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Journal

Earth's Future, 5(2)

ISSN

2328-4277

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et al.

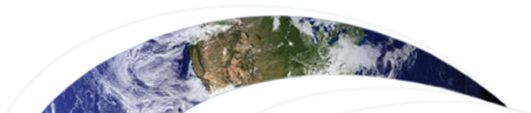
Publication Date

2017-02-01

DOI

10.1002/2016ef000484

Peer reviewed



RESEARCH ARTICLE

Environmental consequences of oil production from oil sands

10.1002/2016EF000484

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Key Points:

- Oil production from oil sands is of growing importance to the global energy mix
- The environmental impacts of this production remain poorly understood
- We assess historical and projected forest loss and water demand
- Local impacts of oil sands exploitation may be substantial for forests and water resources

Supporting Information:

- Supporting Information S1

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Citation:

Rosa, L., K. F. Davis, M. C. Rulli, and P. D'Odorico (2016), Environmental consequences of oil production from oil sands, *Earth's Future*, 5, doi:10.1002/2016EF000484.

Received 20 OCT 2016

Accepted 9 DEC 2016

Accepted article online 16 DEC 2016

Abstract Crude oil from oil sands will constitute a substantial share of future global oil demand. Oil sands deposits account for a third of globally proven oil reserves, underlie large natural forested areas, and have extraction methods requiring large volumes of freshwater. Yet little work has been done to quantify some of the main environmental impacts of oil sands operations. Here we examine forest loss and water use for the world's major oil sands deposits. We calculate actual and potential rates of water use and forest loss both in Canadian deposits, where oil sands extraction is already taking place, and in other major deposits worldwide. We estimated that their exploitation, given projected production trends, could result in 1.31 km³ yr⁻¹ of freshwater demand and 8700 km² of forest loss. The expected escalation in oil sands extraction thus portends extensive environmental impacts.

1. Introduction

In recent years oil sands have received growing attention as important energy sources [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b]. This rise has been driven by increasing global energy demand [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b], continuing dependence on fossil fuels [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b], relative scarcity of conventional oil sources [Gordon, 2012] and technological innovations that have reduced extraction and processing costs [Speight, 2013]. As a result, while global oil demand is projected to rise by about 20% from 2014 to 2040 [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b], the contribution from unconventional oil is expected to increase from 25% to about 40% [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b]. By 2040, oil sands will likely play an important role in meeting growing energy demand [Exxon Mobil Corporation, 2016a; U.S. EIA, 2016a, 2016b], accounting for about 6% of global oil supply [Exxon Mobil Corporation, 2016a] and about 25% of total oil supply in North and South America [Exxon Mobil Corporation, 2016a].

Also known as “tar sands,” oil sands deposits have been discovered in several regions around the world. The two largest oil sands deposits, in term of area and endowment of resources, are in Venezuela and Canada (Alberta), which alone account for almost a third of the proved reserves of global crude oil [U.S. EIA, 2016a, 2016b]. Presently, oil sands are undergoing commercial extraction only in Canada and Venezuela. In Madagascar and the United States, commercial extraction is ready to start, while the development of other deposits around the world (e.g., Republic of the Congo) is still at the exploration or planning stage.

Oil sands are a mixture of sand, water, heavy oil and other minerals; heavy oil is often classified as bitumen [U.S. EIA, 2016c]. These deposits cannot be tapped with standard production methods (e.g., natural flow into production wells [Rogner, 1997] and therefore require more complex and advanced technologies [Chew, 2014]. Depending on the depth of the deposit, two different methods of extraction are commonly adopted, namely, surface mining (i.e., digging into shallow deposits) and in situ drilling (i.e., pumping from recovery wells after injecting high temperature steam to reduce the heavy oil's viscosity) [Chalaturnyk et al., 2002]. Through an energy and water-intensive upgrading process, mined extracted bitumen is subsequently converted into synthetic crude oil (SCO) before being delivered to refineries [Chalaturnyk et al., 2002].

Despite the extensive area of these deposits and their growing importance in meeting future energy demand, little is known about the environmental implications of their extraction and processing. Most of the existing studies have appeared in the “grey literature” as technical reports by government agencies, environmental groups, and corporations working in the oil production sector. In the case of Alberta,

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however, oil sands production has been the focus also of scholarly research [Charpentier *et al.*, 2009; Giesy *et al.*, 2010; Kelly *et al.*, 2010; Brandt, 2012; Jordaan, 2012] that has partly taken advantage of data available through the monitoring process imposed by environmental regulations. Unfortunately, only limited data and scholarly work exist for non-Canadian oil sands. Previous investigations have focused on carbon dioxide equivalent emissions [Charpentier *et al.*, 2009; Brandt, 2012] and the human health effects resulting from oil sands production [Kelly *et al.*, 2010]. However, there are also other important environmental impacts that need to be investigated. First, the amount of water required for oil sands extraction needs to be quantified [Wu *et al.*, 2009; Mielke *et al.*, 2010]. It is also unclear whether these deposits occur in areas of relative water scarcity and whether their extraction may enhance water stress. Moreover, these deposits are often located in forested areas. The effects of oil sands extraction on vegetation cover have yet to be quantified despite conspicuous losses of forest during the excavation of shallow deposits and habitat fragmentation from in situ infrastructure and exploration [Schneider and Dyer, 2006; Jordaan, 2012]. With all these apparent environmental impacts in mind, we examined the oil sands deposits of five countries, namely, Canada, the United States, Venezuela, the Republic of the Congo and Madagascar. Collectively, these deposits account for the majority of assessed reserves of recoverable crude oil from oil sands, and cover an area of 162,750 km², which is comparable to the size of Tunisia. Specifically, the aim of this study is to estimate, given the current and future trend of bitumen production, the amount of water potentially required for the extraction process, the ongoing and expected loss in forest cover, the associated carbon dioxide equivalent emissions due to extraction and processing, and the number of people who live in areas underlain by oil sands deposits.

2. Materials and Methods

2.1. Description and Data

We assessed current and potential impacts of oil sands extraction in terms of forest loss, water use, carbon dioxide equivalent emissions, and inhabitants in areas underlain by oil sands deposits in five countries—Canada, Venezuela, the United States, Republic of the Congo, and Madagascar—whose deposits account for the majority of the oil sands discovered worldwide. Alberta has the most extensive oil sands deposit (16% of Alberta's land area), followed by Venezuela (14% of Venezuela) (Table 1). However, Venezuela's deposits are larger (in terms of recoverable heavy oil) than those of Alberta (Table 2). Madagascar, the Republic of the Congo and Utah have deposit and concession areas that are much smaller than those of Venezuela and Alberta. The oil sands deposits of Alberta and the Republic of the Congo occur in major primary forests that so far have undergone relatively low rates of forest clearing [Potapov *et al.*, 2008]. In Venezuela heavy oil deposits are found in a region where forest vegetation has been more heavily affected by human activities and land use change (e.g., forestry and agriculture) [Vera, 2006; Baynard, 2011], while the forest loss observed in Utah since the year 2000 was due to forest fire [UtahFireInfo, 2016]. In Madagascar no forest cover is present over concessions areas.

Georeferenced data on the spatial extent of oil sands deposits and existing concession areas for oil sands extraction were acquired from various government agencies and private institutions (Table 3). Data on tree cover in the year 2000, annual forest loss between 2000 and 2014, and cumulative forest gain came from a recent high-resolution (30 m) satellite-based dataset were produced by Hansen *et al.* [2013].

2.2. Forest Loss and Fragmentation

Following Hansen *et al.* [2013], we defined forested pixels as areas with at least 50% tree cover (height >5 m) at 30 m resolution. For oil sands areas where exploration and production have already started, historical net changes in forest cover were calculated simply as the difference between cumulative forest loss and cumulative forest gain. Potential forest losses were then calculated over entire deposit and concession areas (Table 3; Figures 1 and 2, Figures S3–S5, Supporting Information), assuming that the entire area is cleared in mining operations and that the clear area needed for in situ extraction is the same as in the case of deposits that are currently under production in Alberta (i.e., \approx 6% of the land area). This is because the removal of forest vegetation associated with extraction technologies, exploration activities, and infrastructure construction (e.g., roads, pipelines) is likely to be similar across regions in order for the enterprise to be globally competitive. Net forest change (i.e., [(forest loss + gain)/forested area in year 2000] \times 100), in Alberta was calculated separately for operational mines and in situ facilities. Because in this region forest

Table 1. Areas of Oil Sands Deposits and Concession Areas. Forested Area in Year 2000 and Net Forest Changes Over the Five Countries Studied. Other Sources Have Estimated an Area of 140,000 km² for Alberta's Oil Sands Deposits [Alberta Energy, 2016a]

	Area Deposit (km ²)	Forested Area 2000 (km ²)	Net Forest Change 2000–2014 (%)
Canada	107,680	75,540	10
Venezuela	49,963	6293	37
Republic of the Congo	1,800	1732	8
Madagascar	352	No forest cover according to the classification used in this study	
USA	2953	292	26

Table 2. Oil Sands Deposits in the World. Actual Production and Projected Production in Year 2040 From Surface Mining and In Situ Extraction [Wykes and Heywood, 2010; Alberta Oil Sands Industry, 2016], Remaining Oil in Place and Proved Oil Reserves. ZERO VALUES Are Used for Areas Where No Extraction Is Expected to Occur; Missing Data Are Reported as “-”. The Deposit in Venezuela Contains Both Oil Sands and Heavy Oil, No Geological Surveys Have Been Done to Define the Boundaries of Oil Sands Deposits. Remaining Oil In-place Is the Volume of Oil Within a Formation Before the Start of Production. Proved Reserves Are Volumes of Oil that Geologic and Engineering Data Demonstrate with Reasonable Certainty to be Recoverable in Future Years Under Existing Economic Conditions and Technology

	Production		Projected Production	Projected Production	Remaining Oil In-place (billion barrels)	Proved Reserves (billion barrels)
	Surface Mining (barrels day ⁻¹)	In Situ Production (barrels day ⁻¹)	(2040) Surface Mining (barrels day ⁻¹)	(2040) In situ (barrels day ⁻¹)		
Canada	1.38 × 10 ⁶	1.43 × 10 ⁶	1.84 × 10 ⁶	2.96 × 10 ⁶	315	170
Madagascar	1.5 × 10 ⁴	1.5 × 10 ⁴	1.8 × 10 ⁵	2.0 × 10 ⁵	200	25
Republic of Congo	0	0	0	3.00 × 10 ⁴	25	2.5
USA	5.00 × 10 ³	0	3.50 × 10 ⁴	0	55	10
Venezuela	0	6.00 × 10 ⁵	0	2.10 × 10 ⁶	2500	300

Table 3. Future Potential Impacts From Extraction and Processing of Oil Sands

Country (Source)	GHG Emissions			Freshwater Use (km ³ yr ⁻¹)	Deforestation (km ²)	Inhabitants	Actual Water Stress (%)
	(Mtonne CO ₂ eq yr ⁻¹)						
Canada actual [Alberta Environment and Parks, 2015a]	102.81	0.486	1476	696	<5		
Canada potential [ArcGIS, 2014; Alberta Energy Regulator, 2016]	179.35	0.680	7482	162,000	<5		
Venezuela potential [acknowledgements]	84.32	0.065	871	455,916	<5		
Republic of Congo potential [Global Forest Watch, 2016]	1.20	0.001	97	20,476	<5		
Madagascar potential (acknowledgements)	13.97	0.064	—	1796	<5		
USA (Utah) potential [USGS, 2005]	1.15	0.011	215	59	Dry year		

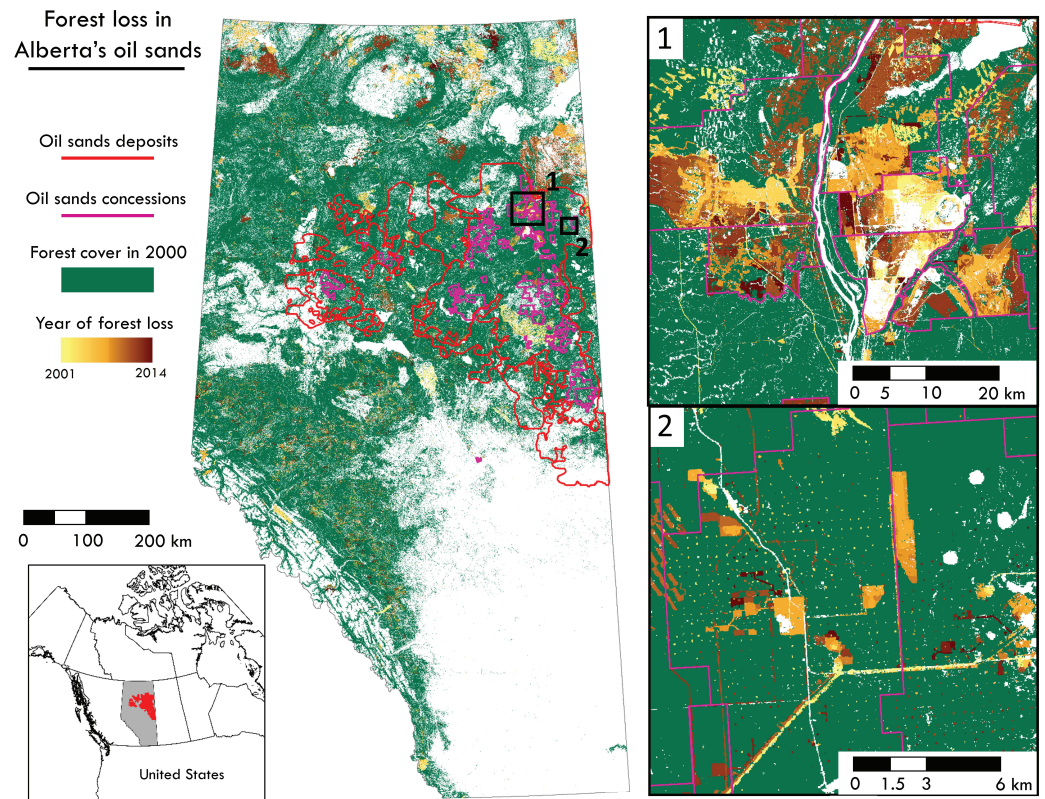


Figure 1. Map of forest cover and forest loss from 2000 to 2015 in Alberta, oil sands concession boundaries [Alberta Environment and Parks, 2015a; Alberta Energy Regulator, 2016] and deposits [ArcGIS, 2014]. The boxed area in the main map are shown in the corresponding local map to the right. Map 1 shows the typical forest loss over an oil sands mining area; map 2 shows forest loss over in situ drilling extraction areas. In situ concession areas exhibit also a massive network of exploration lines (with a typical width of 4 m) that cannot be detected by the 30 m resolution forest cover dataset used in this study.

fires cause substantial forest loss, the effect of fire on deforestation was removed using Alberta's historical spatial wildfire data [Alberta Agriculture and Forestry, 2015], assuming that forest loss by fire would occur even in the absence of oil sands extraction. Hansen's forest maps [Hansen et al., 2013] were validated using the methods from Carlson et al. [2013] by randomly selecting 1500 points for each country or region considered. Points were classified as forested or not forested areas based on land cover maps. Validation followed the method by Carlson et al. [2013]. Briefly, points were classified as forest and no forest. We generated confusion matrices to calculate accuracy (po), the proportion of the total number of predictions that were correct, and the kappa coefficient (k), which takes into account the agreement occurring by chance, from a total of y validation points. The comparison led to the results shown in Table S1.

Forest fragmentation was assessed over the deposits and concessions designated as in situ exploration and extraction areas (Alberta, Venezuela, and Republic of the Congo) following the approach by Vogt et al. [2007]. Using binary land cover maps, this methodology classified each pixel of the area of interest into one of four forest cover categories—core, patch, perforation, or edge. Cores were defined as forested pixels having all adjacent pixels as forested. Core pixels were also further classified into three subcategories, based on the size of the contiguous forest core they belong to (<100 ha, 100–200 ha, or >200 ha). Patches were defined as forested pixels not containing core forest pixels. Edges were defined as forested pixels having at least one adjacent nonforested pixel. Perforations were defined as edge pixels surrounding a nonforested area with a maximum width of 100 m.

To summarize the extent of fragmentation within an area, we used a composite fragmentation index (CFI), defined as the ratio between the sum of number of pixels classified as “edges,” “perforated,” “patches,” or smaller forest core areas (i.e., those <200 ha), and the total number of pixels in that area. CFI varies

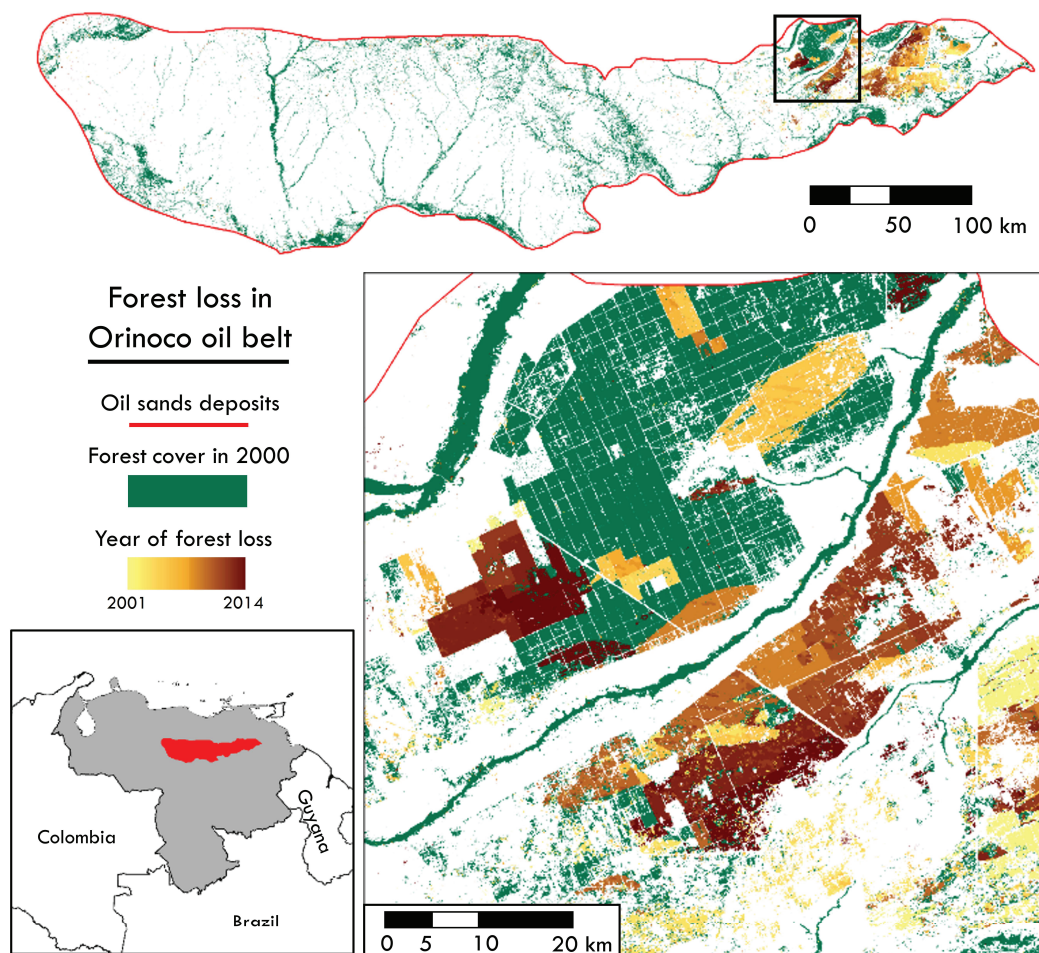


Figure 2. Map of forest cover and forest loss from 2000 to 2015 and oil sands deposit in Venezuela. The boxed area shows the typical trend of exploration lines over an oil sands area suitable for in situ drilling extraction.

between 0 and 1; CFI = 1 in areas with extremely fragmented forest cover, while CFI = 0 in areas with no fragmented forest cores or no forest cover at all. Changes in fragmentation between 2000 and 2015 were expressed in terms of two indices, namely, CCFI (changes in CFI) and CPFI (changes in the number of patch pixels).

2.3. Water Footprint of Extraction

To calculate the amount of water used to extract and treat 1 L of mined bitumen, we considered the amount of water required to attain the two process target densities starting from mined oil sands ore. Details about the calculations of water use for extraction and preparation can be found in Figures 3 and 4. The typical composition of mined oil sands ore in Alberta is reported in Table S2. We calculated the recoverable bitumen (b_{rec} %) from 1 m³ of mined oil sands ore according to the Alberta Energy Regulator Directive 082 formula [Alberta Energy Regulator, 2013]:

$$b_{rec} = -202.7 + 54.1 n \text{ wt\%} - 2.5 n \text{ wt\%}^2 \quad (1)$$

where wt% is the average bitumen content, that ranges from 8 to 12% [Oil Sands Magazine, 2015a] of the mined oil sands ore reported as weight percent.

In Alberta 78% of mined oil sands were also upgraded in year 2015, a process requiring additional water. Data on upgrading water requirements are sparse, but detailed values have been reported by one of the upgraders—Scotford Upgrader—involved in the treatment of bitumen from Alberta's oil sands [Alberta

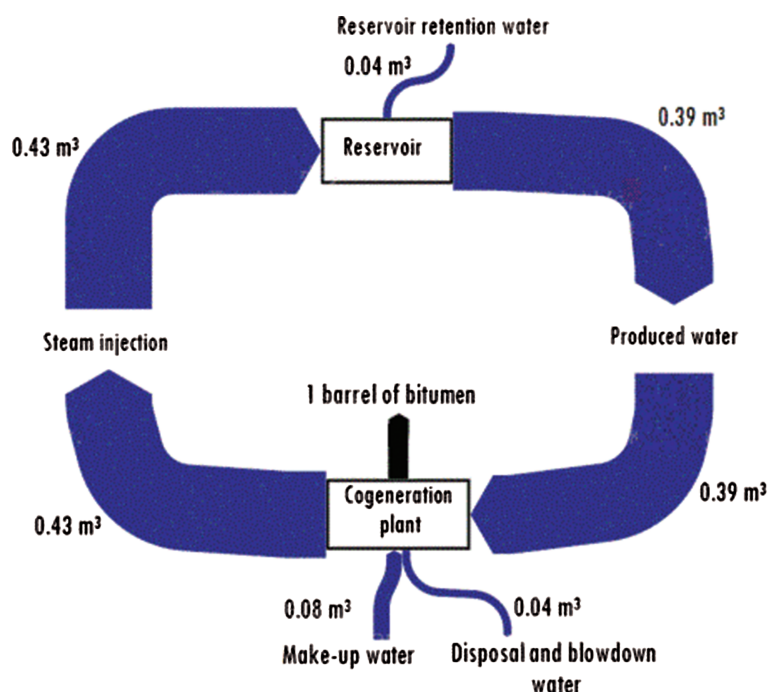


Figure 3. Volume of water required to extract one barrel of bitumen from in situ drilling operation in Canada. 1 barrel = 0.159 m³. Bitumen that is too deep to be mined and is extracted using thermal in situ technologies. In situ facilities use horizontal drilling technology. High pressure and temperature steam are injected into the reservoir to reduce bitumen viscosity. An emulsion of bitumen and condensed steam (produced water) is pumped out to the ground surface. Approximately 10% of the injected steam is retained into the reservoir and another 10% of steam is disposed or lost in disposal and blowdown processes at the cogeneration power plant [Jacobs Consultancy, 2012]. Make-up fresh water is required to compensate these losses and maintain the water balance required by this process. This water is usually withdrawn from fresh or saline groundwater reservoirs. Water from saline aquifers has to be transformed into fresh water (desalination) before it can be used in this process.

Environment and Parks, 2015c]. In this study, we assumed that all other upgraders roughly used the same amount of water per liter of SCO, the product of upgrading from bitumen. Estimates of the total amount of water needed to treat mined oil sands are based on data of production from mines and upgrading facilities in 2015 (Tables S3 and S4).

The volume of water used to produce 1 L of bitumen from in situ operations was calculated using data from annual facility performances expressed in terms of steam to oil ratio (SOR; m³ water /m³ produced bitumen) [Alberta Energy Regulator, 2015; Oil Sands Magazine, 2016d] (Table S5). In situ plant performances are measured through SOR. SOR is a measure of how efficiently energy is used in bitumen recovery from oil sands. SOR is measured as cubic meters of cold water equivalent [Brandt, 2012], i.e., SOR is the volume of water transformed into steam required to produce 1 m³ bitumen [Alberta Energy, 2016b]. The lower the SOR value the higher the efficiency of water and energy usage.

About 20% of the water used in the processes is new fresh water, while the other 80% is recycled [Wu et al., 2009; Mielke et al., 2010; Jacobs Consultancy, 2012]. To convert from barrels of bitumen to cubic meters of bitumen, we considered an American Petroleum Institute gravity of bitumen equal to 8°.

Similar to our calculations for potential forest loss, the potential water use for oil sands extraction and processing in deposits that are not yet under production were estimated assuming that the technology currently used in Alberta will also be adopted in the other regions. Rates of actual and projected production of major oil sands deposits in the world are shown in Table 2. In the calculation of water use the projected production rates are multiplied by the water footprint of bitumen extraction and processing determined for Alberta.

Net water usage from mining and in situ was assessed considering that 80% of the total water footprint is recycled, and adding the water required to upgrade and refine bitumen (Table 4).

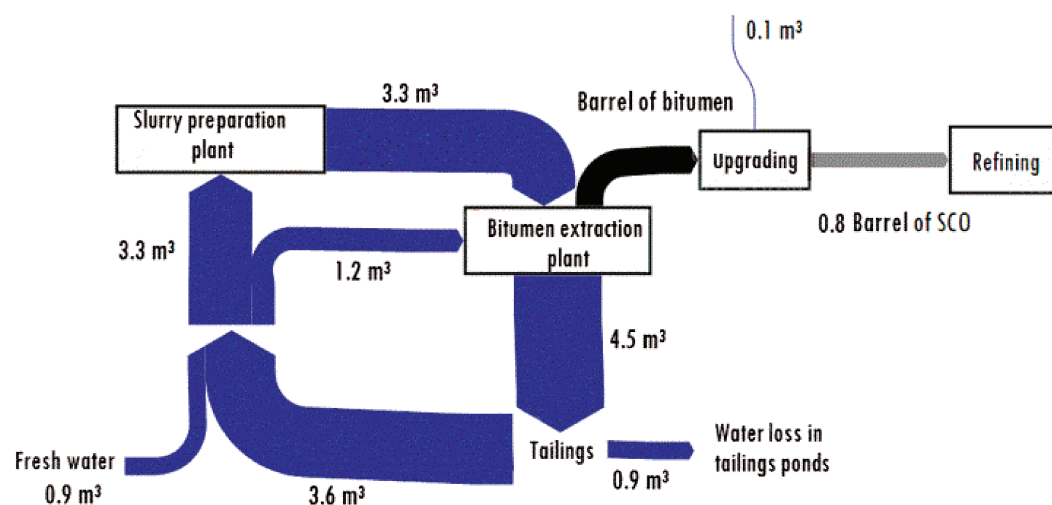


Figure 4. Volume of water required to extract one barrel of bitumen from mined oil sands in Canada. 1 barrel = 0.159 m³. Oil sands close to the ground surface (<75 m in depth) are mined [Oil Sands Magazine, 2015a]. Bitumen is extracted from mined oil sands using a water intensive process known as hot water extraction [Clark, 1944]. First, at the slurry preparation plant water is added to the mined oil sands ore to obtain a slurry with a density of 1500 kg m⁻³ [Oil Sands Magazine, 2016c]. Second, the produced slurry is sent to the bitumen extraction plant, where more water is added to reach a density of 1400 kg m⁻³ [Oil Sands Magazine, 2016c]. Bitumen is separated by gravity from tailings. Bitumen is usually upgraded into SCO before being sent to refineries. Tailings are one of the by-products from mining operations. They are made of water, sands, clay, left-over bitumen and trace amounts of chemicals used in the extraction process. Tailings are stored in large dykes named tailing ponds from 3 to 5 years [Government of Alberta, 2011]. In 2013 the tailing pond area in Alberta was about 220 km² with a volume of fine fluid tailings stored of 0.975 km³ [Alberta Environment and Parks, 2015b]. Approximately 80% of water used in the extraction process is recycled [Wu et al., 2009; Mielke et al., 2010; Jacobs Consultancy, 2012]. The other 20% of water is freshwater withdrawn from Athabasca River.

2.4. Assessing Other Impacts

GHG emissions from oil sands extraction were calculated considering projected production rates of bitumen from in situ or mine operations (Table 2), assuming an 80% bitumen yield to SCO [Kresnavak et al., 2014] and using for mine and in situ the mean values of GHG emissions (Table 4) provided by a previous study [Charpentier et al., 2009]. The number of inhabitants was assessed using data on population distribution taken from CIESIN's Gridded Population of the World map (GPWv4) for the year 2010 [CIESIN- Center for International Earth Science Information Network, Columbia University, 2015] and calculating the number of people living within the perimeters of oil sands deposits and concessions. Water stress areas were assessed overlaying the five oil sands deposit and concessions areas with a water depletion map [Brauman et al., 2016] (Table 4). Water depletion was calculated as the fraction of renewable water consumptively used for human activities [Brauman et al., 2016].

2.5. Uncertainties and Need for Future Work

The results presented in this study are affected by various sources of uncertainty: (1) future projections depend on oil price fluctuations and technological developments that can deeply change both production rates and related environmental impacts; (2) our analyses often rely on information from "grey" literature because only limited scholarly work has been developed on this relatively new research subject; (3) the limited amount of available data does not allow us to estimate the variance associated with the results presented in this study. Nevertheless, these results provide a first quantitative assessment of the potential economic, social, and environmental impacts of oil sands extraction.

3. Results

3.1. Environmental Impacts of Oil Sands Production

The total water footprint of bitumen extraction and processing from oil sands deposits in Alberta differed greatly depending on the extraction method. We found that 2.8 L of water were required to obtain a liter of bitumen using in situ drilling (Figure 3; Table 5), while surface mining required 28.5 L of water per liter of bitumen (Figure 4). The net freshwater used is about 20% of the total water footprint, since about 80% of the water was recycled in both extraction methods [Wu et al., 2009; Mielke et al., 2010; Jacobs Consultancy, 2012;

Table 4. Net water usage and GHG emissions from extraction and processing of petroleum products. GHG emissions are obtained from a review of seven publicly available studies that account for: recovery and extraction, upgrading, electricity supply chain, natural gas supply chain, venting and flaring, fugitive leaks and fugitive tailings ponds [Charpentier et al., 2009]

	Net Water Use	Source	GHG Emissions from Well-to-tank	Source
Bitumen upgrading to SCO	0.6 L water/L SCO	This study	36.9–66.6 kg CO ₂ eq./ bbl BITUMEN	Nimana et al. [2015]
Bitumen upgrading to SCO	1.0 L water/L SCO	Peachey and Eng [2005]		
Oil refining (U.S. average)	1.4 L water/L refined	Wu et al. [2009]	46.3–92.1 kg CO ₂ eq./ bbl REFINED	Nimana et al. [2015]
Gasoline (Alberta oil sands mining)	7.7 L water/L gasoline	This study	62–164 kg CO _{2eq.} / bbl SCO	Charpentier et al. [2009]
Gasoline (Alberta oil sands mining)	5.2 L water/L gasoline	Wu et al. [2009]		
Gasoline (Alberta oil sands in situ) ^a	2.0 L water/L gasoline	This study	99–176 kg CO _{2eq.} /bbl SCO	Charpentier et al. [2009]
Gasoline (Alberta oil sands in situ)	2.6–6.2 L water/L gasoline	Wu et al. [2009]		
Gasoline (U.S. conventional crude-primary recovery)	0.2 L water/L gasoline	Wu et al. [2009]	27–58 kg CO _{2eq.} / bbl GASOLINE	Charpentier et al. [2009]
Gasoline (U.S. conventional crude-secondary recovery) ^b	3.4–6.6 L water/L gasoline	Wu et al. [2009]		
Gasoline (Saudi conventional crude)	2.8–5.8 L water/L gasoline	Wu et al., [2009]		

^aBitumen extracted from in situ drilling is not upgraded to SCO, but it is sent directly to refineries.

^bSecondary recovery via water flooding.

Table 5. Impacts from oil sands extraction and processing in Alberta: in situ drilling versus surface mining impacts on water, forest loss, GHG emissions (in mass of equivalent CO₂ per barrel of SCO), and number of jobs directly created by the oil sands industry

	Surface Mining	In Situ Drilling	Source
Water (L water /L bitumen)	28.52	2.77	This study
Net forest loss (%)	100	6	This study
GHG emissions (kg CO ₂ eq./barrel SCO)	113	138	Charpentier et al. [2009]
Direct job creation (number of workers)	14,750	11,274	PetroLMI [2016]

Oil Sands Magazine, 2016e]. Where information were available, these net water footprint values of bitumen extraction agreed well with previous studies [Wu et al., 2009; Mielke et al., 2010]. Based on these estimates, we find that at current rates of production, the extraction of Canadian oil sands requires about 0.49 km³ H₂O yr⁻¹ (Table 3). This amount of water is transferred to another landscape unit (e.g., placed into tailings ponds). However, while the change in the quantity of water present in the landscape is negligible, the extraction of oil sands leads to an overall decrease in water quality because the used water is contaminated [Kelly et al., 2010]. Substantial carbon dioxide equivalent (GHG) emissions (from well-to- refinery entrance gate) and forest loss have also been associated with this production (Table 5). Currently, oil sands production accounts for emissions of about 103 Mtonne CO₂ eq yr⁻¹ (14% of total Canada's GHG emission in year 2014), an increasing trend with respect to a previous study [Environment Canada, 2012] that estimated 8% of Canada's total emissions in year 2011.

About 1476 km² of Alberta's forests—15% of forests covering Alberta's oil sands concession areas in year 2000—have been removed since the start of the century (Table 3). An additional 6% of forest cover has been lost in wildfires (unrelated to extraction activities) occurring in oil sands concession areas since the beginning of the century. This analysis used forest cover data that were available from 2000 to 2014 and therefore did not include the 2016 “Wood Buffalo” wildfire that burned about 5800 km² of forest within oil sands deposits in Alberta [Alberta Agriculture and Forestry, 2016]. Forest fragmentation has also increased—both in terms of CFI (the areal fraction of sites located at the edges of forested areas, small forest patches, and smaller forest cores; see Methods) and in the number of forest patches. This is especially true for in situ operations where CFI and the number of forest patches have increased by 7% and 81%, respectively, since the year 2000. It should also be noted that our estimate of forest loss for in situ concessions is likely conservative as typical exploration lines are 4 m wide—narrower than the 30 m resolution of the dataset [Hansen *et al.*, 2013]—with 60 m spacing between lines (Figures S1 and S2).

While multiple environmental impacts are apparent, there have, however, been substantial economic benefits with affordable and secure energy to United States and Canadian market, more than 478,000 jobs created in Canada in year 2012 (3% of all jobs in the country) [IHS CERA, 2014], and tax revenues and royalties paid to the governments [IHS CERA, 2014]. Thus there are clear and ongoing tradeoffs between economic development, energy, and the environment.

The effect of oil sands extraction from undeveloped deposits in Alberta and other study countries was estimated assuming that the water use and the land footprint (i.e., fraction of deposit area that needs to be clear of vegetation) of mining or drilling operations were the same as those calculated for operational concessions in Alberta (Table 5). The impact on water resources and forest cover was then evaluated using site-specific water stress and forest cover data (see Methods section). We estimated that extraction of oil sands in the other deposits included in this study will likely have important environmental consequences, particularly in Canada and Venezuela (Table 3). Specifically, total forest loss considering the hypothetical full exploitation of these oil sands deposits (Figures 1 and 2, Figures S3–S5) may eventually reach 8665 km², an area equal to 5% of global forest loss in the year 2014 [Hansen *et al.*, 2013]. In addition, with projected trends of oil sands production (Table 2), annual freshwater use may nearly triple by year 2040 to 1.31 km³ H₂O yr⁻¹ with important impacts on the local water resources if the deposits are located in a potentially water-stressed areas (e.g., the case of Utah). Moreover, projected annual GHG emissions by 2040 (383 Mtonne CO₂ eq yr⁻¹)—due in large part to growth in energy-intensive in situ production—would be commensurate with those from land use and land cover change for all of Indonesia [Carlson *et al.*, 2013], a global hotspot of deforestation [e.g., Naylor, 2011]. Further, as many as 640,000 people live in areas underlain by the oil sands deposits included in this study and are likely to be in some way affected by the development of these deposits (Table 3).

4. Discussion

4.1. Tradeoffs between Economy, Energy, and the Environment

In Alberta the amount of water required to extract and process bitumen from oil sands is of the same order of magnitude as the province's water consumption for irrigated agriculture. Thus, it can be argued that in this state the oil sands industry was able to develop because the region is relatively rich in water resources. While the mining extraction almost entirely relies on water from the Athabasca River (i.e., freshwater resources), the in situ activities use brackish and saline groundwater that is treated before being turned into steam (Figures 3 and 4), likely because of existing regulations limiting the withdrawals of fresh groundwater in Alberta [Alberta Energy Regulator, 2011]. By 2040 the projected growth in oil sands production (Table 2) is expected to lead to a 40% increase in water appropriations by oil sands operations. This will likely not threaten the water resources of the Athabasca River, as water use for mining operators is capped by strict regulations [Alberta Environment and Parks, 2007]. A more likely threat on water resources may be in the in situ region. Groundwater could quite easily become stressed as pumping levels increase, thus also affecting adjacent freshwater aquifers with important ecological and social impacts. The development of oil sands extraction in countries with drier climates is expected to exert relatively greater pressure on the local water resources, likely competing with other water uses such as crop production and flows for aquatic ecosystems. Thus the increasing reliance on oil sands extraction may raise new water security concerns in countries

where deposits are located in water stressed watersheds (Utah), thereby exacerbating competing water uses within the context of the water-energy nexus [Rulli *et al.*, 2016].

Our results show that mining operations and in situ drilling differ substantially in their environmental impacts (Table 5). While in situ technology is more energy intensive, the process requires less water, does not produce tailings, and has less extensive impacts on overall forest cover. For in situ concessions, forest loss tends to be more scattered and limited to areas of intensive exploration activities for the positioning of the extraction wells and construction of infrastructures (e.g., roads, pipelines). Conversely, forest vegetation is completely cleared within mining operations. Even though in situ drilling entails a smaller net change in forest cover than surface mining, its impact on wildlife habitat and landscape fragmentation should not be underappreciated. In addition, while oil sands extraction is not expected to displace a large number of people—as these deposits are located in remote forested areas—these operations are likely to have important impacts on carbon sequestration via land use change and deforestation [Yeh *et al.*, 2010]. As such, regulations in Alberta require oil sands industries to reclaim both mining and in situ project sites once extraction ceases (i.e., reforestation and recovery to the predevelopment levels are required) [Alberta Energy Regulator, 2009]. Hence, deforestation and oil sands extraction operations are expected to be followed by several decades of recovery to again reach land predevelopment abilities of carbon sequestration capacity. However, the “carbon debt” of such comprehensive land use changes likely longer than a decades-scale recovery [Jordaan, 2012; Rooney *et al.*, 2012].

Overall, in situ drilling is more expensive [Humphries, 2008] and has less environmental impacts in terms of water use and forest loss; however, it requires more energy and has a bitumen recovery rate lower than mining (up to 60% for in situ versus 90% for mining) [Oil Sands Magazine, 2015b]. For this reason the current trend, influenced by low oil prices, is to increase mining production instead of in situ extraction [PetroLMI, 2016]. This is counter to previous trends of increasing investments in situ production [PetroLMI, 2016] and indicates that the substantial differences in environmental impacts highlighted by this study are secondary in such decisions.

Ongoing technological innovation offers promise for reducing the environmental impacts of oil sands production (Table 4). GHG emissions per barrel have already decreased by 25%–40% in the last 25 years [The Oxford Institute for Energy Studies, 2016]. Nevertheless, oil sands extraction and processing still requires a large amount of energy, which corresponds to emitting about three times more GHGs than the production of conventional oil [Charpentier *et al.*, 2009]. The water required to upgrade bitumen has decreased by 40% since 2005 (Table 4). Likewise, the amount of water needed to extract bitumen using in situ techniques has decreased, while we found that more water is used to win bitumen from mined oil sands than what was reported by previous studies. Interestingly, the gasoline produced from secondary conventional oil recovery techniques (i.e., water flooding) requires almost the same amount of water used to produce gasoline from mined oil sands (Table 4).

Previously, progress in technology, proximity to the markets, and high prices of crude oil favored the proliferation of the oil sands industry in Alberta. Though this study has focused on the major environmental impacts of oil sands extraction, this source of energy also offers some advantages compared to conventional oil, remaining a very attractive asset, even under the currently depressed oil prices [Exxon Mobil Corporation, 2016b]. First, there is little reservoir uncertainty. Second, the recovery rate of bitumen from oil sands is greater than for conventional oil [Oil Sands Magazine, 2015b]. Third, oil sands deposits decline more slowly (4% decline per year) than those of conventional oil (20% per year), allowing these deposits to last longer (e.g., 30 years in the case of Alberta) than conventional wells [Oil Sands Magazine, 2015b]. Because of their long lifespan (and the consequently lower sensitivity to short-term fluctuations in crude oil price), oil sands deposits are drawing increasing interest from oil and gas corporations. Moreover, oil sands industries have led to considerable job creation. For example, in 2012, the oil sands industry in Canada and U.S. employed—directly and indirectly—almost 558,000 people (80,000 in U.S.) [Canadian Energy Research Institute, 2011; IHS CERA, 2014]. In the most positive scenario of oil sands development, by 2035 employment is expected to grow to 2.2 million jobs in the United States and Canada [Canadian Energy Research Institute, 2011]. By 2020 direct job creation in the oil sands industry in Alberta is expected to add about 5170 new jobs to the existing workforce for a total of 35,070 [PetroLMI, 2016]. As a result of this oil sands “boom,” Alberta has become one of the richest regions worldwide, with a GDP per capita in year 2014 (91,000 U.S.

dollar) among that of the top five countries in the world [The World Bank, 2014; Alberta Government, 2016]. Thus, pairing oil sands extraction with responsible policies can ultimately enhance economic growth and create employment opportunities. Yet despite these obvious benefits, our study clearly demonstrates that environmental considerations need to be better incorporated into decision-making surrounding oil sands.

Most global oil sands reserves are expected to be put under production and exploited in the near future [U.S. EIA, 2016d]. While low oil prices (in years 2014, 2015, and 2016) have presently slowed extraction from oil sands deposits, investments are ongoing, with massive extraction for commercial production likely to take place as soon as oil prices become higher again. Production is expected to increase from the current 3.5 million barrels a day to 7 million barrels a day by 2040 [Exxon Mobil Corporation, 2016a]. The environmental impacts of oil sands extraction are already apparent in places where production is already occurring. Thus areas containing oil sands can expect marked changes in terms of land cover and freshwater appropriations in the near future. This expected escalation in oil sands extraction may therefore alter the existing equilibria in the water-energy system and reshape patterns of water allocations, governance strategies, and associated institutional arrangements.

Acknowledgments

Authors thank Stewart Ahmed for providing information about Madagascar oil sands concession areas; Chris W. Baynard for sharing the shapefile of Orinoco Heavy Oil Belt in Venezuela. L.R., K.F.D., M.C.R., and P.D. designed research; L.R. and K.F.D. performed research; L.R. collected and analyzed data; and L.R., K.F.D., M.C.R., and P.D. wrote the paper. The authors declare no conflict of interest.

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