2014 1990-2019

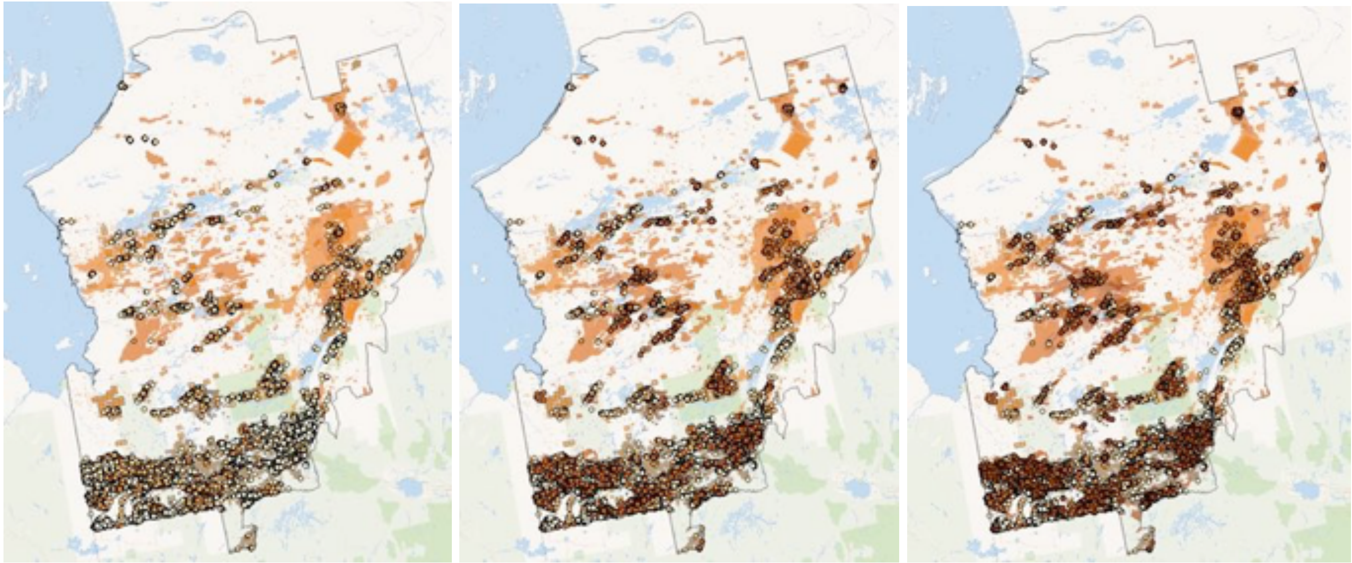
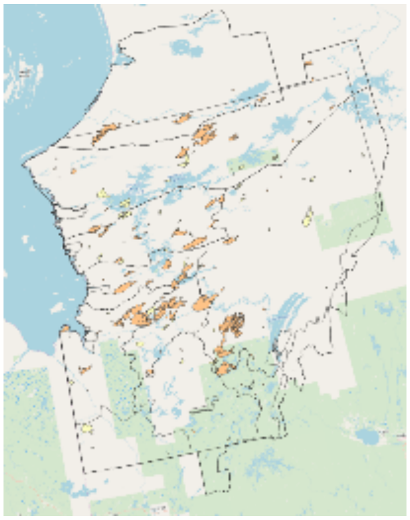


Figure B-6. *Exploratory drilling maps overlaid with titles in EI/J.*

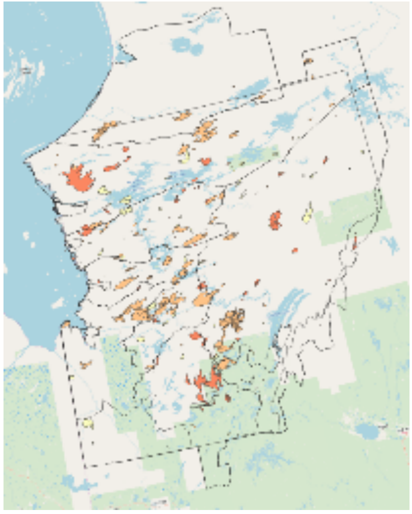
B-IIIc. Fire

1973-1978

1973-1983



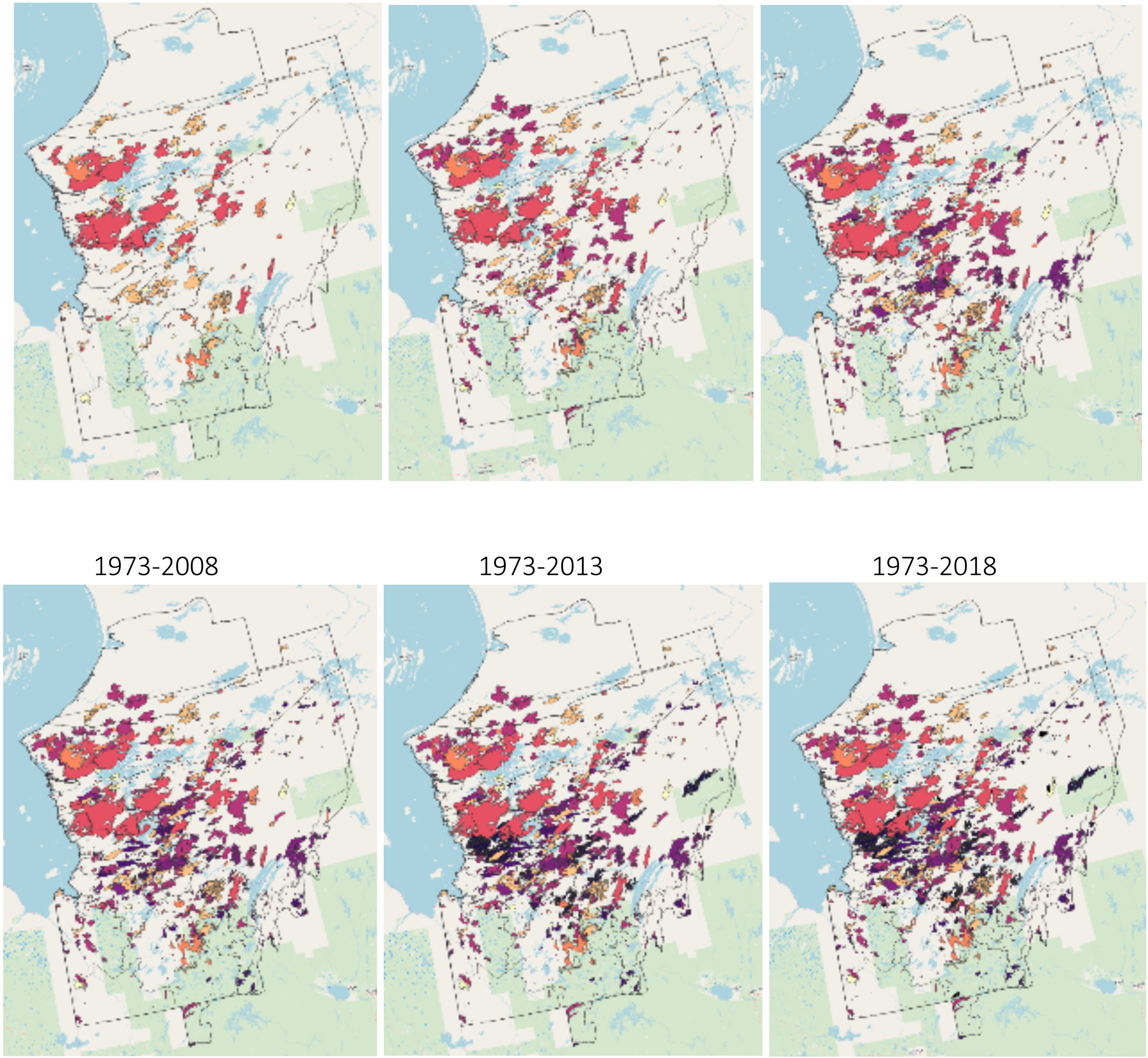
1973-1988



1973-1993

1973-1998

1973-2003

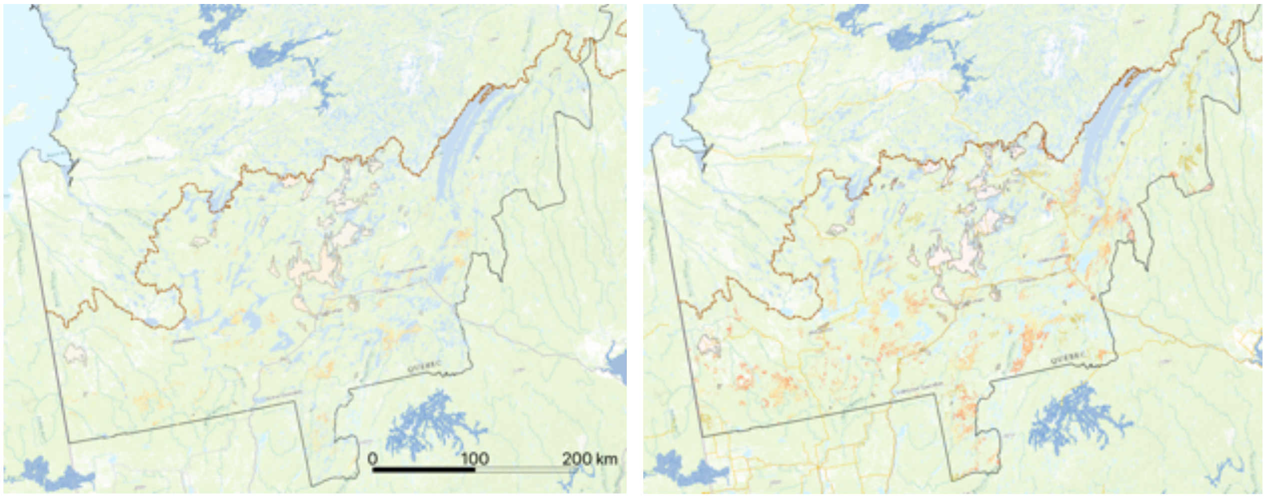


1973-2008 1973-2013 1973-2018

__Figure B-7.__ Time series of forest disturbances due to fire in EI/J. Data source: Canadian National Fire Data Base (Canadian Forest Service, 2019).

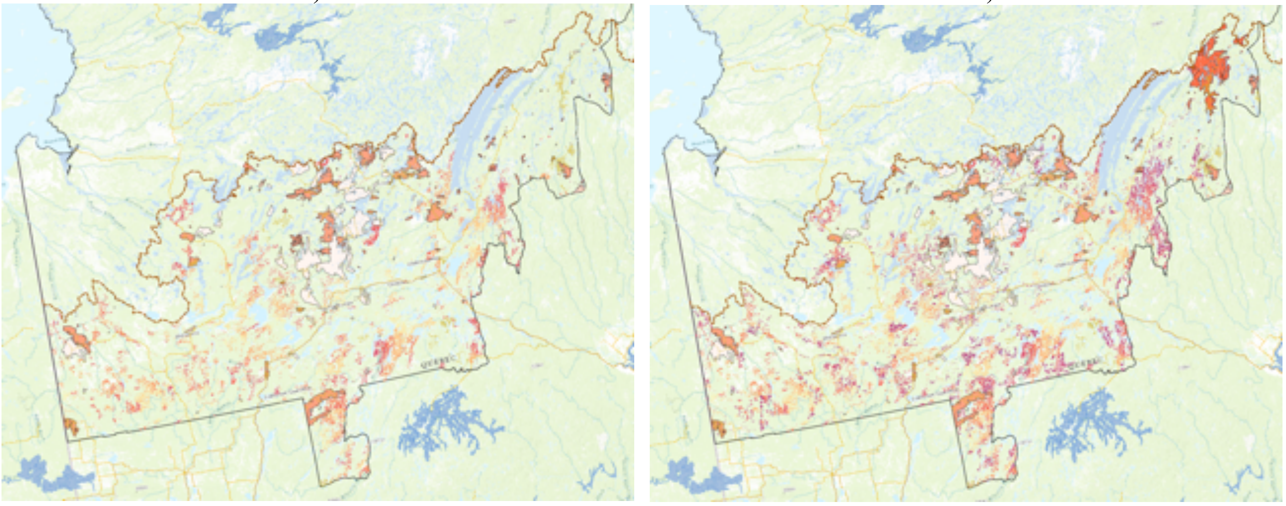
B-IIId. Logging

a) 1984-1988 b) 1984-1993



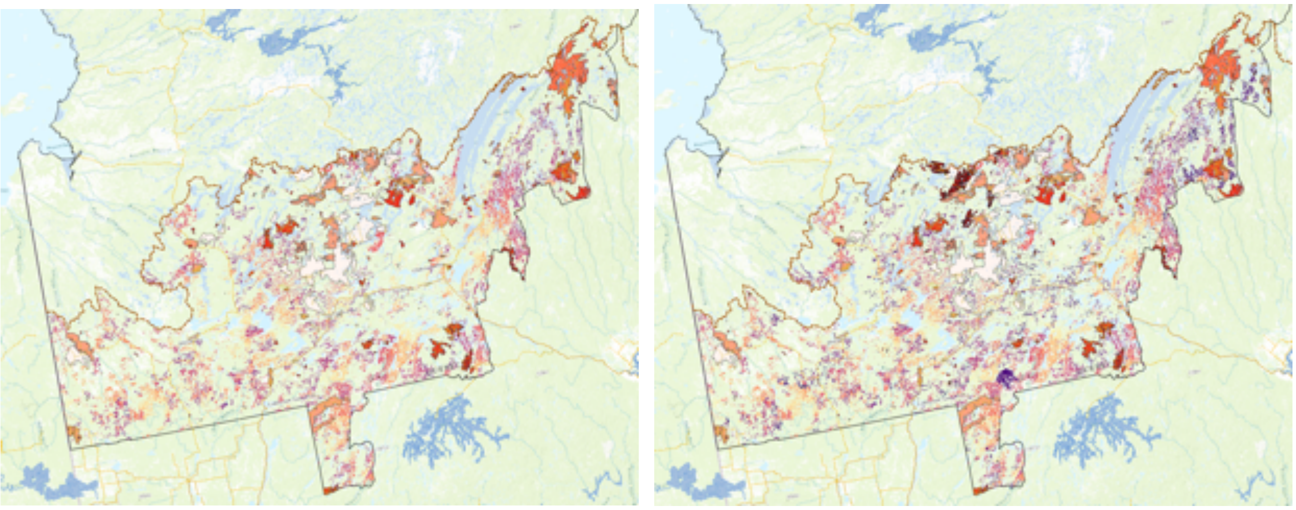
c) 1984-1998

d) 1984-2003



e) 1984-2008

f) 1984-2013



g) 1984-2018

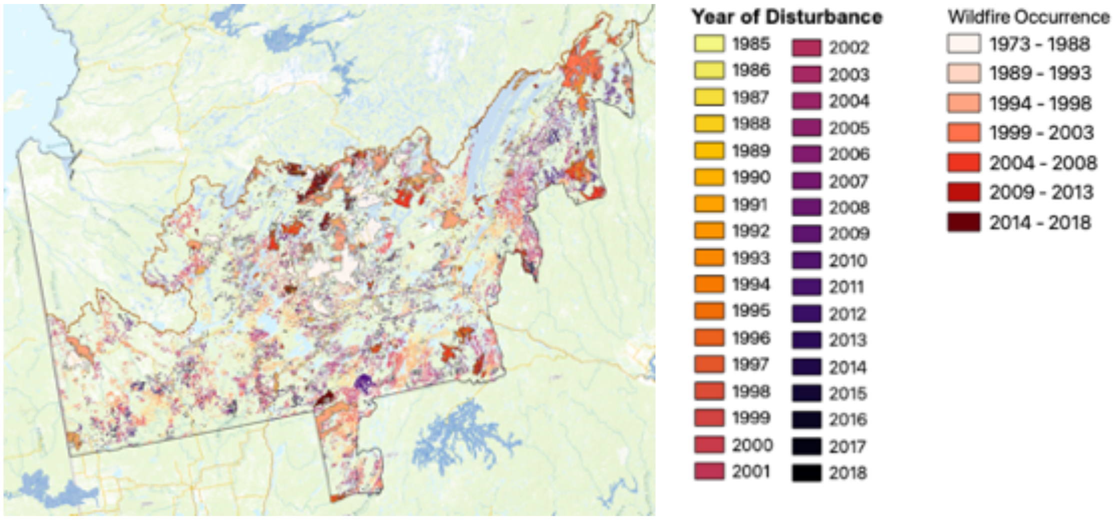


Figure B-8. *Time series reconstruction of cutblocks and fire in the commercial forestry zone in Eeyou Istchee / Jamésie.*

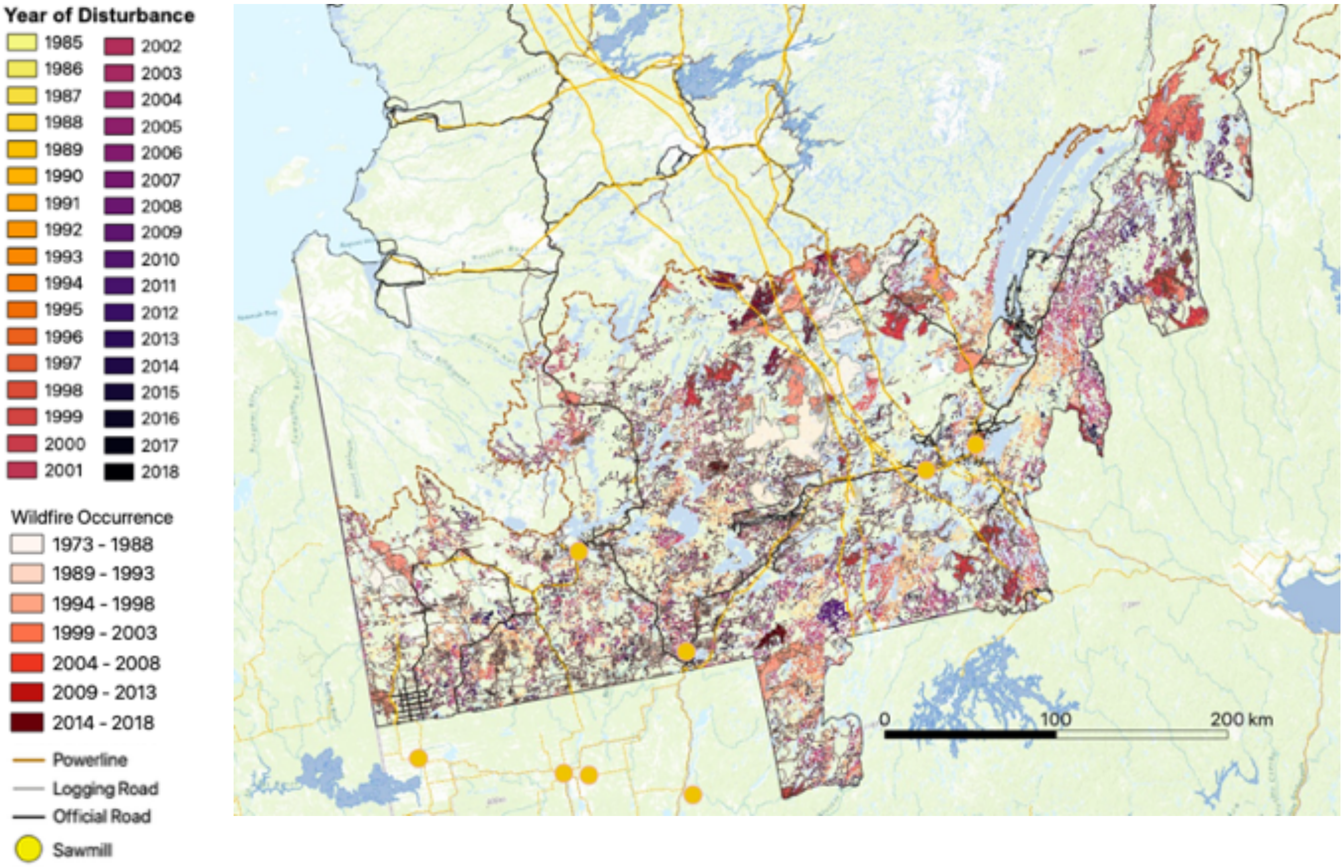


Figure B-9. *System interdependencies: Sawmills are located along both power and major road networks.*

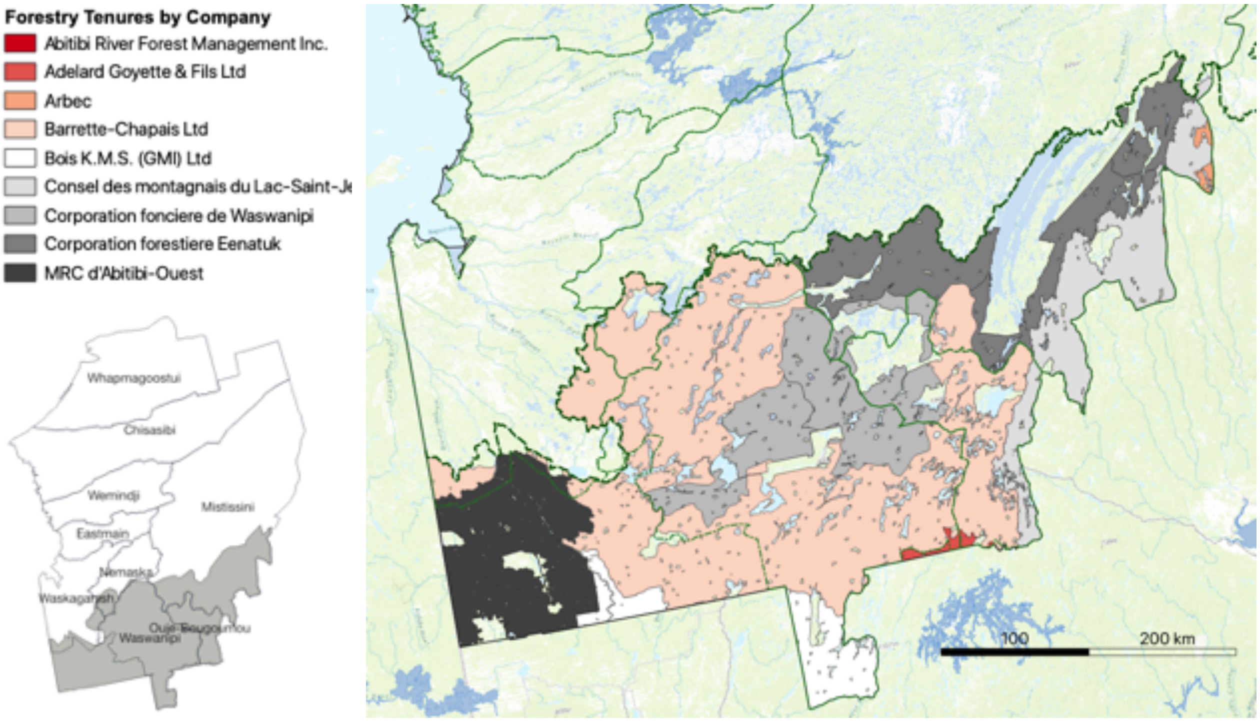


Figure B-10. *Commercial Forestry Tenures in EI/J. Data source: (Global Forest Watch, 2019)*

Linear disturbances due to roads and transmission lines were not reliably identified by Landtrendr, although some roads linking cutblocks are visible at finer scales (Main Text, Figure 12).

Comparing Landtrendr and Disturbance Type Datasets

Table B-4. *Percent of areas in validation data layers identified as disturbed by Landtrendr NBR.*

Disturbance Type Validation Dataset	**Landtrendr-identified Disturbed Area in Validation Dataset (km^2)**	**Validation Dataset: Total Area (km^2)**	**% of disturbance area identified as disturbed by Landtrendr**
Fire / NFDB	47400	81400	58%
Cutblock / EC BEAD	10400	19100 (to 2010)	55%
Mining / EC BEAD	75	188 (to 2010)	40%
Reservoir / EC BEAD	1584	12600	13%

Unclassified	--	19900	--

B-IV. Embodied Injustices

B-IVa. Disturbance Type and Wildlife Capture by Community

Table B-5. *Cree Nation forest losses by type. Data sources: https://www.cngov.ca/community-culture/communities/ and https://www.decrochezcommejamais.com/fichiersUpload/fichiers/20190401094139-web-eng-bj-gto-2019.pdf*

Cree Nation (North to south)	**Population**	**Area (km^2)**	**Reservoir (km^2)**	**Powerline (km)**	**Total Forest Loss (km^2)**	**Fire (%)**	**Cutblock (%)**	**Forest Loss (%)**
Whapmagoostui	1550	67300	-	0	4140	2	-	6
Chisasibi	5000	82200	7500	780	11500	11	-	14
Mistissini	4550	126000	2000	550	28600	11	3	23
Wemindji	1540	28800	850	780	8060	26	-	28
Eastmain	830	15200	1100	460	6080	38	-	40
Waskaganish	2620	29700	-	180	4120	9	1	14
Nemaska	850	14900	120	500	4500	24	1	30
Oujé-Bougoumou		10600	-	400	1960	4	12	16
Waswanipi	2010	37100	-	500	8920	7	16	24

Table B-6. *Mining activity and roads in each Cree Nation. Data sources: Quebec SIGEOM; Statistics Canada 2019 Road Network File (https://www150.statcan.gc.ca/n1/en/catalogue/92-500-X); BEADD, (Pasher et al., 2013).*

Cree Nation (North to south)	**Mines**	**Mining Agreements**	**Exp. Drilling**	**Mining Titles**	**Official Roads (km)**	**Logging Roads (km)**
Whapmagoostui	-	-	190	5970	30	-
Chisasibi	-	-	1700	27200	710	-
Mistissini	1	3	6600	101000	510	3000
Wemindji	1	1	1500	31300	440	-
Eastmain	2	-	1900	19200	240	-
Nemaska	1	1	960	9000	360	350
Waskaganish	-	-	1700	23500	210	550
Oujé-Bougoumou	2	1	11600	29800	380	1300
Waswanipi	3	5	11400	79100	440	6000

Matthew Coon Come, Grand Chief of the Grand Council of the Crees from 1987-1999, describes the impact of the James Bay Complex on wildlife and Cree hunting and fishing as follows, highlighting issues surrounding control over interconnected systems:

> “We have realized that programs to build hunters' campsites beside the reservoirs are not worthwhile, because the animals do not live there. One hunter discovered a beaver lodge twenty feet high on the edge of a reservoir. The beavers had kept building higher to keep ahead of the rising water all summer. When the winter came, the water was drawn down and the beavers froze. We have discovered that the boat access ramps are useless in areas where the trees are left standing underwater, because the trees block boat access to the shore. Furthermore, the fish are highly contaminated by mercury leaching out of the rotting vegetation; if we eat the fish, one of our staples, we get methylmercury poisoning. We have discovered that beaver and lynx relocated by helicopter from the areas to be flooded very often die from the shock of the move. We have discovered that the engineers' promises that they could manage the flows appropriately were untrue, when 10,000 caribou drowned trying to follow their traditional migration paths” (Coon Come, 2004: 158).

Table B-7. *Wildlife capture trends in Eeyou Istchee from July 1, 1989 to June 30, 2019. The three-year average from 1989-1991 is the ‘beginning’ value and the three-year average from 2017-2019 is the ‘end’ value, shown along with percent change. (Three-year averages are rounded, except when the rounded value further explains percent change.) Data source: (Cree Trappers Association - GeoPortal for Eeyou Istchee, n.d.)*

Cree Nation (North to south)	**1000 km^2**	**Forest Loss (%)**	**Caribou % Change (Beg | End)**	**Moose % Change (Beg | End)**	**Beaver % Change (Beg | End)**	**Marten % Change (Beg | End)**
Whapmagoostui	67	6	-54% (154 | 70)	-1% (.6 | 0)	-96% (93 | 3)	-86% (358 | 47)
Chisasibi	82	14	-71% (196 | 56)	10% (27 | 30)	-90% (447 | 46)	106% (84 | 220)
Mistissini	126	23	-93% (297 | 21)	-47% (206 | 109)	-92% (967 | 77)	-72% (968 | 268)
Wemindji	28	28	-99% (48 | .3)	-77% (48 | 11)	-76% (483 | 114)	940% (21 | 224)
Eastmain	15	40	-100% (4 | 0)	-38% (41 | 26)	-80% (246 | 50)	-19%(50 | 40.3)
Waskaganish	30	14	-97% (59 | 1.6)	-39% (49 | 30)	-84% (591 | 96)	-40% (277 | 167)
Nemaska	15	30	-92% (12 | 1)	-7% (41 | 38)	-90% (178 | 17)	-61% (85 | 33)
Waswanipi	37	24	-- (0 | 2)	-57% (237 | 102)	-85% (372 | 55)	-87% (272 | 35)

Cree Nation (North to south)	**Km^2**	**Forest Loss (%)**	**Black Bear Beg/End/ %change**	**Linx Beg/End/ change**	**Mink Beg/End/ change**	**Otter Beg/End/ change**
Whapmagoostui	67,300	6	-59% (16 | 7)	-89% (6 | 1)	-100% (98| 0)	-100% (31 | 0)

Chisasibi	82,200	14	107% (14| 30)	-84% (100| 16)	-98% (104 | 2)	-90% (61 | 6)
Mistissini	126,000	23	-9% (30 | 28)	-89% (25 | 3)	-96% (334 | 5)	-91% (136 | 12)
Wemindji	28,800	28	-71% (18 | 5)	-77% (109 | 25)	-90% (45 | 5)	-65% (47 | 16)
Eastmain	15,200	40	13% (17 | 20)	-87% (39 | 5)	-100% (15 | 0)	-80% (15 | 3)
Waskaganish	29,700	14	14% (2 | 3)	-88% (11 | 1)	-100% (37 | 0)	-89% (28 | 3)
Nemaska	14,900	30	-84% (6 | 1)	-53% (6 | 3)	-100% (22 | 0)	-96% (8 | 0)
Waswanipi	37,100	24	557% (5 | 30)	-60% (10 | 4)	-91% (30 | 3)	-82% (11 | 2)

Cree Nation (North to south)	**Km^2**	**Forest Loss (%)**	**Wolf Beg/End/ change**	**Red Fox Beg/End/ change**	**Silver Fox Beg/End/ change**	**White Fox Beg/End/ change**
Whapmagoostui	67,300	6	-93% (5 | .3)	-93% (19 | 1)	-50% (1 | .3)	-100% (1 |0)
Chisasibi	82,200	14	-97% (22 | 1)	-75% (88 | 21)	-76% (8 | 2)	200% (1 | 3)
Mistissini	126,000	23	-98% (16 | .3)	-94% (37 | 2)	-100% (1 | 0)	--% (0 | 0)
Wemindji	28,800	28	-36% (4 | 2)	-38% (37 | 23)	-83% (2 | .3)--	--% (0| 1)
Eastmain	15,200	40	-100% (1 | 0)	-97% (10 | 0)	--% (0 | 1)	100% (.3 | 0)
Waskaganish	29,700	14	--% (0 | 0)	-72% (32 | 9)	-100% (.3 | 0)	--% (0 | .3)
Nemaska	14,900	30	-100% (3 | 0)	-62% (4 | 2)	--% (0 | 0)	--% (0 | 0)
Waswanipi	37,100	24	-100% (1 | 0)	-93% (9 | 1)	--% (0 | 0)	--% (0| 0)

Cree Nation (North to south)	**Km^2**	**Forest Loss (%)**	**Muskrat Beg/End/ change**	**Weasel Beg/End/ change**	**Skunk Beg/End/ change**	**CFX Beg/End/ change**
Whapmagoostui	67,300	6	-100% (256 | 1)	-100% (135 | 0)	-100% (0.3| 0)	-100% (2 | 0)
Chisasibi	82,200	14	-92% (461 | 39)	-91% (93 | 8)	--% (0 | 0)	-80% (16 | 3)
Mistissini	126,000	23	-97% (293 | 7)	-94% (71 | 4)	--% (0 | 0)	-83% (2 | .3)
Wemindji	28,800	28	-91% (142 | 13)	-45% (35 | 19)	--% (0 | 0)	-43% (8 | 4.3)
Eastmain	15,200	40	-74% (13 | 3)	-100% (11 | 0)	--% (0 | 0)	0% (1 | 1)
Waskaganish	29,700	14	-92% (182 | 15)	-100% (8 | 0)	--% (0 | 0)	-100% (1 |0)
Nemaska	14,900	30	-87% (13 | 2)	-100% (7 | 0)	--% (0 | 0)	-100% (1 | 0)
Waswanipi	37,100	24	-94% (41 | 2)	-44% (5 | 3)	--% (0 | 0)	100% (.3 |.6)

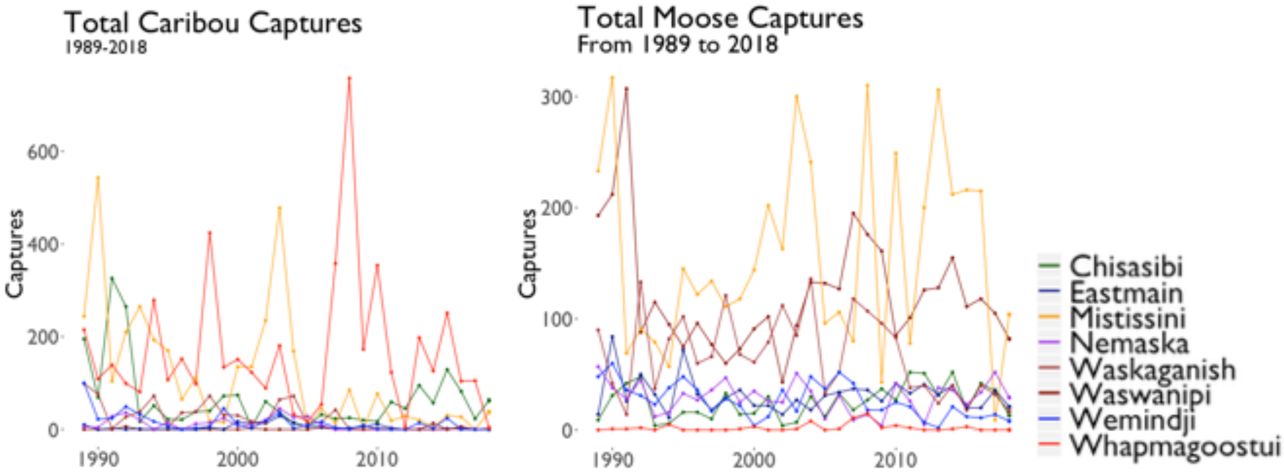


Figure B-11. *Caribou and moose captures in EI.*

B-IVb. Logging

Until 2013, private forestry companies in Quebec were responsible not only for timber extraction, but also for forest planning and management. In 2013 Quebec introduced a new forest policy regime, under the Sustainable Forest Development Act, which introduced government-led planning in Quebec's forested regions, which are largely the unceded territories of eleven First Nations in Quebec, including 55 communities (Teitelbaum et al., 2019; SI Section IVa). Teitelbaum et al (forthcoming) note the PDB's adapted forestry regime strengthened the role of the Crees with respect to forestry governance in Eeyou Istchee, creating new consultative mechanisms at the regional and local levels. The Cree-Quebec Forestry Board, comprised of five representatives from the Cree Regional Authority and five from Quebec was given responsibility for PDB implementation. At the community level, Joint Working Groups were formed, including two appointees from each Cree community and two provincial appointees, with the responsibility for implementation of specific PDB provisions and addressing forestry-related conflicts.

As the governance landscape has become more varied, Crees have adopted new strategies, including engagement with the Forest Stewardship Council, an international non-state, market-driven forest certification regime requiring 'free and informed consent' in order to provide certification of forest products (Teitelbaum et al., 2019). The new provincial regime included a commitment to undertake specific consultations with Indigenous communities (a policy known as "consultation and accommodation") but specifically does not go as far as the "free and informed consent" required for FCS certification, leading the province reverse its decision to become FSC certificate holder, instead collaborating "with the forest industry to allow private companies to remain the parties responsible for certification. The government would play a backseat role, setting up advisory committees for each forest management unit to ensure communication between industry and government on issues related to FSC certification and forest management planning" (Teitelbaum et al., 2019: 17).

B-IVc. Water

In the 2009 study *Nituuchischaayihtitaau aschii* ("Let us know our land"), commissioned by the Cree Board of Health, total coliforms, E. coli, and enterococci were detected at least once in all tested drinking water sources used by the Cree community of Mistissini apart from tap water. Although existing water harvesting and storage practices were found to decrease microbial counts, the study recommended that raw water be boiled before consumption (Bernier et al., 2009). A study by the Public Health Department of the Cree Board of Health and Social Services of James Bay and local First Nation Councils in 2005 found that drinking water from some springs and streams and water used in camps were contaminated (Cree Board of Health and Social Services of James Bay, 2018). Closed or abandoned mining sites around the Chibougamau region are also of major concern due to water contamination affecting the watershed (*Cree Vision of Plan Nord*, 2011: 99).

Elevated mercury levels in fish as a result of reservoir formation were first detected in South Carolina in the mid 1970s and have been recorded in a variety of tropical, temperate and boreal areas around the world (Rosenberg et al., 1995).

Table B-8. *Restrictions on Fish Consumption due to mercury contamination in Eeyou Istchee / Jamésie. Data Source: Northern Fish Nutrition Guide: James Bay Region. (https://www.creehealth.org/sites/default/files/Guide_BaieJames_Ang_BasseR.pdf) (Blanchet, n.d.).*

	LaGrande - Western Sector		*LaGrande - Eastern Sector*		*Eastmain 1 Sector*
Fish Species	Reservoirs	Natural Lakes	Reservoirs	Natural Lakes	Reservoirs
Lake Whitefish	🟩	🟩	🟩	🟩	🟩
Speckled Trout		🟩		🟩	
Walleye	🟥	🟧			🟥
Pike	🟥	🟧	🟥	🟧	🟥
Lake Trout	🟥	🟧	🟥	🟧	🟥

	Eastmain 1 Sector	*Rupert Sector*		
Fish Species	Natural Lakes	Rupert Division Bays & Upper Nemiscau R.	Natural Lakes & Rupert R.	Lemare & L. Nemiscau Rivers
Lake Whitefish	🟩	🟨	🟩	🟨
Speckled Trout	🟩		🟩	🟨

Walleye	🟧	🟥	🟧	🟥
Pike	🟧	🟥	🟧	🟥
Lake Trout	🟧	🟥	🟧	🟥

Table B-9. *Restrictions on Fish Consumption due to mercury contamination in Eeyou Istchee / Jamésie. Source: Healthy Fish Eating in Eeyou Istchee (https://www.creehealth.org/library/online/healthy-fish-eating-eeyou-istchee-map) (Cree Board of Health and Social Services of James Bay (CBHSSJB), 2015).*

	Drainage Basin			
Fish Species	*Little and Great Whale*	*LaGrande Reservoirs and rivers downstream from powerhouse*	*La Grande Natural Lakes and Rivers*	*La Grande Rupert forebay and tailbay*
Lake Whitefish	🟩	🟩	🟩	🟨
Sucker	🟩	🟩	🟩	🟨
Lake Sturgeon	🟩	🟩	🟩	🟨
Cisco	🟩	🟨	🟩	🟨
Speckled Trout	🟩	🟨	🟩	🟨
Pike	🟧	🟥	🟧	🟫
Walleye	🟧	🟥	🟧	🟫
Lake Trout	🟧	🟫	🟧	🟫

Fish Species	*La Grande Eastmain 1 Reservoir and Rivers downstream from powerhouse*	*Rupert*	*Nottaway*	*Broadback*
Lake Whitefish	🟨	🟩	🟩	🟩
Sucker	🟨	🟩	🟩	🟩
Lake Sturgeon	🟨	🟩	🟩	🟨
Cisco	🟨	🟩	🟩	🟩
Speckled Trout	🟨	🟩	🟩	🟩
Pike	🟫	🟧	🟥	🟥
Walleye	🟫	🟧	🟥	🟥
Lake Trout	🟫	🟧	🟧	🟧

🟩	0-0.29	Unrestricted
🟨	0.30-0.49	8 meals per month
🟧	0.5-0.99	4 meals per month

🟥	1.0-1.99	2 meals per month
🟥	2.0-3.75	1 meal per month

B-V. Discussion

B-Va. Fire

Wildfires in California show an overall decline in ignition sources in recent decades, yet powerline ignitions have increased (Keeley & Syphard, 2018) and tend to burn larger areas than fires ignited by other causes (Collins et al., 2016). Powerline-ignited fires tend to be much more dangerous and capable of rapid spread because they generally occur during high winds, which have three effects: tree contact, line arcing, and metal fatigue resulting in downed lines (Mitchell, 2009). In southern Australia a disproportionate number of electricity-caused wildfires occurred when fire danger was high (Miller et al., 2017). Powerline distribution along roads may contribute to burning patterns that are closely correlated with road distribution in southern California (Faivre et al., 2014; Keeley & Syphard, 2018).

B-Vb. Transboundary Sustainability

An emphatic clean energy rhetoric surrounds Hydro-Quebec's initiatives to export hydropower to neighboring states and provinces, including the New England Clean Energy Connect (NECEC), a new 1200 MW interconnection deliver electricity to the New England grid from Quebec via Maine:

> The contract will meet 17% of Massachusetts' electricity needs while cutting its GHG emissions by more than 36 million tons of CO_2 equivalent—roughly comparable to taking 413,000 cars off the road. The deliveries will help reduce

> dependency on costly and emissions-generating fuels like oil and natural gas. Overall, the contract will benefit not just Quebec and Massachusetts, but Maine and all of New England as well (*Hydro-Quebec 2019 Annual Report,* 2020: 27).

As power demands in neighboring provinces and in nearby U.S. states increase, Hydro-Quebec is increasingly able to market the huge storage capacity of its reservoir generating stations as 'clean' energy that can meet baseload demand, complementing solar and wind initiatives. The utility is committed to "stepping up initiatives to increase electricity exports to all markets in northeastern North America." In 2019, hydropower exports from Quebec permitted their neighbors to obtain, "at competitive prices, a large quantity of green energy that they could use to offset the intermittent nature of their renewables, such as solar and wind power" (*Hydro-Quebec 2019 Annual Report,* 2020: 27).

Quebec's industrial sector consumed 84.1 TWh of electricity in 2017 while its residential and commercial sectors consumed 66.6 TWh and 23 TWh, respectively (Government of Canada, 2020a). In neighboring Ontario, by contrast, electricity consumption is split roughly equally between the three sectors: in 2017 the commercial sector consumed 47.0 TWh and the residential and industrial sectors consumed 44.2 TWh and 42.1 TWh, respectively (Government of Canada, 2020b).

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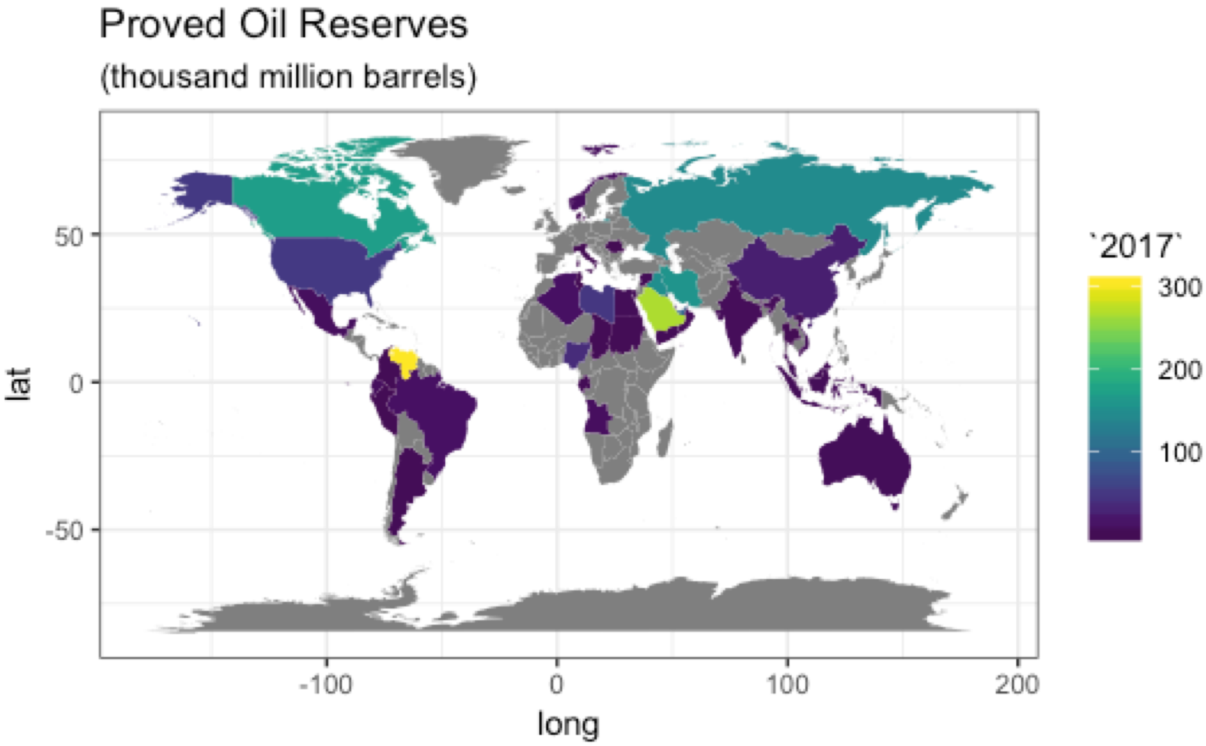
APPENDIX C: CHAPTER 4 Supplementary Information (SI)

Table C-1. *Major datasets for each process in the generalized global production network for oil at the national level.*

National-Level Global Datasets	**Company-level datasets**
• Global Resources / Proved Reserves 1980-2017: USGS, EIA, BP STATS, OPEC] • Production 1965-2017 (EIA, BP STATS, OPEC) • Transportation & Trade 2000-2017 (BP STATS, UNCOMTRADE, EIA) • Refining and Processing 1965-2017 (BP Stats, OPEC, US EIA) • Consumption**,** 1965-2017 (BP STATS, EIA) • Carbon Dioxide Emissions**,** 1965-2017 (BP STATS);	• Global Resources / Proved Reserves ResourceContracts.org: Online repository of petroleum and mining contracts • Production Chevron 'Alternative Annual Report' (2009-2011) NRGI: National Oil Company dataset • Transportation & Trade EIA Energy Imports to US by Company • Carbon Dioxide Emissions Carbon Underground; Carbon Majors Database • Env Impacts: World Resources Institute: BP Operations in Ecologically Sensitive Areas


Proved Oil Reserves
(thousand million barrels)
lat
50
0
-50
long
-100
0
100
200
`2017`
300
200
100

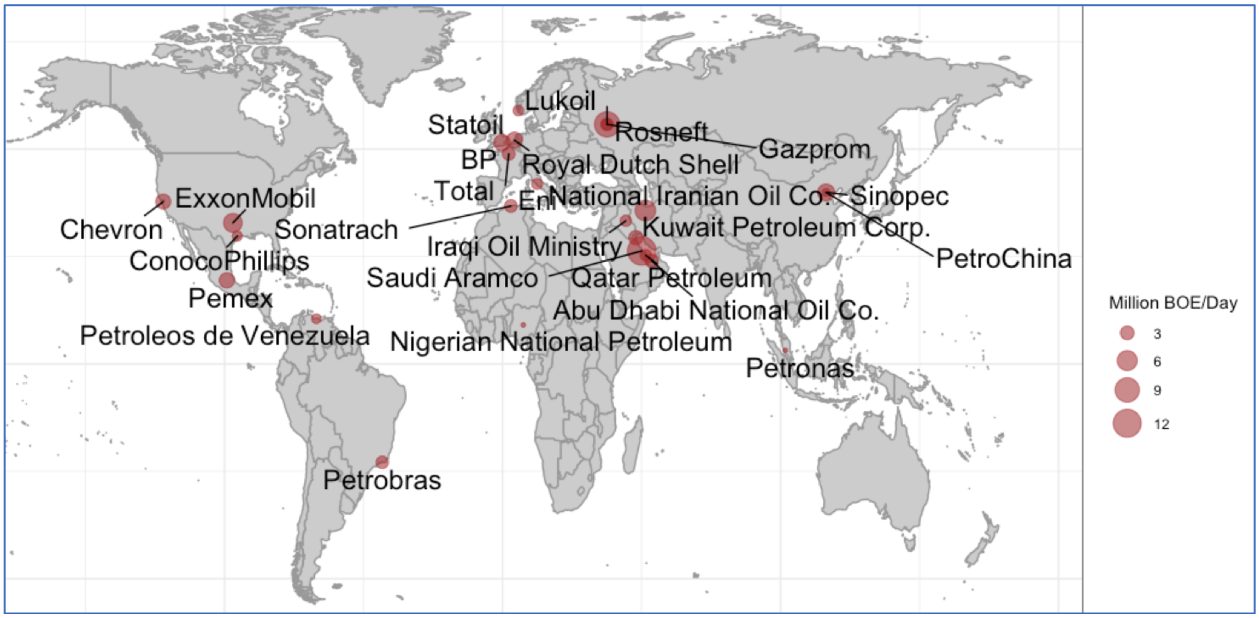

Lukoil
Statoil
Rosneft
Gazprom
BP
Royal Dutch Shell
Total
Eni
National Iranian Oil Co.
Sinopec
ExxonMobil
Chevron
Sonatrach
Kuwait Petroleum Corp.
ConocoPhillips
Iraqi Oil Ministry
PetroChina
Saudi Aramco
Qatar Petroleum
Pemex
Abu Dhabi National Oil Co.
Petroleos de Venezuela
Nigerian National Petroleum
Petronas
Petrobras
Million BOE/Day
3
6
9
12

Table C-2. *Network metrics across multiplex production network time series at the national level: Big Oil, Hybrid Companies and NOCS as separate networks (in R).*

Big Oil	**2014**	**2015**	**2016**	**2017**	**2018**
Nodes *N* (Company; Country)	7 58	7 60	7 59	7 60	7 58
Edges *m*	383	378	435	439	469
Assortativity	-0.117	-0.081	-0.125	-0.113	-0.157

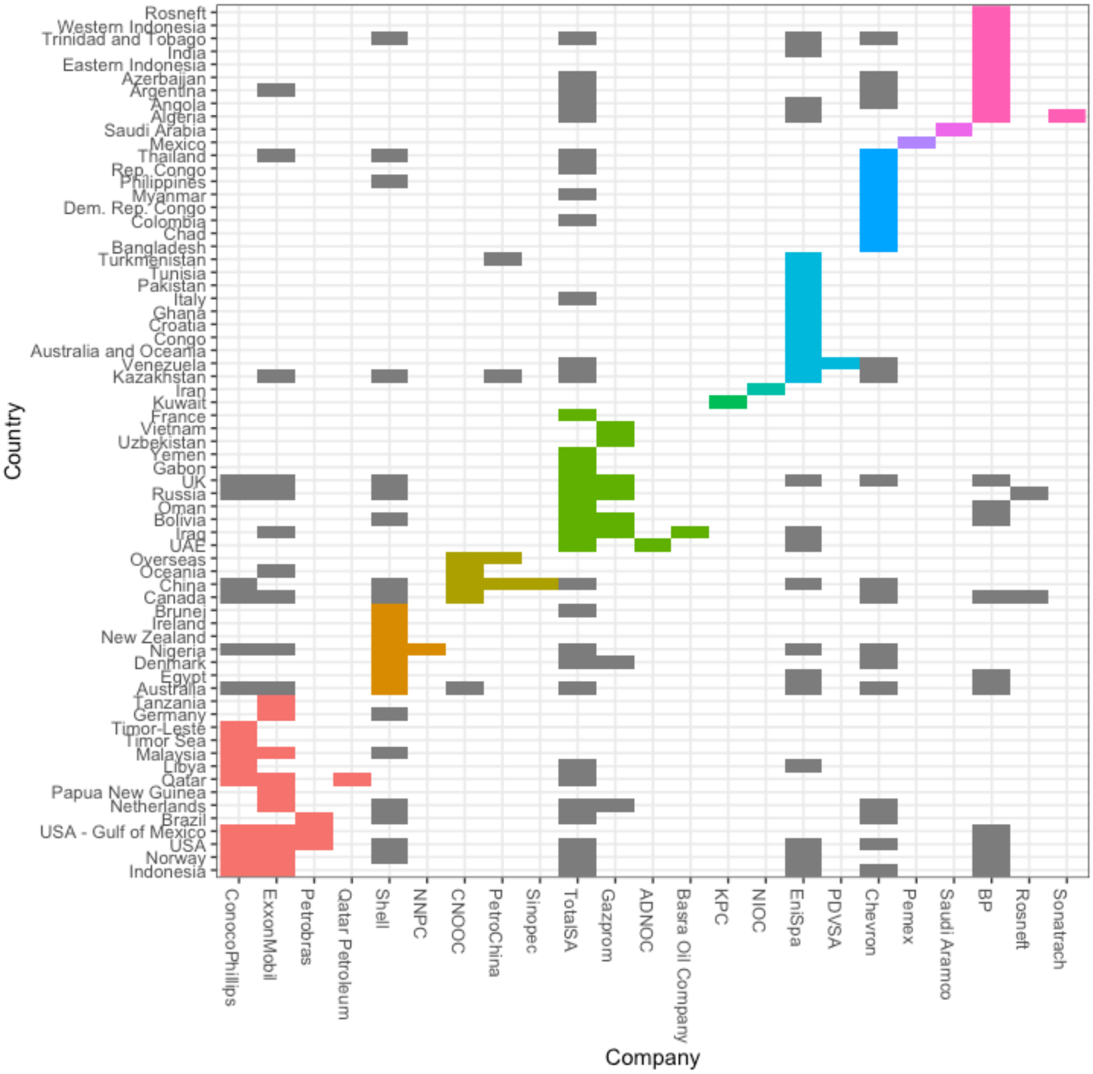
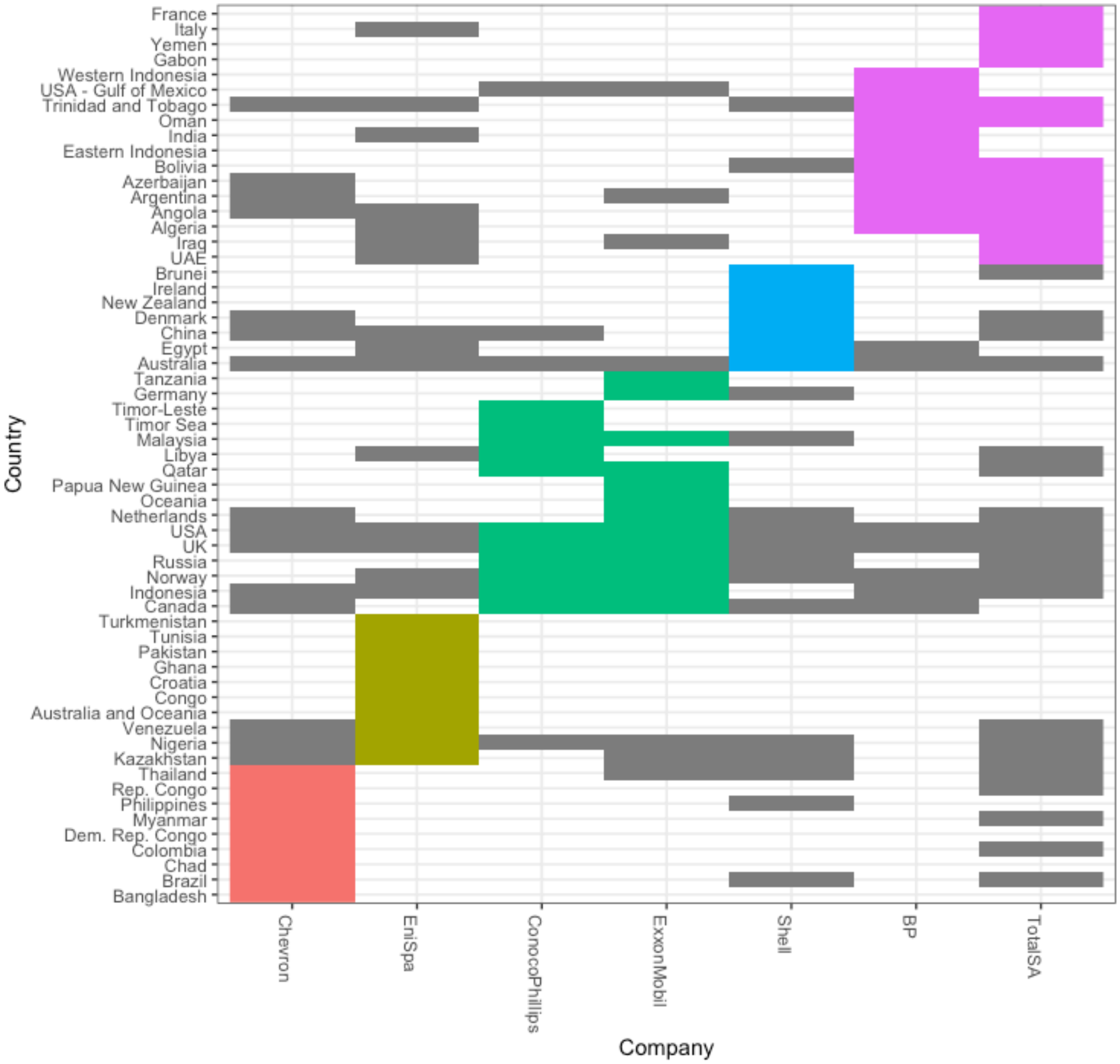


Figure C-1. *Larger versions of adjacency matrices appearing in main text. Gas (top) and liquids (bottom) for all companies across 2014-2018. The gas network displays more modularity (0.269) than the liquids network (0.104).*


Country
France
Italy
Yemen
Gabon
Western Indonesia
USA - Gulf of Mexico
Trinidad and Tobago
Oman
India
Eastern Indonesia
Bolivia
Azerbaijan
Argentina
Angola
Algeria
Iraq
UAE
Brunei
Ireland
New Zealand
Denmark
China
Egypt
Australia
Tanzania
Germany
Timor-Leste
Timor Sea
Malaysia
Libya
Qatar
Papua New Guinea
Oceania
Netherlands
USA
UK
Russia
Norway
Indonesia
Canada
Turkmenistan
Tunisia
Pakistan
Ghana
Croatia
Congo
Australia and Oceania
Venezuela
Nigeria
Kazakhstan
Thailand
Rep. Congo
Philippines
Myanmar
Dem. Rep. Congo
Colombia
Chad
Brazil
Bangladesh
Chevron
EniSpa
ConocoPhillips
ExxonMobil
Shell
BP
TotalSA
Company

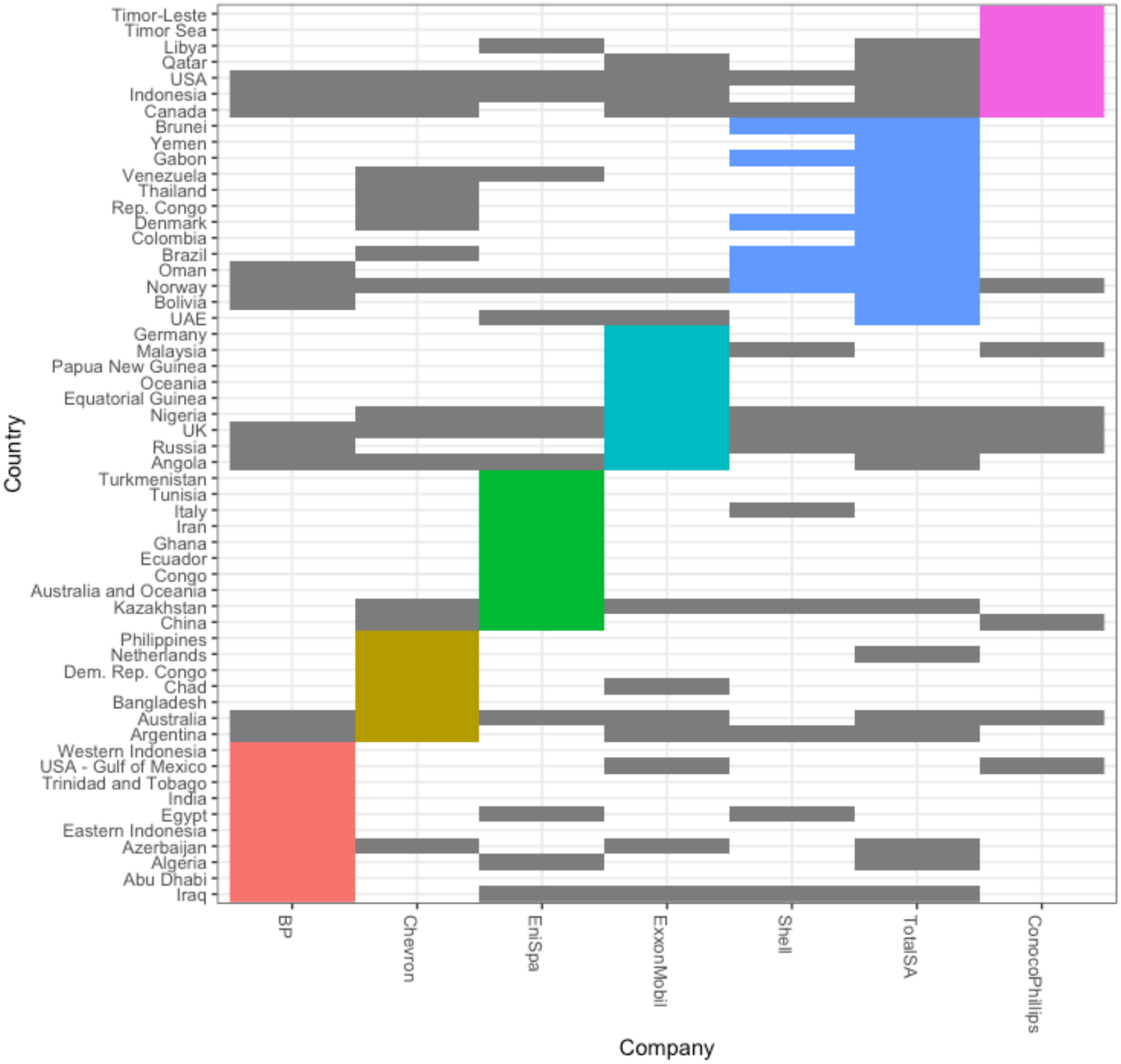


Figure C-2. Larger versions of adjacency matrices appearing in main text. Communities for gas (top) and liquids (bottom) production of Big Oil.