Land Use Greenhouse Gas Emissions from Conventional Oil Production and Oil Sands

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Debates surrounding the greenhouse gas (GHG) emissions from land use of biofuels production have created a need to quantify the relative land use GHG intensity of fossil fuels. When contrasting land use GHG intensity of fossil fuel and biofuel production, it is the energy yield that greatly distinguishes the two. Although emissions released from land disturbed by fossil fuels can be comparable or higher than biofuels, the energy yield of oil production is typically 2–3 orders of magnitude higher, (0.33–2.6, 0.61–1.2, and 2.2–5.1 PJ/ha) for conventional oil production, oil sands surface mining, and *in situ* production, respectively). We found that land use contributes small portions of GHGs to lifecycle emissions of California crude and *in situ* oil sands production (<0.4% or <0.4 gCO_2e/MJ crude refinery feedstock) and small to modest portions for Alberta conventional oil (0.1–4% or 0.1–3.4 gCO_2e/MJ) and surface mining of oil sands (0.9–11% or 0.8–10.2 gCO_2e/MJ). Our estimates are based on assumptions aggregated over large spatial and temporal scales and assuming 100% reclamation. Values on finer spatial and temporal scales that are relevant to policy targets need to account for site-specific information, the baseline natural and anthropogenic disturbance.

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1. Introduction

Though significant attention has been paid recently to the greenhouse gases (GHG) arising from land use change (LUC) due to biofuels production, little has been paid to similar emissions from fossil fuel development. Studies that examined the land use impacts of oil and gas production have focused on habitat loss, fragmentation, and other ecological impacts associated with these developments (*1*–*5*), yet GHG emissions from LUC are yet to be examined in a systematic manner.

In this paper, we examine the GHG emissions associated with the direct land use of fossil fuel production, using California and Alberta as examples for conventional oil production as well as oil sands production in Alberta as an example of unconventional oil production. We chose these regions due to data availability; however, other regions could also be analyzed using similar methods. We first determine land use change (hereafter, land disturbance) associated with conventional oil and Alberta oil sands production on an intensity basis. We then determine the carbon emissions changes associated with this land disturbance compared to the reference case (without disturbance due to oil extraction).

2. Land Disturbance and Land Disturbance Intensities

The physical disturbance from conventional oil development results from infrastructure such as well pads, pipelines, access roads, and seismic surveys (*2*, *5*, *6*). During development, well density increases until oil production rates drop below economically recoverable levels. Wells are shut in and abandoned afterward. In Alberta, a company is required to reclaim a well or pipeline once it is no longer in use (*7*), though this is often not the case. Once a company can apply for a reclamation certificate and once standards are met, Alberta Environment issues the reclamation certificate. The challenge is that wells are often abandoned without being reclaimed. From 1998–2008, the certification rate was approximately 45% of the abandonment rate (*8*). The number of wells being abandoned and not certified is increasing over time. In addition, linear features may persist though time without managing recreational access or if transferred to other land uses (*9*).

Oil sands projects are generally located in northeast Alberta, with some development extending to the northwest of the province and east into Saskatchewan, an area classified as boreal forest (*10*). Bitumen is extracted from oil sands using *in situ* recovery or surface mining. In 2007, 40% of bitumen was produced with *in situ* recovery, while the other 60% was produced with surface mining (*11*), though approximately 80% of recoverable bitumen deposits is estimated to be only extractable using *in situ* technologies. *In situ* recovery involves drilling wells into deposits typically deeper than 100 m and injecting steam into the reservoir, reducing the bitumen viscosity, and allowing it to be pumped to the surface. Land disturbance for *in situ* recovery requires infrastructure such as central processing facilities and networks of seismic lines, roads, pipelines, and well pads.

Surface mining of bitumen, used for more shallow deposits, requires the clearing and excavation of a large area. The total land disturbance includes a mine site, overburden storage, and tailing ponds (*3*). Surface mining involves draining and clearing of vegetation and the removal of peat. Subsoil and overburden are removed and stored separately. Disturbed peat is stockpiled and stored until reclamation, where it may be used as soil amendment. The drained and/or extracted peat will begin to decompose, releasing a

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combination of CO_2 and CH_4 depending on peat moisture conditions (*12*). By removing the functional vegetation layer at the surface of a peatland, the disturbed ecosystem loses its ability to sequester CO_2 from the atmosphere. Reclamation of surface mines typically involves reconstructing self-sustaining hydrology and geomorphology on the landscape (*13*). A mixture of peat and soil from the original lease and surrounding sites is used to cover the end substrates. The landscape is subsequently seeded and revegetated. Currently, only 12% of the total oil sands surface mining area (66 km^2 of 520 km^2) is reported as reclaimed, but only 1 km^2 has been certified (*14*).

2.1. Methodology. The production of fossil fuels from a new deposit can result in carbon release from land disturbance. The amount of land disturbed per unit of fuel produced depends on the following characteristics:

1. The areal energy density of the deposit;
2. The rate at which the primary energy resource is extracted from the deposit;
3. The conversion efficiency between the primary energy resources and the intermediate or the refined fuel product;
4. The amount of carbon contained on the land before and after the land disturbance occurs.

We calculated both historical and marginal land disturbance intensity for conventional oil. Historical well productivity was found to be higher for both California and Alberta. For the historical case we used the total land disturbance over the history of oil production in a region as well as the total cumulative MJ of oil produced. The marginal land intensity represents the land disturbance associated with the production of the marginal MJ of petroleum. We approximate marginal well production by taking the total number of new wells from the year of analysis and divide them by MJ of crude oil produced in that year.

2.2. Data and Analysis on Land Disturbance.

2.2.1. Land Disturbance per Well Pad. To determine land disturbance intensity for California and Alberta oil production, we divided the total disturbed area calculated from image analysis shown in Figure S1 by the number of well pads counted in each image to estimate land area disturbed per well (*15*).

Cumulative crude oil produced to date in California is 25.1 Gbbl. Our data set contains 301 California oil fields covering 3×10^9 m^2 (1180 square miles) (*6*). As of 2005, these fields contained over 58,000 active production wells, 22,000 shut-in production wells, and 25,000 injection wells, over 6000 of which are shut-in. In studied California oil fields, the land disturbed per well ranged from 0.33 to 1.8 ha/well, while the average of all images was 1.1 ha/well (which includes all access roads and other facilities included in each image).

Alberta had 35,557 conventional oil wells in 2007, producing 515,000 barrels per day (*16*). We found the land disturbed per well pad ranged from 1.6 to 7.1 ha/well pad (averaged 3.3 ha/well pad over 10 fields analyzed) for Alberta oil production (*15*), which is consistent with the literature review provided in Jordaan et al. (*3*) which ranged from 1.4−9.9 ha/well (excluding exploration).

2.2.2. Land Disturbance per Energy Output. For the historical impact analysis (production per ha of land disturbed, PJ/ha) in California, we multiplied the number of well pads per oil field (including active and shut in production and injection wells and estimated abandoned and unrecorded wells) by the area disturbed per well pad estimated from the image analysis and divided by the cumulative production for each oil field from 1919−2005. The marginal impacts were calculated by multiplying the wells drilled in 2005 and the area disturbed per well pad divided by crude production in 2005 across the state (*15*). The same approach was used to calculate the marginal impact of Alberta oil production in

TABLE 1. Energy Yield (PJ of Crude Refinery Feedstock[a]/ha Disturbed) of Conventional Oil Production in California and Alberta and Oil Sands Production[b]

energy source		energy yield (PJ/ha)
California oil	historical impacts	0.79 (0.48−2.6)
	marginal impacts	0.55 (0.33−1.8)
Alberta oil	historical impacts	0.33 (0.16−0.69)
	marginal impacts	0.20 (0.092−0.40)
oil sands - surface mining		0.92 (0.61−1.2)
oil sands - in situ		3.3 (2.2−5.1)

[a] Crude refinery feedstock refers to conventional oil or synthetic crude oil (SCO) in high heating values (HHV). [b] Values shown are averages and the upper-bound and lower-bound estimates are reported in the parentheses. The summary statistics for California and Alberta oil fields (numbers of wells drilled, area disturbed), oil production, and land disturbance intensity (in m^2/m^3 SCO or m^2/MJ crude oil) are shown in Tables S1−S4 in the SI.

2007 and the historical impact from 1948−2007 (see Section 2 of the Supporting Information, SI).

Land use intensity estimates for oil sands surface mining and *in situ* are based on Jordaan et al. (*3*), which reviewed data that characterizes the land area disturbed by oil sands projects in Alberta (see SI Section 3). The authors reported land use intensity of 0.33−0.63 m^2/m^3 synthetic crude oil (SCO) and 0.07−0.16 m^2/m^3 for mining and *in situ* production, respectively (excluding land use from upstream natural gas production). The results in energy production per disturbed area are summarized in Table 1.

3. Changes in Carbon Stock, Carbon and CH_4 Emissions and Uptake

Natural carbon stocks increase and decrease as a result of land disturbance through a variety of mechanisms. The mechanisms we examined include clearing of vegetation, loss of soil carbon, forgone sequestration, and resequestration due to reclamation and forest regrowth. Foregone sequestration refers to the carbon that would have been sequestered had a GHG sink not been cleared for development (*17*). We also assess CH_4 emissions from tailings ponds and peat stockpiled during oil sands surface mining operations. Though CH_4 emissions from tailings ponds are different from biological carbon typically included in land use analysis, their emissions are included due to the large land areas covered by tailings ponds, high CH_4 emissions, and the extent that emissions can be affected by mitigation decisions related to land use management.

3.1. Carbon Stocks in Natural Regions Where Oil is Produced. Given that nearly all California oil fields are in the southern half of the state, it was assumed that the land containing California fields is 25% chaparral and 75% grassland. Chaparral has carbon stocks in soil and biomass of 80 and 40 t C/ha (8000 and 4000 g C/m^2), respectively. For grassland, these figures are 80 and 10 t C/ha, respectively (*17*).

In the Alberta case, to estimate the distribution of conventional oil wells across the natural regions, wells were mapped using ArcGIS. Oil wells in Alberta are found in all but one natural region (the Canadian Shield). Within the boreal region, 68% of the oil wells are located within the dry-mixedwood subregion, where peatland coverage (9.3%) (*18*) is smaller than the rest of the boreal subregions, including Central and Northern mixedwood (31 and 38%, respectively) and highlands (23%) (*18*). We estimated that 15% of conventional oil development areas occur in peatland (*15*). Oil sands developments occur in the boreal forest natural region, and, consistent with other analyses,

TABLE 2. Changes in Carbon Stock and CH_4 Emissions Per Unit Area Disturbed by Conventional and Unconventional Oil Production in California and Alberta over a Modeling Period of 150 Years, Assuming 100% Reclamation[h]

	initial C loss (year 1 to 20)		net carbon/GHG changes (year 1 to 150)				
energy source	soil C (t C/ha)	biomass C (t C/ha)	soil C (t C/ha)	biomass C (t C/ha)	foregone seq. (t C/ha)	tailings (t CH_4/ha)	total (t CO_2e/ha)
California oil[a,g]	20 (16−32)	18	20 (16−32)	0	0	−	73 (59−117)
Alberta oil[a,b,f]	55 (44−88)	70 (67−74)	31 (17−67)	9.2 (1.9−16)	2.6 (2.2−3.1)	−	157 (81−313)
oil sands - mining[c,d,e,f]	350 (306−394)	71 (65−78)	312 (246−357)	19 (10−21)	6.9 (5.9−8.3)	96 (0−192)	3596 (953−6201)
oil sands - *in situ*[a,c,f]	109 (88−175)	71 (65−78)	59 (6.5−130)	−0.8 (−12 −2.0)	6.9 (5.9−8.3)	−	205 (23−495)

[a] Assumed 84−100% and 100% biomass lost at year 20 and 100, respectively, and 20−40% of soil carbon oxidation after disturbance. [b] Assumed disturbance is 15% peatland and 85% upland. [c] Assumed disturbance is 23% peatland and 77% upland. [d] Assumed 25% disturbance is tailings pond and the rest (75%) is reclaimed to forest after mining/extraction ends. Assumed 84−100% and 100% biomass lost at year 20 and 150, respectively, and 70−90% of soil carbon oxidation after disturbance (*15*). [e] Assumed that tailings pond starts to emit CH_4 15 yrs after the project starts (*15, 33*) and ends at year 50 (continuous emissions for 35 years). Forest regrowth after reclamation does not include areas of tailings pond. [f] Assumed disturbance is 30 yrs and reclamation starts at year 31. [g] Since grassland regrowth is faster and the baseline has faster natural turnover (*45*), we assumed no net effect over modeled time period (foregone sequestration and net biomass loss is negligible). [h] Positive values represent net sources of emissions or foregone sequestration, while negative values represent net sinks compared to the reference case. Values shown are single estimates or the mid-range values (the upper-bound and lower-bound estimates are reported in the parentheses) (*15*). CH_4 emissions from stockpiled peat soil and from peatland in the reference case were studied and found to be orders of magnitude smaller than other emissions and are therefore omitted in this table.

it was assumed that roughly 23% of oil sands development occurs in peatlands (*15, 18, 19*). The carbon stocks in soil and above ground biomass in Alberta are estimated by matching the available ecosystems in the Supporting Online Material of Searchinger et al. (*17*) (temperate evergreen forest, temperate deciduous forest, boreal forest, and temperate grassland) with the qualitative description of the natural regions as outlined by Alberta Sustainable Resource Development (*20*). We then calculated the weighted carbon in soil and vegetation and carbon uptake for each of the six natural regions (Table S5 of the SI). Due to the carbon-rich nature of boreal peatlands, we developed a separate methodology to quantify the soil and biomass carbon of peatlands (see SI Section 4).

3.2. Carbon Stock Changes, Foregone Sequestration, Reclamation, and CH_4 Emissions. The evolution of carbon stocks over time was modeled for a reference scenario with no land disturbance for fossil fuel production and a land disturbance scenario over 150 years. Key assumptions of carbon stock changes and CH_4 emissions are briefly summarized below, and detailed descriptions of data sources, assumptions, and calculations are offered in the SI Section 4.

3.2.1. Carbon Stock Loss. We assumed a 20−40% soil carbon loss from infrastructure activities to support conventional oil and gas extraction and *in situ* production (e.g., scraping of soil at surface for roads, drainage, drill pads, drilling wells, etc.) (*21*) and a 70−90% soil C loss for surface mining accounting for higher disturbance in mining sites (*19*) and other facilities. Since current seismic practices only remove above-ground biomass and not soil carbon, we assumed that seismic will remove 100% biomass but will result in negligible soil carbon loss. Our study uses two approaches to account for biomass carbon loss after conversion: (1) a complete loss after conversion and (2) accounting for carbon storage in harvested wood products (HWP). Based on these two approaches we estimate 63−100%, 84−100%, and 100% of total (including aboveground and belowground) forest biomass loss at 0, 20, and 150 years after disturbance, respectively (see calculations in the SI Section 4 and Table S8).

3.2.2. Foregone Sequestration. Southern California ecosystems (chaparral and grasslands) are characterized by growth and cycling of vegetation due to frequent fires. Thus, biomass in these ecosystems is not considered a net source or sink of carbon over our modeled time period (150 years), and all long-term effects are due to soil disturbance. Therefore, all impacts to vegetation changes due to oil field development are assumed to be mitigated over modeled time period (see Table 2 for biomass and foregone sequestration values).

Canadian forests have been shown to provide a net sink for carbon through much of this century, but there has been a decrease in this sink since late 1990 due to increased disturbance such as fire and disease outbreak such that Canadian forests may now be a net source of carbon or a very small sink (*22*). Thus we assume in this paper that Canadian boreal forests are carbon neutral, i.e. the boreal forest system in Alberta is neither a C sink nor a source and the long-term C sequestration rate is zero after disturbances (natural and anthropogenic other than oil sands extraction) are taken into account. Peatlands, however, still remain a long-term carbon sink with annual carbon accumulation rate (accounting for historical fires) of 0.24 t C/ha/yr across continental, western Canada (*19*). The small foregone sequestration in Table 2 reflects the loss of carbon accumulation from peatlands.

3.2.3. Reclamation. Regrowing forests accumulate carbon in aboveground, underground biomass, and soil organic matter at various rates depending on the type of vegetation, climate condition, and other complex factors (*23−26*). To better understand the change of carbon stock when land has been disturbed, we selected a modeling period of 150 years to capture the assumed conventional oil and oil sands production period and reclamation. Peatland restoration has been successful following peat extraction for horticultural products in eastern Canada (*27*). Research is ongoing to test the feasibility of restoring peatlands in the oil sands region of Alberta (*13*). Given the difficulty of restoring peatland hydrology and the long periods of time needed to restore vegetation, peatlands disturbed by both surface mining and *in situ* recovery predominantly are expected to be reclaimed to a mixture of upland forest and wetlands.

Depending on the type of technology employed (e.g., surface mining or *in situ*) and the assumptions about forest regrowth rates, most biomass carbon loss and some soil carbon loss in forests can be eventually resequestered within our modeling period if reclamation was successful (Table 2). However, only a small portion of soil carbon can be recovered for areas where peatlands have been converted and reclaimed to upland. Disturbed peatlands will have a much smaller soil carbon stock after it is reclaimed to upland (Figure S3).

3.2.4. Tailings Pond CH_4 Emissions. Bitumen is recovered from mined oil sands by a caustic hot-water extraction process. Waste water, which includes clay, sand, silt, organics, and residual bitumen, is sent to tailings facilities for containment. After tailings water is delivered to a tailings pond, sand particles rapidly settle. Once separated, water is recycled into the extraction process, and the remaining fine suspended particles and water form mature fine tailings (MFT). Earlier studies suggest that MFT may take decades (*28*) or even a century to settle (*28−30*); however, new treatment technologies may significantly reduce the settling time. Tailings pond CH_4 emissions have been reported in many major MFT sites in Northern Alberta (*31−34*). One of the most studied MFT is the Mildred Lake Settling Basin (MLSB) operated by Syncrude, which started operation in 1978. By 1999, methane bubbles were found on 40−60% of the 12 km^2 pond with an estimated daily flux of 12 g $CH_4/m^2/d$ (44 t CH_4/ha/yr or 1100 t CO_2e/ha/yr) in the most active areas (*33*). Suncor Energy Inc.'s MFT site, operational in 1968, started to release methane gas after 15 years (*33*). In addition to being a GHG that has 25 times the potency of CO_2 (*35*), the presence of methane gas may provide faster transport of toxic compounds to the capping water, reduce the oxygen level of the lake, and produce a toxic compound, ethylene, that also affects plant growth (*31, 32*). Each of these factors may reduce reclaimed ecosystem function and hinder remediation effort when the wet landscape approach is used (*33*). Our analysis assumes tailings ponds emit CH_4 at 0−12 g $CH_4/m^2/d$ fifteen yrs after sites begin operating until the end of year 50 (i.e., constant emissions for 35 yrs), and half of the tailings surface will emit methane emissions (*15*).

Gupta et al. (*30*) hypothesized that naphtha diluents, used for oil sands processing, and citrate, used as a water softening agent (*34*), both support methane (CH_4) biogenesis in large anaerobic settling basins. Tailings reclamation management is an actively researched area, thus it is challenging, if not impossible, to predict the evolution of tailings pond management and the associated land disturbance as new reclamation management practices are developed and become less expensive (*13*). There are currently two primary approaches that have been used in large scale reclamation, wet or dry landscape. In the former, the MFT would be transferred to an abandoned mine pit and then capped with water to form a "lake" (*28, 31*). In the latter approach, fine tailings are dewatered and capped with soil, allowing revegetation of the dried landscape. Due to the uncertainty in future reclamation technologies and tailings ponds management practices, our analysis of the tailings sites emission factors assumes no change in management practice, and the emission rate is based on the literature published before 2009 (*30−33, 36*). Detailed assumptions and calculation of tailing emissions can be found in the SI Section 4. We also determine the effects of using dry landscape reclamation by examining the impacts of carbon resequestration if tailings pond areas are capped and revegetated (Section 3.4).

We found that the greatest changes in GHG stock are due to soil carbon loss, notably from surface mining, and CH_4 emissions from tailings ponds (Table 2). Surface mining has the largest soil carbon loss per unit disturbed area due to the amount of soil and peat displaced in these operations.

3.3. Land Use GHG Emission Intensity. Land use GHG intensity (g CO_2equivalent/MJ crude refinery feedstock, including SCO or crude oil) of Alberta conventional oil production is found to be 5−10 times greater than that of California conventional oil production. This is due to the low density of wells in the images analyzed for Alberta which results in high disturbance per unit energy output (energy yield in PJ/ha ratio California (CA)/Alberta (AB) ≈ 2−5 (Table 1)) and higher net carbon loss in Alberta (AB/CA ≈ 1−3) due to the carbon richness of Alberta landscapes compared to

TABLE 3. Net Land Use GHG Intensity of Conventional and Unconventional Oil Production in California and Alberta over a 150 Year Modeling Period[g]

		soil CO_2	biomass CO_2	foregone seq. CO_2	tailing CH_4	total (g CO_2e/MJ)[a]	lifecycle GHG emissions (g CO_2e/MJ)[b,c]	% of total lifecycle[f]
California oil	historical	0.09 (0.02−0.25)	0	0	–	0.09 (0.02−0.25)	85.4[d]	0.1 (0.0−0.3)
	marginal	0.13 (0.03−0.35)	0	0	–	0.13 (0.03−0.35)	85.4	0.2 (0.0−0.4)
Alberta oil	historical	0.34 (0.09−1.55)	0.10 (0.01−0.38)	0.03 (0.017−0.05)	–	0.47 (0.12−1.98)	85.4	0.6 (0.1−2)
	marginal	0.57 (0.16−2.65)	0.17 (0.02−0.65)	0.05 (0.03−0.09)	–	0.78 (0.20−3.39)	85.4	0.9 (0.2−4)
oil sands - mining		1.21 (0.77−2.16)	0.04 (0.03−0.13)	0.03 (0.03−0.04)	2.61 (0−7.91)	3.9 (0.83−10.24)	94.8[e]	4 (0.9−11)
oil sands - *in situ*		0.07 (0.0−0.21)	0.0 (−0.01−0)	0.008 (0.006−0.01)	–	0.07 (0.0−0.23)	105.3[e]	0.04 (0−0.2)

[a] The energy unit is MJ of refinery feedstock (HHV), including synthetic crude oil (SCO) or crude oil. [b] Source: GHGenius 2008 Version 3.13a Natural Resources Canada available from http://www.ghgenius.ca. [c] The energy unit is MJ pf refined gasoline (HHV). [d] The crude that we compare here is a generic mix of crude for Canada West from GHGenius. Ideally we would like to compare California LU emissions with California crude oil lifecycle emissions, and Alberta LU with Alberta crude oil lifecycle emissions. California crude oil is likely to have higher lifecycle emissions than the average crude (*46*) due to its lower average API values. [e] Source: Charpentier et al. (*43*) minus the GHGenius' default land use and fugitive emissions to avoid double counting. [f] The comparison here is only approximate as the energy units in the previous two columns are not exactly the same (MJ refinery feedstock vs MJ refined gasoline). To make consistent comparison, additional steps to take into account refinery efficiency loss and allocation of refinery emissions to products (e.g., gasoline and diesel) need to be considered. See Charpentier et al. (*43*) for examples for calculation. [g] Values shown are single estimates or the mid-range values (the upper-bound and lower-bound estimates are reported in the parentheses) (*15*). Positive values represent net carbon emissions, while negative values represent net carbon gain compared to the reference case. The comparison with LU emissions is only approximate for reasons noted in footnote *f*.

TABLE 4. Comparison of *Direct* Land Use Impact of Biofuel vs Fossil Fuels Production[b]

energy source		energy yield (PJ/ha)	GHG emissions per disturbed area (t CO_2e/ha)	GHG emissions per energy output (g CO_2e/MJ)
Fossil Fuel				
California oil	historical impacts	0.79 (0.48−2.6)	73 (59−117)	0.09 (0.02−0.25)
	marginal impacts	0.55 (0.33−1.8)		0.13 (0.03−0.35)
Alberta oil	historical impacts	0.33 (0.16−0.69)	157 (74−313)	0.47 (0.12−1.98)
	marginal impacts	0.20 (0.092−0.40)		0.78 (0.20−3.39)
oil sands - surface mining		0.92 (0.61−1.2)	3596 (953−6201)	3.9 (0.83−10.24)
oil sands - in situ		3.3 (2.2−5.1)	205 (23−495)	0.04 (0.0−0.23)
Biofuel				
palm biodiesel (Indonesia/Malaysia)[a]	tropical rainforest	0.0062	702 ± 183	113 ± 30
palm biodiesel (Indonesia/Malaysia)[a]	peatland rainforest	0.0062	3452 ± 1294	557 ± 209
soybean biodiesel (Brazil)[a]	tropical rainforest	0.0009	737 ± 75	819 ± 83
sugar cane (Brazil)[a]	cerrado wooded	0.0059	165 ± 58	28 ± 10
soybean biodiesel (Brazil)[a]	cerrado grassland	0.0009	85 ± 42	94 ± 47
corn ethanol (US)[a]	central grassland	0.0038	134 ± 33	35 ± 9
corn ethanol (US)[a]	abandoned cropland	0.0038	69 ± 24	18 ± 6

[a] Based on data from Fargoine et al. (*47*) Supporting Online Material. Assume 50 years biofuel production period. [b] Values for fossil fuel are single estimates or the mid-range values and the upper-bound and lower-bound estimates are reported in the parentheses. Values for biofuels include standard deviations.

California (Table 2). The land use GHG intensities of surface mining and *in situ* are 3.88 (0.83−10.24) gCO_2e/MJ SCO and 0.04 (0.00−0.23) gCO_2e/MJ SCO, respectively.

3.4. Sensitivity Analysis. We also examine the sensitivity of GHG emissions to the following cases: (1) 0−100% of oil sands development occurs on peatlands, (2) the land use impacts of upstream natural gas extraction for use in oil sands production is included, and (3) dry landscape reclamation is employed. The results are summarized in Section 6 of the SI and Table S9.

There are several aspects that are not considered in our model, most notably regarding the dynamic nature of the climate system and time horizons within land use change models. We have assumed a constant climate and do not consider factors such as CO_2 fertilization, inactive soil carbon, changes in albedo, and climate-ecosystem interactions. Climate change already has initiated changes in the boreal fire regime (*37*) and has triggered widespread permafrost thaw (*38*), both of which impact carbon cycling. In undisturbed peatlands, research has shown that 40% and 86% of the carbon held in shallow and deep peat, respectively, may be lost due to warming of 4 °C over 500 years (*39*). On the other hand, there is also evidence suggesting that long-term drying via drainage can lead to increased soil carbon storage in peatlands through afforestation (*40*), though this would have consequences for fire activity in Canada. Short-term warming and drying reduced plant productivity but increased soil respiration, with no net effects on net ecosystem exchange of CO_2 (*41*). Due to the uncertainty in ecosystem vulnerability over long time scales, LUC and fossil combustion may not be directly compatible (*42*), bringing to question whether or not they should be combined within a single lifecycle matrix. Alternative methodologies, such as ton-year accounting, may be one way to address one of the concerns, particularly on the inconsistency of time scale of emissions (see Section 6 in the SI).

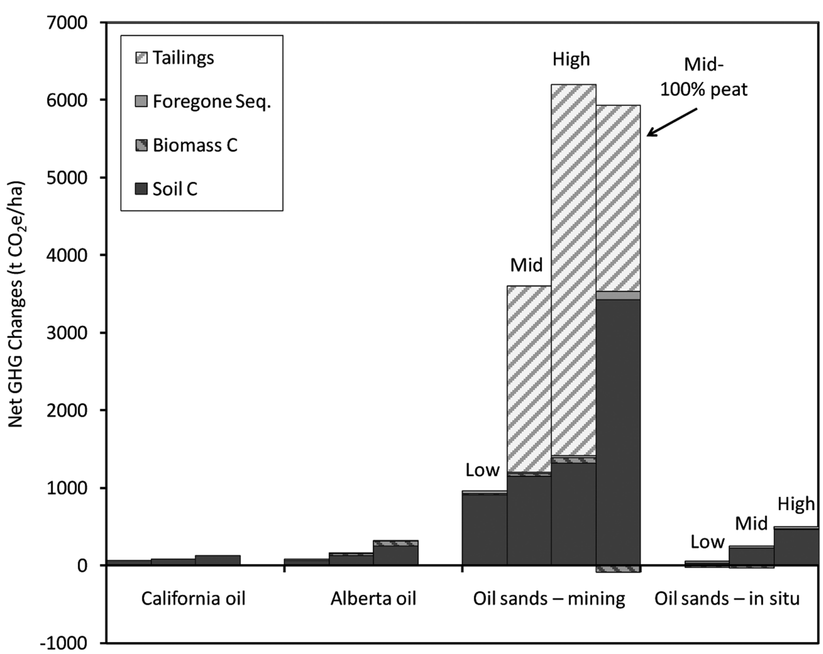

FIGURE 1. Changes in carbon stock and CH_4 emissions per unit area disturbed by conventional oil production and oil sands over a modeling period of 150 years, assuming reclamation back to natural state after projects complete.

4. Discussion

Our results highlight the importance of the GHG emissions associated with soil carbon emissions from peatland conversion and tailings ponds methane emissions, because both can potentially cover large tracts of land. Three important variables determine the direct GHG intensity of land disturbance on liquid transportation fuels: energy yield per disturbed land, GHG emissions per disturbed land, and GHG emissions per energy output (Table 4). When contrasting land disturbance from fossil fuel and biofuel production, it is the energy yield that greatly distinguishes the two. Although compared with biofuels, LU GHG emissions (per disturbed land area) from fossil fuel development can be comparable or higher than biofuels (Figure 1); biofuels, however, have a very low spatial energy density compared to conventional and unconventional oil production. Since fossil fuel extraction has significantly higher energy yield, the land use emission per unit energy output are thus significantly lower than biofuels.

It is, however, important to note that CO_2 emissions derived from the use of oil (*43*) are orders of magnitude higher compared to land use emissions (Table 3). As Canadian oil sands production may reach 1.5 billion barrels per year in 2030 (*44*), this may result in additional 50−96 and 9.1−21 thousand ha of cumulative land disturbance and 47−580 and 0.1−10 Mt CO_2e LU GHG emissions between 2010 and 2025 from surface mining and *in situ* production (not including upstream disturbance from the use of natural gas), respectively. These numbers, though large, are orders of magnitude smaller compared with 5400 and 4800 Mt lifecycle CO_2e emissions from surface mining and *in situ* production, respectively, and use.

Our study estimates are based on assumptions aggregated over large spatial and temporal scales. Values on finer spatial and temporal scales that are relevant to policy targets need to be dedicatedly balanced against site-specific information, the baseline natural and anthropogenic disturbance, and the annual variations in carbon storage due to climate and natural disturbance such as fires or pest outbreaks. Our largest uncertainties are the assumptions regarding the proportion of soil carbon loss on mining sites, CH_4 emissions from tailings ponds, and the success rate of reclamation. Local measurements, monitoring, and model simulations to estimate project-level land disturbance GHG emissions can significantly reduce many of the key uncertainties that we attempt to capture in this paper and improve the accuracy of the estimates. Postmining reclamation such as the restoration of habitat can reduce land-related CO_2 emissions from oil sands development, but more importantly they serve a critical purpose to recover ecological landscapes, sustain high biodiversity, hydrologic cycles, and forest ecosystems from heavily mined areas after oil sands production has been completed (*13*).

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Supporting Information Available

Detailed information on the equations for calculating land use GHG intensity; data sources, assumptions, and the methodology of calculating land use GHG intensity; and detailed results and sensitivity analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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