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

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.

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 with lifecycle 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).

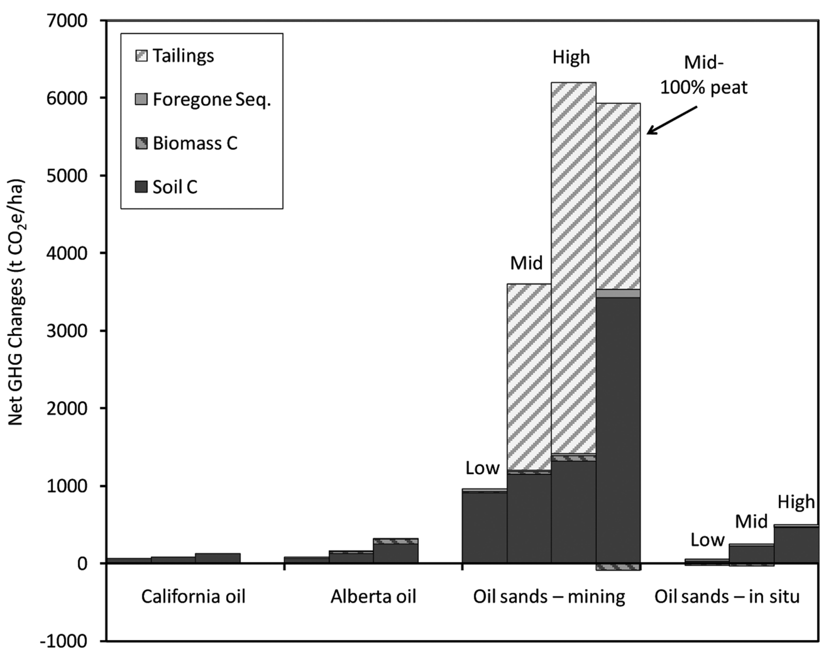

FIGURE 1. Changes in carbon stock and CH_4 emissions per unit area disturbed by conventional oil production and oil sands over a modeling period of 150 years, assuming reclamation back to natural state after projects complete.

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

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1. Formula for Estimating Land Use Greenhouse Gas (GHG) Intensity

The land disturbance intensity *I* for conventional oil production and *in situ* bitumen production can be calculated as:

$$I = \frac{A}{E} = \frac{A_W W}{E} \qquad \text{(Equation S1)}$$

where A is the total disturbed area by the fuel production, A_W is the area of land disturbed for each production well. *W* is the total number of wells and *E* is the total energy of fuel produced in MJ. The methods for estimating *A* are described in Sections 2 and 3. For the case of surface mining of petroleum resources, the land disturbance intensity is calculated by the disturbed area divided by the energy in the petroleum produced in that area.

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. As reserves decline, wells produce less oil on average. For the historical case we use 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 wells drilled from the year of analysis and divide them by MJ of crude oil produced in that year. We then use the disturbance per well to calculate the land disturbance intensity. This approach assumes a relatively “steady state” production pattern, such that drilling in the current year is approximately equal to the drilling that was required for the current year’s production.

The inverse of Eq S1 can be interpreted as the energy yield per unit disturbed area (e.g., in PJ/ha). The greenhouse gas emission intensity associated with land disturbance (CI_{LU}) in grams of CO_2 equivalent per MJ of energy in fuel can be expressed as follows:

$$CI_{LU} = C_{LU} I \qquad \text{(Equation S2)}$$

C_{LU} is the GHG emissions associated with land disturbance in grams or tons of CO_2e per unit area. Carbon stock and emission changes before and after the disturbance were estimated.

The total carbon stock in the reference case without land disturbance for oil development at the end of modeling period can be represented as:

$$C_{ref} = C_{soil} + C_{bio} + C_{seq} \times T \qquad \text{(Equation S3)}$$

where,

C_{soil} = Initial soil C stock (t CO_2e/ha),

C_{bio} = Initial aboveground and underground biomass C stock (t CO_2e/ha),

C_{seq} = long-term annual carbon/CH_4 sequestration rate (positive value represents net sequestration) (t CO_2e/ha/yr),

T = modeling period.

The total carbon stock and GHG missions in the land disturbance case at the end of modeling period:

$$C_{oil} = (1 - F_s) \times C_{soil} + (1 - F_v) \times C_{bio} - C_{tailings} \times (t - n) + C_{rec} \times (T - r) \qquad \text{(Equation S4)}$$

where,

F_s = the fraction of soil C loss due to land disturbance,

F_v = the fraction of total biomass loss due to land disturbance,

$C_{tailings}$ = tailings pond emission rate, only applicable to oil sands surface mining (negative value represents net emissions) (t CO_2e/ha/yr),

t = years that tailings emissions end.

n = years that tailings emissions start,

C_{rec} = the annual net CO_2 uptake after reclamation (positive value represents net sequestration) (t CO_2e/ha/yr),

r = years that reclamation starts (yrs).

The total GHG changes due to land disturbance for oil development can be characterized by:

$$C_{LU} = C_{ref} - C_{oil} = \underbrace{F_s \times C_{soil} + F_v \times C_{bio}}_{\text{Initial C loss}} + \underbrace{C_{seq} \times T}_{\text{Foregone sequestration}} + C_{tailings} \times (t - n) - \underbrace{C_{rec} \times (T - r)}_{\text{C re-accumulation}} \qquad \text{(Equation S5)}$$

The foregone sequestration is defined as the sequestration associated with forest clearing when this forest would have continued to sequester carbon had it been left undisturbed (*S1*). Our modeling period is assumed to be 150 years, which encompasses the assumed conventional oil and oil sands production period of 30 years, and reclamation. Once C_{LU} is known, GHG emissions of land disturbance associated with crude and oil sands production can be calculated based on Equation S2.

2. Land disturbance Intensity: Conventional Oil

We used two study areas, Alberta and California, to estimate the greenhouse gas emissions released from land disturbance. We chose these regions due to data availability; however, other regions could also be analyzed using similar methodology.

California Conventional Oil

Data for California conventional oil production was obtained from the California Department of Oil, Gas, and Geothermal Resources (DOGGR) (*S2*).[1] In 2007, California produced 0.22 billion barrels of oil (11 percent of US production). California oil production peaked in 1985 but has since declined steadily, and production has fallen from 394 million barrels in 1985 to 215 million barrels in 2008 (*S3*). Fifty-one percent of California is heavy crude, having API gravity[2] of 18 degrees or less. Cumulative crude oil produced to date is 25.1 billion bbl.

Our dataset contains 301 oil fields covering 3×10^9 m^2 (1,180 square miles). As of 2005, these fields contained at least 58,000 active production wells, 22,000 shut-in production wells, and 25,000 injection wells, over 6,000 of which are shut-in. These figures do not include wells that are not in current DOGGR field-level data tables, including: a) wells in abandoned fields, b) wells that were drilled before 1915 when oil and gas drilling records were first kept, c) exploratory wells that were abandoned before successful production, and d) other wells of unknown origins. Using historical DOGGR reports from 1919 to 2005, we calculate that the total number of wells drilled in this time period was at least 188,000, or approximately 80,000 more than are contained in current data tables.

To estimate the amount of land in California oil fields disturbed per well drilled, we used an image analysis program (ImageJ) to convert satellite images of three oil fields (the Elk Hills, San Ardo, and Lost Hills fields) into binary files (black and white). All images were taken at eye elevation of 2 km. The binary conversion algorithm converts vegetation, which is darker than dirt roads and areas around wells, to black. The software then performs pixel-based area counting, classifying as “disturbed” all light areas larger than 1000 m^2.

Ten images from these oil fields were analyzed. The percentage of land without vegetation (the disturbed areas) range from 25–36% for the 3 fields analyzed. Figure S1A shows an example of our land

[1] ftp://ftp.consrv.ca.gov/pub/oil/Data_Catalog/Oil_and_Gas/Oil_fields/
[2] American Petroleum Institute (API) gravity standard, which measures the weight of crude oil in relation to water.

disturbance analysis for California oil production. To determine the land disturbed per well, we divided the total disturbed area by the number of well pads counted in each image. The number of distinguishable well pads on each image ranged from 45 to 122. The land disturbed per well ranged from 0.33 to 1.8 ha/well, while the average of all 10 images was 1.1 ha/well (which includes all access roads and other facilities included in each image). Our analysis assumes that land use practices do not change over time.

A

B

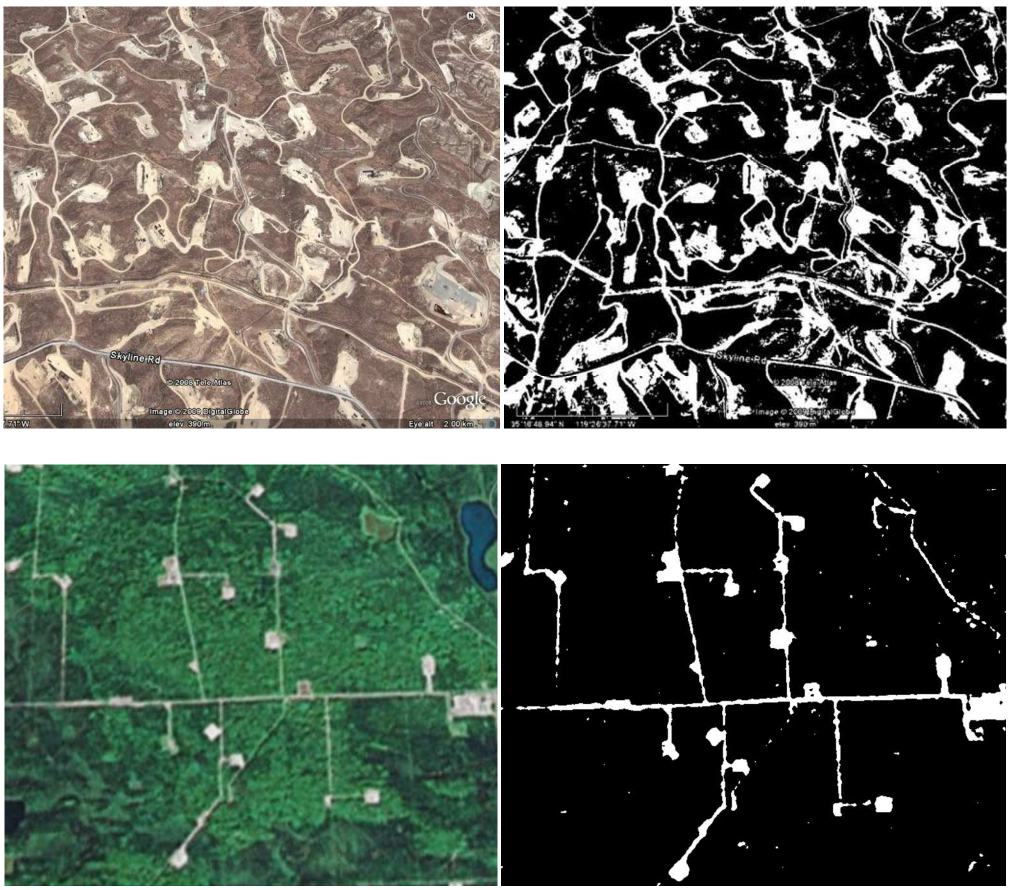

Figure S1. A. Image analysis of land disturbance for California Elk Hills oil field. Left: images extracted from Google Earth and attributed to Telemetrics, TeleAtlas and Digital Globe 2009. Right: Converted black and white image to estimate the percent of disturbance (white area). B. Illustrative image analysis of land disturbance for Alberta oil field. Left: images extracted from Google Earth and attributed to Telemetrics, TeleAtlas and Digital Globe 2009. Right: Converted black and white image to estimate the percent of disturbance (white area).

The average, low, and high disturbance per well was then used to calculate both historical and marginal emissions intensities. For historical emissions, we multiply per-well disturbance by the number of active and shut-in wells in each field, including both production and injection wells. We adjust for the missing wells in current DOGGR data tables by multiplying known wells in each field by a scaling factor to account for missing wells. A number of oil fields are completely abandoned, with no well counts available. In total, 210 of the 301 oil fields had all required data available, accounting for 97.4% of cumulative oil production.

Many oil wells co-produce oil and gas. The gas to oil ratio (GOR, ft^3/bbl) ranges from 0 (no gas co-produced with oil) to thousands (negligible oil co-produced with gas). California GORs at the county level ranged from 15 to 2,100 in 2007, and the state average was 850 ft^3/bbl (*S4*). Because oil and gas today are co-produced, the carbon emissions associated with land use should be assigned proportionally based on GOR. However, when most California fields were discovered and drilled (before the 1960s), gas was considered a secondary byproduct of oil production. We therefore attribute land disturbance occurring during field development solely to oil. More work in this area may show that a proportion of the land disturbance should be attributed to co-produced natural gas.

The summary statistics for California oil fields, oil production, and land disturbance intensity are shown in Table S1. The energy yields based on the average disturbance (1.1 ha/well) and the low and high disturbance cases (0.33 ha/well and 1.8 ha/well respectively)) are 0.79 (0.48-2.6) PJ/ha disturbed and 0.55 (0.33-1.8) PJ/ha disturbed for historical and marginal impacts, respectively.

Table S1. Summary of California crude oil land disturbance intensity based on historical and marginal impact analysis.

	Wells Drilled (no. of wells)	Area Disturbed (ha)	Oil Produced (bbl)	Oil Produced (MJ)	Production: Wells Drilled (m3/well)	Energy yield (PJ/ha disturbed)
Historical impacts	> 188,508[a]	202,000	2.6E+10	1.6E+14	2.2E+04	0.79 (0.48-2.6)
Marginal impacts	2,641	2,800	2.6E+08	1.6E+12	1.5E+04	0.55 (0.33-1.8)

a – This figure includes exploratory and development wells drilled from 1919-2005. Wells drilled before 1919 were not available in dataset used, so it is a lower-bound estimate. Note that cumulative production includes oil produced before 1919.

Alberta Conventional Oil

Data for Alberta conventional oil production was obtained from the Energy Resources Conservation Board (*S5*). The province had 35,557 conventional oil wells in 2007, producing 515,000 barrels per day (*S5*). Of this, 60% of production was light and medium crude, with the other 40% heavy. Alberta's conventional crude oil production peaked in 1973 at 1.4 million barrels per day and declined to 0.5 million barrels per day in 2007.

The methodology used for estimating the land disturbance of conventional oil wells for California was also used for Alberta. Using ImageJ software, 10 images from various oil and gas developments were analyzed to determine the land disturbance per well. Figure S1B shows an example of our land disturbance analysis for Alberta conventional oil production.

To determine the land disturbed per well, we divided the total disturbed area by the number of well pads counted in each image. The elevation for the California analysis was 2 km, which was suitable for the state's well density of approximately 31 wells/km^2. However, well density in Alberta was found to range between 0.3 and 2.5 wells/km^2 in the images analyzed. As a result, an image at an elevation of 2 km generally captures only 1-3 wells and omits associated infrastructure (e.g., the full extent of the access road). We ran the analysis at elevations of 2 km and 5 km on the same regions and verified that the latter captured more of the infrastructure required for development. Running similar analyses at greater regional scales would result in a larger land disturbance yet, capturing more of the required infrastructure (*S6*). The disturbed land ranges from 1% to 10% for each of the 10 images analyzed at a 5 km elevation. The images captured between 4 and 31 wells, disturbing 1.6 to 7.1 ha/well, while the average of all 10 images was 3.3 ha/well. As with the case of California, we assume that the land use practices do not change over time.

The Energy Resources Conservation Board (ERCB) provides historic well production and drilling from 1948-2007 (*S5*)(Figure S2).

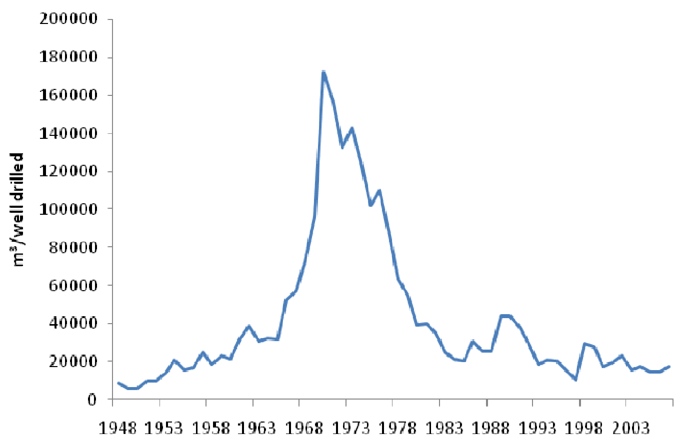

Figure S2. Marginal production per well, 1948-2007. Wells included are exploratory and development wells as reported by the ERCB (2008) (*S5*).

The historic production was calculated by dividing the total wells drilled by Alberta's total production. The total conventional oil production from 1938-2007 was used as the historic production (17 Gbbls), so may slightly overestimate total well productivity. It is assumed that the number of wells drilled before this time was not significant when compared to the number of wells drilled between 1948 and 2007. The marginal production per well was determined as the production to drilling ratio for 2007. The summary statistics for Alberta conventional oil fields, oil production, and land disturbance intensity are shown in Table S2. The energy yields based on the average disturbance (3.3 ha/well) and the low and high disturbance cases (1.6 ha/well and 7.1 ha/well respectively) are 0.34 (0.16−0.69) PJ/ha and 0.20 (0.092−0.40) PJ/ha for historical impacts and marginal impacts, respectively.

Table S2. Summary of Alberta conventional oil land disturbance intensity based on historical and marginal impact analysis.

	Wells Drilled	**Area Disturbed**	**Oil Produced**		**Production: Wells Drilled**	**Energy yield**
	(no. of wells)	**(ha)**	**(bbl)**	**(MJ)**	**(m3/well)**	**(PJ/ha disturbed)**
Historical impacts	85,272	282,000	1.6E+10	9.6E+13	2.9E+04	0.33 (0.16−0.69)
Marginal impacts	1,769	5,800	1.9E+08	1.2E+12	1.7E+04	0.20 (0.092−0.40)

3. Land Disturbance Intensity: Oil Sands Surface Mining and *In Situ* Production

Land use intensity estimates for oil sands surface mining were extracted from ERCB (*S5*) and compared to CEMA-SEWG (*S7*) (Table S3). CEMA-SEWG developed modeling assumptions for ALCES landscape simulations. These values were developed in a series of workshops with industry, government, and environmental organizations.

Table S3. Land use intensities for surface mining.

Project	Project area (ha)	Initial mineable volume in place (10^6 m^3)	Initial established reserves (10^6 m^3)	Cumulative production (10^6 m^3)	Remaining established reserves (10^6 m^3)	Land use intensity (m^2/m^3 SCO)	Land use intensity (m^2/MJ)
Albian Sands		672	419	41	378	0.38	9.6E-06
Forthills	18976	699	364	0	364	0.61	1.5E-05
Horizon	28482	834	537	0	537	0.63	1.6E-05
Jackpine	7958	361	222	0	222	0.42	1.1E-05
Suncor	19155	990	687	235	687	0.33	8.3E-06
Syncrude	44037	2071	1306	351	1306	0.40	1.0E-05
CEMA-SEWG model	-	-	-	-	-	0.42	1.1E-05
Total	132189	5627	3535	627	3494	0.44	1.1E-05

** The project areas correspond to the areas defined in the project approval. This entire area will be disturbed.

The data used for *in situ* recovery was derived from CEMA-SEWG (*S7*), which provided a range of land use intensities (shown in Table S4). Jordaan, Keith, and Stelfox (*S8*) reported land use intensity of 0.33–0.63 m^2/m^3 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). We assumed the volumetric energy density of SCO is 39,536 MJ (HHV)/ m^3 SCO (*S9*). Ranges for land disturbance from oil sands development are shown in Table S4.

Table S4. Ranges of land use intensities (m^2/m^3 SCO) for oil sands and upstream natural gas development. Adapted from Jordaan, Keith, and Stelfox (*S8*).

Technology	Literature range (m^2/m^3 SCO)	Estimate (m^2/m^3 SCO)	Seismic activity (biomass disturbance only)	Other activity (biomass + soil disturbance)
Mining	0.33–0.63	0.42		0.42
In situ	0.070–0.16	0.11	0.066	0.044
Upgrading	0.0075–0.023	0.011		0.011
Natural gas (mining and upgrading)	0.030–0.11	0.11	0.010	0.11
Natural gas (*in situ* and upgrading)	0.070 – 0.26	0.26	0.010	0.24

Crude recovery, bitumen production, processing and upgrading to SCO uses natural gas, which is used to heat water to extract the bitumen, and to generate heat and produce hydrogen for upgrading and refining. Based on Dunbar (*S10*), Jordaan et al. (*S8*) report that 70, 220, and 50 m^3/m^3 SCO natural gas purchases were required for surface mining, *in situ* extraction, and upgrading, respective, and that the extraction and transport of natural gas has a land use footprint of 2.6×10^{-4}–9.5×10^{-4} m^2/m^3 natural gas (*S8*). If upstream natural gas mining and upgrading are included, the total land use footprint for surface mining is estimated to be 0.37−0.76 m^2/m^3 SCO (best estimate 0.55 m^2/m^3 SCO or 0.73 PJ SCO/ha) and 0.15−0.44 m^2/m^3 SCO (best estimate 0.38 m^2/m^3 SCO or 1.0 PJ SCO/ha) for *in situ* production. The lower bound estimates represent minimum accounting for natural gas land use and the upper bounds represent the inclusion of natural gas land use via extensification (*S8*).

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

Carbon Stock

Alberta has six natural regions (Rocky Mountain, Foothills, Grassland, Parkland, Boreal Forest, and the Canadian Shield), each with several subregions. Each of these natural regions has varying carbon stocks and well productivities. The locations and production for all pumping, flowing, and producing oil wells in Alberta were extracted using AccuMap software (excluding gas wells that produce some oil). In order to understand the distribution of conventional oil wells across the natural regions, wells were mapped using ArcGIS. Data for wells with the same surface hole locations were merged to account for wells that are drilled from the same well site but produce from different pools. A well shapefile was created and spatially joined with shapefiles for natural regions and subregions to determine which wells occurred in each region and their daily oil productivity. For the Boreal Forest Natural Region, we subtracted the number of bitumen-producing wells (8,900 wells in 2007, as reported by the ERCB). 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%)(*S11*) is smaller than the rest of the boreal subregions, including Central and Northen mixedwood (31 and 38% respectively) and highlands (23%) (*S11*). We found that the average peatland coverage weighted by the number of oil wells is 15% within the boreal region.

The carbon stocks in soil and biomass in Alberta are estimated by matching the available ecosystems in the Supporting Online Material of Searchinger et al. (*S12*) (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 (*S13*). We then calculated the weighted carbon in soil and in vegetation and carbon uptake for each of the six natural regions (Table S5).

Table S5. Summary of the estimated soil and biomass carbon content in natural regions of Alberta.

Natural Region	% oil well	Vegetation	Classification	Weighted C stock* (t C/ha) vegetation	soil	Weighted C uptake* (t C/ha/yr) re-grow forest
Rocky Mountain	0.01%	Mixed conifer where oil development occurs	100% temperate evergreen	160	134	2.4
Foothills	15%	Lower: Mixed conifer in closed coniferous forests	100% temperate evergreen	147	134	2.0
		Upper: Mixedwood (assumed 50:50 evergreen:deciduous)	50% evergreen, 50% deciduous			

Grasslands	23%	Generally agricultural areas, some natural grasslands (fescue, needle and thread grass)	100% temperate grassland	7	189	0
Parkland	32%	Primarily aspen (deciduous) forests, grasslands, agriculture. Some lodgepole pine stands on sands	45% deciduous, 45% grassland, 10% evergreen	80	159	1.0
Boreal Forest	29%	Mixedwood forests (deciduous + evergreen), peatland, cultivation. Subregions described as having 15-70% wetlands	85% boreal, 15% peatland	82[**]	357[**]	1.4
Canadian Shield		Mostly rock barrens with pockets of mixedwood forests, some wetlands	No producing oil wells	N/A	N/A	N/A
Weighted Average				74	221	1.05

Note: 1 hectare (ha) = 0.01 km^2.
[*] Estimated based on values reported in Searchinger et al. SOM (*S12*) .
[**] Based on the weighted average of the boreal forest biomass of 90 t C/ha and boreal forest soil C storage of 206 t C/ha (*S12*) (85%), and peatland biomass of 36 t C/ha (*S14*) and soil C storage of 1213 t C/ha (Table S6)(15%) to get the weighted average of 82 t C/ha for biomass and 357 t C/ha for soil C (206 × 85% + 1213 × 15%).

Peatlands Carbon Stock

To get a more accurate estimate of soil and biomass carbon in the boreal region in Alberta, we developed a separate methodology for boreal peatlands. Table S6 summarizes the soil carbon (t C/ha) of various peatland types in continental western Canada estimated by Vitt et al. (*S15*). We assumed the distribution of peatland types in the Alberta boreal forest region is similar to that in the “mid boreal” in Table S6 below, yielding a weighted soil carbon of 1213 t C/ha. Peatland distribution is estimated to be 23% of the Alberta boreal region based on Vitt et al. (*S11*). Our assumption is consistent with Turetsky et al.’s estimate that 22% of current oil sands surface leases is covered by peatland (*S16*).

Table S6. Soil carbon (in t C/ha) of peatland of continental western Canada (Alberta, Saskatchewan, and Manitoba). Based on Tables 1 and 3 of Vitt et al. (*S15*).

Peatland Type	Arctic	Subarctic	Montane	High Boreal	Mid Boreal	Aspen Parkland and Interlake	Average	% total
Permafrost frost bogs	738	1261	0	1166	1295	0	743	0.28
Nonpermafrost bogs	0	1692	0	1360	1236	1109	900	0.08
Treed fens	0	1317	675	1425	1347	1208	996	0.28
Shrubby fens	775	1353	667	1298	907	788	965	0.07
Open nonpatterned fens	787	1355	658	1275	910	788	962	0.20
Open patterned fens	0	1706	704	1668	1389	2244	1285	0.09
Weighted average	**781**	**1315**	**676**	**1357**	**1213**	**1107**	**934**	

Carbon Uptake in the Base Case and Carbon Uptake after Reclamation

Forest after disturbance (e.g. fire) can be reclaimed back to forested state after a long period of time (*S14, 17-19*). Forest re-growth accumulates C in aboveground, belowground biomass, and soil organic matter at various rates depending on the type of vegetation, climate condition, and other complex factors (*S14, 17, 18*). To represent carbon sequestration rates after reclamation, based on available data we make the assumption that primary succession (following reclamation) follows a similar recovery rate to secondary succession (following wildfire). Based on Carrasco (*S20*) and Amiro (*S21*), the net primary productivity (NPP) post-fire range from 1.35 –2.25 t C/ha/yr^{-1} in the boreal plain region. NPP is a good indicator of forest recovery following fire and is the primary driver for potential carbon sequestration. Trajectories of NPP for longer periods at the ecoregion level are difficult to assess. The observed NPP rates for boreal forest were reported to be relatively stable (*S20-23*), though Luyssaert shows an increasing trend of NPP with age and declining beyond 80 years of age (*S23*). In their simulation of soil C model, Carrasco (*S20*) assume constant NPP between fire return interval of 150 and 200 years, though other studies suggests fire cycles are 40-110 years through much of the boreal region (*S22, 24*). Thus we make a simple assumption that reclaimed forest will sequester carbon at a constant NPP rate of 1.35 –2.25 t C/ha/yr^{-1} until the aboveground biomass of the reclaimed forest reaches the pre-disturbance level or for 80 years (whichever constraint is met first). We further assumed that roughly 30% of sequestered C is stored in soil C (*S23*) and the soil carbon sequestration rate is constant throughout the modeling period. We assumed that after 150 years, the carbon uptakes and disturbances (natural and anthropogenic) are indistinguishable between the reference case and the land disturbance case.

Tailings Pond CH_4 Emissions

CH_4 emissions from tailings ponds are also among the largest sources of uncertainty in our study. CH_4 emissions from a tailings pond vary widely, and few measurement data have been collected. Siddique et al. (*S25*) reported a range of 0.9–114.2 g CH_4/m^2/d based on measured and modeled estimates for Mildred Lake Settling Basin (MLSB), and on average, 25% of the study site is thought to be methanogenic (*S25*). Holowenko et. al. (*S26*) reported 12 yrs after the observation at MLSB, 40–60% of the surface has a daily flux of 12 g CH_4/m^2/d. Holowenko et. al. (2000), however, also stated that “methanogenesis in the fine tailings appears to be a finite process, slowing when usable substrate is depleted.”

We used the reported range of daily methane flux of 0 – 12 g CH_4/m^2/d (0 – 44 t CH_4/ha/yr) to represent methane emissions from tailings sites. Because only portions of the surface areas have been reported to emit methane gas, we assumed half of the tailings surface will emit methane gases (*S25, 27*). Though tailings pond CH_4 emissions have been reported for many major mature fine tailings (MFT) sites in Northern Alberta (*S26, 28, 29*), we do not know whether CH_4 emissions will occur in *all* tailings and whether the assumed rate will sustain.

Consistent with actual observations mentioned above, we assumed CH_4 emissions begin 15 yrs after the site begins operating (*S26*). For the upper bound assessment, we further assume that the emission rate is constant until the end of year 50 (i.e. constant emissions for 35 yrs). There is currently no better study to guide this assumption and it may need to be revised when more empirical or modeling studies are published in the future.

The total reported oil sands disturbed area is 460-530 km^2 (*S30, 31*), of which 70-130 km^2 is tailings pond. As such, tailings ponds are about 13-28% of the total disturbed area.

Oil sands producers and the Government of Alberta are making efforts to improve water use efficiency and reclamation management to "minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape" (*S32, 33*). One reclamation plan for fine tailings waste is the "wet landscape" approach in which the MFT would be transferred to an abandoned mine pit and then capped with water to form a "lake" (*S28, 33*). Alternatively, some "dry landscape" reclamation experiments such as composite tailings (CT) by adding calcium sulfate to MFT to quickly release most of water within hours and tailings reduction operations (TRO) allow re-vegetation on the dried landscape. Studies suggest methane was not detected in CT when sulfate was added to tailings samples (*S26, 34*). However, Fedorak et al. (*S28, 29*) suggested that some methanogenic activities may be present in CT samples after sulfate concentration is sufficiently decreased.

Assumptions of Carbon Lost

For conventional oil and gas extraction and *in situ* production, we assumed that on average 20–40% of soil carbon (e.g. scraping of soil at surface for roads, drainage, drill pads, drilling wells, etc.) is oxidized once the lands are disturbed. The assumption is based on the IPCC guideline (*S35*) on the calculation of soil C loss after land use conversion, which recommends a 20 – 40% soil C loss factor from the conversion of grassland and forest land to crop land, and 20% from disturbance from settlement activities such as infrastructure (e.g. roadways, houses, and buildings). Since there is limited data on soil C loss due to settlement activities such as infrastructure and it is highly uncertain (*S36*), we use 20 – 40% to represent the range uncertainties for average land use disturbance associated with conventional oil and gas extraction and *in situ* production. Surface mining involves complete removal of surface soil and transport to offsite facilities for processing, thus we assume a complete loss of soil carbon over a 50-yr time interval for soil and peat disturbance due to oil sands mining (*S16*). Since our total land disturbance estimates includes mine sites and other facilities, 70–90% range is selected for surface mining sites. It is unclear to us how soil (and peat) is treated after project completes. If soil overburden is used as amendment for reclamation, then most of the soil (peat) carbon is decomposed under aerobic condition assuming an exponential decay function (*S37*). If however, most of the soil (and peat) is stored as overburden and later put back onsite for peatland restoration, then soil (and peat) carbon loss rate could be lower than what we assumed here. However, methane emissions could increase as a result of stockpiling (*S37, 38*) or flooding to maintain waterlogged peatland conditions during restoration. We also note that our assumptions err on the conservative side because we only consider the direct footprint, and not additional areas impacted by land-use impacts (which vary from 50% to 130% (*S39*) or 200% (*S40*) of the affected area) or increased fires associated with peatland drainage and degradation (*S41*).

Estimates for land disturbance intensity of oil sands production included seismic activity (*S8*). Since current seismic practices only remove above-ground biomass and not soil carbon, we assumed that it will result in 100% biomass but negligible soil carbon loss.

Table S7 summarizes the assumptions of the parameters defined in Equation S5, including initial carbon stocks, emission factors, rates of carbon loss, and time durations of the activities.

Table S7. Summary of parameters and emission factors for estimating GHG balance in Equation S5. Values include single estimates or the mid-range estimates (the lower- and upper-bound estimates are reported in the parenthesis). Positive values represent carbon loss or net emissions, while negative values represent avoided emissions or net uptake.

			Calfiornia Crude Oil	**Alberta Crude Oil**[1]	**Oil sands – mining**[2]	**Oil sands – *in situ***[2]
C_{soil} **(t C/ha)**	Soil carbon		80	221	438	438
F_s	Fraction of soil C loss		25% (20–40%)	25% (20– 40%)	80% (70– 90%)	25% (20– 40%)
C_{bio} **(t C/ha)**	Biomass carbon		18	74	78	78
F_v	Fraction of biomass C loss	Year 20 Year 150	100% 100%	95% (90-100%)[3] 100%	92% (84-100%) 100%	92% (84-100%) 100%
C_{seq} **(t C/ha/yr)**	Long-term carbon uptake	Forest Peatland		0[4] 0.2 (0.17–0.24)[5]	0 0.2 (0.17–0.24)	0 0.2 (0.17–0.24)
C_{rec} **(t C/ha/yr)**	Carbon uptake of regrowing forest	Forest/ Peatland[6]		1.4 (1.35–2.25)[7]	1.4 (1.35–2.25)	1.4 (1.35–2.25)
$C_{tailing}$ **(t CH_4/ha/yr)**	Emissions from tailings ponds				0–44[8]	
R	Year when reclamation starts			30	30	30
N	Years that tailings				15	

	pond starts to emit CH_4				
T	Years that tailings emissions end			50	
T	Modeling period	150	150	150	150

[1] Weighted avg across Alberta oil producing regions. See Table S5; [2] Assumed 23% peatland and 77% boreal forests; [3] Weighted by total forested area calculated from Table S5; [4] Assumed the long-term net carbon accumulation rates (including natural and human disturbances) are zero for all ecoregions except peatlands. [5] based on (*S16*). [6] Reclaimed to upland after disturbance. [7] Based on Carrasco (*S20*) and Amiro (*S21*). [8] Applied only to 50% of the tailings area (based on *(S26)*).

A conceptual illustration of the dynamics of carbon stock changes after land disturbance and reclamation is presented in Figure S3. Tailings emissions are ignored in this illustrative example. Reclaimed peatlands will have a much lower soil carbon after it is reclaimed to upland.

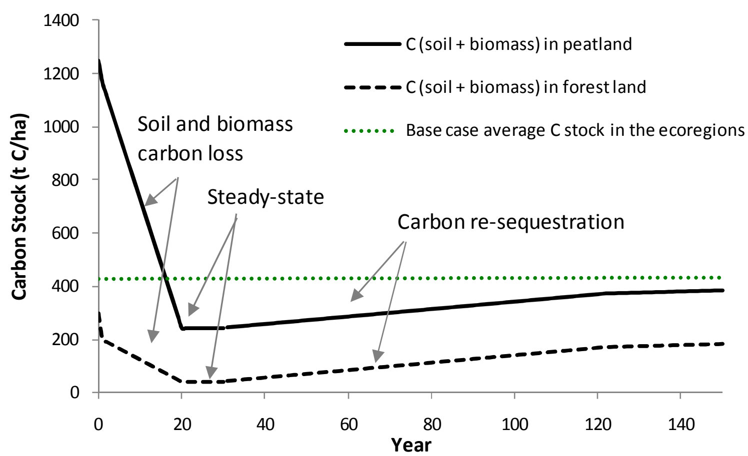

Figure S3. Conceptual illustration of carbon stock changes for the case of surface mining. Parameters are defined in Table S7 and the results for soil and biomass carbon are summarized in Table 1 for the surface mining scenario (using the single/mid-range values).

Assumptions of Carbon Lost – Forest Biomass

Our study assumes removals of biomass as instantaneous emission to the atmosphere (i.e. 100% biomass C loss) based on the IPCC guidelines (*S35*). Alternatively, methods that account for the long-term storage of carbon in harvested wood and in landfills can also be considered (*S42, 43*). Harvested wood products have different lifespans that range from 2–100 years, with longer lifespan for lumber and shortest for paper. We estimate that the fractions of *above-ground* biomass carbon remaining in end- uses and landfills (i.e. not emitted to the atmosphere) after 0, 20 and 100 years are 45.7%, 19.6% and 14.4%, respectively (Table S8). The C storage factors in end-uses after 150 years could not be obtained but should be very close to zero. Based on these two methods, we estimate 54–100%, 80–100% and 100% carbon loss of *above-ground* forest biomass at 0, 20 and 150 years after disturbance, respectively.

Assuming a root to shoot ratio of 20% (*S44*), this results in 63–100%, 84–100% and 100% carbon loss of *total* forest biomass at 0, 20 and 150 years after disturbance, respectively.

Table S8. Estimates of the disposition of above-ground forest biomass carbon at 20 and 100 years after disturbance.

		Fraction of biomass in end-use		Fraction of carbon remaining in end-uses and landfills after 20 years [d]	Fraction of carbon remaining in end-uses and landfills after 100 years [d]
Non-merchantable biomass[a]			54%		
Merchantable biomass[b]			**46%**		
	Logs and bolts	Softwoods	28%[c]	47%	35%
		Hardwoods	7%[c]	41%	30%
	Pulpwood	Hardwoods	10%[c]	32%	23%
	Others		<1%[c]		
Weighted Average of total biomass (merchantable and non-merchantable)				**20%**	**14%**

a. These are nonstemwood, above-ground tissues including the bark, branches and leaves. These biomass are mostly left onsite to provide ecological service (including conservation and protecting soil health). We assume 100% biomass loss for non-merchantable biomass once it is removed from the forestry system.

b. The fraction of carbon remaining in end-uses immediately after disturbance is assumed to be 1 for merchantable biomass. Source: Wood and Layzell (*S45*).

c. Source: Canadian Council of Forest Ministers (*S46*).

d. Other categories of carbon disposition include energy use and emissions to the atmosphere. We assume biomass C loss = 100% if it is not in the end-use or landfill categories. Source: Table 1.6 in U.S. Department of Energy (*S43*). We assumed the end-use patterns of wood products in Canada is similar to those in the US.

5. Land Use GHG Intensity

We combine land disturbance intensity *I* (Sections 2 and 3) with the carbon change from land disturbance C_{LU} (Section 4) to get the GHG intensity associated with land disturbance (CI_{LU}). We examine both historical and marginal production of conventional oil in our analyses. The production from oil sands surface mining and *in situ* recovery can be considered marginal as the technologies and reserves are relatively young when compared with conventional production.

Figure S4 illustrates the distribution of historical GHG emission intensity by oil field in California, calculated by multiplying the number of wells per field and the average GHG emissions from land disturbance per well, plotted both by number of fields and by amount of oil production.

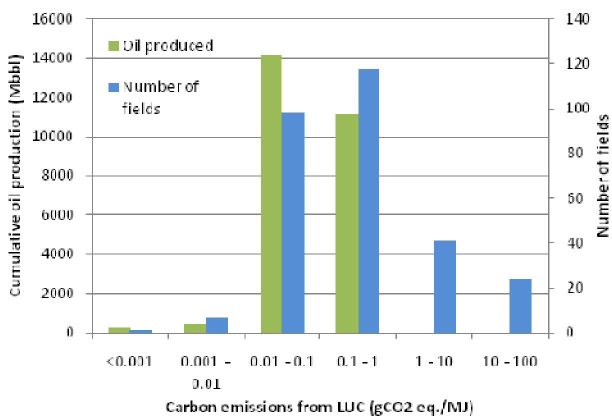

Figure S4. Distribution of historical land use GHG emissions for California oil production. Two bin types are used in histogram: number of fields with a given amount of emissions, and quantity of oil produced with the given amount of emissions.

6. Sensitivity Analysis

We examine sensitivity analysis of 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. Table S9 shows results of land use GHG intensity from oil sands mining (Cases (1) and (3)).

Table S9. Sensitivity analysis of land use GHG intensity and net soil C loss from oil sands mining.

	Land Use GHG Intensity ($g\ CO_2e$/MJ crude oil)			Net Soil C Loss
	Best	Low	High	(t C/ha)
Base Case	4.0	0.8	10.2	312 (246-357)
100% Peatland	6.4	2.5	14.4	933 (788-1055)
0% Peatland	3.2	0.3	9.0	127 (83-149)
No CH_4 emissions and dry landscape reclamation	1.2	0.7	2.1	300 (225-345)

Upstream natural gas use can also increase land-related greenhouse gas emissions for some technologies. Crude recovery, bitumen production, processing and upgrading to SCO all use natural gas for heating water to extract the bitumen, generating heat and producing hydrogen for upgrading and refining. When the land disturbance of upstream natural gas production is included, total disturbance of unconventional oil extraction and production can increase by 26 percent and 210 percent for surface mining and *in situ* production respectively (*S8, 47*). This increases the land use GHG emissions of in situ recovery by up to 145% (to a total of 0.18 (0.02–0.40) g CO_2e/MJ SCO) if we assume a grassland landscape where the highest number of natural gas wells in Alberta are found (*S8*). Depending on the design flexibility of a syncrude facility, natural gas consumption for syncrude production may be reduced by replacing natural gas with produced bitumen or petroleum coke (*S48*). Although this displacement would reduce the land use intensity of *in situ* production (less natural gas used), the CO_2 emissions are likely to increase (increased use of bitumen or petroleum coke). In California, ≈40 percent of crude is produced using thermal enhanced oil recovery (TEOR) methods, which use steam injection to recover heavier oil products. The amount of natural gas used for TEOR is similar to that for *in situ* production.

Net Emission versus Ton-Years Calculation

Net emissions are calculated by summing carbon release and sequestration activities over time within the modeling period of 150 years. If we would like to capture a plausible proxy for the total damage to the planet from the CO_2 emissions stream over a finite analytic/policy horizon, t_a, we can use a tonne-year approach to determine the relative climate effect of different emissions profiles over time as suggested by the IPCC (*S49, 50*). One method is to calculate the net effect of carbon released based on a reduced form of the carbon cycle model used to calculate Global Warming Potentials in the Second Assessment Report (*S19*). Physically speaking, once carbon is released to the atmosphere, it is subject to removal through natural processes. Carbon can be transferred to sinks such as oceans and the biosphere but it can remain in the atmosphere for a very long period of time. As illustrated in the IPCC LULUCF, 1 t CO_2 released to the atmosphere will result in atmospheric burden of 46 tonne-years within the 100-year time horizon.[3] Thus the climate burden (cumulative CO2-C loading) of 1 t C release in year 1 will have a cumulative C loading of 61 tonne-years over a 150 analytic year compared to -46 tonne-years for 1 t C re-sequestered in year 50. Thus instead of a net impact of zero (1 t C + (-1 t C), 100% removal), the result is an increase in atmospheric burden of 15 tonne-years (61 + (-46) tonne-years, 75% removal) (*S19*). Using this approach, carbon emissions and removals in earlier time period are assigned higher "weights" when compared with emissions/removals that occur at later time period. Using this tonne-year approach, we recalculate the "net atmospheric burdens" of the different streams of emissions and removals occurring at different time during the modeling period in the surface mining case shown in Table 2 of the main text, and found a higher net atmospheric burden of 87.2% by the end of 150-years (Figure S5b) compared with 79.6% using a straight forward approach that does not take tonne-year into account (Figure S3a).

[3] This method is discussed in detail in the IPCC LULUC Special Report Chapter 2.3.6.3 Equivalence Time and Ton-Years. The decay function is the approximation of the output of the Bern model version used (but not published) in the SAR is given by:

$$F[CO2(t)] = 0.175602 + 0.137467 \exp(-t/421.093) + 0.185762 \exp(-t/70.5965) + 0.242302 \exp(-t/21.42165) + 0.258868 \exp(-t/3.41537)$$

where F is the fraction of CO2 remaining in the atmosphere and t is the time after emission in years.

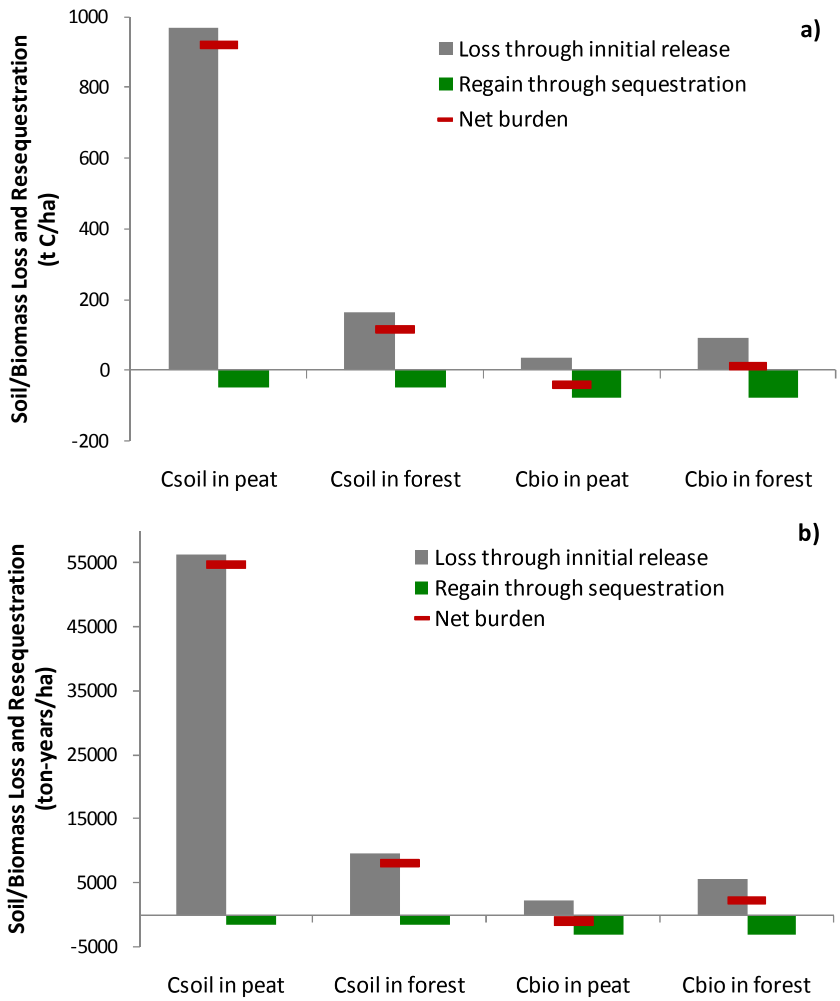

Figure S5. Comparison of calculations capturing the net effect from activities that release and sequester carbon at different time period using a net emission accounting system (a) versus a tonne-year system (b) (*S19*) converting C-fluxes to concentrations using Bern impulse-response model, integrated without discounting over 150 years with infinite discounting after that. The example shown here is oil sands surface mining scenario using median values shown in Table 2 (foregone sequestration and tailings emissions are ignored here. Carbon sequestration in HWP is not considered in this example).

7. Comparison of Direct Land Use Emissions with Biofuels

To compare the direct land use emissions of biofuel with fossil fuels, we estimate the direct land use emissions of biofuel for continuous cultivation over 50 years:

Table S10. Carbon stock changes and emissions from land conversion for biofuel production. Data based on Fargoine et al. (2008) SOM.

			(t CO_2e/ha)	(MJ/ha/yr)	(PJ/ha)	g CO_2e/MJ
Palm biodeisel	Tropical rainforest	Indonesia/Malaysia	702	124500	0.0062	112.8
Palm biodeisel	Peatland rainforest	Indonesia/Malaysia	3452	124500	0.0062	554.5
Soybean biodiesel	Tropical rainforest	Brazil	737	17770	0.0009	829.4
Sugarcane	Cerrado wooded	Brazil	165	118200	0.0059	27.9
Soybean biodiesel	Cerrado grassland	Brazil	85	17770	0.0009	95.7
Corn ethanol	Central grassland	US	134	76360	0.0038	35.1
Corn ethanol	Abandoned cropland	US	69	76360	0.0038	18.1

Based on Fargione et al, (2008), converting tropical peatland rainforest to palm production causes an additional sustained emission of ~55 Mg of CO_2 /ha/yr from oxidative peat decomposition, resulting biofuel carbon debt of ~3000 Mg of CO_2/ha after 50 years.

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