Oil sands mining and reclamation cause massive loss of peatland and stored carbon

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We quantified the wholesale transformation of the boreal landscape by open-pit oil sands mining in Alberta, Canada to evaluate its effect on carbon storage and sequestration. Contrary to claims made in the media, peatland destroyed by open-pit mining will not be restored. Current plans dictate its replacement with upland forest and tailings storage lakes, amounting to the destruction of over 29,500 ha of peatland habitat. Landscape changes caused by currently approved mines will release between 11.4 and 47.3 million metric tons of stored carbon and will reduce carbon sequestration potential by 5,734–7,241 metric tons C/y. These losses have not previously been quantified, and should be included with the already high estimates of carbon emissions from oil sands mining and bitumen upgrading. A fair evaluation of the costs and benefits of oil sands mining requires a rigorous assessment of impacts on natural capital and ecosystem services.

wetland reclamation | tar sands

An area larger than the state of Rhode Island will eventually be mined by oil sands companies in northern Alberta. These boreal lands must be reclaimed, but despite claims to the contrary (1), operators are not required to return the land to its original state (2). This study was precipitated by the disparity between statements made by the oil sands industry regarding the extent and anticipated success of mine reclamation and their official closure plans, which serve as agreements between mine operators and the Alberta government regarding actual reclamation expectations.

Oil sands deposits accessible by open-pit surface mining cover about 475,000 ha of boreal Alberta, 99% of which is already leased (3). Currently, 10 mines have government approval to operate, covering about 167,044 ha (Fig. 1). This is a conservative estimate that excludes the pipelines, roads, seismic lines, and other infrastructure that support the mines. It also excludes impacts from aerial deposition (4) and aquifer dewatering (5) that extend off-site and the area of land associated with the three additional mines currently undergoing environmental review.

Constraints imposed by the postmining landscape and the sensitivity of peatland vegetation prevent the restoration of peatlands that dominated the premining landscape. Mine proponents are required to describe the premining landscape and produce closure plans that detail the postmining landscape. Current reclamation regulations do not require the restoration of previous land covers or the restitution of lost carbon formerly stored in soils and vegetation. In place of destroyed peatlands, operators plan to construct upland forest with well-defined drainage channels and subsaline shallow open water wetlands draining into large tailings ponds capped with freshwater. The net effect of this landscape transformation on biodiversity and ecosystem functions has not been assessed. Here we quantify the land cover changes that will result from approved oil sands mine projects and their impact on carbon storage.

Pre- Versus Postmining Landscapes

The oil sands mining area was originally wetland-rich, covered in forested and shrubby fens. In 2002, Canadian Natural Resources Ltd. mapped vegetation cover types within a 2,277,376-ha area that encompasses the surface-mineable area (Fig. 1) (details in ref. 6). They found that 64% of the land supported wetland vegetation, whereas only 23% of the land supported upland vegetation (Table 1). The most common land cover type was fen vegetation, whereas deep water, shallow open water, and marsh habitat were scarce (Table 1). Due to the heterogeneous distribution of wetlands in the region, the exact proportion of wetland habitat differs among the 10 approved mining projects (Table 2). Generally, the east bank of the Athabasca River supports more wetland habitat than the drier west bank (Fig. 1 and Table 2).

Despite efforts to standardize industry reporting (*SI Text*), many inconsistencies remain that impede assessment of cumulative effects and direct comparison between pre- and postmining landscapes. For example, the taxonomic and spatial resolutions used to make predictions about the postmining landscape are coarser than those detailing baseline conditions, mainly due to difficulty in predicting drainage and nutrient conditions.

A direct comparison of pre- and postmining landscapes is only possible for 4 of the 10 approved mines: The Horizon, Jackpine–Phase 1, Muskeg, and Kearl mine closure plans provided the relative abundance of pre- and postmining vegetation cover (7–10) (Table 3 and Table S1). These four mines represent only 42% of the area approved for mining, although they are representative in their distribution: 59% on the wetter east bank and 41% on the drier west bank, compared with 61% and 39% of the total leased area approved for mining on the east and west banks, respectively. Suncor Energy Inc. and Syncrude Canada Inc. did not provide data on the relative abundance of vegetation covers for the six mines they operate, but did provide figures contrasting the pre- and postmining landscapes (e.g., Fig. 1 and Fig. S1). Thus, although we cannot quantify changes to land cover across the entire region, we can make generalizations about vegetation changes with confidence that they apply to all mines.

The most striking change to result from reclamation will be the conversion of wetland habitat to upland forest. According to company closure plans, uplands will increase by 15,030 ha on the leaseholds of the four mines, mainly at the expense of peatlands, which will decrease by 12,414 ha (67% of their premining coverage). Wetlands in general will decrease by 11,761 ha, with the loss of peatlands slightly offset by the creation of marsh and riparian shrublands (Table 3). Operators will create end-pit lakes by capping tailings ponds with freshwater (*SI Text*), boosting the amount of deep water and littoral habitat (Table 3). End-pit lakes will be fed by extensive drainage networks (e.g., Fig. 1) that may support riparian habitat (Table 3). Scaling up, assuming similar land conversion ratios for the additional six mines, about 29,555 ha of peatlands will be lost as a result of currently approved mining (net wetland loss = 28,002 ha).

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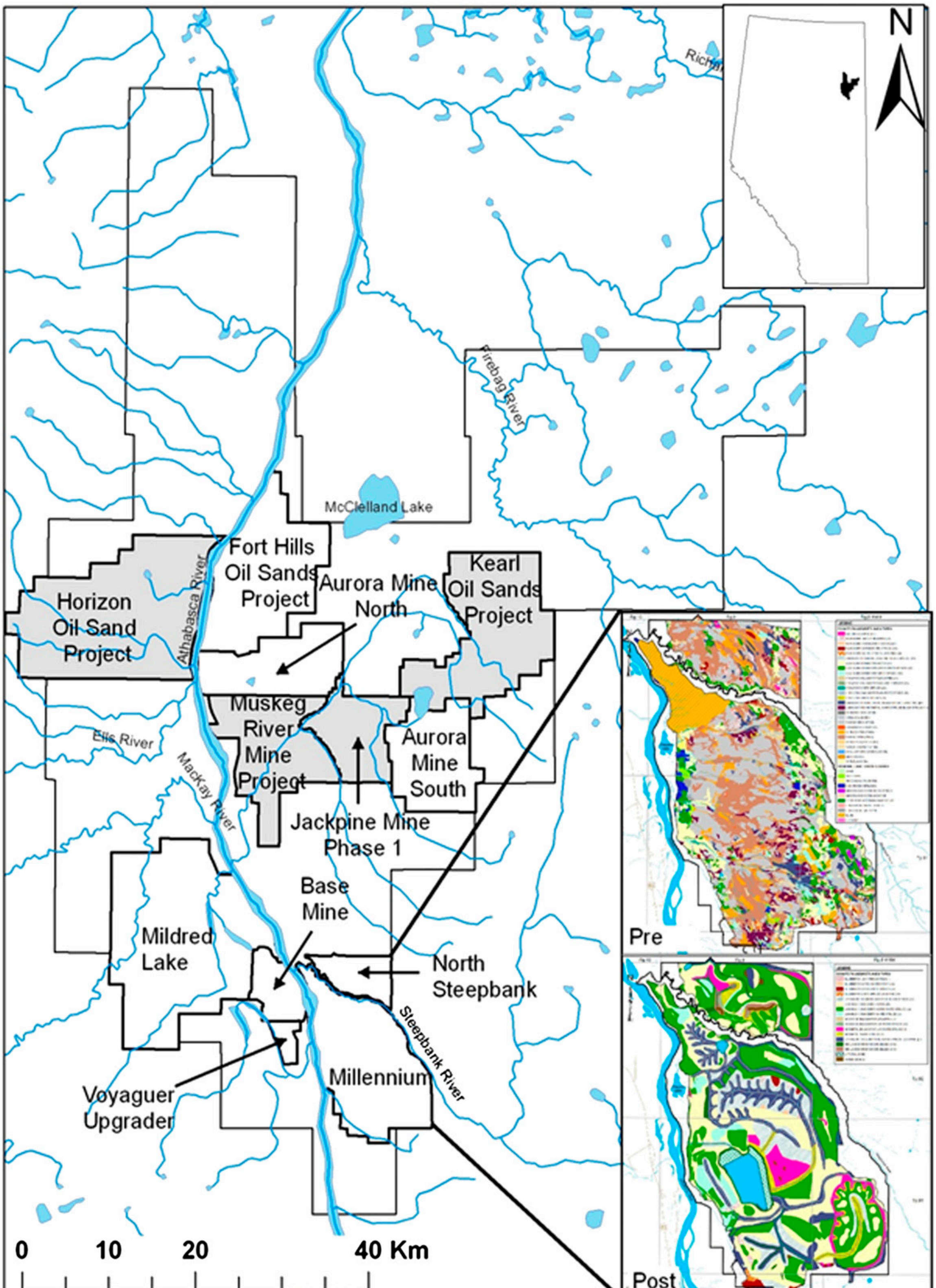

Fig. 1. Map of the surface-mineable area and the footprints of oil sands mining projects with approval to operate as of March 2011. Data are adapted from the Energy Resources Conservation Board's online Scheme Approval Map Viewer. Gray lease areas are included in our detailed comparison of pre- and postmining land cover. Short arrows connect labels to smaller lease areas. (*Insets* titled Suncor 2009) Pre- and postmining land cover for the Millenium and North Steepbank mines, adapted from Suncor (11). An expanded version of the *Insets* is available as Fig. S1.

Table 1. Vegetation cover within and surrounding the surface mineable oil sands area.

Land cover class	Total area (ha)	Regional study area (%)
Terrestrial vegetation		
Coniferous	25,309	1
Deciduous	273,050	12
Mixedwood	217,990	10
Terrestrial vegetation subtotal	516,349	23
Water		
Deep water (>2 m)	13,352	1
Shallow open water (<2 m)	27,728	1
Water subtotal	41,080	2
Wetlands		
Graminoid fen	61,395	3
Marsh	41,320	2
Poor wooded fen/wooded bog	187,349	8
Shrubby fen	231,109	10
Wooded fen	923,895	41
Wetlands subtotal	1,445,068	64
Other		
Burn (within 20 y)	144,227	6
Cloud	25	<1
Cutblocks	57,648	3
Disturbances	63,492	3
Shrubland	8,619	<1
Urban/industrial	868	<1
Other subtotal	274,879	12
Total	2,277,376	100

Data are adapted from table B3-2 in Raine et al. (6).

In terms of the vegetation, reclamation will mean the replacement of low-productivity tamarack (*Larix larcina*) and black spruce (*Picea mariana*) fens and bogs with higher-productivity forests of white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), and trembling aspen (*Populus tremuloides*). Understory vegetation will change from sedges, ericaceous plants such as labrador tea (*Ledum groenlandicum*), and mosses such as *Sphagnum* spp. and *Drepanocladus* spp. (which can deposit up to several meters of peat) to blueberry (*Vaccinium myrtilloides*), dogwood (*Cornus* spp.), and low-bush cranberry (*Viburnum edule*) (which accumulate much less carbon in the soil). Reclamation will also mean a shift in age structure, as reclaimed forests will begin as seedlings and will take 50–70 y to reach harvestable age (11). The shift to a drier forest will also mean a change in fire regime, as drier forest types are more susceptible to fire (12) and thus support younger stands than wetter forests on average.

Impediments to Wetland Restoration

There are several reasons closure plans favor the creation of well-drained habitat over wetlands (e.g., 8, 11). First, Alberta has no wetland policy requiring compensation for wetland loss in the boreal region. Second, because the volume of tailings and upgrading by-products exceeds the size of mine pits, the closure landscapes will consist of hills instead of the level topography that dominated the region before mining. Thus, wetlands will be restricted to the depressions between hills and surrounding end-pit lakes (e.g., Fig. 1, *Inset*). Third, to foster geotechnical stability, the closure landscapes are channelized to drain quickly (e.g., Fig. 1, *Inset*). Creating wetland habitat that slows the flow of water can result in soil saturation, gully formation, and landform collapse (13). Fourth, end-pit lakes are designed to remediate tailings water (*SI Text*), and extensive wetlands would increase the evaporative surface area of the closure landscape, reducing end-pit lake function. Given that precipitation is less than potential evapotranspiration in the oil sands-mineable area, water availability will limit wetland area in the reclaimed landscape.

No closure plan calls for the restoration of lost peatlands (7–9, 11, 14). Cattails and other marsh plants may tolerate the salt, metals, and naphthenic acids present in groundwater and surface runoff in reclaimed areas (15), but peatland vegetation is very sensitive to high conductivity and ion concentrations (16). Two pilot fen construction projects are under way to study survival of fen species in a tailings-contaminated environment and the capacity of reclamation materials to support fen-type hydrology. Recreating fen-type hydrology in the postmining landscape is possible, but requires a minimum 2:1 upland to peatland ratio for uplands to supply adequate seepage to maintain peat wetness (17). Thus, even if the entire closure landscape were designed to maximize fen habitat, it could not recreate the area of fens that was lost. Other considerations, such as the need for end-pit lakes and the limited availability of suitable substrate and vegetation (e.g., pilot fens were constructed by transfer of live peat from natural fens), ensure that constructed fens will only constitute a small fraction of the postmining landscape.

Implications

No large-scale oil sands reclamation project has undergone independent evaluation, and thus the ultimate success of closure plans remains uncertain (18). Upland habitat has been created (e.g., the 104 ha of Syncrude's Gateway Hill certified as reclaimed in 2008, representing 0.15% of land reported as disturbed by industry), but efforts to create marsh and shallow open water wetlands are less successful at restoring biological integrity (19, 20). Even if the goals outlined in closure plans are achieved, peatland loss will occur with substantial impacts to ecosystem services, including carbon storage.

Oil sands mining is frequently criticized as a carbon-intensive means of acquiring oil. Its contribution to the global carbon imbalance has provoked numerous calls to slow oil sands development, including, most recently, a letter to Canada's prime minister signed by eight Nobel Peace Laureates. Greenhouse gas emissions from mining and upgrading oil sands bitumen are

Table 2. Summary of baseline vegetation cover within the development (DA) or local study areas (LSA) of mines with approval to operate granted by March, 2011

	Horizon mine	Mildred Lake and expansion	Suncor Basemine	Muskeg and expansion	Jackpine mine–phase 1	Kearl mine	Suncor Steepbank and Millenium mines	Fort Hills mine	Aurora North mine
Bank	West	West	West	West	East	East	East	East	East
Units	ha in LSA	ha in LSA	ha in LSA	ha in LSA	ha in DA	ha in LSA	ha in DA	ha in DA	ha in LSA
Terrestrial vegetation	17,040	14,662	16,745	2,775	4,408	15,416	2,806	3,350	17,733
Peatlands	5,355	1,870	16,813	3,075	1	9,986	6,422	751	19,714
Riparian communities	2,600	708	0	1,216	1,434	7,804	100	1,012	199
Graminoid marsh	318	0	0	36	523	1	19	6	435
Shallow open water	332	175	61	61	21	42	8	0	249
Wetlands subtotal	8,605	2,753	16,874	4,388	1,979	17,833	6,549	1,769	20,597
Lakes and rivers	267	175	61	43	1,359	561	0	0	580
Disturbed land	1,874	909	1,300	5,270	38	206	0	419	1,197
Total	27,786	18,499	34,980	12,476	7,784	34,016	9,355	5,538	40,107
% wetland	31	15	48	35	25	52	70	32	51
% terrestrial	61	79	48	22	57	45	30	60	44

The west bank is typically drier and supports more upland habitat relative to the east bank, which supports more wetland habitat. As a part of their environmental impact assessments (EIAs), mine operators designate DAs, which represent the footprint of all facilities directly associated with mining, i.e., mine pits, tailings storage, bitumen recovery plants, etc., and LSAs, which include both the DA and a buffer around the DA that is intended to accommodate any potential indirect effects of the proposed development. Baseline conditions are typically presented for either the DA or LSA, but not for both. The vegetation cover values were obtained through a review of baseline studies in EIAs and the most recently updated reclamation, conservation, and closure plans (see *SI Text* for references).

estimated at between 62 and 164 kg CO_2 equivalents per barrel of oil produced, two to three times more than emissions from conventional oil production (21). With daily production of mined bitumen exceeding 1,142,000 barrels in 2010 (22), emissions add up quickly (>70,000 t CO_2/d) and hundreds of millions of dollars are being invested in reducing and capturing CO_2 (23). These tallies, however, completely neglect the carbon emissions resulting from peatland loss, yet our analysis suggests that carbon storage loss caused by peatland conversion could be equivalent to 7-y worth of carbon emissions by mining and upgrading (at 2010 levels).

The boreal forest is the world's largest and most important forest carbon storehouse (24), but its continued storage depends on future land management practices (*SI Text*). Based on extensive work in the Mackenzie River Basin, the range in peatland carbon storage is estimated at 530–1,650 metric tons (t) C/ha (25), equivalent to 1,943–6,050 t CO_2/ha. The breadth of this range reflects uncertainties associated with variability in peat depth, composition, and bulk density. Unfortunately, this information is not available from baseline studies, and we therefore chose to be conservative and represent the effects of this uncertainty on the range of C values. Reclamation prescriptions for postmining soils

Table 3. Net change in land cover types to result from oil sands mining reclamation based on baseline reports and closure plans for the Horizon, Jackpine–Phase 1, Kearl, and Muskeg mines

Description	Total pre (ha)	Total post (ha)	Net change (ha)	Net change (%)
Upland forest	39,114	54,587	15,473	40
Meadow	1	0	−1	−100
Shrubland	524	82	−442	−84
Bog	5,179	1,320	−3,859	−75
Fen	13,238	4,683	−8,555	−65
Graminoid marsh	878	2,595	1,717	196
Swamp	13,054	9,795	−3,259	−25
Shallow open water	456	94	−362	−79
Lake	2,059	5,702	3,643	177
River	171	152	−19	−11
Riparian shrubland	1	2,327	2,326	232,600
Littoral zone	0	230	230	Infinite
Clearcut	730	98	−632	−87
Disturbance	6,658	395	−6,263	−94
Peatland subtotal (bog and fen)	18,417	6,003	−12,414	−67
Wetland subtotal (peatland, graminoid marsh, swamp, shallow open water, riparian shrubland, and littoral zone)	32,806	21,045	−11,761	−36
Total	82,060	82,060	0	0

This constitutes 42% of the total area approved for mining as of March 2011, but is a representative sample of the region in terms of east and west bank distribution.

contain much less carbon: between 50 and 146 t C/ha (26). Thus, the replacement of 12,414 ha of peatlands with reclaimed soils will result in the loss of 4.8–19.9 million t of stored carbon. Based on the carbon value estimated by the Intergovernmental Panel on Climate Change at $52/t of carbon sequestered (27), this equates to a $248 million to $1 billion loss of natural capital, yet we have only considered 42% of the area currently approved for mining. Scaling up, as we did with land cover, a loss of between 11.4 and 47.3 million t of stored carbon (between $590 million and $2.5 billion of carbon storage capital) will occur. Converting from units of carbon to CO_2 equivalents, this is between 41.8 and 173.4 t of CO_2 lost, as much as 7-y worth of mining and upgrading emissions at 2010 production levels.

Peatland loss will also influence the region's potential to sequester carbon in the future. Vitt et al. (28) estimated that western continental peatlands sequester 19.4 g C/m^2 of peatland/y. Accounting for forest fires, Turetsky et al. (29) suggest that the true rate of carbon sequestration is 24.5 g C/m^2 of peatland/y. Thus, the loss of 12,414 ha of peatland translates into 2,408–3,041 t of annual carbon sequestration potential. Scaling up, as with carbon storage, this equates to 5,734–7,241 t C/y (21,025–26,550 t CO_2/y) lost due to approved mines. The reclaimed landscape will sequester carbon at a much lower rate (28), determined by complex interactions between plant species (and the chemical composition of their litter), climate, soils, management, and the fire regime (30). Looking at Imperial Oil's Kearl Lake mine, Welham found that the vast majority of carbon sequestered in the reclaimed landscape was derived from peat amendments made to the soil during the first stages of reclamation (31). Given that the peat used in these amendments is obtained by stripping and stockpiling peat from adjacent land in preparation for mining, this fraction is actually residual storage from historical peatlands, not newly sequestered carbon. Additionally, Turcotte's study of soil organic matter in reclaimed land on oil sands mine leases has demonstrated unexpectedly rapid decomposition of the peat in soil amendments, even the relatively recalcitrant lignin phenols (32). This suggests that conversion of peatlands to uplands with peat soil amendments transforms a relatively permanent carbon storage pool (historical peatlands) to a temporary one that leaks carbon rather than sequesters it. This is supported by Welham's model, which predicts that reclaimed forests will require 15 y of growth before carbon sequestration by vegetation begins to exceed the carbon emissions from decomposing peat amendments, suggesting that for years following mining and reclamation, reclaimed land will be a net carbon source (31).

Conclusion

Claims by industry that they will "return the land we use - including reclaiming tailings ponds - to a sustainable landscape that is equal to or better than how we found it" (33) and that it "will be replanted with the same trees and plants and formed into habitat for the same species" (34) are clearly greenwashing. The postmining landscape will support >65% less peatland. One consequence of this transformation is a dramatic loss of carbon storage and sequestration potential, the cost of which has not been factored into land-use decisions. To fairly evaluate the costs and benefits of oil sands mining in Alberta, impacts on natural capital and ecosystem services must be rigorously assessed.

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